NordDesign 2012
August 22 – 24, 2012
Aalborg, Denmark

Consideration of Anisotropic Material Properties in Mechanical Design within Early Design Phases

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Abstract
To achieve the goal of simulating the structural behavior of parts made of short fiber reinforced polymers with satisfactory accuracy and justifiable modeling effort, a new approach adapted to the needs of the early design steps was developed at the Chair of Engineering Design (*KTmfk*). Hereby, the various effects of material behavior are modeled by overlapping two different material models in one finite element definition. The anisotropic material properties are determined by an injection molding simulation. The complexity of the resulting fiber distribution is reduced to just three values per finite element. The paper's focus is the introduction of an automated method supporting the determination of the numerical material parameter and a new tensor based method enabling the averaging of the complex orientation state. The benefits of the new methods and a validation are presented.

Keywords: early design steps, lightweight design, simulation, fiber reinforced polymers

1. Introduction

The important role of lightweight design leads to an increasing deployment of short fiber reinforced polymers (SFRPs). These materials are characterized by beneficial stiffness respectively strength properties and low density. Furthermore their positive energy dissipation capability benefits their application for crash relevant parts [1]. With help of the injection molding technique an economic method to produce parts in large quantities is given as well. However, the simulation based prediction of the mechanical behavior of parts made of SFRPs can be considered as challenging. On the one hand, their material behavior is characterized by various effects (non-linearity, plasticity, strain-rate dependency, etc.) being difficult to cover in total within a structural simulation. One the other hand, the mechanical properties are anisotropic and depend on the process induced fiber orientation. In order to save modeling and calculation effort, especially in the early design steps simplified simulation methods neglecting effects like anisotropy are deployed. Due to the assumed simplifications only results of minor accuracy can be obtained. However, from the point of view of engineering design the deployment of inaccurate, isotropic approaches should be avoided. These approaches don't allow an adequate exploitation of the freedom of design offered by early design steps. Consequently, the following research question arises: How can the product developer be supported suitably at the process of mechanical design in early design phases?
To achieve the goal of simulating the crash behavior of SFRP-parts with satisfactory accuracy and justifiable modeling effort, a new modeling approach based on the Finite Element Method (FEM) was developed at *KTmfk*. Hereby, the various effects of material behavior shown by parts made of SFRPs are modeled by overlapping two different material models in one finite element definition. The anisotropic material properties are determined by an injection

molding simulation. The complexity of the resulting fiber distribution is reduced to just three values per finite element of the structural simulation model. The approach is customized for thin walled parts since SFRP-structures are usually of laminar shape.

The present paper is structured as follows. First, the requirements for a simulation approach for early design steps as well as state of the art simulation methods are briefly discussed. Afterwards the above mentioned approach of *KTmfk* will be described. The paper's focus is to explain further developments regarding an optimized method to determine the numerical material parameters as well as a new method enabling averaging the orientation state given by the process simulation. The paper ends with a conclusion.

2. Structural simulation of compound structures in early design steps

According to Pahl/Beitz [2] the design process can be classified into four steps: product planning, conceptual design, embodiment design and detail design. The first geometrical design proposal is generated at the beginning of the embodiment design phase considering the specifications defined in the first and second phase. The CAD based geometry developed in the embodiment design phase is the foundation for following structural simulations usually based on the FEM. Since the focus of the early embodiment design phase is the definition of the geometry, lots of different design variants have to be investigated. The aim of the approach being discussed in this paper is supporting the design engineer at this particular task. To be applicable in the early phases, the following requirements shall be fulfilled:

- Delivering accurate results while considering all relevant effects of material behavior (anisotropy, strain-dependency, etc.)
- Enabling simulations with low computational and manual effort
- Ideally using standard CAE-software
- Providing reproducible results regardless of the CAE engineer's experience

A very accurate structural simulation of the SFRP-parts can be achieved by using software add-ons (see [3], [4]) for standard FE-codes, which enable the coupling between process and structural simulation. Since these existing tools are connected with high modeling and computational effort, rather simplified approaches are deployed. Hereby, the anisotropic behavior is neglected and the resulting uncertainties are considered by global decreasing parameters [5] for the mechanical properties like stiffness and strength. Properties like strain-rate dependency and nonlinear behavior are often disregarded entirely. The easy applicability of this method is linked to imprecise simulation results and consequently leads to a non-adequate exploitation of the early design steps.

A simplified simulation approach considering the orientation properties determined within a process simulation is introduced by Nutini [6]. In this approach a material model originally implemented for modeling sheet metal structures is used. The determination of the material parameters is carried out automated by a multi-objective optimization. The consideration of the orientation data (obtained by a process simulation) is performed with the help of a self-developed mapping software, enabling reproducible results. The legitimacy of the approach could be proven by several experiments. However, the method is subject to certain restrictions. The deployed material model only allows the representation of anisotropic properties in the plastic phase. The introduced mapping software is limited to shell-mesh based process simulations. This only allows for a two dimensional flow analysis and consequently leads to minor accuracy. The influence of the varying degree of the orientation state, resulting from the manufacturing process is not considered.

3. Simplified simulation approach of KTmfk

Basically the structural simulation of SFRP-parts can be split up into two main tasks. On the one hand, a numerical material representation and the associated material parameters have to be defined. On the other hand, the anisotropic material properties have to be extracted from the results of a process simulation. More specifically, for each finite element of the model of the structural simulation a angle α defining the orientation of the fibers, as well as a value θ characterizing the degree of the orientation has to be taken into account. The methods being used to fulfill both tasks are displayed in figure 1 and explained in the following.

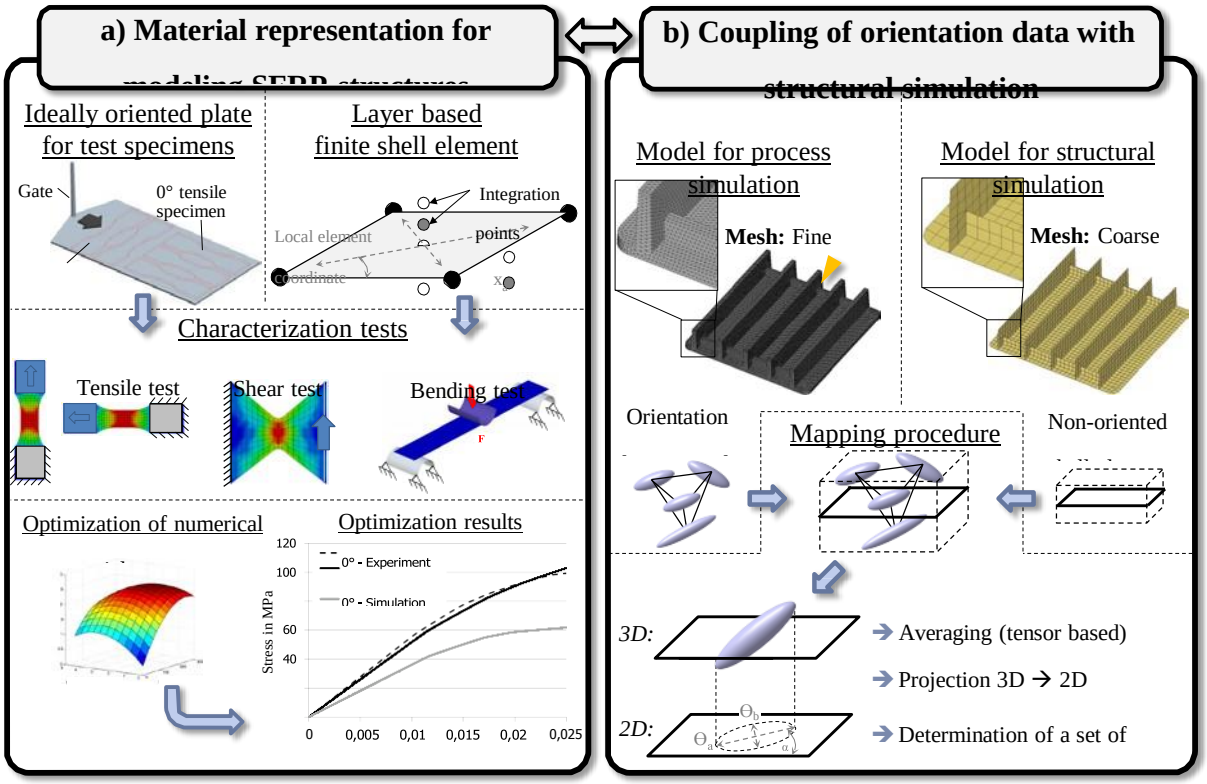

Figure 1. Overview of the simulation approach for SFRP-structures

a) Material representation

As material representation a phenomenological approach is pursued. This means the stress-strain curves obtained by physical characterization tests will be approximated with corresponding virtual tests by adjusting the numerical material parameters adequately. This procedure is referred to as "parameter fitting". To be able to represent a multi-axial stress state the fitting procedures have to be carried out for tensile, shear and bending tests. Since SFRPs show a variety of effects of material behavior (see section 1), their mechanical properties cannot be represented using standard material models already implemented in commercial FE-codes. To be able to consider all relevant effects, Schöpfer's [7] basic idea was picked up: Through overlapping two basic material models in one finite element by using a user defined integration rule, the desired effects of material behavior can be covered by several material models in total. Within the approach of KTmfk, a linear-elastic anisotropic material model (*Mat_A*) enables the representation of the direction-dependent properties. The second material model, an elastic-plastic isotropic description (*Mat_B*) allows covering non- linearity, plasticity, strain-rate and temperature dependency. A detailed differentiation to the work of Schöpfer can be withdrawn [8]. A unique feature of the approach of KTmfk is the adjustment of the bending behavior of the virtual model. The two material models assigned to the integration points through the thickness of the layer based finite elements (see figure 1)

are characterized by alternating stiffness properties. Consequently, by moving stiff layers towards the outer layers, respectively by increasing or decreasing the layer thickness adequately, the bending behavior can be adjusted without affecting the in-plane behavior.
Within the first approach the parameter identification was performed manually, which can be considered very time consuming. In the present paper an automated method using optimization methods will be introduced (see section 4).

b) Coupling of orientation data with the structural simulation

The anisotropic material parameters depend on the fiber distribution within the part. Via process simulation orientation tensors (defined by Advani/Tucker [9]) describing the orientation state can be determined. These 3x3 tensors a_{ij} are calculated at each node of the model of the process simulation. By performing a principal axis transformation, a_{ij} can be displayed as orientation ellipsoid (see figure 2). The eigenvectors e_i portray the principal direction of the fiber distribution (*orientation angle*), whereas the eigenvalues λ_i indicate the *orientation distribution probability* (ODP) of the corresponding principal axis.

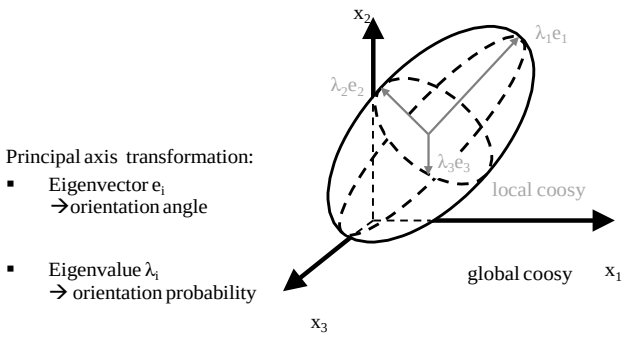

Figure 2. Fiber orientation tensor a_{ij} and orientation ellipsoid

In order to predict a realistic fiber distribution, a fine 3D tetrahedron mesh is recommended for the process simulation. For the structural (crash) simulation of laminar structures, a rather coarse shell mesh is preferable in order to keep the calculation time within an acceptable range. Due to this mesh inconsistency a mapping procedure of the orientation data has to be performed. Therefore, bounding boxes around each shell element are defined collecting the corresponding orientation tensors. In the previous approach [10], orientation vectors were extracted from the grouped tensors and were projected on the shell plane and averaged afterwards. With the help of these vectors an angle α and two ODP values Θ_a/Θ_b describing the orientation of the projected ellipsoid respectively it's shape are defined for each element (see figure 1). The derivation of the anisotropic stiffness properties and the implementation of the simplified approach of KTmfk in commercial FE-Software is described in [11].
Since the vector based averaging method showed problems at precisely predicting the degree of the orientation (Θ_a/Θ_b), a new averaging method will be introduced in section 5.

4. Automated optimization of the numerical material parameters

The use of optimization algorithms for the parameter fitting procedures requires the representation of the virtual characterization tests by analytical equations (meta models). To be precise, the stress-strain behavior respectively the displacement behavior shown by the tensile, the shear and the bending tests have to be approximated by the meta models. Within the presented approach the meta model is set up by a linear regression based on supporting points delivered by the associated virtual characterization model. The supporting points are selected according to the theory of d-optimality [12]. For the linear regression model n_s+1 supporting points are needed, whereas n_s stands for the amount of material parameters of the

focused virtual characterization test. In order to improve the prediction quality, an additional

amount of 50% of supporting points is recommended. This so called “over sampling” is used to take into account the approximation error. As optimization objective the minimization of the mean square error between virtual and experimental force-displacement curves is defined. The whole optimization procedure is performed automatically in several iteration loops (Successive Response Surface Method), leading to a gradual improvement of the quality of the meta model. Within the described activities 15 analysis iterations were performed.
The anisotropic stiffness behavior is controlled by two orthogonal young-moduli E_a and E_b, which have to be determined within two separate tensile tests. Since the distinct material parameters of the characterization tests hardly affect each other, four separated optimizations are performed sequentially. The material parameters to be determined in each test procedure and the resulting deviations between physical and virtual material test are shown in Figure 3.

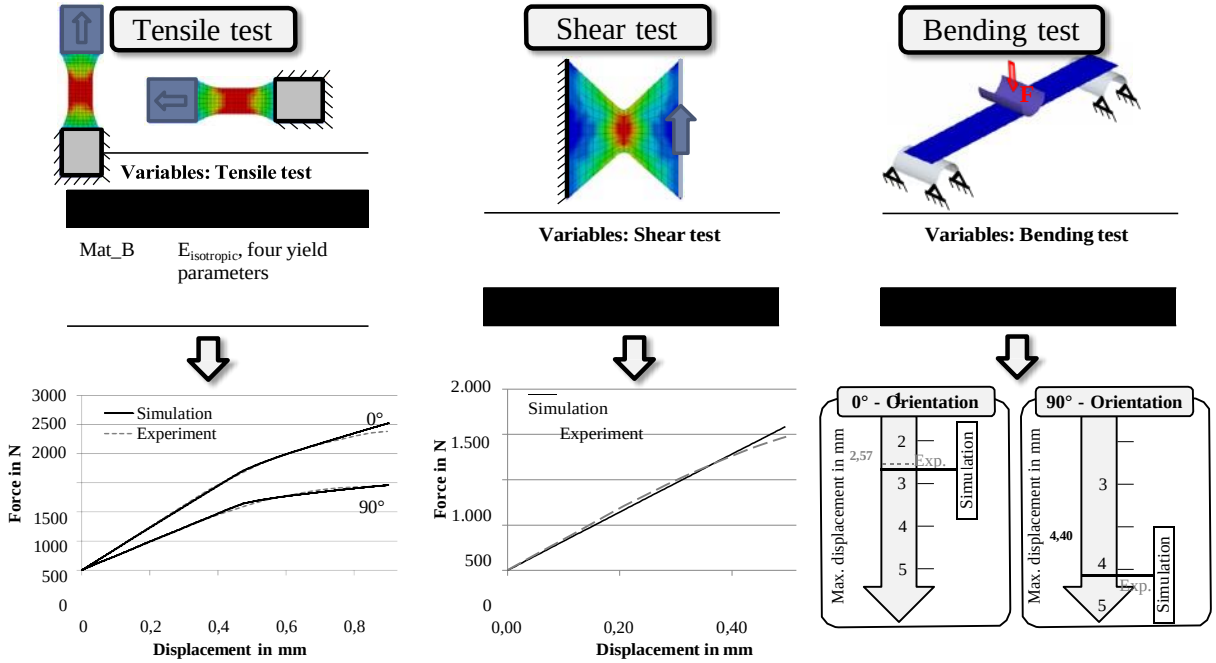

Figure 3: Optimization models, variables and results

The deviation of the force-displacement curve of the tensile test in 0° and 90° direction is just approx. 1.6 and 1.9 %. The non-linear shear behavior measured in the experiment cannot be obtained in the simulation model. Since the degree of non-linearity is very weak, an acceptable deviation of 4.5 % is resulting. The deviation of the maximum displacement of the virtual and experimental bending test conducts 5.1 % for 0° orientation respectively 1.3 % for 90° orientation. Considering the fact that most phenomenological approaches don‘t consist of a bending fitting at all, the bending results can be regarded as quite satisfactory.
The main advantage of the presented optimization method compared to the manual procedure is a significant time-saving. The whole optimization calculation takes less than two hours, whereas the manual approach takes at least one working day for a skilled CAE-engineer.

5. Tensor based averaging of orientation information

Instead of the vector based averaging method mentioned in section 3 b), the averaging procedure can be performed more efficiently by forming the mean values of the corresponding components of each tensor. The legitimacy of this tensor based averaging procedure is proofed by investigating the characteristic properties of the fiber distribution function ψ, which is the basis of the orientation tensor a_{ij} [9]. $\psi(\Theta, \varphi)$ describes the chance of finding a fiber at a given angle combination of Θ, φ (see figure 4). ψ has to be defined for each space of a given continua. Instead of declaring the distinct angles, the fiber distribution

function can also be defined as function of the unit vector **p**.

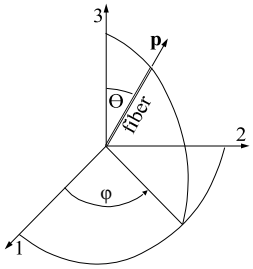

Figure 4. Orientation of a fiber within the continuum according to [9]

According to [9] ψ has to fulfill the following physical conditions. First, the values of ψ have to be non-negative. Moreover, the fiber distribution function must show a symmetric behavior, since an ideal cylindrical fiber shape is assumed. Consequently ψ must subject

$$\psi(\Theta,\varphi)=\psi(\pi-\Theta,\varphi+\pi) \quad \text{respectively} \quad \psi(\mathbf{p})=\psi(-\mathbf{p}). \qquad (1a) \text{ and } (1b)$$

Finally the closed surface integral of ψ for each space in the continuum, must equal the scalar value 1, as ψ is a density function. This normalization condition is described by the equation

$$\int_{\Theta=0}^{\pi}\int_{\varphi}^{2\pi} \psi(\Theta,\varphi)\sin\Theta \,d\Theta\, d\varphi = \oint \psi(\mathbf{p})\,d\mathbf{p}=\underline{1}. \qquad (2)$$

A group of fiber distribution functions ψ_i can be averaged by summing up the functions and dividing the result by the amount of functions. This procedure delivering the mean distribution function $\bar{\psi}$ is described by

$$\bar{\psi}=\frac{1}{4}\sum_{i=1}^{4} \psi_i. \qquad (3)$$

Prove is needed that the conditions mentioned above are kept up after the averaging procedure. Since ψ is non-negative, $\bar{\psi}$ is trivially non-negative, too. The fulfillment of the normalization condition can be shown by integrating eq. (3) over the sphere of the unit vector $\mathbf{p}$ (see eq. (4)). Within eq. (4) the sum can be extracted from the integral due to its finite character, which is emphasized by the term "finite sum" (f.s.).

$$\oint \bar{\psi}(\mathbf{p})\,d\mathbf{p}=\frac{1}{4}\oint\sum_{i=1}^{4} \psi_i(\mathbf{p})\,d\mathbf{p} \overset{f.s.}{=} \frac{1}{4}\sum_{i=1}^{4} \oint \psi_i(\mathbf{p})\,d\mathbf{p} = \frac{1}{4}\sum_{i=1}^{4} \underline{1}=\underline{1} \qquad (4)$$

$$\oint \psi_i(\mathbf{p})\,d\mathbf{p}=\underline{1} \;\; see\ eq.(2)$$

By inserting eq. (3) in eq. (1a), the maintenance of the symmetric behavior can be proven, as inserting the sum does not affect the symmetry condition:

$$\bar{\psi}(\Theta,\varphi)=\frac{1}{4}\sum_{i=1}^{4} \psi_i(\Theta,\varphi) = \frac{1}{4}\sum_{i=1}^{4} \psi_i(\pi-\Theta,\varphi+\pi)=\bar{\psi}(\pi-\Theta,\varphi+\pi) \qquad (5)$$

By forming the dyadic product of the unit vectors $\mathbf{p}$ and then integrating this product over all directions of ψ, the orientation tensor a_{ij} describing the orientation state is derived. Eq. (6) proofs that the proposed component wise averaging approach is a valid method for the given application. It can be shown, that by forming a_{ij} with the use of averaged orientation tensors $\bar{\psi}$ (eq. 3), it leads to the perused component wise averaging of the distribution function

$$a_{ij}=\oint p_i p_j \bar{\psi}(\mathbf{p})\,d\mathbf{p}=\oint p_i p_j \frac{1}{4}\sum_{k=1}^{4} \psi_k(\mathbf{p})\,d\mathbf{p} \overset{f.s.}{=} \frac{1}{4}\sum_{k=1}^{4} \oint p\,p\,\psi\,d(\mathbf{p}) = \frac{1}{4}\sum_{k=1}^{4} a \qquad (6)$$

$$\bar{a}_{ij} = \frac{1}{4}\sum_{k=1}^{4} a_{ij} \qquad \text{eq.3}$$

$$\bar{a}_{ij} = \frac{1}{4}\sum_{k=1}^{4} a_{ij} \qquad \text{f. s.}$$

The key advantage of the new tensor based averaging method is a significantly improved quality of the reproduction of the degree of orientation Θ. In figure 5 the initial orientation state determined by the injection molding application and the orientation state after the tensor based averaging are opposed. A good correlation between both images can be obtained. Since the 3D orientation state is projected on the 2D shell elements (see figure 1), the orientation share normal to the shell-plane is lost. Reduced Θ values after the mapping process can

clearly be observed in figure 5. As expected this effect especially appears in areas with turbulent fiber distribution (regions close to the gates and edges of the part).

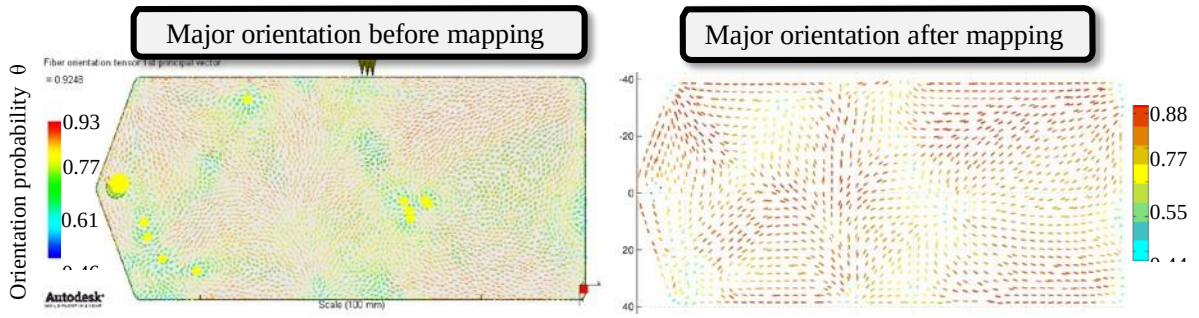

Figure 5. Fiber orientation of a plate with chaotic gate set-up

6. Validation

The validation of the approach was carried out by opposing experimental and virtual results of a drop weight test. The set-up of the experiment is displayed in figure 6. The test object is an injection molded plastic plate, made of a thermoplastic polymer containing 20% short glass fibers. The plate shows a homogenous orientation along the y-axis. Due to this preferred orientation state an initial crack along the y-axis appears in the experiment, followed by a crack in the x-axis. This order of the crack growth could have been verified by tests at low impact velocities (less than 1 m/s), which lead only to a crack in y-direction. Figure 6 shows a snap shot shortly after the impact. By the use of the presented anisotropic approach the initial crack in y-direction can be represented. However, in an isotropic simulation a crack growth in x- and y-direction appears almost concurrently. Moreover, the length of the crack parallel to the y-axis can be approximated more realistically with KTmfk approach. Consequently, even for the chosen simple example, an isotropic simulation is not capable of representing the test results sufficiently.

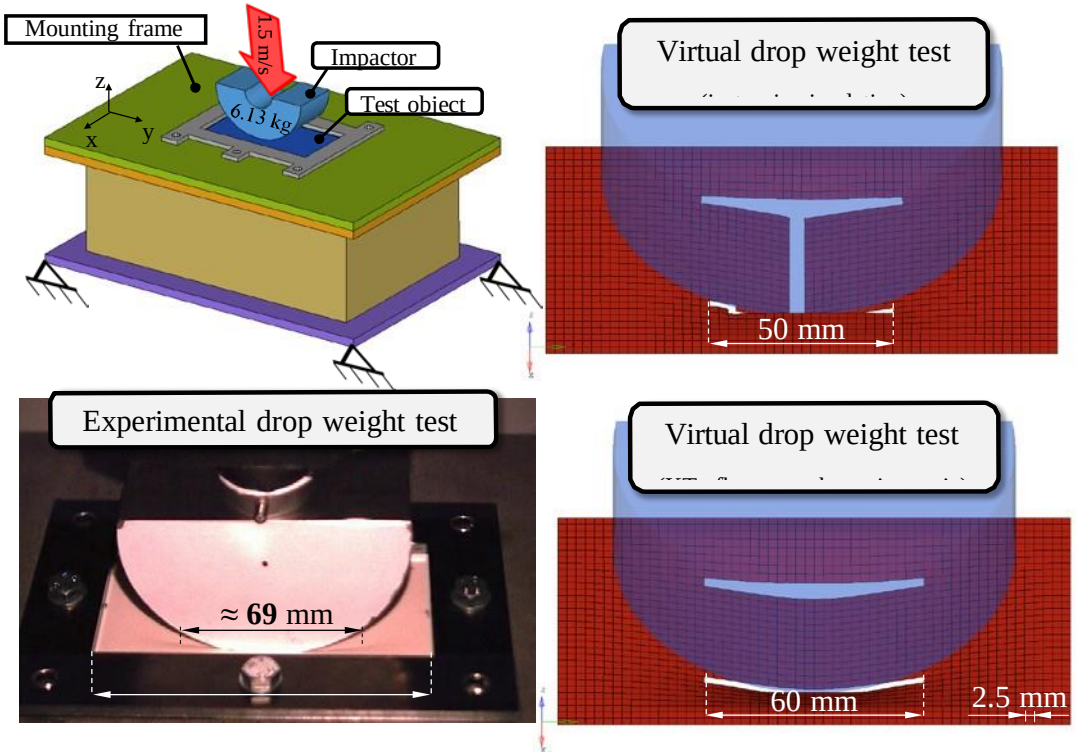

Figure 6. Drop weight test of a homogenous oriented plastic plate

7. Conclusion

In the present paper a simplified simulation approach allowing the consideration of orientation properties of SFRPs within a crash simulation is introduced. The new approach enables the desired adequate exploitation of the freedom of design, offered by the early phases. As shown in the following, the requirements for simulation methods to be deployed in early phases as stated in section 2 can be fulfilled.

By using the technique of overlapping existing material models, no costly implementation of additional user defined material descriptions is necessary. Compared to isotropic approaches, more accurate results can be achieved (see figure 6) with an acceptable modeling effort. Contrary to previous simplified approaches (e.g. [6]) besides the direction of the fibers (angle α) also the degree of the orientation (Θ_a, Θ_b) is taken into account, enabling a more realistic representation of the anisotropic stiffness properties. The averaging of the orientation state is performed by a tensor based method enabling the reduction of the orientation state with good reproduction quality. The introduced automated optimization method allows a quick and accurate fitting of the numerical material parameters. By just changing the experimental target curves (stress-strain curves), a quick adaption for other polymer grades can be accomplished. Since the whole approach is based on a detailed documented methodical fundament, the achievable simulation results hardly depend on the CAE-engineer's experience.

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