

An Integrated Modeling Scheme for Sensor Embedded Woven Composite Structures in Manufacturing Simulation

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Abstract

This work focuses on an integrated modeling scheme of a sensor embedded woven composite structure which is created for the joint project “Digitaler Fingerabdruck” (DFA) or in English: “Digital Fingerprint” within the research campus ARENA2036 [4]. The process chain includes a draping simulation of a woven fabric and a trimming simulation using LS-DYNA®, optimization of a tailored-fiber placement process on top of this woven fabric structure using Optistruct®, fiber direction mapping from weaving simulation results using beam elements to shell element target meshes and handling of reinforcing patches using the mapping tool Envyo® [5]. The final goal is to establish an integrated process chain with parametrized variables using LS-OPT® for robustness analysis. A new feature of ***MAT_REINFORCED_THERMOPLASTIC (*MAT_249)** is also demonstrated to introduce fiber directions as an integration point history variable in global coordinate system to the subsequent simulations [7].

The modeling scheme is designed to integrate sensor data and to demonstrate the initial steps to an enhanced digital twin. Furthermore, respective developments of Envyo to realize the scheme by coupling consecutive simulation steps are presented. An overview of the virtual process chain and some detailed information about the methods are provided.

1 Introduction

Sensor embedded composite structures and structural health monitoring have been an interesting research topic in the recent past. Embedded sensors can provide an insight into the structure’s condition during its lifetime – from manufacturing to usage in the field and may help to plan the frequency of required maintenance operations [1,2,3]. Moreover, the acquired data can be combined with a digital twin of the structure using recent developments in Computer Aided Engineering (CAE).

Since flexibility and cost-effective solutions of CAE are essential for all industrial approaches, predicting capabilities, model scales and the size of manageable complexity have been improved. Almost every individual step of the life cycle of a product can be modeled, 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* [9]. Maximizing the utilization of the potential of a digital twin concept is a challenging task and requires strong collaboration of different industrial branches.

In this paper, the fundamental idea is to establish a virtual simulation chain that includes all performed simulation steps from preliminary design to final component evaluation, integrates and transfers the data between different simulation disciplines, compares different possibilities to optimize the component manufacturing process and the component itself considering all relevant sensor data acquired during the component’s lifetime to enrich the digital twin with real-life information. LS-DYNA, LS-OPT, the mapping tool Envyo and Optistruct are used to realize an integrated modeling scheme of a sensor embedded woven composite structure on a macroscopic scale (as it is displayed in fig. 1).

In following section, the preliminary work done during the research project Digital Prototype (DigitPro) is introduced shortly since DFA is the consecutive project of DigitPro. Therefore, results from DigitPro can be used in the DFA. Section 3 describes the virtual modelling scheme established within the DFA. Software couplings, mapping solutions and the process chain properties are discussed. The target

simulation process chain is shown in Fig. 1, whereas the focus in this work is on the steps one to five. In section 4, the parameterized setup for LS-OPT is explained and in section 5, the results are evaluated. Finally, the paper is concluded, and some future improvements are proposed.

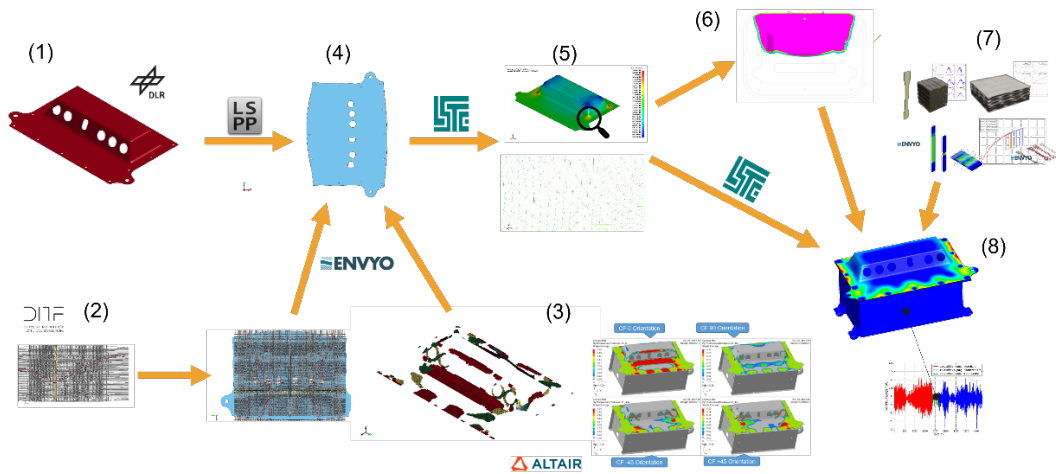


Fig.1: A final virtual process chain with an integrated sensor for a fiber reinforced plastic component.

2 Preliminary Work: DigitPro

In the first phase of the research campus ARENA2036, the project DigitPro dealt with the development of a closed simulation chain for the simulation of braided structures from manufacturing to impact loading across different length scales. Further enhancements of the mapping software Envyo allowed for the coupling of manufacturing simulation results from draping, braiding and infiltration simulation generated by different solvers and structural simulations, using a neutral HDF5 data container. The mapping of local data such as fiber orientation, matrix regions, and thicknesses increased the predictability of the following structural analysis, also considering material data derived from virtual testing procedures [11].

The follow-up project “Digital Fingerprint” benefits directly from these mapping methods and from the knowledge gained in DigitPro and therefore aims for the extension of the process chain with regards to sizing and the consideration of sensor-embedded woven composite structures. Through the comparison of simulation results and on-board data collected with these sensors, the process chain shall be adapted and modify the structure in an intelligent manner to optimize its potential and to allow for predictive maintenance.

3 Established simulation process chain

In this section, the steps of the established simulation process chain will be discussed one by one. The enhanced mapping and interoperability capabilities of Envyo will be demonstrated. The process chain is realized as LS-OPT robustness analysis to benefit from the automated file manipulations, variable definitions, and the evaluation abilities. The process chain consists of nine steps. It starts with a sensor integrated woven fabric modeled with beam and shell elements and ends with an elastic 3-point bending simulation as an exemplary structural simulation.

3.1 Initializing fiber directions on shell element mesh

A sensor integrated flat woven fabric modeled with beam elements is the starting point of the process chain and the sensor band structure inside the woven fabric is represented by shell elements. Fiber directions oriented in 0° and 90° with respect to the main direction are represented by beam elements, considering typical undulations observed in fabric materials due to the weaving process. These characteristics represented in meso- or micro-scale models need to be transferred to macro scale models to increase accuracy.

The main mapping option used is called **ENVYO=BEAM-SHELL**, which indicates that the finite element (FE) data is mapped from a beam element source mesh to a shell element target mesh. Independent from the mapping goals, a good geometrical match is essential for an accurate mapping result. Thus, necessary mesh transformation options were declared.

Since the woven fabric for the subsequent draping analysis should be represented by a shell element mesh, undulations cannot be represented by the mesh anymore. Partially, the undulation effect can be modeled using the ***ELEMENT_SHELL_COMPOSITE** keyword. The advantage of this keyword is that each through thickness integration point (IP) can have a different thickness, material ID, and orientation to account for the varying upper and lower fiber bundles transferred onto each element. Since fiber interactions and fiber shearing should also be considered, ***MAT_249** is selected as target material model. It is an anisotropic hyper-elastic material model that supports up to three distinguished fiber directions per IP. The new **IHS=1** feature of this material model provides the possibility to initialize fiber directions in the global coordinate system using IP history variables in the ***INITIAL_STRESS_SHELL** keyword. The number of through thickness and in-plane IPs should be known to generate the correct ***INITIAL_STRESS_SHELL** data for each element. Four in-plane and five through thickness IPs are used in the presented simulations.

To account for inaccuracies during manufacturing, the influence of small rotations of the source mesh about the z-axis on the overall behavior shall be investigated. Since the source beam mesh is a repeating representation of representative volume elements (RVE), it is extended to cover the target shell mesh so that an accurate mapping is possible for the range of considered rotation angles.

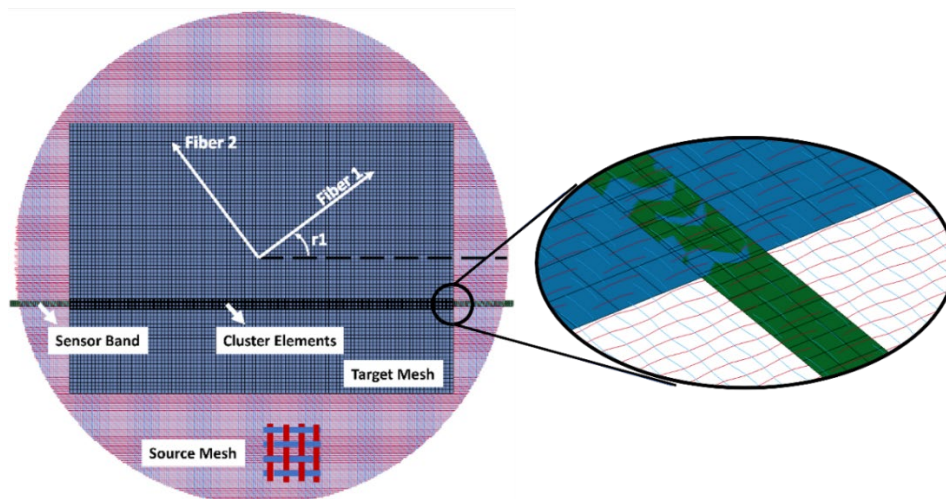


Fig.2: Illustration of parametrized angle r_1 and beam mesh with embedded sensor. The target shell mesh is colored in blue.

The sensor band can be mapped onto the target mesh using a clustering method which is realized with the *equation parser* implementation in Envyo. Respective target mesh element layer material IDs are modified to distinguish between these elements. It is assumed that the sensor band has an isotropic material behavior. Thus, ***MAT_249** properties are modified to handle both fabric and sensor band behavior.

3.2 Draping simulation using BEAM-SHELL mapping result

After mapping the beam source mesh data onto the shell mesh, a draping simulation can be performed to predict the local orientations in the final geometry. The woven fabric is modeled as 420x296 mm² rectangular mesh and discretized using quadrilateral fully integrated shell elements with 4 mm element length and it is positioned between an upper and a lower mold, as illustrated in Fig. 3. The upper and lower molds are modeled with ***ELEMENT_TSHELL**. Depending on the real boundary conditions, a holder plate can be introduced to the FE-model to clamp or pretension the textile and therefore reduce potential manufacturing defects.

The fiber directions are initialized according to ***MAT_249 IHIS=1** option. ***MAT_249** supports up to three distinguished fiber directions on a single IP, where shearing between fibers is also considered [7].

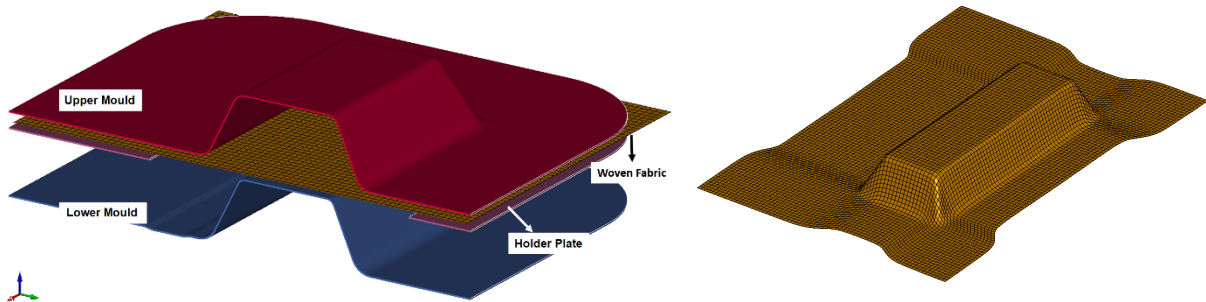


Fig.3: Section view of the draping simulation setup (left) and woven fabric after the draping simulation (right).

Due to the nature of the process, fiber directions will be re-arranged according to element deformations. Since composite materials have an anisotropic material response, element fiber directions in deformed configuration should be mapped onto the consecutive simulation mesh to increase accuracy.

3.3 Introducing reinforcement patches according to optimization simulation onto draping simulation mesh – Patch Handling

An optimization of the woven plies and additional reinforcing tailored fiber placement (TFP) patches has been performed by Altair using the software Optistruct [10]. The process will not be explained in detail in the present paper, but the results are used as an external input to the process chain. The reinforcement patches in 0° , $\pm 45^\circ$ and 90° directions are exported from Optistruct to LS-DYNA format. Since the patches are optimized on the final structure geometry, it is necessary to determine their directions in undeformed configuration to apply them on the flat fabric prior to the draping process.

To do so, three different mesh files can be defined in the Envyo command file:

- *Undeformed mesh file*, BEAM-SHELL mapping result in initial geometry (see Sec. 3.1)
- *Deformed mesh file*, draping simulation result using BEAM-SHELL mapping result file in deformed geometry (see Sec. 3.2)
- *Designed mesh file*, the optimization result from Optistruct, deformed geometry

The undeformed and deformed mesh files are required to compute the deformation gradient and to pull fiber direction vectors back in the reference configuration. The deformed mesh file from the draping simulation and the mesh file from the optimization simulation are used to find relevant source mesh elements to apply reinforcing patches which have been determined by the optimization. The main mapping option for this case is called **ENVYO=PLYBOOK-SHELL**. This option activates the required routines to handle reinforcement patches.

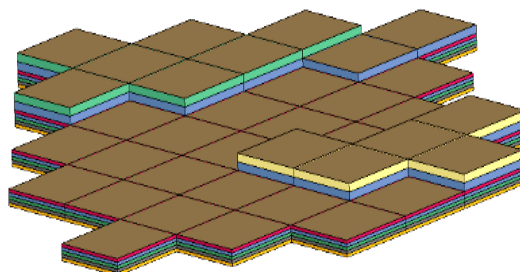


Fig.4: Shell elements thickness plot using **FLAT_LOWER** option.

Reinforcing patch files contain only a portion of the designed mesh and the user may assign a reinforcing direction and thickness to each patch for the mapping operations. The reinforcing direction is altered by

the user defined angle with respect to the user defined global zero direction. The patch angle and the patch thickness can be defined as LS-OPT variables inside the mapping command file as follows:

```
REINFORCEPATCH#1=Reinforce_0_dyn;2001;<<patch_1_angle:0>>;<<patch_1_thick:0>>
```

As in Sec. 3.1, composite shell elements are generated. The user needs to ensure that the reinforcing patches are stacked on top of each other. To obtain such a fabric with a flat bottom surface, **OFFSET_OPTION=FLAT_LOWER** is defined. This option assigns an offset to shell elements to generate a flat bottom surface as can be seen in Fig. 4. As explained in Sec. 3.1, the fiber directions are handled according to ***MAT_249 IHIS=1** option. An overview of the patch handling process, effects of the reinforcement patches on element thicknesses and patch fiber directions in reference configuration can be seen in Fig. 5.

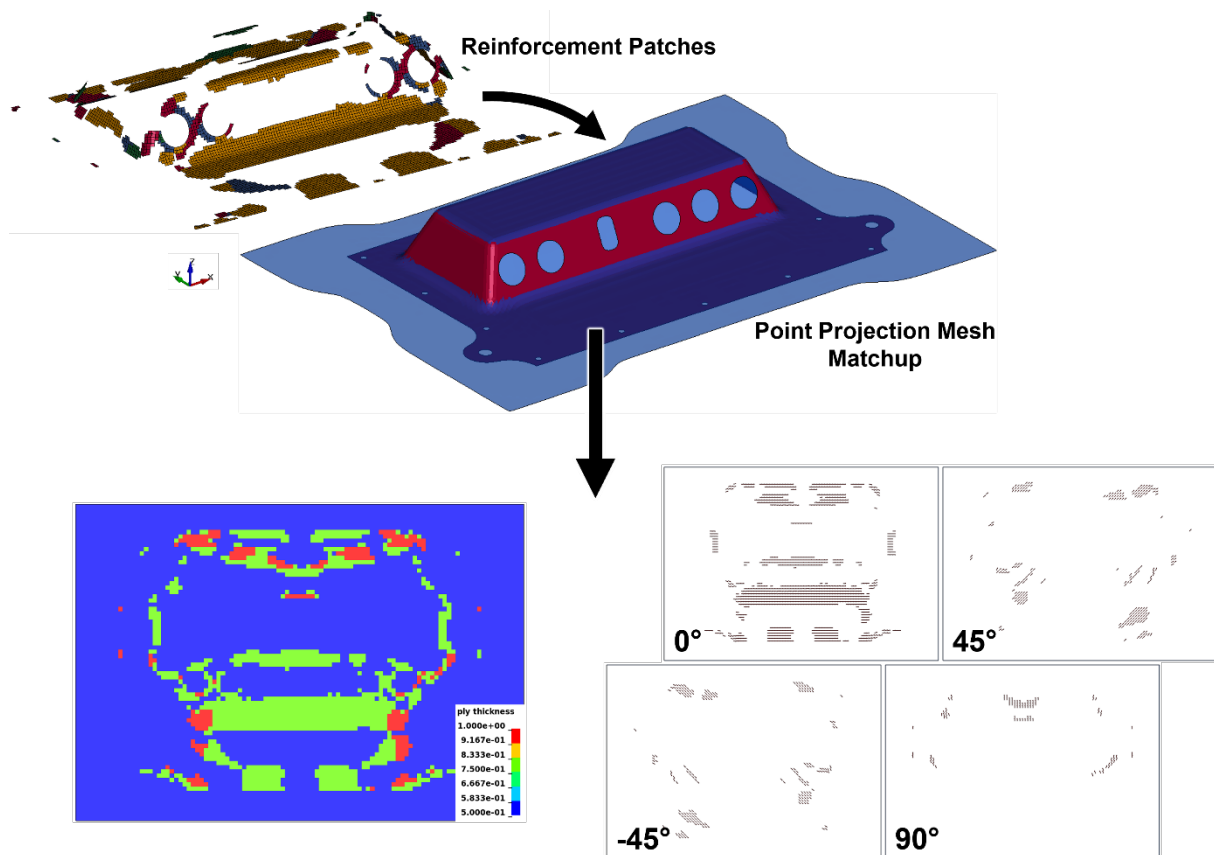


Fig.5: Overview of reinforcement patch handling. Reinforcement patches and mesh matchup in deformed configuration (top), element thicknesses after the patch handling (bottom left) and reinforcement patch fiber directions in the reference configuration (bottom right).

3.4 Draping simulation using reinforced mesh

A second draping simulation after the patch handling is done to obtain the draping simulation result considering reinforcing patches. The simulation setup is the same as for the first draping simulation in Sec. 3.2. Due to additional patches, the results differ. Moreover, the final directions of the patches do not comply perfectly with results from the optimization simulation since the reinforced elements deform differently than the other elements. This can be avoided by using an iterative method between patch layup optimization, patch assignment to the initial configuration and draping simulation, to find the best layup definition for the reference configuration. The mentioned approach is omitted, and the effects are neglected in this paper since the main goal is to establish and demonstrate a working virtual process chain. The result of this step includes all necessary fiber directions as history variables according to ***MAT_249 POSTV** flag. The staking sequence and the discontinuity of reinforcement patches are considered as well.

3.5 Handling draping simulation result to preserve composite layer properties

The resulting *dynain* file of the draping simulation described in the previous section contains standard shell elements. These elements cannot represent the stacking sequence of composite layers properly. Thus, shell elements are redefined using the `*ELEMENT_SHELL_THICKNESS_OFFSET_COMPOSITE` keyword [6]. This keyword can model shell elements with different thickness information, discontinuous layer stacking sequences and respective thicknesses of each layer within the element individually. To benefit from these advantages, Envyo reads the draping simulation result file and the patch handling mapping result, recognizes element properties, and generates the aforementioned keyword. As a result, a possible thickness variation of elements due to the draping simulation can be mapped to a following simulation without losing the layups stacking sequence. Thereby, thickness change of an element will be distributed to all layers equally.

3.6 Trimming simulation

Up to this step, the simulated model does not include any holes necessary for fixation through bolts or for the positioning of cables or electric plugs. The creation of these features on the FE-mesh is performed in a trimming step using the result mesh of the draping simulation with reinforcing patches and the commands `*CONTROL_FORMING_TRIMMING` and `*CONTROL_ADAPTIVE_CURVE`. The input curve containing all holes to be cut in the mesh is imported with `*DEFINE_CURVE_TRIM_3D` in the *iges* format. The trimming of the mesh is performed automatically in an implicit step resulting in the geometry shown in Fig. 6.

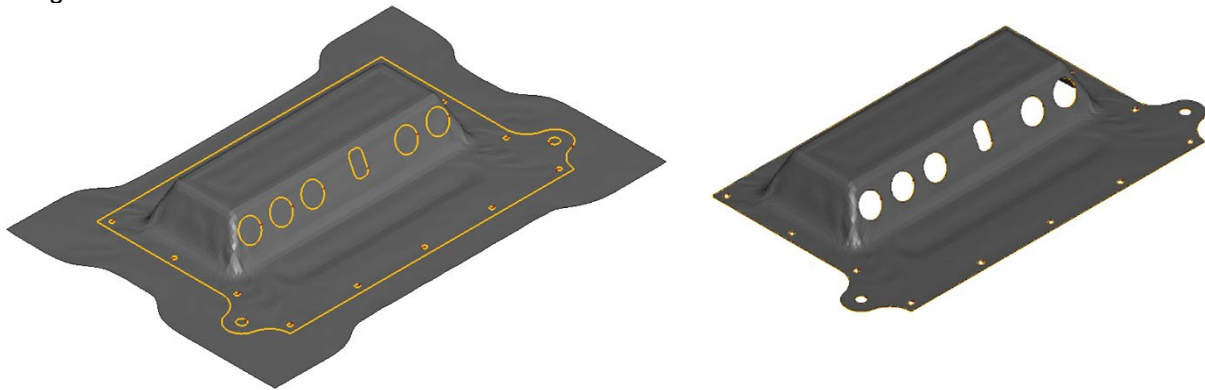


Fig.6: Draping simulation result mesh and trim curves (left), trimmed mesh (right).

3.7 Generating structural simulation mesh

During the draping simulation in Sec. 3.4, the aspect ratio of the element diagonals around the corners of the geometry may increase (illustrated in Fig. 7). Since the wave propagation velocity for membrane deformations determines the critical time step for shell elements and the membrane deformation has a direct effect on the characteristic length of an element [9], deformed elements with poor aspect ratios decrease the time step size, which results in higher computational cost and numerical instability. Therefore, the part geometry is reconstructed using the trimming simulation result in LS-PrePost and a new mesh with improved aspect ratios is generated. The procedure is automated using a simple script which creates and regulates required LS-PrePost command files.

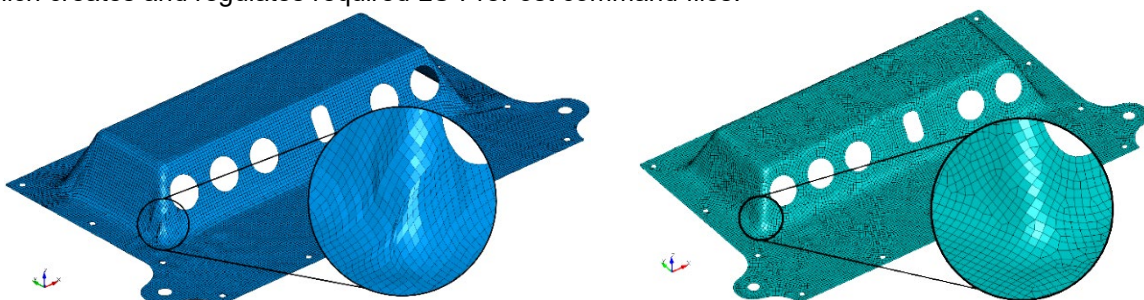


Fig.7: Trimming simulation result after draping simulation (left) and regenerated mesh (right).

3.8 Mapping draping simulation data onto structural mesh

The regenerated mesh from the previous step is used in the structural simulation to finalize the process chain. However, the regeneration process yields a blank mesh which only provides nodes' coordinates and element connectivity. The composite structure information needs to be mapped onto this mesh using the result mesh from Sec. 3.5.

Since Envyo needs to know the storage location of fiber directions, the user needs to provide this information as POSTV option to the program. This information is used to retrieve the fiber direction data and to map it onto the target mesh according to the target material model. For this case the fiber directions are restored on history variables according to `*MAT_249 POSTV=8` option and they are stored on the target mesh according to `*MAT_249 IHIS=1` option.

3.9 A simple structural simulation

The final step is an exemplary elastic 3-point bending simulation. It is a simple setup with two rigid support bars and a rigid moving bar to deform the structure placed between them as shown in Fig. 8. This step is essential to evaluate the current iteration in sequential metamodel-based Monte Carlo analysis, where the contact force between the moving bar and the structure is defined as response for the LS-OPT study and the metamodel built by LS-OPT is evaluated according to this response.

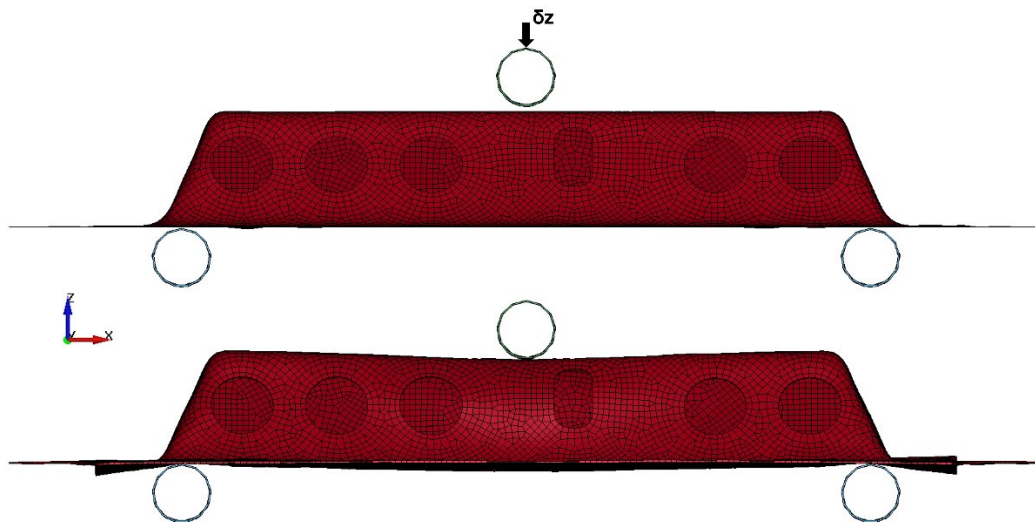


Fig.8: Elastic 3-point bending simulation, undeformed mesh (top) and deformed mesh (bottom).

In previous sections, `*MAT_249` parameters are set to represent dry-fabric properties. In this section, the structural mesh material model contains also resin properties to account for matrix material effects.

4 Parameterization setup for LS-OPT

A sequential metamodel-based Monte Carlo analysis is used to conduct a statistical survey on the process chain by investigating the nine parameters listed in Tab. 1. These parameters were modeled as a normal distribution around a mean value with a given deviation. Therefore, effects of manufacturing tolerances or material defects can be simulated. The parameterization of the woven fabric angle and reinforcement patch angles provides approximately $\pm 6^\circ$ of deviation, and the parameterization of reinforcement thicknesses provides approx. ± 0.015 mm of deviation. Since this is an evolutionary procedure, the feedback from simulations or the results from the field can be also used as input to improve the process chain. A convenient mathematical model can be generated after evaluating the feedback from the field and can be applied for all respective boundary conditions on the process chain. Furthermore, the results provide information about the scatter of resulting component properties based on manufacturing inaccuracies and which manufacturing error leads to more fatal behavior of the final structure.

Table 1: Variables used for the parameterization of the virtual process chain in LS-OPT.

Variable name	Description	Nominal	Deviation	Applied in step
r1	Woven fabric rotation angle with respect to global x-axis	0.0	2.0	BEAM-SHELL Mapping (step 1)
patch_1_angle	Fiber angle of the first reinforcing patch with respect to global zero direction	0.0	2.0	Patch Handling (step 3)
patch_2_angle	Fiber angle of the second reinforcing patch with respect to global zero dir.	45.0	2.0	Patch Handling (step 3)
patch_3_angle	Fiber angle of the third reinforcing patch with respect to global zero dir.	-45.0	2.0	Patch Handling (step 3)
patch_4_angle	Fiber angle of the fourth reinforcing patch with respect to global zero dir.	90.0	2.0	Patch Handling (step 3)
patch_i_thick	Thickness of the ith reinforcing patch	0.25	0.005	Patch Handling (step 3)

5 Evaluation of the process chain results

To benefit from evaluation metrics in LS-OPT, the contact force between the rigid moving bar and the deformable structure is defined as response. The computed response value is then used to formulate the metamodel of the process chain. Since FE simulations are computationally expensive, metamodel approximations are used to evaluate statistics.

The selected evaluation plots of this study can be seen in Fig. 9. The scattered data in the accuracy plot is generated using computed and predicted response values which indicates the quality of the metamodel. A high-quality metamodel yields close approximations between predicted and computed responses. It should be noted that the structural simulation is an exemplary model, and the process chain is a prototype with many assumptions. Therefore, the primary goal of this setup is not to obtain a good quality metamodel but to demonstrate the applicability of the process chain and coupling of the individual steps. Therefore, the parameter correlation plot is more meaningful. It can be used to determine the most significant parameters. Thus, some computational effort can be saved by focusing on those parameters rather than the whole nine-parameter model. Parameters which can be excluded may also allow for the assumption that manufacturing errors for these specific variables have less influence on the overall performance of the final part. As can be seen in the Fig. 9, the parameter *r1* has the most influence on the response value, which satisfies the expectations since it changes the global orientation of the underlying woven fabric material. In addition, the stochastic contribution plot verifies the correlation plot, and the histogram provides the response distribution of 10000 samples as well as the mean value and standard deviation range.

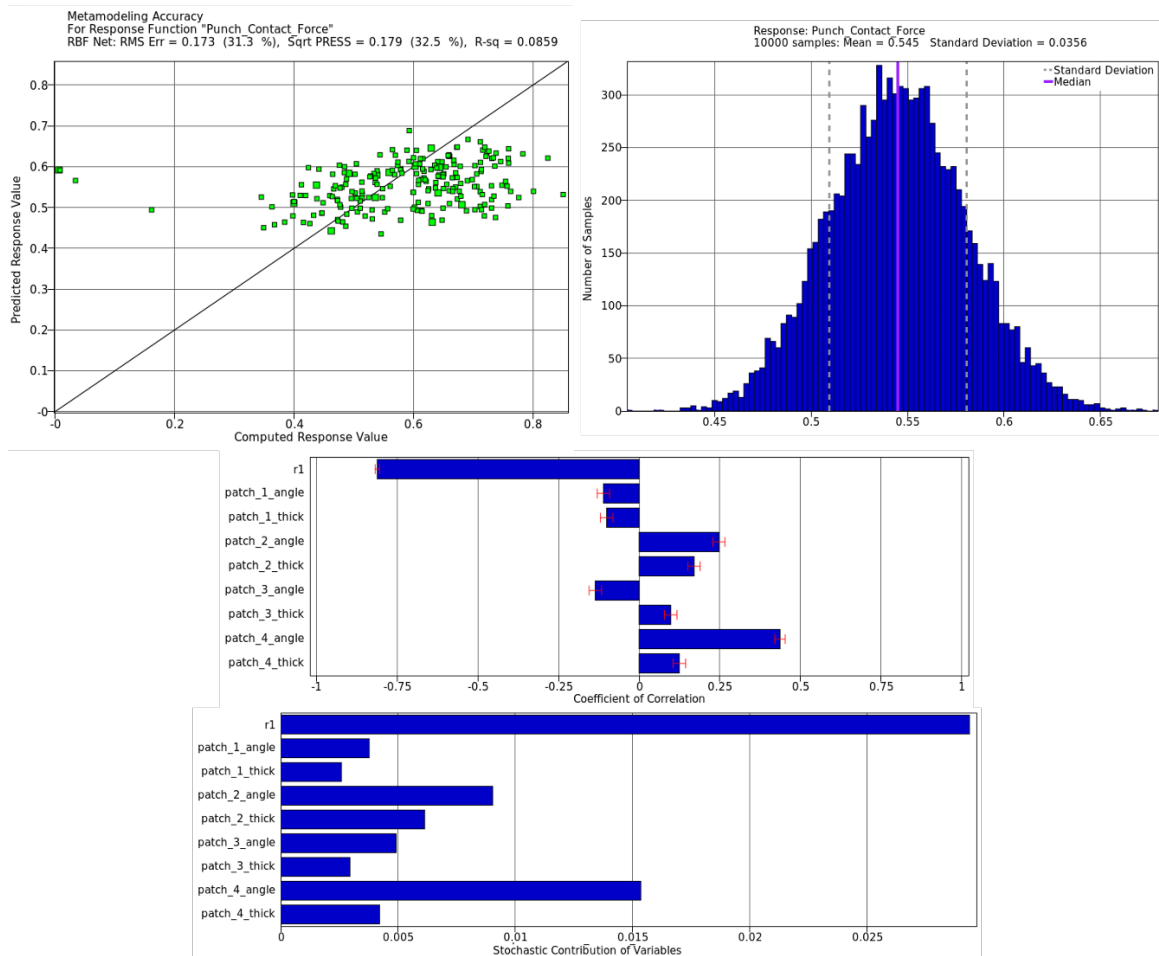


Fig.9: Metamodel accuracy plot (top left), the response value distribution histogram (top right), the linear parameter correlation plot (middle) and the stochastic contribution of variables (bottom).

6 Conclusion

In the present paper, the development of an automated process chain for the simulation of sensor-embedded composite structures was demonstrated. The modelling scheme developed in the project "Digital Fingerprint" combines the potential of the mapping tool Envyo and the integration capabilities of the software LS-OPT to perform consecutive simulations, to automatically transfer the data between each step, and to evaluate the influence of different parameters on the overall component behavior. The established LS-OPT flow-chart can be seen in Fig. 10. In its current state, the modelling scheme can consider and map embedded sensors and local reinforcement patches onto the underlying woven laminate. The first test process chain integrates draping and trimming simulations and is based on material model *MAT_249. The mapping of information between the simulation steps and the postprocessing of the meshes occurs in a fully automated manner.

In a later project stage, a database filled with results from virtual testing will be coupled to the process chain to reduce the effort for material characterization. Furthermore, it shall integrate the possibility to consider on-board data as simulation input or as comparison basis to optimize the structure. It might also allow for the detection of potential structural defects before fatal failure. The coupling process might need to support additional third-party software, which can be easily established using LS-OPT.

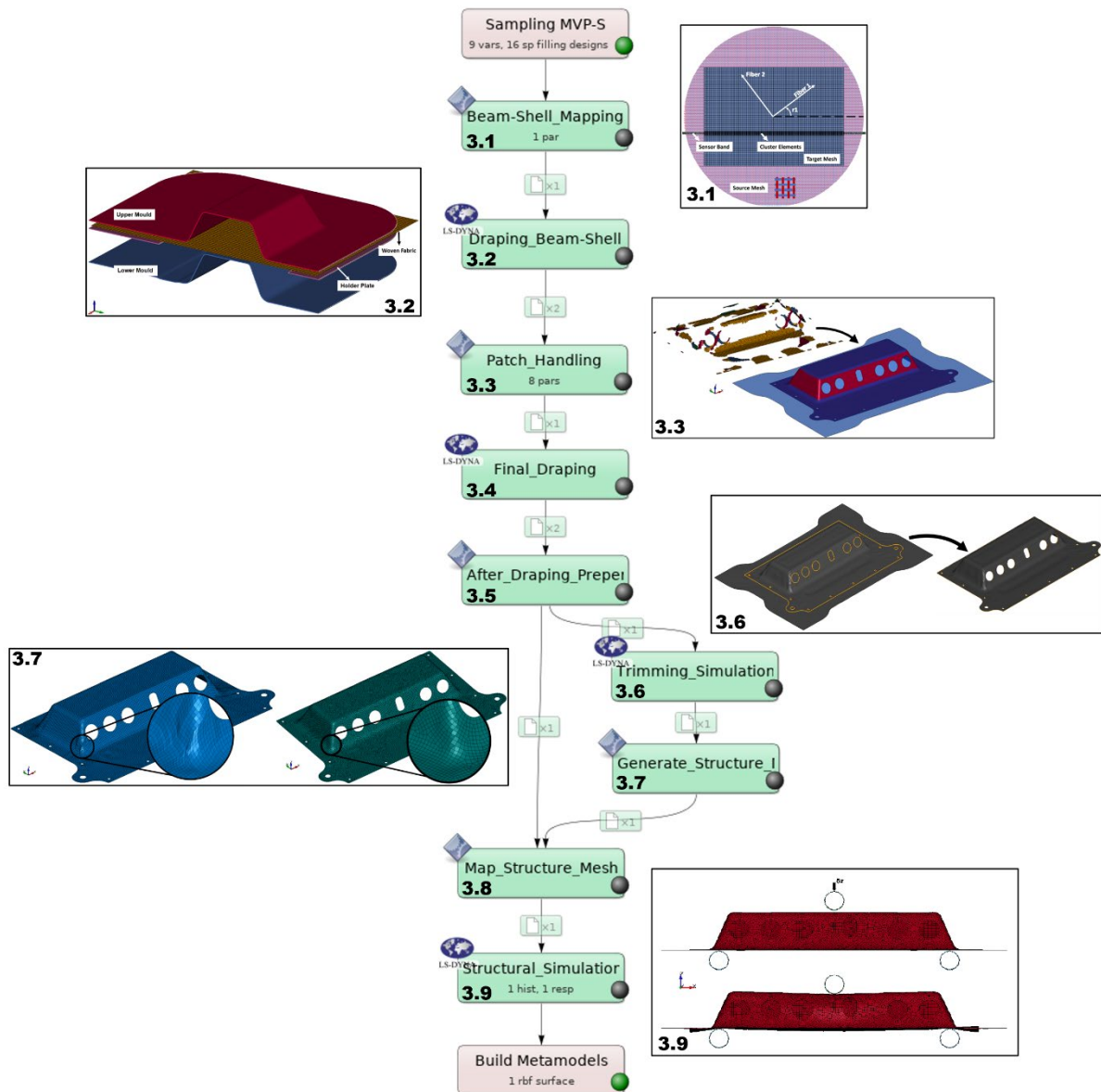


Fig.10: Overview of the virtual process chain with corresponding section IDs.

7 Literature

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