

ADVANCED PRE-PROCESSING TOOLS FOR PROCESS SIMULATION OF CARBON FIBER SHEET MOULDING COMPOUNDS IN AUTOMOTIVE INDUSTRY

³Romaneko V.*, ¹Duhovic M., ¹Hausmann J., ²Tryfonidis M., ³Eschl J.,

¹Institut für Verbundwerkstoffe GmbH, Germany

²BETA CAE Systems S.A., Greece

³BMW Group, Germany

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ABSTRACT –

Carbon Fiber Sheet molding compounds (CF-SMC) are fiber-reinforced thermosetting semi-finished products. Common Glass Fiber Sheet molding compounds (GF-SMCs) are already widely used in automotive applications for roof panels, spoilers and support structures. As the usage of more expensive carbon fibers as reinforcement becomes common, process simulation tools to predict manufacturing and final part properties and help keep development costs low are gaining significant importance. So far, existing process simulation tools are unreliable for predicting important process and part behavior e.g. fiber orientations for CF-SMCs. In this work a new closed process chain workflow for a CF-SMC will be presented which couples virtual production steps by using ANSA pre-processing functionalities for data transfer and evaluation. First, the new ANSA functionalities will be explained in detail. Second, their usage will be demonstrated on a trial part geometry.

TECHNICAL PAPER –

1. INTRODUCTION

Since the introduction of the BMW i3 and i8, it has been proven, that composites can be used for automotive body parts and can be manufactured efficiently in an industrial environment in small to medium series production runs. The next step is to qualify composite parts for large series applications. The first step in this direction has been realized with the new BMW 7 series carbon core, which successfully combines different composite manufacturing technologies to produce CFRP parts combined with advanced metals in a hybrid body structure. In particular, for the production of geometrically complex three-dimensional parts with medium stiffness and strength requirements, carbon fiber sheet molding compounds (CF-SMC) provide an attractive alternative for the common materials used in automotive series applications. In the new BMW 7 series, CF-SMCs were first used in parts for the reinforcement of the C-pillar as illustrated in Figure 1.

The key for reliable evaluation of the manufacturability of such parts is not only accurate stand-alone simulation solutions (e.g. molding and distortion simulation for SMCs) but also their coupling and transfer to subsequent simulation steps e.g. crash and structural analysis. The increase in accuracy and operability of such an integrative approach has been shown by Dix (2), who couples draping, filling and distortion simulation solutions for a resin transfer molding (RTM) process. Such a closed and validated virtual process chain is not yet available for CF-SMCs, because of the limited knowledge about the material behavior of CF-SMCs during compression molding, which is crucial for the simulation of the process. Details on state-of-the art simulation solutions for mold filling of SMC and further literature can be found in Romanenko (3).

An integrative approach for the simulation of GF-SMC has been shown by Sanwald (4). For short fiber composites recent developments for integrative simulation have been shown by Liebold (5), Reithofer (6) and Pazour (7).

The focus of this work is to show an integrative simulation approach for CF-SMC on a trial part, taking into account its specific material behavior as described in Romanenko (2).



Figure 1 – Reinforcement of the C-pillar (right side) made of Carbon Fiber Sheet molding compound (CF-SMC) in the body structure of the BMW 7 (G11/G12) series (1).

The possibility of operative evaluation of different part properties is shown by using compare and scripting functionalities available in ANSA. The main requirements from a modelling point of view are summarized as follows where the pre- and post-processing environment must allow:

- Definition of local laminate structures for solid elements with differing fiber orientation angles, due to the material flow of CF-SMCs.
- Transfer of part properties e.g. fiber orientation from molding simulation to distortion simulation
- Transformation of solid to shell elements to make results applicable for structural and crash analysis
- The comparison of local final part properties to evaluate differences due to changed processing conditions

2. SELECTED FEATURES OF ANSA THAT FACILITATED THIS PROCESS

The design of the process and the requirements have been outlined in the introduction. Before implementing them and showcasing some selected use cases, several selected software features of the pre-processor ANSA that made the implementation possible will be briefly introduced.

- Solid laminates features

The FE-Modelling of composite and non-orthotropic materials is a highly sophisticated task in itself, since the nature of the field involves a variety of material characteristics that need to be represented in the simulation model.

The choice of solid elements though becomes inevitable, when in-depth simulations of CFRP-materials are analyzed. This choice raises the difficulty of handling the required pre-processing information, compared to that of regular shell elements. And that's where ANSA serves as the management tool that allows the control of the full composite design structure as a whole through the features provided by the Laminate Tools Module.

Regardless of shells or solids, the full data set, which is quite large when one takes into account their local character (two scalar results, layer thickness and material orientation which needs to be defined per element per layer) is loaded in ANSA. But it is the laminate tool which gives the ability to deal with this huge data set in such a way, that the engineer can examine the design of the composite structure at a glance.

Meshing tools facilitate this process in the sense that they provide the interoperability between shell and solid structures through the Volumize or the Unvolumize functions. Even at the solid element level, a switch between one solid per layer and on solid for all layers can be applied at any time. This combined with the fact that these features are also available through ANSA scripting, makes an automatic conversion to the desired composite description easily possible.

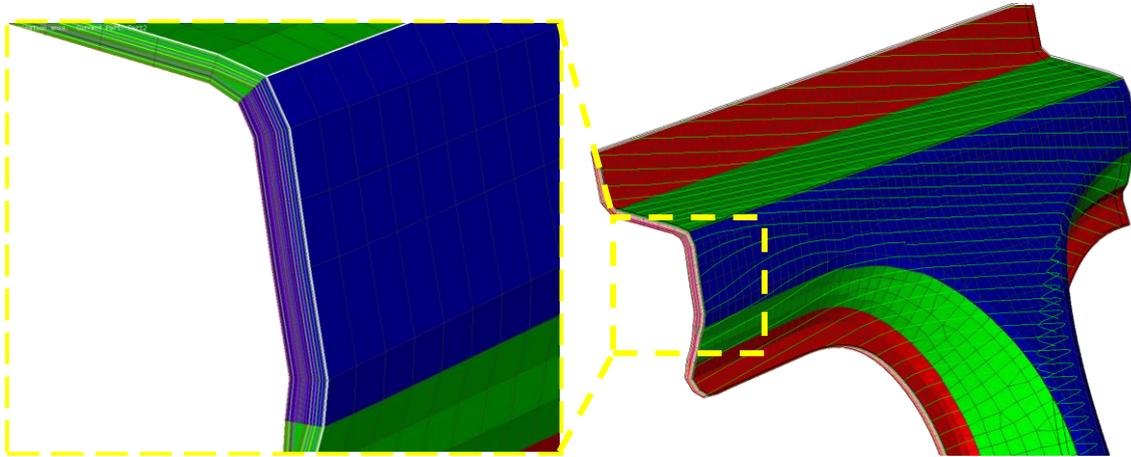


Figure 2 – Composite definition on solid elements level with material orientation display

- Results mapping tool

The FE model data transfer and mapping capabilities of ANSA have become extremely important when taking into account material properties that result from a previous simulation. In order to improve accuracy and achieve closer results to that observed experimentally of a particular mechanical test, these simulations which need to be considered are:

- Mechanical properties as a result of the production techniques used during the manufacturing of the parts (such as the mould filling simulations)
- Simulation of subsequent effects following filling or forming such as distortion and warpage, where these effects have to be included in the current simulation.

The ANSA Results Mapping tool that is designed for meeting these pre-processing tasks masters the following hurdles:

- Works between different element types supported with a variety of interpolation algorithms.
- The source results might be calculated in a different position that the target part is located in, for which auto-positioning can be performed.
- Works for a variety of scalar and tensor results (thickness, plastic strain, material orientation, draping simulation results etc.)
- Adapter settings can be tuned, for connecting the Results Mapper with a completely user defined source results reader and results interpretation algorithm.

- Compare tool

The Compare tool is used for the comparison between two models and the identification of differences in geometrical location/shape and properties of surfaces, shells/solids parts, connections and other FE-elements. Its powerful features span also into comparing the composite properties of laminate parts, see Figure 3. The Compare tool dialogue serves as an information panel presenting the encountered differences in 2 columns, one for each model. For further detail, difference in terms of local angles can also be represented in a

fringe plot. Further features such as a navigation mode, report generation tool and the capability of generating a new model by combining information from the compared models, provide a tool of high pre-processing value assisting the user in resolving the engineering task being simulated.

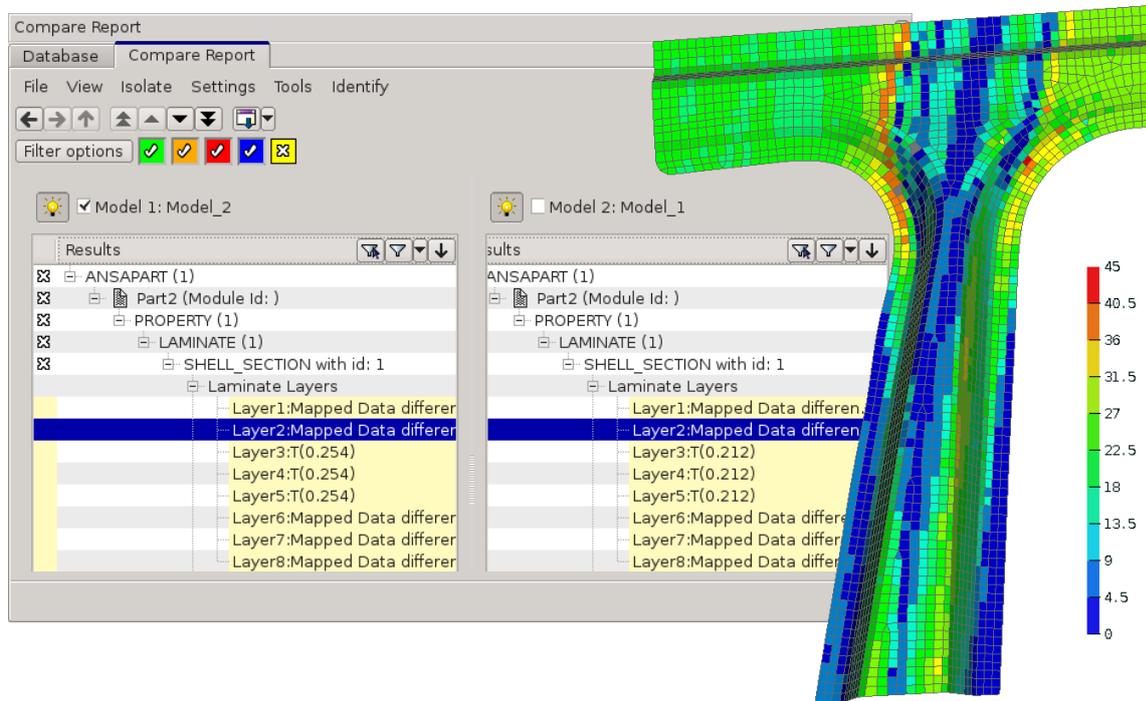


Figure 3 – Comparison of two composite structures, fringe mode shows angle differences at layer level.

- User defined drawing modes

During the course of pre-processing operations regarding CFRP-materials modelling, various parameters are calculated that are not always represented by a regular keyword that ANSA or any other commercial solvers support directly. For instance, the material orientation tensor and anisotropy are examples of tensor and scalar functions and that are mapped and/or calculated with a combination of scripts and results mapping actions. For their visualization, ANSA provides the capability of creating user defined drawing modes with fringe colours, as shown in Figure 4.

Untitled, Current Part: Untitled

Shell
 quads : 250000
 trias : 0
 total : 250000

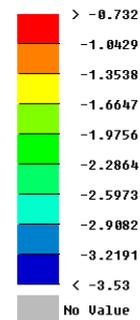
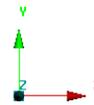
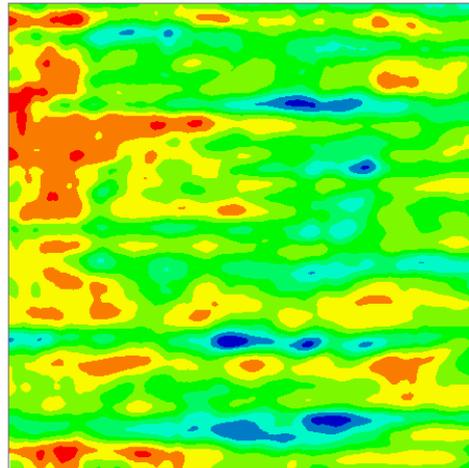


Figure 4 – Example for a fringe drawing mode in ANSA of a user-calculated scalar variable.

3. APPLICATION OF A CLOSED PROCESS CHAIN WORKFLOW FOR CF-SMC

The previously discussed functionalities will be demonstrated on a trial component called “Small hat profile” (SHP), which is usually used for mold filling studies.

3.1 Filling simulation

To simulate the mold filling behavior the Coupled-Eulerian-Lagrangian (CEL) approach is used. Details on this approach, part and material modelling can be found in the work of Romanenko (3). The material pattern defines the initial location of the SMC Material and can be seen in Figure 5 a). Figure 5 b) and c) show the material flow during compression (upper and lower tool have been hidden). In Figure 5 d) the final part filling is achieved and the main fiber orientation is symbolized by blue arrows.

3.2 Mapping, Clustering and Homogenization

In Figure 6 a) an intermediate model of the SHP is shown. It represents an extraction of elements with a material volume fraction $V_F = 1$ from the spatially fixed eulerian mesh (filling mesh) and their redefinition as lagrangian elements. This is why this intermediate model has a non-uniform thickness, which can be seen in the zoomed in view. The fringe plot shows the v. Mises Strain. This field value is in place of the 3D fiber orientation information, because the definition of a symmetric fiber orientation tensor or arbitrary second order tensor is not yet supported in ANSA. In Figure 6 b) the mapped values are shown for a warpage analysis mesh, which should be used for further studies. The values are transferred automatically using scripting functionalities and the results mapping tool described in Section 2. For areas with missing elements the values are extrapolated based on the surrounding information.

Following the mapping step two ASCII files are written. The first file contains the magnitude of the main fiber orientation A for every element of the warpage mesh. The second file contains the direction of the main fiber orientation for every element of the warpage mesh as a normalized vector \mathbf{a} . A represents the magnitude of the local anisotropy. This file is used as an input for a clustering procedure using a dynamic programming algorithm for optimal one-dimensional clustering as developed by Wang (14). The result for 10 clusters can be seen in Figure 6. Every color represents a cluster, which also has weighted means. Details on the calculation of weighted means can be found in (14). The clustering procedure exports an ASCII-File with the new values for A , which are the weighted means of the associated cluster. The procedure for the input and output is visualized in Figure 8.

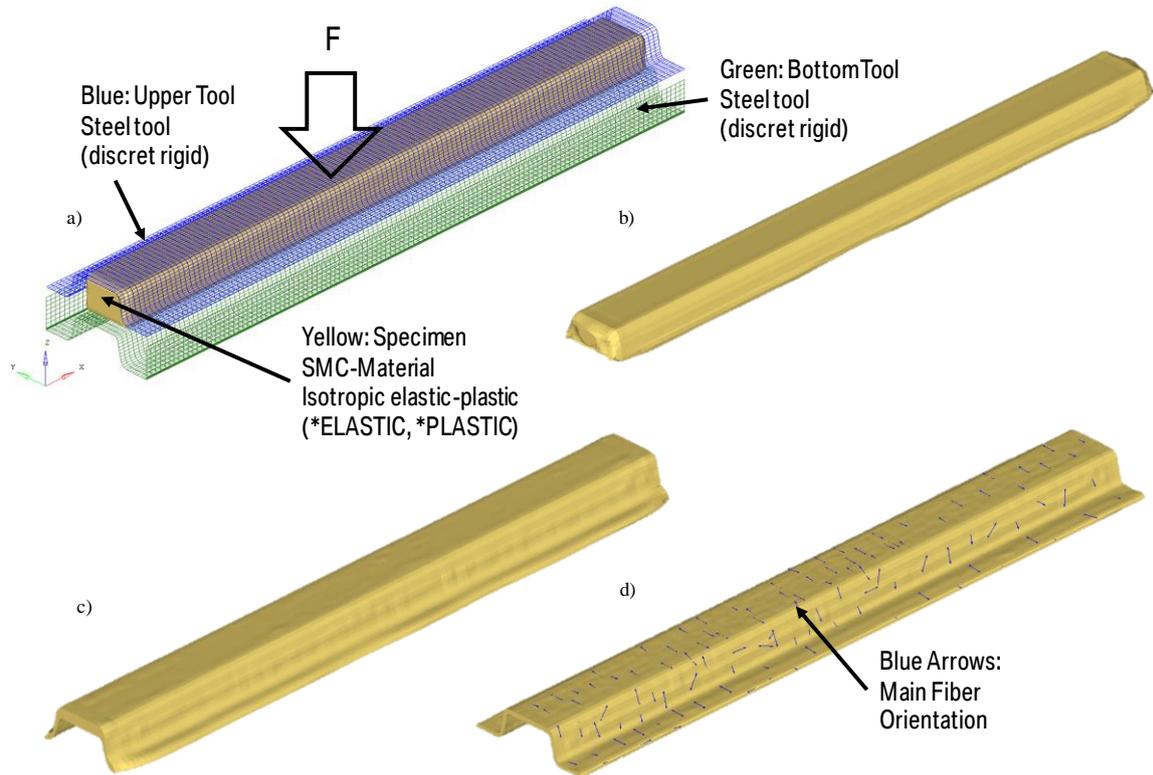


Figure 5 – a) Model for the SHP compression molding simulation with initial position of SMC-Material b) Material position at 24.1 mm tool closing distance c) Material position at 11.25 mm tool closing distance d) Final material position at 3.5 mm tool closing distance with blue arrows showing the main fiber orientation for selected elements

The step of clustering is necessary for practical reasons of further model handling. Without clustering every element would have its own material card (MAT-ID) and element section definition (PID). For the particular case of the SHP it would yield 51200 MAT-IDs and PIDs. To gather the mechanical and thermal properties necessary for the distortion simulation an analytical approach is used. First, four different states of anisotropy for the CF-SMC are generated through one-dimensional rheology experiments described more in detail in the work of Reiß (8). The output of these experiments are analytical functions $f_n(A)$ for the engineering constants $E_{11}, E_{22}, \alpha_{11}, \alpha_{22}$ (see Figure 6, 3.Homogenization), which are implemented in an ANSA script. The $f_n(A)$ for $G_{12}, G_{13}, G_{23}, \nu_{12}, \nu_{13}, \nu_{23}, \alpha_{33}$ are gathered virtually by using a two scheme Mori-Tanaka Homogenization procedure described by Liebold (5) for RVEs which represent the four different states of anisotropy described by their fiber orientation tensor.

The last step in Figure 6 (4. Material cards) contains the Material card creation for every cluster and the local assignment. Two different approaches for the assignment will be discussed in the next section from a numerical point of view. A *SOLID SECTION definition is used and compared to a *SOLID LAMINATE definition.

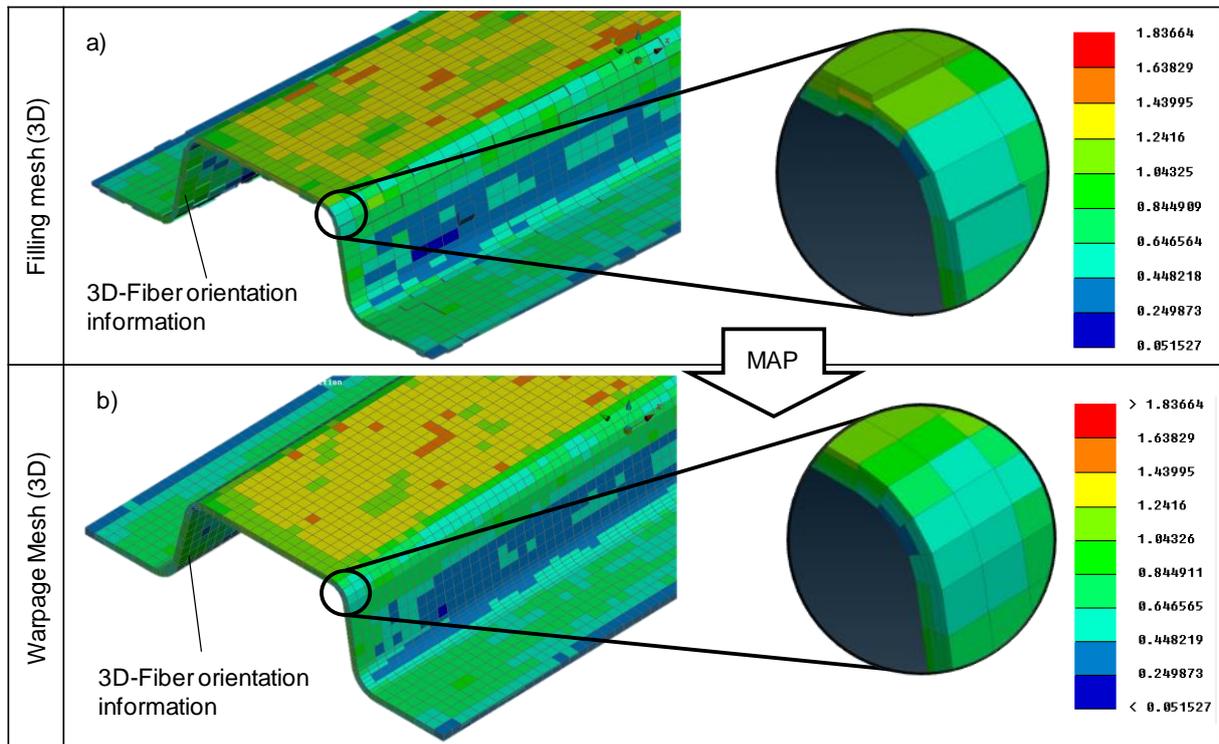


Figure 6 – a) Intermediate mesh for the SHP with an extraction of elements with a material volume fraction $V_F = 1$ from the fixed eulerian mesh (Filling mesh) and their redefinition as lagrangian elements b) Warpage mesh with mapped 3D fiber orientation information

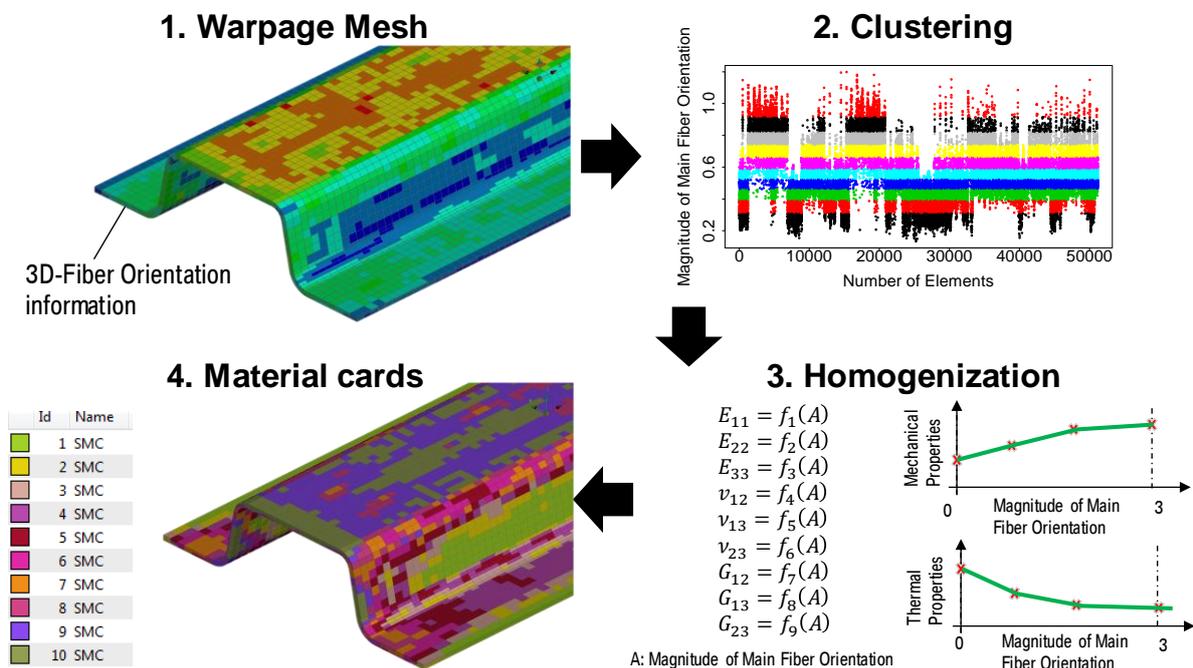


Figure 7 – Workflow of material card creation for distortion simulation

3.3 Distortion simulation

For the previously discussed SHP two main modelling approaches will be studied which are used for different composites depending on their microstructure. The first approach has its roots for short fiber composites in the work of McCullough (9) and is already implemented in LS-Dyna (5). The second one is widely used for continuous Non-Crimped Fabrics (NCFs),

which is well described in the work of Amann (10) and was adapted for discontinuous long fiber composites by several authors (11),(12),(13).

EID	A	EID	A	Cluster	A_mean
	1 0.381426		1 0.381426	2	0.35511458
	2 0.444187		2 0.444187	3	0.42947382
	3 0.319286		3 0.319286	2	0.35511458
a)	4 0.2769	b)	4 0.2769	1	0.26669495

Figure 8 – a) Part of ASCII-File for Cluster Input b) Part of ASCII-File for Cluster Output.

In table 1 the material properties for the 10 clusters from figure 6 are shown. The values are constant throughout the cooldown. To simulate the distortion the initial boundary conditions from table 2 are considered.

Table 1 – Material properties for distortion simulation.

MAT-ID	E1 [MPa]	E2 [MPa]	E3 [MPa]	G12 [MPa]	G13 [MPa]	G23 [MPa]	v12 [-]	v13 [-]	v23 [-]	a11 [1/°C]	a22 [1/°C]	a33 [1/°C]
1	26087.4	15218.1	11301.6	7735.3	5550.7	4705.8	0.35	0.35	0.36	5.00E-06	1.70E-05	3.00E-05
2	27733.1	14997.7	10763.7	7860.1	5340.1	4487.6	0.36	0.36	0.37	4.00E-06	1.70E-05	3.30E-05
3	29066.1	14818	10339.1	7928.6	5169.4	4313.2	0.37	0.36	0.38	4.00E-06	1.70E-05	3.50E-05
4	30167.8	14668.5	9996.4	7963.1	5028.2	4170.7	0.38	0.36	0.39	3.00E-06	1.70E-05	3.70E-05
5	31201.8	14527.4	9682.2	7977.5	4895.6	4038.6	0.39	0.36	0.4	3.00E-06	1.80E-05	3.90E-05
6	32306.7	14375.7	9355.3	7973.6	4753.9	3899.2	0.4	0.36	0.41	2.00E-06	1.80E-05	4.10E-05
7	33517	14208.3	9008.8	7946.9	4598.5	3748.9	0.4	0.36	0.41	2.00E-06	1.80E-05	4.30E-05
8	34754.4	14035.5	8668.8	7895.9	4439.5	3598.2	0.41	0.36	0.42	2.00E-06	1.80E-05	4.50E-05
9	35860	13879.7	8379	7830.7	4297.4	3466.5	0.42	0.36	0.43	2.00E-06	1.80E-05	4.70E-05
10	37351	13666.9	8012.4	7715.5	4105.5	3293.9	0.43	0.36	0.44	2.00E-06	1.80E-05	4.90E-05

Table 2 – Boundary and initial conditions for distortion simulation.

Location	TYPE	Property
Node 1	Displacement	$u_x = u_y = u_z = 0$
Node 2	Displacement	$u_x = u_z = 0$
Node 3	Displacement	$u_y = 0$
All Nodes	Start Temperature	145°C
	End Temperature	20°C

In figure 9 the results for the distortion for both approaches are shown, which are scaled by a factor of 10 to make the difference to the CAD geometry visible. For Approach 1 reduced integrated 8-node hexahedral elements were used. In Approach 2 for every layer the same thickness and one integration point through thickness is used.

It can be observed that both mechanisms for anisotropic composites (spring-in and warpage) discussed by Amann (10) superimpose. Approach 1 and Approach 2 lead to almost similar results.

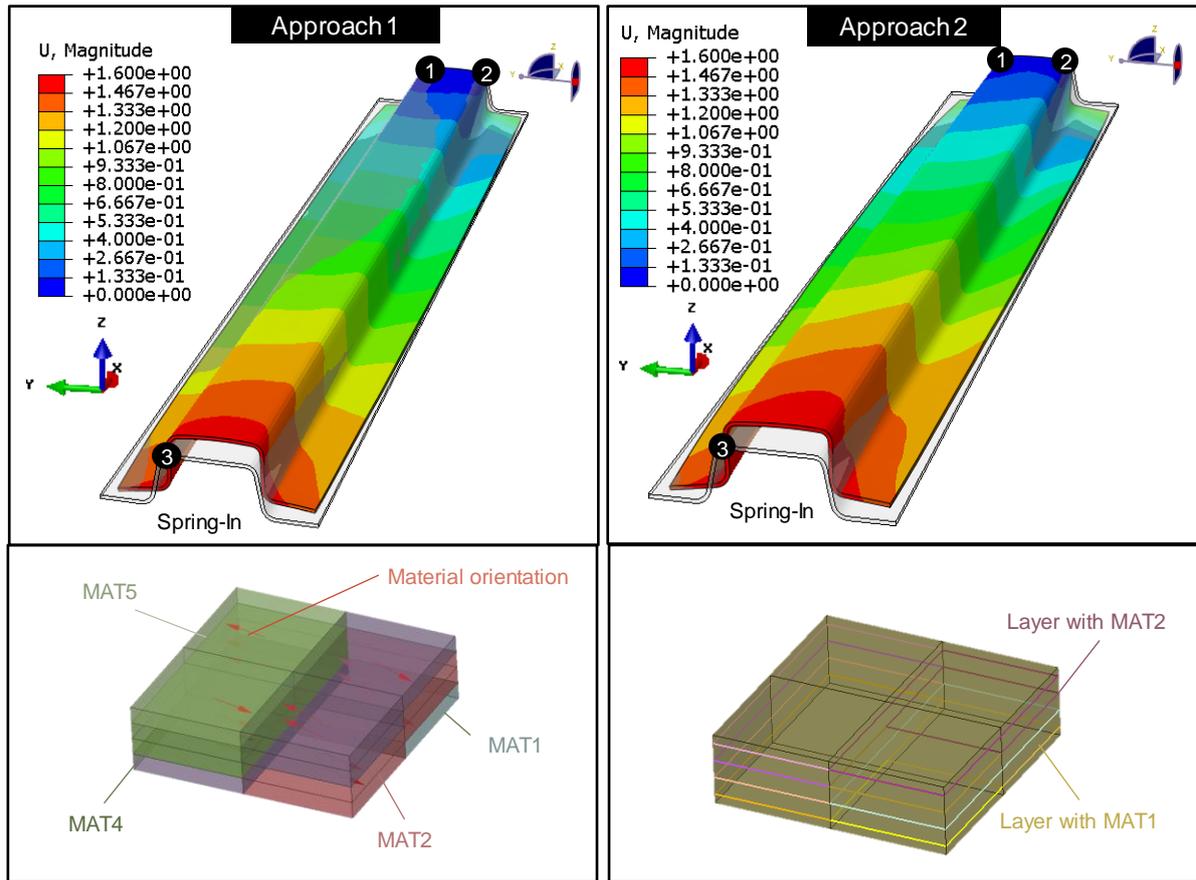


Figure 9 – Two modelling approaches to simulate the distortion with boundary conditions from table 2 on nodes 1, 2, 3.

3.4 Comparison

One key difference of SMC to commonly known composites is that, the mechanical and thermal properties depend on the material pattern which is initially used. In Figure 5 a) a rectangular block charge was used and placed in the initial material position shown within the cavity. To evaluate the differences in material properties when different charge shapes and initial positions are used, it is necessary to compare the two models locally after material card creation (step 4 in Figure 6). This is where the compare functionalities combined with the user-defined drawing mode from Section 2 are used. This case will be demonstrated for two models, which have different local material properties. The first model is the SHP from Figure 5 a) with 10 material cards (10 Clusters). The second model is the SHP from Figure 5 a) with 3 Material cards (3 Clusters). Both models have different local material properties because of the clustering.

First, both models have to be transformed from a solid laminate definition to a shell laminate definition to use the compare functionalities. This is realized by a script without loss of information. Such a transformation is shown in Figure 10 for 4 elements.

After unvolumizing both models their local material properties are stored as variables and can be visualized as a common fringe plot e.g. shell element thickness. The difference in model 1 and model 2 in their α_{33} values are shown in figure 11. The green arrows show the main fiber orientation. Therefore, the direction of α_{33} is perpendicular to the element surface. At this stage of the evaluation it can be seen, that the biggest differences are in the radius. This will later lead to a different spring-in and to different shapes. Without this functionality it would be difficult for the application engineer to identify critical areas, and to interpret reasons for differences in final part simulation results.

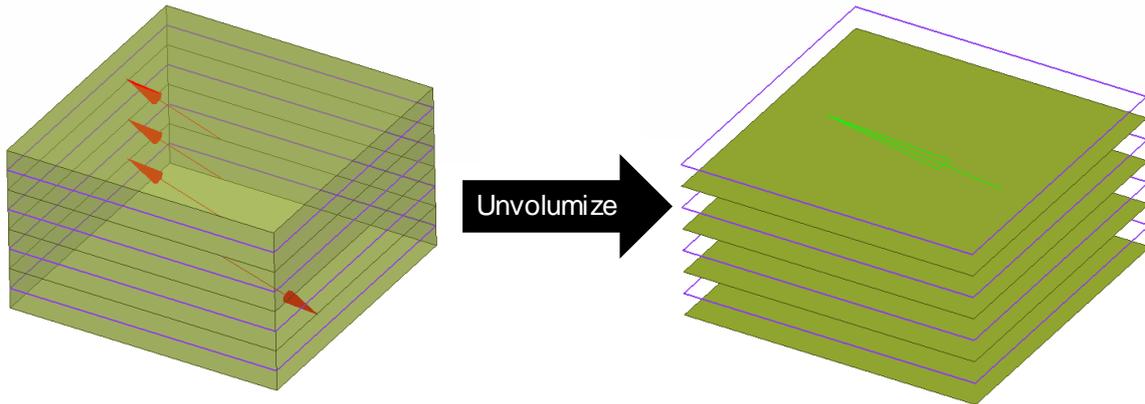


Figure 10 – Transformation of 4 solid elements in a composite definition to 4 shell elements in a composite definition using the unvolumize function.

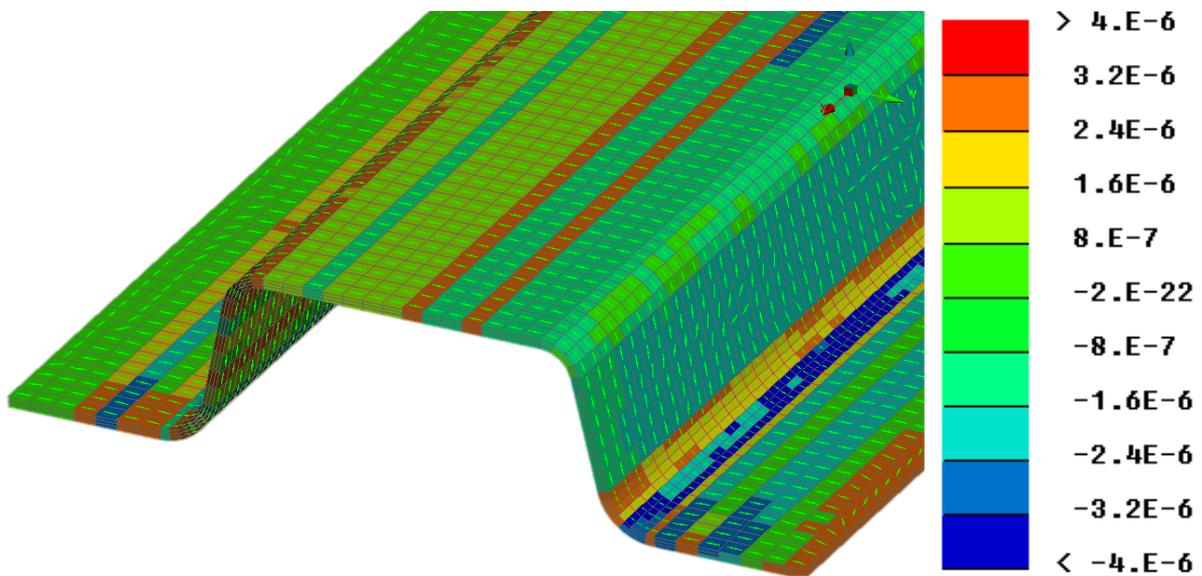


Figure 11 – User-defined fringe plot for the difference in α_{33} for model 1 (10 Cluster) and model 2 (3 Cluster) for Approach 2 from figure 8.

4. CONCLUSION

In this paper a new solution for integrative simulation of carbon fiber sheet molding compounds has been presented on a trial part using four main pre-processing functionalities available in ANSA. The workflow of the virtual process chain includes the compression molding simulation from Romanenko (3), mapping, clustering, homogenization and distortion simulation. An additional functionality for transferring the results from a solid mesh to a shell mesh has been demonstrated. This makes it possible to use the fiber orientation information for further structural and crash simulations. For operability it is also possible to use the shell element models to compare their assigned thermo-elastic material properties locally and visualize their differences.

Further work includes the application of the workflow demonstrated here on the pre-series version of the c-pillar shown in Figure 1 and to evaluate the prediction accuracy of the approach. A sensitivity study on the number of clusters and discretization of distortion meshes will be performed and the results will be compared to optical measurements of the part distortion.

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