From manufacturing to performance analysis for composite structures – efficient data handling and exchange

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Abstract

The performance of modern composite structures is substantially determined by the material handling and the involved manufacturing processes. Especially the material forming and the resin injection are known to influence the local mechanical properties and the final part geometry. Numerical analysis of both the manufacturing processes and the subsequent part performance have been found to allow for an efficient analysis of the composite part design, especially in an early design state. The predictability of the latter simulation can be improved by including the results from the different preceding manufacturing steps.

To be able to incorporate results efficiently from different sources, a common and open data exchange format is mandatory. To this end, the partially funded collaborative R&D project VMAP (A new Interface Standard for Integrated Virtual Material Modelling in Manufacturing Industry) aims to develop a vendor-neutral data storage concept.

To support this development, the AUDI AG and the ESI Group examined a continuous fibre-reinforced plastics (FRP) demonstration case, which allows to identify the requirements for the VMAP standard based on an industrial application.

1. Introduction and motivation

The structural performance of FRP parts is substantially determined by the chosen fibre and matrix material, the fibre orientation and volume fraction as well as the involved manufacturing processes with its contribution to the final part. Especially the material forming by draping and the resin injection are known to influence the local mechanical properties and the final part geometry. Numerical analysis of both the manufacturing processes and the subsequent structural performance have been found to allow for an efficient analysis of the composite part design in an early design state. The predictability of the latter simulation can be improved by including the results from the different preceding manufacturing steps.

Depending on the specific software solutions chosen by the industrial end-user and by potential third-party suppliers for the numerical analysis of the different process steps, the assurance of consistency of the simulation data can be cumbersome. Single party solutions exist that cover the complete range from manufacturing to performance analysis, such as the software suites *PAM-Composites* and *Virtual Performance Solution (VPS)* by ESI Group. Here, the complete virtual assessment of the design process is covered. From the different manufacturing steps, composite forming – resin injection – curing and demoulding, to the analysis of the part's structural performance in different domains (e.g. statics, NVH and crash analysis). However, the import and export of data from and to third-party software solutions commonly requires manual data manipulation and consistency checking. To overcome these difficulties, the R&D project VMAP (within the ITEA3 programme, BMBF funded, funding sign - 01IS17025K) aims to develop a common and open data exchange format that is vendor-neutral.

In the present contribution, the requirements for an open data exchange format are determined based on an industrial use-case. To this end, in section 2, the complete CAE process chain for a continuous FRP demonstration case is presented. Based on the defined analysis steps, section 3 demonstrates the simulation workflow by combining different software tools of the ESI Group. Here, a special focus will be given to the illustration of the exchanged data and the specifics of the used format. Section 4 will subsequently summarize how the obtained findings are incorporated to the currently developed VMAP data standard.

2. Definition of numerical demonstration case

In a previous R&D project SMiLE funded by the BMBF (funding sign - 03X3041A) the AUDI AG has worked on a car body structure in multi-material design for a battery electric vehicle including a complete floor module made of carbon fibre-reinforced plastic (CFRP) in resin transfer moulding technology (RTM) [1]. This floor module consists of an upper, integrally designed structure made of sub-preforms with anisotropic layup and designated load transferring sandwich cross members with integrated inserts as well as a lower anisotropic underbody structure assembled to the upper structure resulting in a stiffened CFRP floor module. Based on the developed module a smaller subsection of the structure has been selected for the numerical studies in the VMAP project (cf. Figure 1). The selection assures reasonable simulation runtimes and data sizes, while maintaining use-case specific challenges such as the double curvature of the part geometry. The focus will be on the consistency of the simulation data transfer between different simulations steps along the development process of the car body structure rather than on the design process of such a complex structure itself which was shown in [1-3].

Figure 1: CFRP lower floor panel from SMiLE car body structure used for demonstrating structure.

The CAE process chain for the previous described use case consists of four successive simulations steps – draping, resin injection, curing/distortion and structural performance simulation. Based on the final part geometry and the initial layup definition the fibre orientations (orthotropy can be lost during forming), e.g. defined by NCF (non-crimped fabric) or woven fabric, is calculated by a draping simulation. The results of this first simulation step are the spatial field of the local draped fibre orientation and the variation of thickness per ply within the layup. In the subsequent second simulation step, the obtained layup with a local varying fibre orientation is infiltrated with resin by Resin-Transfer-Moulding (RTM) simulation. Here, the local permeability of the composite material is determined by the orthotropic directions. A third simulation step consists of the analysis of the resin curing cycle and the subsequent part distortion. In a final step, the obtained information on the local fibre orientation and the part shape is used in a structural performance simulation, e.g. stiffness or crash analysis within the full car body structure.

A comprehensive overview of the CAE process chain and the obtained and potentially exchanged data is given in Figure 2. It can be seen, that both the data format (scalar, vector and tensor), the data location (nodal, element and integration point) and the discretization (solid and shell elements) can vary along the process chain.

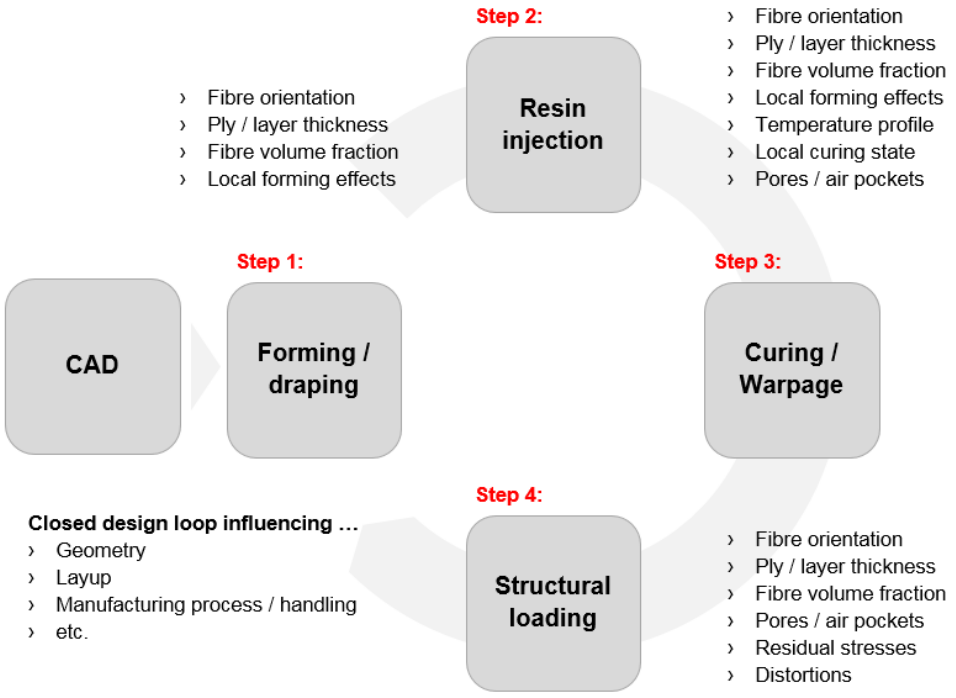

Figure 2: CAE process chain and simulation data exchange.

3. Linked manufacturing and performance simulation for composite structures

Based on the previously defined CAE process chain for composite structures (cf. Figure 2), the present section will focus on the combined application of the different software solutions provided by the ESI Group for the virtual assessment of the manufacturing steps and the final part performance [4].

a. Composite forming simulation

The effect of the composite forming on the local material structure is assessed in a forming simulation. To this end, the deformation of an initial composite preform is simulated in an explicit finite element analysis (FEA). In the present contribution, the *PAM-Form* module of the *ESI PAM-Composites* suite is applied [5]. A sketch of the forming model is shown in Figure 3. The preform model consist of a 300 mm x 300 mm blank, discretized by a homogeneous quadrilateral shell mesh with a uniform element edge length of 3 mm. The material consists of a single layer of a biaxial NCF, with an overall initial thickness of 1.28 mm. Both the die and the punch are modelled as rigid bodies. While the position of the die is fixed, the velocity of the punch is prescribed in negative z direction. The punch movement is stopped when the distance between the tools is equal to some target material thickness.

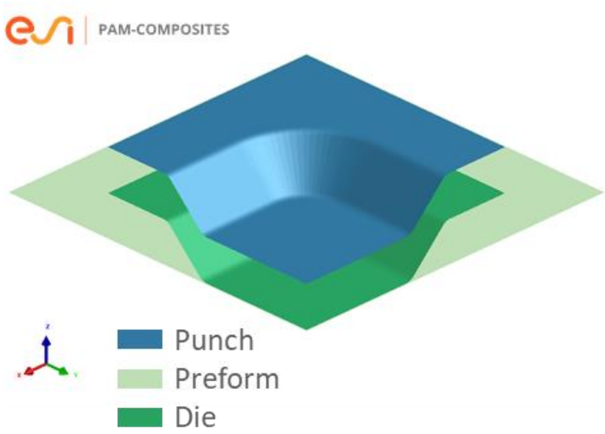

Figure 3: Composite forming simulation: model setup.

Due to the double curvature of the tooling in the corner region, the angle between the two initially perpendicular fibre directions is changed during the forming. A contour plot of the resulting shear angle is given in Figure 4 along with a detailed sketch of the first fibre direction in the corner region.

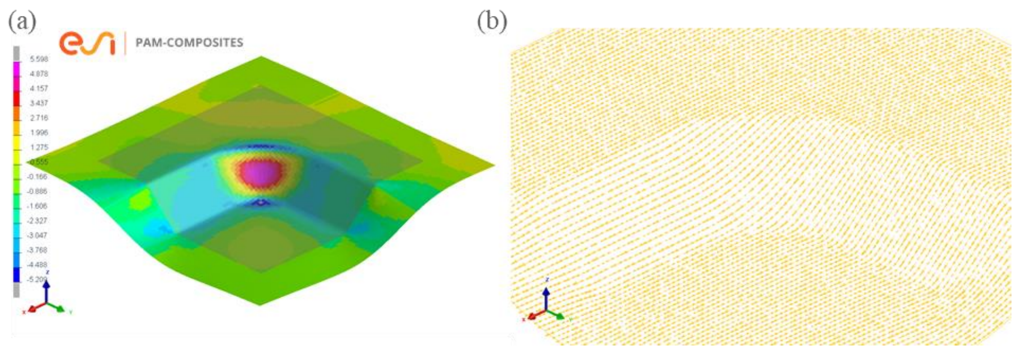

Figure 4: Composite forming results: (a) Shear angle, (b) detail of the first fibre direction in the corner region.

A complete set of results at the end of the forming simulation, including the information on the local fibre orientation and the composite thickness, is exported by *PAM-Composites* into a data container file based on the ESI Result File (ERF) standard. The results are stored as nodal and element quantities of scalar, vector and tensor data. Beside the result data, the file contains the description of the mesh and the model subdivision into parts. A detailed description of the ERF format is available to the public through the ESI website (cf. [6]). The HDF5 based file can be accessed through ESI post-processing software *Visual-Environment*, as well as through the widely available APIs (Application Programming Interface) for the HDF5 format (cf. [7]). It contains all necessary information on how to interpret the simulation results.

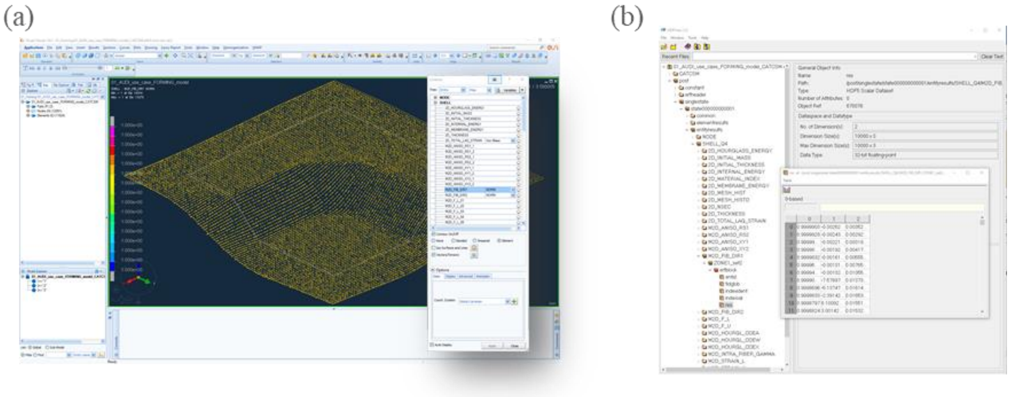

Figure 5: Composite forming result data stored in a HDF5 based ESI Result File (ERF): (a) Visualization using ESI Visual-Environment, (b) data access using the open tool HDF-View [7].

b. Composite injection and curing simulation

The simulation of the resin injection into the dry preform has been simulated using the *PAM-RTM* module of the ESI *PAM-Composites* software suite [4]. While the forming simulation was based on a shell mesh, here a tetrahedral solid mesh has been used to simulate the resin flow [cf. Figure 6 (a)]. Since the local permeability of the material is defined by the orientation of the fibres, the forming results need to be imported. To this end, *PAM-RTM* offers a workflow to import a *PAM-Form* result file. By selecting the target part, the results are automatically mapped from the shell forming mesh to the solid injection mesh. The result of the process is show in Figure 6 (b).

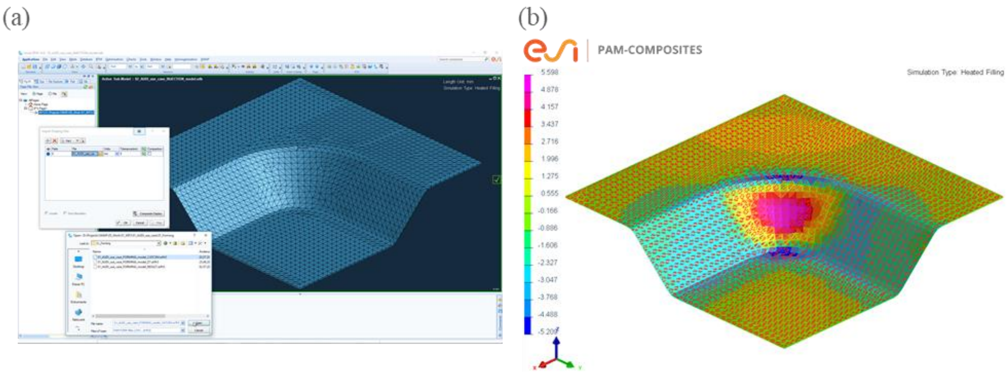

Figure 6: Fibre orientation import to PAM-RTM: (a) import workflow and (b) mapped first fibre orientation and shear angle.

The location of the inlet and outlet are given in Figure 7 (a). While the volumetric flow rate is given for the inlet, the constant vent pressure is prescribed at the outlet. A homogenous temperature field is applied throughout the model. The part edges are assumed to be impermeable. The mould filling can be evaluated by reviewing the filling factor. This scalar result field defines if the resin has completely infiltrated the composite (filling factor = 1) or not (filling factor < 1) in a certain location. Further simulation results are e.g. the temperature field and the scalar degree of cure, respectively. All three spatial fields are defined at the nodes of the underlying mesh.

The obtained results build the initial values for the subsequent curing simulation. Since both simulations are carried out with the *PAM-RTM* solver, the data exchange between the two simulations is based on an internal file format. Once imported to the curing model, the user can review the mapped result fields from the injection simulation (cf. Figure 8).

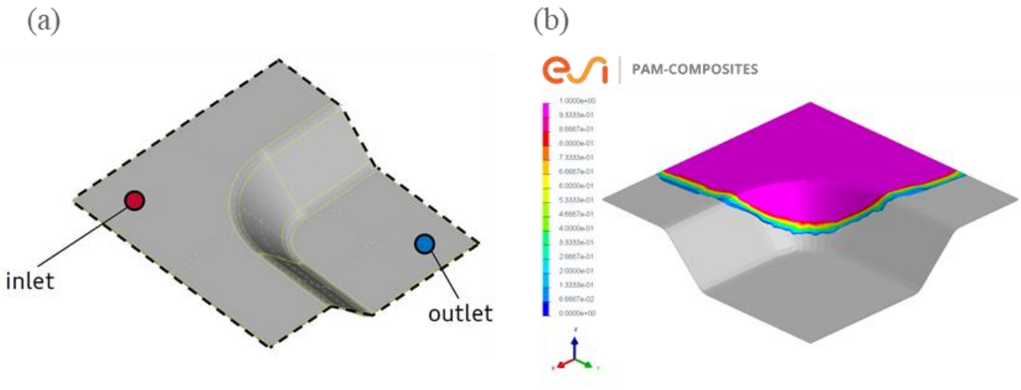

Figure 7: Composite injection model: (a) inlet and outlet location and (b) exemplary plot of the filling factor (0 = dry, 1 = filled) during the injection process.

The curing of the resin is calculated based on the definition of a proper kinetics model and a corresponding temperature cycle. In the present case it consists of an elevated temperature plateau and a subsequent controlled cooling of the part. Finally, the time evolution of the temperature field and the degree of cure is obtained. Both are again stored in a ERF as timeseries of scalar nodal quantities.

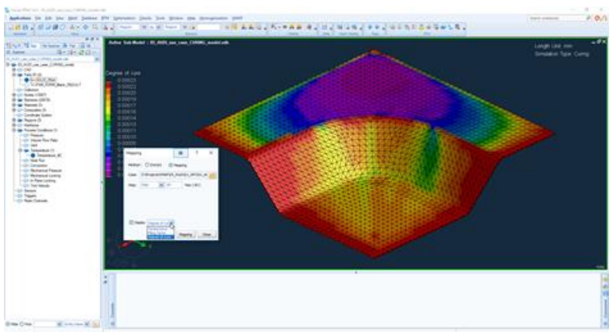

Figure 8: Composite curing simulation: import of results from the injection simulation as initial values.

c. Composite distortion analysis

The chemical processes during the curing of the resin may cause composite part distortions such as spring-in and warpage. To analyse these effects, the results obtained in the curing simulation (e.g. spatial and time evolution of degree of cure and temperature) need to be transported in a structural simulation and linked against a suitable material model. The latter need to be able to calculate the thermal and chemical strains generated during the curing cycle. These strains may cause part deformations and residual stresses after demoulding. In the present study *PAM-Distortion* from the *PAM-Composites* software suite [4] is used to calculate these effects. The solver uses the material history from the curing process and the thermal and mechanical interaction of the part with the mould. To this end, the ERF based *PAM-RTM* result file is loaded during the model creation process (cf. Figure 9 (b)).

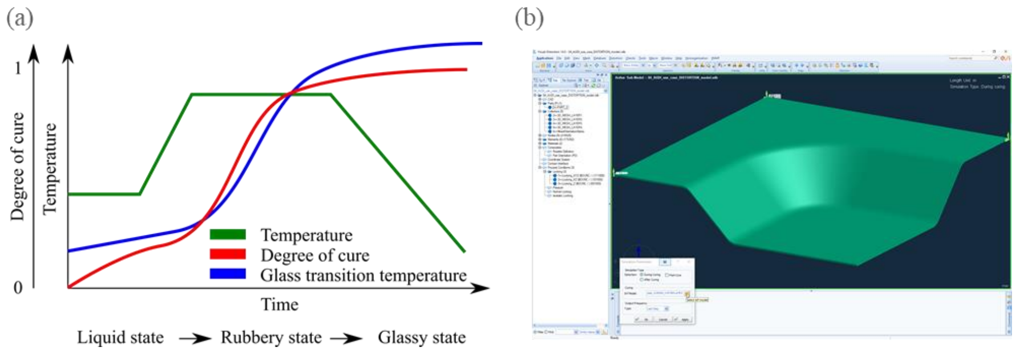

Figure 9: Composite distortion simulation: (a) resin state evolution during curing and (b) import of curing results in PAM-Distortion via ERF.

The underlying structural solver will perform the mapping of the curing results from the *PAM-RTM* mesh on structural analysis mesh during the solver initialization. During the curing process, the resin passes three distinct material states – liquid, rubbery and glassy state (cf. Figure 9 (a)). While there are no strains and stresses in the liquid state, the material can sustain them once it enters the rubbery state and especially in the final glassy state. Since the composite material is non-isotropic, the solver will calculate the induced strains separately for all three material directions, based on their individual coefficients of thermal expansion and chemical shrinkage.

To visualize the effect of the curing process on the part shape, Figure 10 shows the final deformation after curing for the present demonstrator model. Due to the clamping in the three upper corners of the part, the displacement is most pronounced in the lower corner section of the part. The results of the simulation, e.g. displacements, stresses and strains, are once again exported in a HDF5 based ERF and can therefore be utilized as initial conditions in a subsequent structural analysis. While the displacement field is exported as a nodal vector field, the residual stresses and strains are stored as symmetric second order tensors per element.

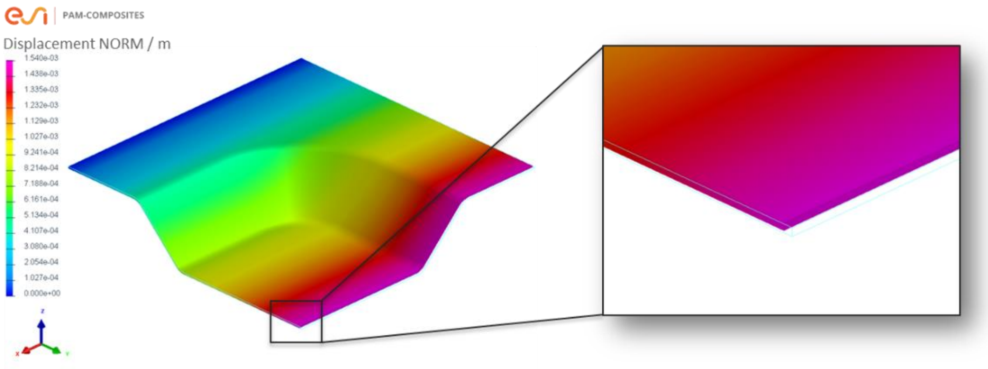

Figure 10: Composite distortion simulation: resulting part deformation after the curing cycle.

d. Composite structural performance analysis

The final structural performance analysis of the composite structure can make use of multiple results from the different manufacturing simulations. In a first step the final part shape from the distortion analysis is used to create the performance mesh. While a solid mesh has been used for the distortion analysis, a multilayer shell mesh is commonly preferred for the performance model. Its creation can be based on the extraction of the model midplane, or if not possible of the surface element faces from the solid mesh. Furthermore, the local fibre orientation can be defined using the results of the forming simulation. To this end, the structural analysis solution ESI *Virtual Performance Solution* (VPS) [8] offers the import of the *PAM-Form* results stored in the corresponding ERF. The loading condition for the present demonstration model is shown in Figure 11 (a).

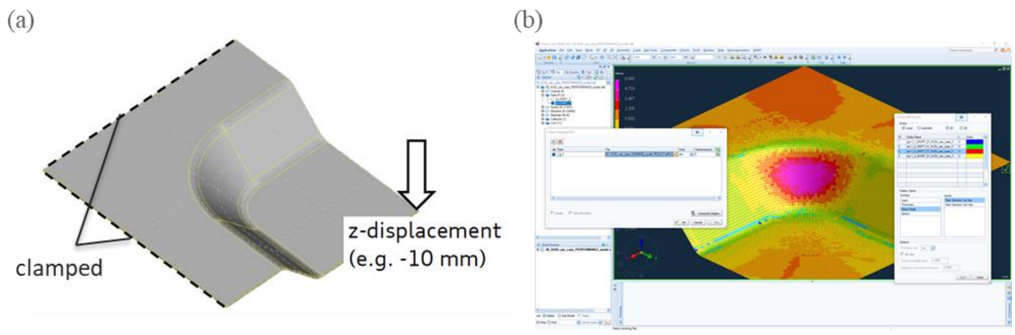

Figure 11: Composite structural performance simulation: (a) model boundary conditions and (b) forming simulation result import in ESI VPS.

To import the *PAM-Form* forming results, VPS offers a dedicated import function that extracts and maps the fibre orientation field from the manufacturing simulation mesh on the performance mesh (cf. Figure 11 (b)). A detailed plot of the local fibre orientation after the mapping is shown in Figure 12 (a).

To analyse the impact of the forming result, the model has been solved with and without the forming result import. The obtained force-displacement curves are compared in Figure 12 (b). In the present case, the import of the forming results causes a reduction of the reaction force compared to the model with an idealized homogeneous fibre orientation.

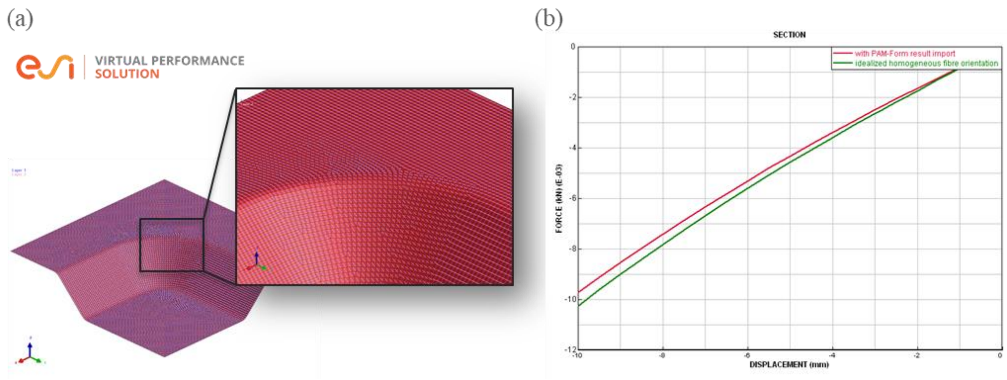

Figure 12: Composite structural performance simulation: (a) local fibre direction after PAM-Form result import (b) force-displacement curves with and without forming effect.

4. Data exchange summary and VMAP format requirements

The experiences obtained in the linked modelling of the manufacturing and the structural performance of a composite part are subsequently summarized to formulate the requirements for the development of a common and open data exchange format. To this end, the data exchange of the combined manufacturing and structural performance analysis using the ESI Group software suites *PAM-Composites* and *VPS* is summarized in Figure 13.

From the simulation steps, it can be seen that each step has its own unique discretization requirements. While forming and performance analysis of a continuous FRP part is commonly based on multi shell and multi-layer shell meshes, respectively, a solid mesh is applied for the impregnation/curing and distortion analysis. In the latter two steps different solid meshes are used due to the requirements of the individual solvers. Since it is not possible to foresee all potential mesh and element types, the currently developed VMAP exchange standard needs to support arbitrary mesh topologies. To this end, a framework needs to be implemented that allows for the efficient and comprehensible definition of element types based on the definition of vertices, element connectivity, faces, edges and neutral coordinates.

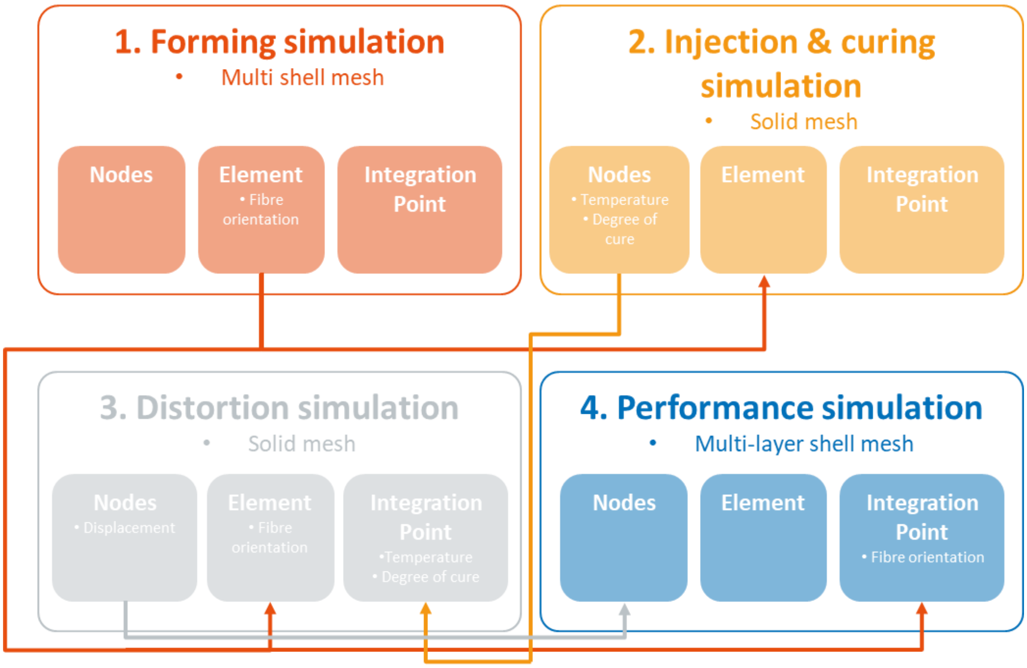

Figure 13: Current data exchange between ESI PAM-Composite modules and ESI VPS, during the combined subsequent simulation of the manufacturing and structural performance of continuous fibre-reinforced composites.

Furthermore, the exchanged result data is defined at different positions, in general at nodes, elements or integration points. The latter yields to an additional requirement for the VMAP data storage format. The comprehensible definition of quadrature rules. To this end, it is required to store the integration point position in the neutral element coordinates and the associated weight factor.

Reviewing the generated data in the individual simulation steps, it can be seen that besides the storage of scalar and vector fields it is also required to store higher-dimensional tensor fields. Again, it is not possible to foresee the possible complexity. Concerning this, the data format should support the definition of variables with a specific data type and reference coordinate frame. Since higher dimensional quantities are commonly stored in two-dimensional data arrays, it is required to define the component order. This can be achieved by the storage of metric arrays which are defined as the inner product of the basis vectors (cf. [5]).

5. Summary and outlook

In the present contribution, the linked manufacturing and structural performance simulation of a continuous fibre reinforced composite part has been analysed. Special attention has been given to the exchange of result data between the subsequent simulation steps. It has been found, that data format, data type and data location vary due to the different requirements of the involved solvers.

The findings have been used to formulate requirements for the open VMAP data storage standard. To assure a universal application of the format, it is required to develop a generic framework for the storage of arbitrary discretization topologies, data locations and data types. The embedding of a definition block in the file, will allow for a self-explanatory and future-proof usage of the format. For instance, the extension to new finite element types could be performed by the user and would not require a new version of the data standard.

6. Acknowledgement

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