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Numerical Material Property Characterization of Long-Fiber-SMC Materials

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Abstract

Compression molding using sheet molding compounds (SMC) is a promising composite manufacturing technology in terms of time and cost efficiency. The discontinuous long fiber reinforcement promises comparatively high mechanical properties. Unlike endless fiber reinforcements, which are usually cured near their final shape, the SMC is pressed into shape. The inherent material flow can cause tremendous off-design fiber deflections. The hypothesis of this contribution is that the fiber architecture highly influences the mechanical properties, so it is crucial to evaluate the effects of the manufactured (as-built) fiber architecture on the properties of the produced part. To this end, a methodology is presented to identify the actual fiber morphology on complex SMC cross sections (ribs) using CT imaging and statistical image analytics from which fiber orientations both in-plane and out-of-plane are derived. On this basis, a micromechanical analysis procedure is set up incorporating the actual fiber orientations to derive the actual as-built mechanical properties. These properties can then be used to perform larger scale analyses of the final SMC part while still capturing the smaller scale as-built behavior. The authors present a validation approach based on four point bending specimens with rib cross sections to evaluate the validity of the hypothesis.

1 INTRODUCTION

Fiber reinforced composites can be categorized by the reinforcement fiber length. For mechanically significantly loaded structures, usually endless fiber reinforcement is the most obvious choice. Their performance and lightweight potential is undoubtedly superior over all other kinds of reinforcement. However, endless fiber materials tend to be expensive and limited in terms of geometrical complexity of the final product. Since these products usually involve autoclave processes, the manufacturing times are comparatively high making them less attractive for high-volume series. On the other end of the spectrum, short fiber reinforcements can be manufactured in injection molding as well as even in additive manufacturing processes [1]. These techniques are ideal for geometrically complex parts for both small series or prototypes (additive manufacturing) as well as high volums (infection molding). However, since short fibers (order of magnitude: up to one millimeter) range below the so called critical fiber length, their mechanical properties are limited. Due to the heterogeneity of a fiber reinforced material, a global mechanical load leads to different stresses in the fiber and the surrounding matrix. The axial fiber loads are transferred through the matrix into the fiber mainly via shear stresses. Below the critical fiber length the matrix fails in shear mode before the fiber is loaded to its maximum load carrying capacity. With longer fibers, the matrix shear loads are distributed over a larger area resulting in a reduced matrix shear stress allowing to introduce higher loads into the fiber. At and above the critical fiber length, the fiber stresses can technically reach the fiber strength allowing a full utilization of the superior fiber properties.

The herein investigated sheet molding compounds are reinforced with long fibers (order of magnitude: a few centimeters), which are by definition above the critical fiber length. SMCs try to combine the flexibility and high volume capabilities of the short fiber reinforcements with the superior mechanical performance of the endless fiber reinforcement. SMCs are manufactured in a compression molding process, i.e. the highly viscous compound is pressed into shape in according molds without having to pre-form the material. This allows for complex and near-net shaped products while still limiting the process time to a minimum. However, the material flow can cause fiber deviations that might result in final fiber morphologies to be off-design. Since the fiber morphology can have a crucial effect on the mechanical material properties, an as-built simulation methodology might be needed in order to accurately predict long fiber reinforced composites.

There are numerous approaches to predict the stiffness of discontinuous fiber reinforcement, namely Eshelby/Mori-Tanaka [2] or Hill's self-consistent homogenization schemes [3]. From the latter, the Halpin-Tsai equations [4] are derived which are practically the standard "rules of mixture" for discontinuous fiber reinforced composites and are explained in further detail for instance in [5]. For further details of the individual methods the interested reader is referred to the review composed by Tucker et al. [6]. The assumption of all analytical models is a straight fiber which does not interact with neighboring fibers. However, in reality we observe fiber waviness as well as strong interactions in-between the fibers due to the dense fiber packing which is encouraged by the press process. Thus, for more realistic predictions micromechanical models have to be used. Within these models the constituents are modeled explicitly so that the above mentioned effects can fully be taken into account. One challenge with modeling long fiber reinforced composites are the high aspect ratios of the fiber. The required model size directly depends on the size of the largest inclusion. While endless fibers can be "cut" at the end of the model, doing the same with a discontinuous fiber leads to the effect that the long fiber appears to have the same properties as an endless fiber since the interaction of the fiber to its neighbor is neglected. Thus, the model size has to be sufficiently large in order to avoid this effect. Additionally, placing individual long fibers in a model quickly results in a problem which is referred to as "jamming limit" which describes the maximum density of fibers that can be validly placed without collisions [7, 8]. This modeling problem can be overcome in various ways [9, 10, 11]. The most promising approach is presented by Fliegener et al. [11] which utilize a virtual compression process to overcome the jamming limit and at the same time additionally induce realistic and process motivated out-of-plane waviness deviations into the model. This approach is adapted here and extended by the fiber orientation mapping procedures in order to evaluate the as-built properties of SMC materials.

Note that this work group has already published a preliminary state of this work [12]. Since then, the constitutive model of the neat resin was changed to capture the nonlinear behavior, the model is now capable of incorporating out-of-plane fiber deviations from CT imaging, the model was extended to predict material properties of complex rib cross sections, and bending tests of specimens with rib cross sections have been conducted to eventually validate the model.

In the following, the constituents are characterized, the modeling strategy is laid out, and finally the experimental validation procedure is explained. At the end, the contribution is summarized and conclusions are drawn.

2 CONSTITUENT MODELS

The SMC material used in the work is HUP 63 GF25 provided by Polynt Composites Germany GmbH. It consists of 25 wt% (20 vol%) 25 mm long glass fiber bundles with a nominally random fiber orientation. This material is certified for use in aircraft cabin components which means a large amount of additives and flame resistants (aluminum trihydrate) is added to the neat unsaturated polyester resin.

While the glass fibers are characterized with standardized test methods, the matrix material cannot be processed without the fibers. This way, this constituent's material behavior has to be determined inversely from the known, i.e. measured, composite and fiber properties. To this end, an analytical fitting framework based on the Halpin-Tsai equations [4] is setup. Since the material behavior of the SMC composite is highly nonlinear, rf. figure 1, the analytical framework has to be able to deal with nonlinear material properties, i.e. the rules of mixture have to be evaluated at every single strain

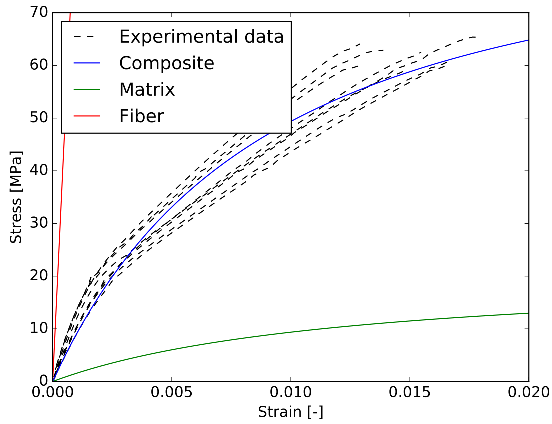


Figure 1 – Inverse determination of the nonlinear matrix properties.

value. The model chosen is a nonlinear elastic model proposed in [13]. The constitutive relation between stresses σ and strains ε are given by

$$\sigma = \frac{E}{1+\alpha|\varepsilon|}\varepsilon \tag{1}$$

with E being the Young's modulus (which describes the initial stiffness in this case) and α the degree of nonlinearity of the model. Note that that model includes linear elasticity as a special case with $\alpha = 0$. The multiaxial generalization and information on implementing this model in commercial FE software packages can be found in [13, 14].

With this model, the fitting framework reads the experimental data from the SMC composite[1] as well as the measured, linear elastic fiber properties[2]. Then, an optimization is performed which basically follows four steps:

1. Vary the matrix material properties E_{matrix} and α.
2. Calculate the composite material properties using the Halping Tsai method and calculating the according stresses for each strain value in the measured composite material data.
3. Calculate the residual $\sum_i \left((\sigma_{measured,i} - \sigma_{model,i})^2\right)$.
4. Continue with 1. until residual has reached a minimum.

Figure 1 shows the results of this fitting. The depicted material properties of the matrix are $E_{matrix} = 1682\,MPa$, $\alpha = 79.7$. Together with the measured fiber linear elastic properties, all constituents are now characterized which is the basis for the upcoming micromechanical analysis.

[1] raw stress/strain data from standardized tensile tests based on DIN EN ISO 527
[2] $E_{fiber} = 95\,GPa$

3 FIBER MORPHOLOGY CHARACTERIZATION AND MODELING STRATEGY

The aim of this contribution is to provide a methodology to evaluate the influence of the fiber morphology on the mechanical properties. Thus, the morphology is an input to the modeling approach. While in this contributions we have focused on x-ray computed microtomography (μCT) as an experimental basis for this input, completely numerical approaches are conceivable where the fiber morphology e.g. could be derived from flow/filling simulations. The source of the data is irrelevant for the algorithms and methods used in this chapter.

For the used material HUP 63 GF25 by Polynt, the long fiber reinforcement consists of 25 mm long fiber bundles which practically keep their bundle character even during the compression molding process, rf. figure 2. The CT images are evaluated in terms of fiber orientation via automated image processing algorithms. The orientations are grouped into angle classes of 10° increments. This way, the in-plane fiber orientation can be described with a simple statistical frequency over angle class relation.

The out-of-plane orientations are only evaluated if a considerable fiber reorientation is expected due to the special out-of-plane shape of the mold, e.g. a rib cross-section. If only flat plates are investigated, the characteristic out-of-plane waviness of the fibers is already taken into account due to the process-oriented modeling strategy. This strategy does not, however, capture the mold flow of the material so that the characteristics of this flow have to be drawn from the fiber morphology and mapped into the model. The (experimental or numerical) basis of the extraction is identical to the in-plane characterization. An image processing algorithm extracts the local fiber orientations, rf. figure 3(a). These orientations are then processed into deviated layers, rf. figure 3(b), which are the basis for mapping the out-of-plane orientations into the model. Even though the layer representation of the orientation is not a precise replica of the grid layer distribution, it captures the general characteristics of the fiber orientation which is important in the following modeling process.

Now that the fiber morphology is characterized, the micromechanical FE model

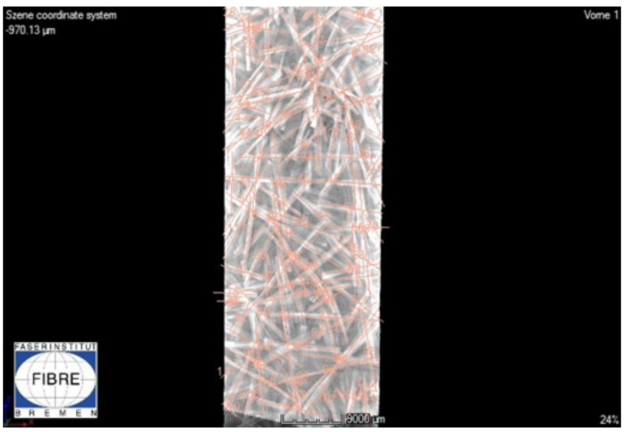
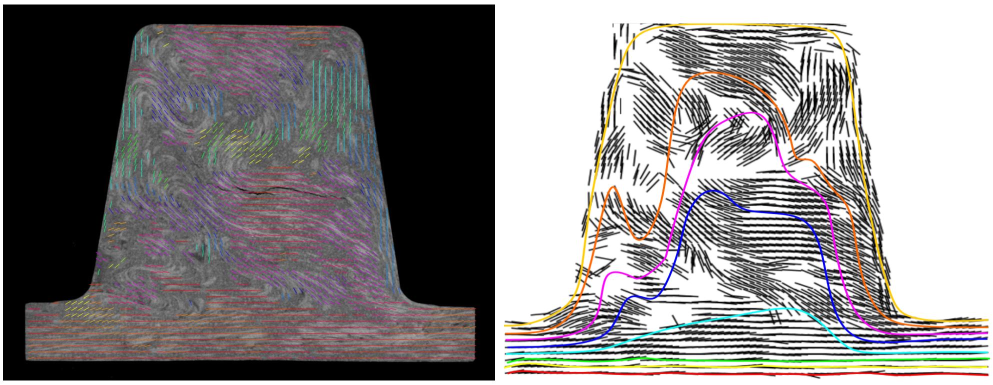


Figure 2 – In plane fiber bundle orientation.



(a) *Processed CT data with local fiber orientation*

(b) *Derived deviated layers*

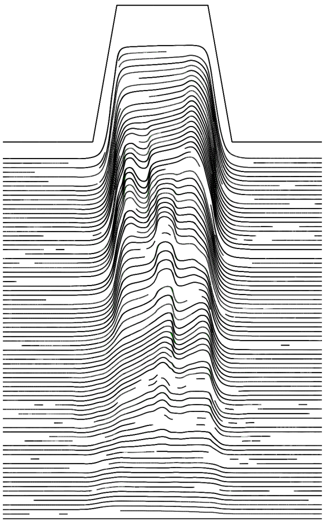
Figure 3 – Out of plane fiber orientation for a rib cross section with an aspect ratio of 0.67 (width to heigth).

can be set up. This has been described in great detail in the previous publication of this work group [12]. Thus, the following description briefly summarize the setup and focuses on the orientation mapping procedure which is not described in the aforementioned publication.

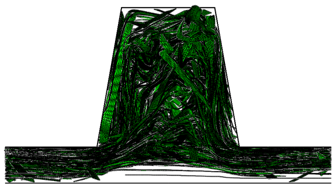
The model framework is based on the commercial finite element software package Abaqus. First, the relative fiber orientation distribution has to be translated to specific fibers with specific orientations. The fiber volume fraction and the model size determine the total number of fibers needed and the orientation distribution determines how these fibers have to be oriented in order to meet the distribution. These fibers have to be placed in the model in order to meet the distribution. These fibers are then individually placed in flat layers without collision. Once all fibers are placed, the flat layers are transformed according to the deviated layers depicted in 3(b) and 4(a). After the layer deviation, the layer stack is virtually compressed, i.e. an explicit FE simulation of the deviated fiber model is conducted. The result of this analysis, rf. figure 4(b), is the coordinates of the deviated, compressed fibers. These fibers now carry the characteristics of the fiber morphology as the specimen that was investigated in the CT scans.

To derive material properties from this fiber stack, the fibers are embedded in a block of solid elements which represents the matrix. Note that the fibers are represented as linear, 4-node, reduced integrated 2D shell parts while the matrix consists of linear, 8-node, fully integrated solid elements. The fibers are embedded in the matrix via constraints. This modeling strategy is chosen to reduce modeling effort [12].

The classical approach to derive material properties from a micromechanical model using unit strains is not applicable to nonlinear material behavior and complex model shapes. Instead, a virtual material test is conducted by applying a displacement controlled, uniaxial tensile load to the model. From the resulting force-displacement response, the effective stress-strain response is derived which represents the global material law of the model. This law contains the actual as-built fiber morphology in-



(a) *Before*



(b) *After*

Figure 4 – Virtual fiber compression.

formation and can easily be transferred to be applied to larger scale models.

4 EXPERIMENTAL VALIDATION PROCEDURE

In order to verify the modeling strategy described in the previous section, bending specimens with various rib cross-sections are manufactured. Five different aspect ratios of rib width to rib height are considered in addition to two different rib shapes, trapezoidal or drop shaped, rf. figure 5 and table 1.

A four point bending test is conducted for all configurations mentioned in table 1. All specimens are equipped with two strain gauges while an external displacement sensor tracks the bending of the specimen. The outer support length is 189 mm and the inner support length is 63 mm. The force-displacement curves of the specimens with aspect ratio 0.67 are shown in figure 6. Note that the differences of the curves between the drop and the trapezoidal specimens are mainly due to the differences in the geometrical moment of inertia and are not to be confused with the pure influence of the different fiber morphologies.

With these results, a validation of the modeling procedure can be performed by conducting a virtual bending test, rf. figure 7. This solid model consists of linear 8-

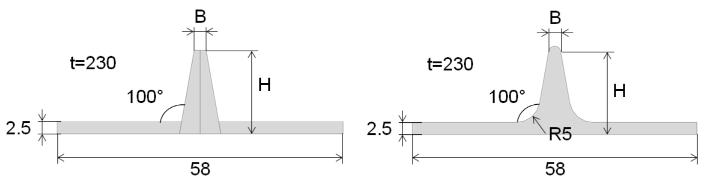


Figure 5 – Definition of trapezoidal and drop rib specimen (measurements in mm).

Table 1 – Investigated combinations of geometrical rib parameters.

Rip shape	Rib width	Rib height	Aspect ratio
Trapezoidal	2.5 mm	15 mm	0.17
Trapezoidal	5 mm	15 mm	0.33
Trapezoidal	10 mm	15 mm	0.67
Trapezoidal	10 mm	10 mm	1.0
Trapezoidal	10 mm	5 mm	2.0
Drop	...		

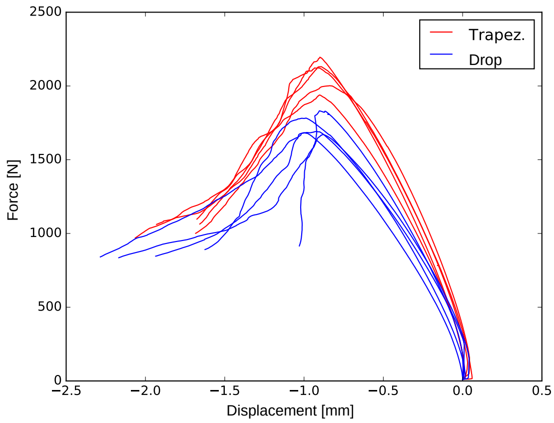


Figure 6 – Four point bending test results of rib specimen with 0.67 aspect ratio.

node, 3D solid, fully integrated elements with discrete rigid supports and appropriate contact definitions. The reference solution is to use the isotropic SMC material properties which are measured using flat specimens, i.e. with no off-design fiber deviations. From the above described modeling approach, we obtain SMC material properties that include the effects of the fiber deviations that are apparent in the CT scans. When these material properties are used in the virtual bending tests, the results are expected to further improve the predictions of the experimental tests. Additionally, the error of neglecting the fiber morphology in the calculations can be determined, thus enabling the evaluation of the benefit of the herein presented modeling strategy.

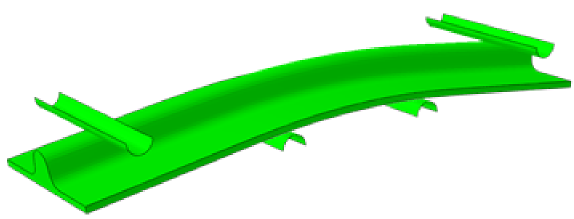


Figure 7 – Virtual four point bending test of a rib specimen with 0.67 aspect ratio.

5 SUMMARY AND CONCLUSIONS

This contribution deals with the numerical prediction of material properties of long fiber reinforced composites using sheet molding compounds (SMCs) as a use case. The suggested approach is based on a micromechanical FE model. An approach is presented that is able to inversely obtain the nonlinear matrix material properties from the composite and the fiber properties. It turns out that taking the nonlinearity of the material into account, the prediction quality of the model can be drastically improved compared to the widespread approach of assuming linear elastic matrix properties.

The hypothesis of this work is that the observed fiber rearrangement during the press process highly influences the composite material behavior. To this end, the authors present an approach to incorporate the actual fiber orientations in the model. While it is technically possible to obtain the fiber orientations numerically from flow simulations, the authors have utilized CT imaging as the basis for the fiber morphology investigations. Using automated image processing techniques, both the in-plane and out-of-plane fiber orientation distributions are obtained and mapped into the numerical model. The effective nonlinear material law of the as-built composite can thus be obtained.

The authors propose a validation procedure on the basis of bending tests of complex rib cross sections in order to evaluate the developed method. This way, the benefit of the method can be elaborated on a most realistic SMC design feature.

ACKNOWLEDGEMENTS

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