The Digital Prototype as Part of Envyo® - Development History and Applications within the ARENA2036 Environment

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1 Abstract

DigitPro, a sub-project of the government funded research project **A**ctive **R**esearch **E**nvironment for the **N**ext generation of **A**utomobile (ARENA2036) deals with the development of a **Digit**al **Pro**toype, a closed simulation process chain which not only covers different simulation disciplines such as crushing or process analysis, but also various material modeling approaches on the micro-, meso-, and macro level. Various software tools are being used by the project partners, namely the German Aerospace Center (DLR), the Institute of Textile Technology and Process Engineering (ITV), and the Institute of Aircraft Design (IFB) at the University of Stuttgart.
Within recent years, the capabilities needed to close the simulation process chain have been implemented into the mapping tool ENVYO® which was officially introduced at last year's German LS-DYNA users meeting. This paper will give an overview on recently implemented features and will point out the significance of ENVYO® for a closed simulation process chain and data management during the component's design and verification lifetime. Within this context, an overview on future topics which will be realized within the succeeding project "Digital Fingerprint" will be given.

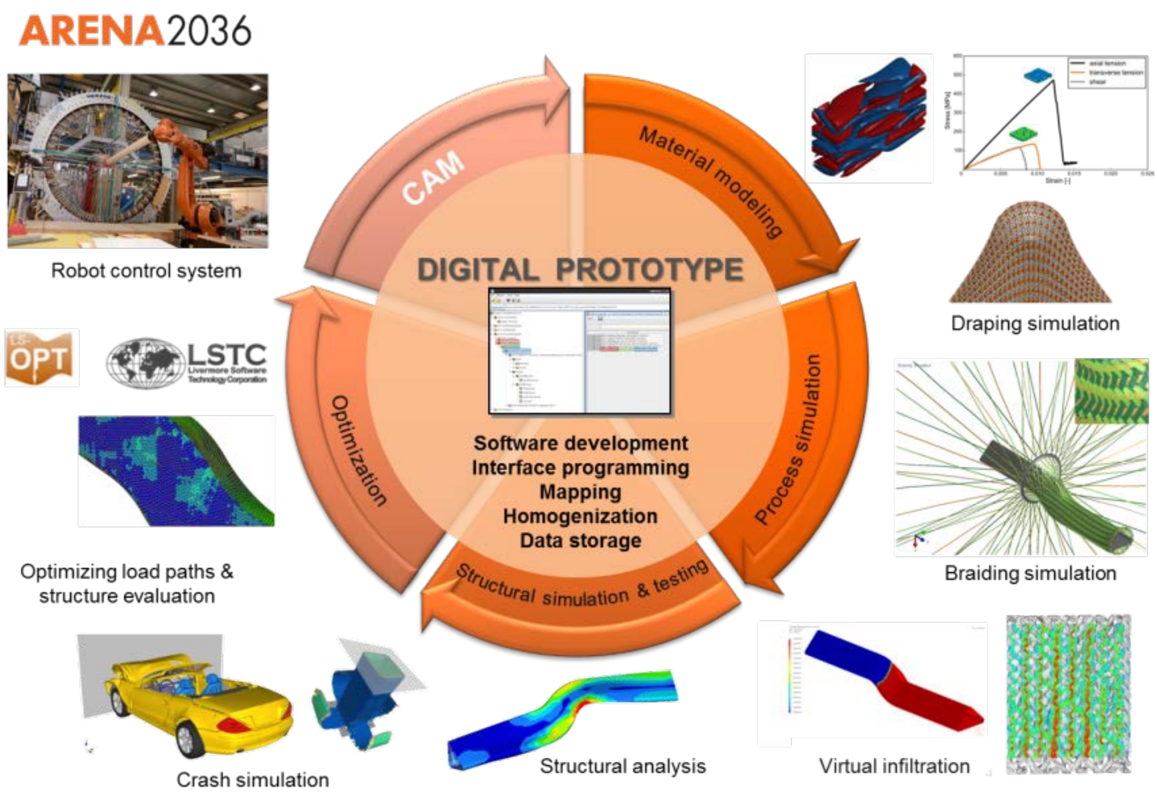

Fig.1: The Digital Prototype, bridging the gap between virtual testing, process simulation, structural analysis and computer aided manufacturing [1].

2 Introduction – ARENA2036

The research project ARENA2036 is divided into three main sub-projects, considering all necessary topics that need to be addressed to build the automobile of the future: the development of a future research factory and improving manufacturing processes for highly flexible production lines of tomorrow (ForschFab), lightweight design and an intelligent integration of sensors within automotive structures to improve the structural response during standard operations and in crushing situations (LeiFu), as well as a fully automatized simulation and process data management chain, which allows for a faster and more accurate design and verification of newly designed vehicle components (DigitPor), using new materials with a high lightweight design potential such as carbon fiber reinforced plastics (CFRP). On top of that, an interdisciplinary project which evaluates the creativity, the transfer of competence and the coordination (Khoch3) between the three engineering research groups is established, also considering the different educational background of the engineers, and shall help to improve the communication and interaction between the different research groups.
In late 2016, a new research campus was opened at the University of Stuttgart and will allow a strong collaboration between industries and research institutions under one roof. Figure 2 gives an overview on the different research projects (left) within the ARENA2036 and shows the new building (right). This research- and development project is funded by the German Federal Ministry of Education and Research (BMBF) and is supervised by the Project Management Agency Karlsruhe (PTKA).

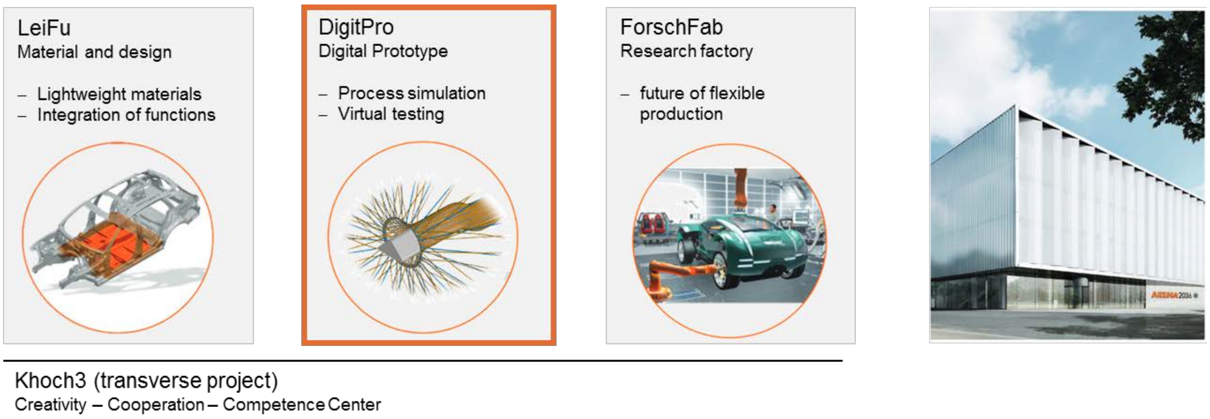

Fig.2: Overview on the main ARENA2036 research projects (left) and a picture of the new campus building (right) [2].

2.1 ARENA2036 and the digital prototype

All the research and work described in this paper is done in the subproject **Digit**al **Pro**totype, which investigates several topics along the simulation process chain for continuous fiber reinforced composites. With the development of a data storage and exchange platform based on the HDF5 data format, DigitPro plays an interdisciplinary role as well, which will be further addressed in chapter 5 “Digital Fiberprint”. The idea behind the digital prototype is to be able to store and exchange all data during the life-time of a component. These can be data generated during the design phase such as CAD data, simulation data, but also testing data for the used materials or results from component tests. Furthermore, information about loads during the life time of a component should be stored, monitored, and accessible by all the related project partners.
Within this first project phase, the focus lies on the development of such a data exchange platform, and from an engineering point of view, on the data transfer, mapping, and homogenization of simulation results. This shall be available for different finite element solvers being used within the research group, but also for various types of discretizations being used for the different process simulations and structural analysis. It is well known, that especially for fiber reinforced composites, it is crucial to consider the manufacturing process simulation results within further analysis, but also to proof producibility. Due to the large number of available resin and fiber materials, various production techniques and different combinations of them all, physical testing becomes very expensive and therefore shall be replaced by virtual testing based on representative volume elements (RVE) in order to reduce expensive material testing, to exclude material combinations, which are not suitable for the required load case and to avoid the design of components which cannot be manufactured. This of course leads to a significant increase of the number simulations which will be performed in the future, the transfer of the data between the different simulation disciplines has to be ensured and a proper

data mapping has to be established as well as a data access platform for all project partners and the engineers working on the respective components.
This closed simulation process chain shall help to improve part design and to decrease the amount of testing as well as the amount of simulation time which is used during a component design. The target of weight reduction due to the usage of lightweight materials shall be around 10%, with an overall reduction of the simulation time of up to 50%. These data shall be applicable for a standard passenger car. In addition to the linkages between the different disciplines of the computer aided engineering (CAE), a linkage to computer aided manufacturing (CAM) shall be established as well, e.g. the optimized path of the movement of a braiding core which has been verified using finite element analysis will be transformed into machine readable data so that the braiding robot will perform the movements which are needed for an optimized part design.
Since there exists a large number of manufacturing and processing techniques as well as fiber and resin materials which can be used for the design of fiber reinforced components, within DigitPro, four different manufacturing methods were chosen, namely the resin transfer molding (RTM) process, the open reed weaving (ORW) process, the draping and the braiding process. Further information about the different processes, especially for braided structures can be found in [3].

2.2 Targets, Challenges and Solution

As mentioned in the section before, one of the main targets will be to reduce the weight of a standard passenger car for about 10%, using new materials and production techniques incorporating a fully digitalized, numerical process chain which bridges over several simulation tools and length scales and allows a proper averaging, interpolation and homogenization between the different steps along the simulation process chain. In cooperation with fully automatized simulation procedures and model setup, the overall required simulation time shall be reduced by up to 50%. Considering the results from process simulation within structural analysis thereby plays an important role increasing the predictability and therefore is essential for reaching this time saving target.
Another challenge is to generate software independent data exchange platform which can be read and is accessible for all the engineers working on the same project. This data platform shall be solver-independent as well as storage-efficient since a large amount of simulation data will be produced during a closed simulation process chain. The software tool being used for the structural analysis within this paper is LS-DYNA®, but other tools are used by project partners for the different simulation approaches for the process simulation.

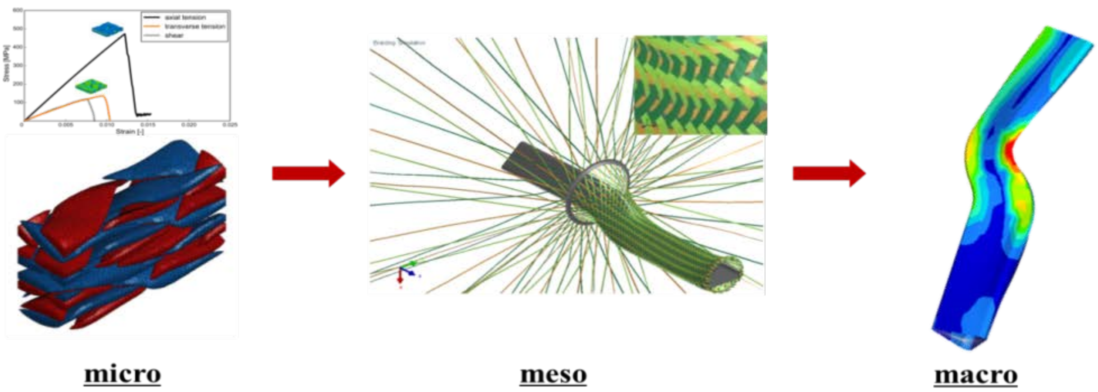

Fig.3: Bridging the gap from micro-scale modelling (left) to the meso-models being used for process simulations (middle) to a structural analysis (right).

Another important step is to be able to bridge the gap between the different length scales being used within the various simulation approaches for virtual testing, process simulation and structural analysis. Virtually testing is usually performed using representative unit cells (RUC) and therefore allows depicting between the matrix and the fiber material. This allows to model fiber and matrix failure independently as well as to consider failure within the fiber-matrix adhesive zones. Such phenomena cannot be represented in meso-scale process simulations or even macro-scale structural analysis. Nevertheless, RUC models allow predicting the behavior of a material on a macroscopic level and therefore will result in a material card which can be used for process simulations or structural analysis.
Process simulations are used to predict the producibility of components and will give information about resulting part thicknesses, fiber orientations, or depending on the material model being used, pre-

damage of the material in certain areas. These simulations are usually performed on a mesoscopic scale; using smeared material models which do not described fiber and matrix properties independently, as it was the case for the microscopic scale. Nevertheless, material properties being derived from virtual testing can be used at this stage. When it comes to the modeling and failure prediction on a macroscopic scale, different models are used as well. This is due to the fact the highly detailed models which are usually used for the process simulation cannot be used for the crushing analysis. The results of roving orientations therefore have to be mapped onto the crushing structure as well, considering resinous areas with respective material models and the resulting thicknesses from such a simulation. The element size for such a structural analysis is usually in the area of 3 mm to 5 mm, so that it is clear, that phenomenological material models have to be used, smearing matrix, fiber and failure properties into one material model. Figure 3 gives an overview on the different length scales being used for these simulations.

In order to close the simulation process chain within DigitPro, a tool is necessary which bridges the gap between the different simulation tools, the different length scales and also between the different simulation disciplines. It is obvious, that a transformation over the different length scales requires proper homogenization, averaging, interpolation, and extrapolation techniques. To overcome the problem of different software codes being used, a solver independent data exchange platform is implemented within the developed tool. This allows the project partners to define their own data format which is then readable for all the project partners. Important data such as fiber orientations or other necessary history variables can be highlighted in respective subfolders whereas non-important data such as standard control cards which of course are solver independent can be pushed directly into the data storage container. The idea behind that is that it can be easily extended for further data which become available during a components lifetime such as results from sensor measurements for life-cycle monitoring or experimental test data which become available during the material selection process.

All the challenges and proposed solutions shall be part of the newly developed mapping tool Envyo®.

3 Introduction – ENVYO®

The following sections will give a short overview about the development history and the most important implementation features regarding the digital prototype. The mapping tool Envyo® is based on the C++ programming language, the main input commands can be defined in ascii format and it is available for the most important windows and linux distributions so far [4].

3.1 Historical overview

In 2011, DYNAmore started with the development of a mapping tool within the framework of the government funded research project TPult and first implementations were made to make the results from braiding simulations accessible for structural analysis, using the `BEAM -> SHELL` mapping capability as well as an approach to make the fiber orientations from computer tomography measurements accessible for FE analysis [5]. Afterwards, this was extended to map results from draping simulations (e.g. with `*MAT_249 - *MAT_REINFORCED_THERMOPLASTICS`), onto shell or solid meshes to perform crushing analysis. These basic implementations were made on a Fortran program and added to an in-house tool at DYNAmore. In 2013, it was decided that the program should be a stand-alone software and was transferred to a C++ code.

By that time, several names existed for that tool – one was “Fibermap”, the other one was “DYNAmap”. Within the research project ARENA2036 which is the focus within this work, other software tools can be considered such as FiberSim® or PamRTM®. Nevertheless, the focus stays on the output of meshes which can be used with LS-DYNA.

Within the ARENA2036 research projects, the link to a used define HDF5 data format was generated. Since then, HDF5 data can be read and converted to a used defined format which is readable for everyone within the project. Furthermore, ascii data can be read and directly linked to the HDF5 data container. A mapping from within the HDF5 data base is also conceivable, so that a output to the respective solver used for further analysis is also possible.

In 2015, additional features were implemented to investigate the influence of resinous areas on the results of structural analysis. This is available for different processes such as braiding simulations or multi-layer draping analysis. Within the work of [6], it was proven that a proper consideration of the fiber orientation as a result of the draping analysis improves the prediction of spring back analysis for continuous fiber reinforced components. Furthermore, implementations were made to perform homogenization for short fiber reinforced composites and to allow an integration point-wise definition

of the stiffness and plastic behavior with the material model *MAT_157 - *MAT_ANISOTROPIC_ELASTIC_PLASTIC. For further information please refer to [7]-[9].
Since last year, it is also possible to take into account the results from metal forming simulations and to estimate damage and failure properties depending on the element size with the GISSMO damage and failure model available in *MAT_ADD_EROSION.
Also in 2016, the tool was officially released at the LS-DYNA Forum in Bamberg, Germany and has since then the official name Envyo®.

3.2 Implemented features

The target is to be able to map the most important features regarding to the customer's needs. Nevertheless, there are a large variety of conceivable applications, such as it is illustrated in figure 4.

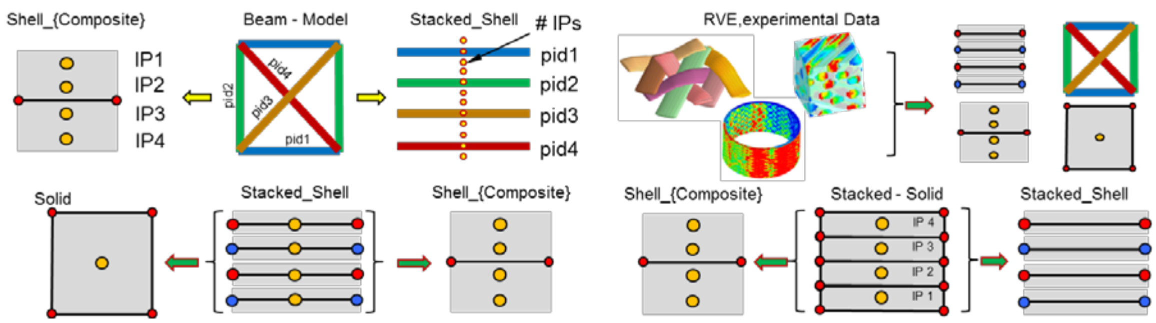

Fig.4: Overview on various mapping applications.

Therefore, it is necessary for the user to report back their needs so that the tool can be improved for further applications. The following list shall give an overview on mapping possibilities, which are already realized within ENVYO®:

- SHELL -> SHELL
  - Stresses
  - Strains
  - Thicknesses
  - Orientation data (*ELEMENT_SHELL_COMPOSITE)
  - GISSMO damage estimation
  - Consideration of resinous areas
- SHELL -> STACKED_SHELL
  - Stresses
  - Strains
  - Thicknesses
  - Orientation data (*ELEMENT_SHELL_COMPOSITE)
- SOLID -> SOLID
  - Stresses
  - Strains
  - Orientation data (*ELEMENT_SOLID_ORTHO)
- STACKED_SHELL -> SOLID
  - Stresses
  - Strains
  - Orientation data (*ELEMENT_SOLID_ORTHO)
- SHELL -> SOLID
  - With mesh generation
- BEAM -> SHELL
  - Orientation mapping
  - Consideration of resinous areas
- STACKED_SHELL -> STACKED_THICK_SHELL
  - Stresses
  - Strains

    - o Orientation mapping
    - o Consideration of resinous areas
- MOLDFLOW -> SHELL
    - o Homogenization for *MAT_157 (*MAT_ANISOTROPIC_ELASTIC_PLASTIC)
    - o Tensor mapping for *MAT_215 (*MAT_4a_Micromec)

4 Application examples

This section will give an overview on the most important features implemented within the ARENA2036 project.

4.1 HDF5 data exchange platform

As described, a solver independent data exchange platform has been implemented based on the binary HDF5 data format, which can be manually structured and edited. The data format is open-source and can be hierarchically structured. It supports an unlimited number of file formats and allows for efficient in- and output of a large amount of data. Since it is easily extendable and allows the consideration of new data types, it was chosen to be sufficient for the work done within the project. The data within one data container can be viewed with the open-source viewer HDF-View which allows for a structured visualization of the contained data. Figure 5 illustrates the input data of an HDF5 data container, being used for one component, with the different steps take along the process chain: preliminary design, optimization, process simulation, mapping and structural analysis. A status overview is created on the top of the folder and allows for tracking of the process steps.

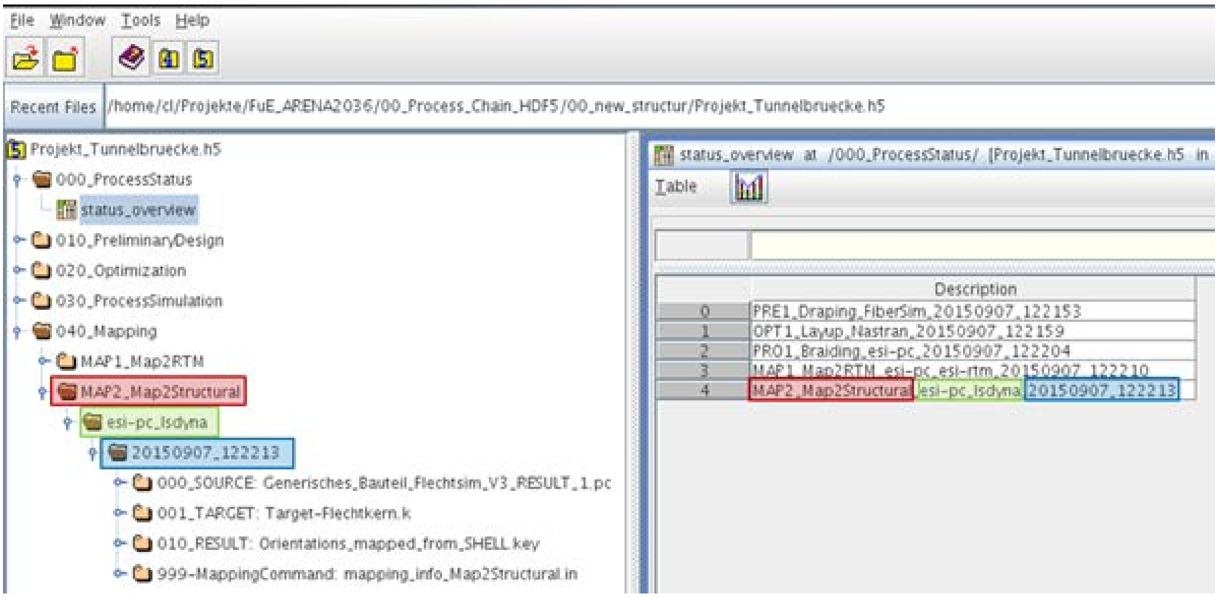

Fig.5: Visualization of HDF5 data with HDF5-View and the status overview of the project folder.

4.2 Mapping of fiber orientations from process simulations

Most of the investigations were made for the mapping of results from braiding simulations onto structural analysis. The braiding simulations are usually performed using beam or shell meshes, so that orientations have to be transferred. A basic scheme which shows different target discretizations is shown in figure 6. Target discretizations studied here are either single layered shell which would need nine integration points through the thickness to represent the three different directions of the three layers of a tri-axial braid, or three layers of stacked elements, each representing the orientations of the three orientations of one layer of the tri-axial braid. Both mapping options are conceivable.

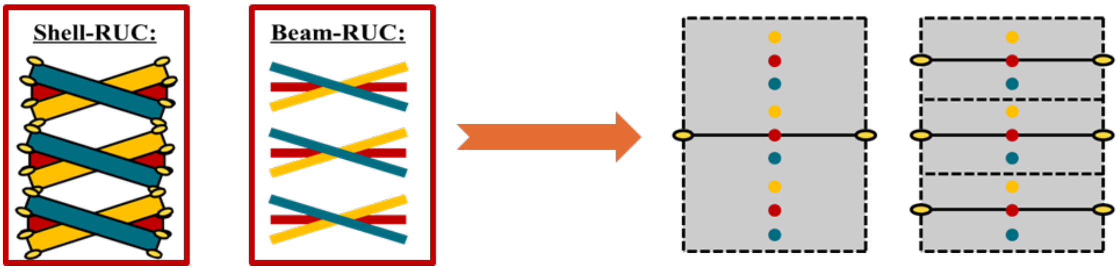

Fig.6: Source representative volume elements (left) and target configurations (right).

Furthermore, thicknesses can be considered during the mapping. Therefore, the highest and the lowest roving of the braided structures are detected. Offsets of the rovings in between should also be considered in the near future to have more accurate results. Figure 7 shows the resulting thickness distribution for the mapping from beam- or shell meshes onto single-layered or multi-layered stacked shell elements for these tri-axially braided structures.

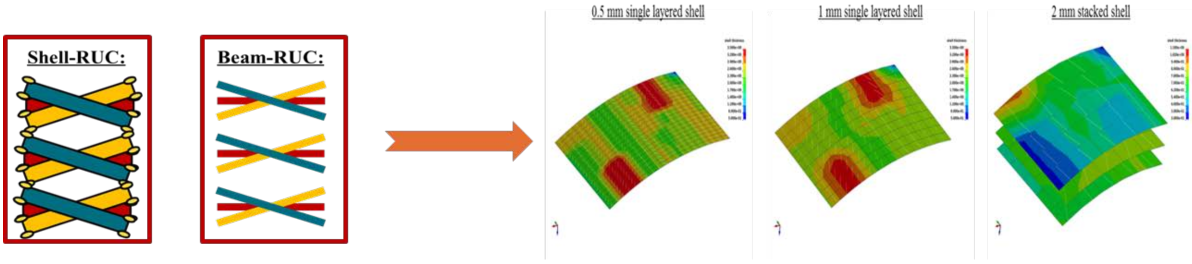

Fig.7: Results of thickness distribution after the mapping process, considering the offset between the rovings.

Another example shows the consideration of resinous areas within the mapping process. Therefore, the user can define different search radii and investigate the influence of such areas on the structural response of the component. This can be done by assigning a matrix material model to the respective integration point. Integration points which have a fiber roving within the respective searching area are assigned with a respective uni-directional material model to consider the reinforcement properly. The main mapping idea is illustrated in figure 8.

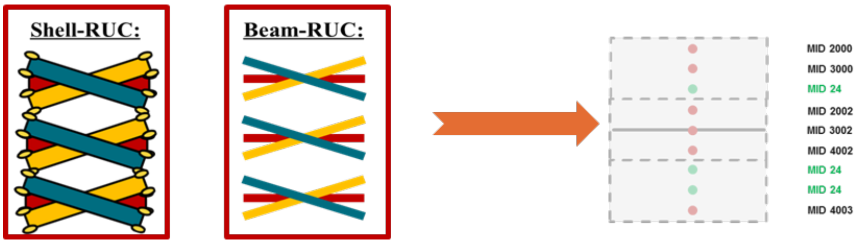

Fig.8: Assigning resinous areas at certain integration points where no roving can be detected within the respective search area.

Figure 9 illustrates the influence of the search radius on the target mesh. Vertical lines indicate that there is a matrix material used, the horizontal lines indicate, that a roving (in this case the reinforcing yarn) was found within the respective search area. This is also mesh size dependent and will be investigated in the near future.

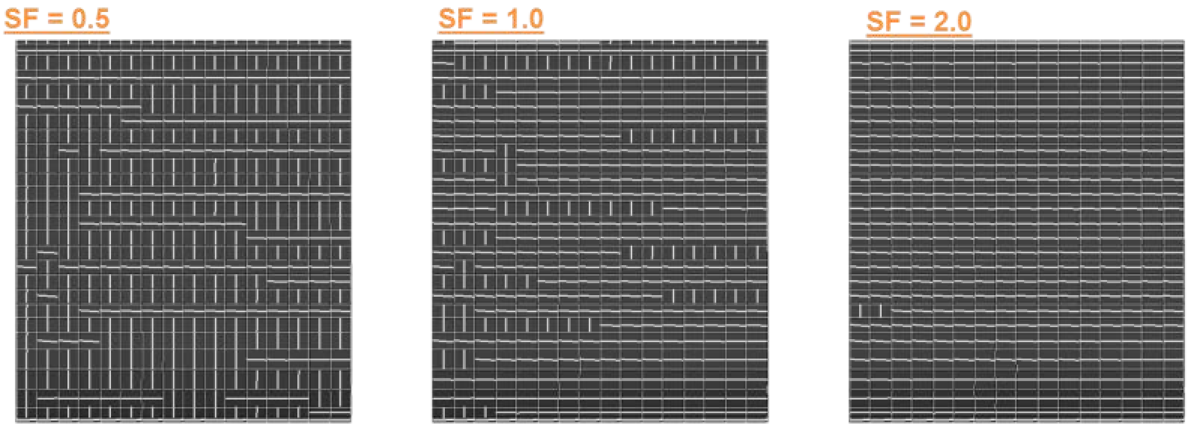

Fig.9: Influence of the search radius on the fiber orientation in the mesh. Horizontal lines indicate that no fiber was found, vertical lines indicate fiber orientation. This is shown for three different search radii.

The influence of the mapping approaches which are introduced here will be shown in the various presentations of the ARENA2036 session of the 11th European LS-DYNA Users meeting.

5 Digital Fingerprint

The project which will be following the DigitPro project and is supposed to be initiated in 2018 is called Digital Fingerprint. The simulation process chain will also play an important role within that project, even though the focus will be on the transfer of results from fatigue analysis onto crushing analysis in order to predict remaining material stiffness and strengths. This is ongoing research and will hopefully be published in the near future.

With the HDF5 data format, a standard has been established which shall also be used in the future to store data within the Digital Fingerprint project. It shall be extended for sensor data which can be used for life cycle monitoring and non-normal behaviour can be return to the manufacture to evaluate the remaining life time of the component and to allow for an early replacement before fatal failure.

6 Summary and Outlook

This paper shall give an overview on the ongoing research within the ARENA2036 research campus. Therefore, the mapping tool Envyo® has been introduced, and mapping examples have been illustrated to understand the different mapping procedures which have been implemented within the research project. Of course, there are already more implemented, as was shown in the overview, and there are more to come, since every users has its own strategies for the modelling of process and structural analysis.

In addition, the HDF5 database has been introduced such as it is implemented within Envyo®, allowing the participants of the research project to store and exchange there simulation data on a used-defined platform which is readable for everyone and be extended easily. An overview has been implemented which allows to track the process within the project.

In the last chapter, an outlook on the upcoming research project “Digital fingerprint” has been given which will extend mapping capabilities for results from fatigue analysis but also make use of the implemented data storage capabilities in the HDF5 container.

Within DigitPro, further investigations will be made within the remaining year to allow a mapping of material data gained with virtual testing onto structural or at least process meshes and to couple these data to optimization tools which not only allow to optimize the components structure or characteristics such as thicknesses or fiber orientations, but also to take into account the manufacturing process for the optimization loop.

7 Acknowledgement

We like to thank our project partners from the Institute of Textile Technology and Process Engineering (ITV), the Institute of Aircraft Design (IFB), and the Daimler AG for their support within this work.

This research- and development project is funded by the German Federal Ministry of Education and Research and is supervised by the Project Management Agency Karlsruhe (PTKA).

The authors are responsible for the contents of this publication.

GEFÖRDERT VOM
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8 Literature

[1] Dittman, J., Böhler, P., Vinot, M., Liebold, C., Finckh, H., Middendorf, P.: "DigitPro – Digital Prototype Build-up Using the Example of a Braided Structure", IMTC, Chemnitz, GER, 2015.

[2] Liebold, C., Vinot, M.: "Utilizing the Digital Prototype for a Closed Simulation Process Chain and Data Management", 17th Stuttgart International Symposium, Stuttgart, GER, 2017.

[3] Vinot, M., Holzapfel, M.,Michaelis, D., Dittmann, J., Böhler, P., Middendorf, P., Liebold, C.: "Numerische Prozesskette für die Auslegung von geflochtenen Fahrzeugkomponenten – Nutzen und Herausforderungen", Symposium Hybrider Leichtbau, Wolfsburg, GER, 2016.

[4] Liebold, C.:"Workshop Envyo®", 14th LS-DYNA Forum, Bamberg, GER, 2016.

[5] Finck, H., Liebold, C., Fritz, F.: "About the usage of LS-DYNA and modern CT technology for braided structures for lightweight design", 13th LS-DYNA Forum, Bamberg, GER, 2014.

[6] Amann, C., Liebold, C., Kreissl, S., Grass, H., Meinhardt, J., Merklein, M.: „Berücksichtigung der Umformbedingten Faser-Reorientierung in der Verzussimulation von CFK-Bauteilen", 14th LS-DYNA Forum, Bamberg, GER, 2016.

[7] Liebold, C., Erhart, A.: "Recent Enhancements on Short-Fiber Reinforced Plastics Modeling in LS-DYNA", 10th European LS-DYNA Conference, Würzburg, GER, 2015.

[8] Liebold, C., Erhart, A.: "The significance of the production process of FRP Parts for the Performance in Crashworthiness", 14th International LS-DYNA Users Conference, Dearborn, USA, 2016.

[9] Lauterbach, B., Erzgräber, M., Liebold, C., Helbig, M., Haufe, A.: "Closed simulation process chain for short fiber reinforced plastic components with LS-DYNA", 14th LS-DYNA Forum, Bamberg, GER, 2016.