A modified approach for simulating complex compound structures within early design steps

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Abstract

Owing to increasing relevance of lightweight design the deployment of compound structures with their beneficial material characteristics becomes more and more important. These growing demands for lightweight design cannot be met by improving constructive details at the end of the development cycle. On the contrary already the early design steps have to be exploited adequately, since these steps offer the highest freedom of design. The present paper shows a modified approach for simulating complex compound structures adapted to the requirements of early design steps. The basic idea is overlapping several basic material models (characterized by a low amount of input parameters) within one finite shell formulation to describe any combination of material effects. The benefit of the approach is a more accurate simulation of complex compound structures with reduced modeling effort. A validation of this phenomenological material superposition approach is performed by opposing the results of virtual material tests to experimental results published in the literature.

1. Introduction

1.1 Motivation

In times of declining natural resources and increasing environmental awareness of the population the demand for energy efficient solutions is growing, especially in the automotive sector. Besides new drive train concepts weight reduction is an essential instrument to create efficient vehicles. In case of cars with internal combustion engines a weight reduction of 100 kg leads to a cutback of the fuel consumption up to 0.3 l per 100 km [1].
According to a tns-survey [2], fuel economy and safety recently evolved to the most important reason for customers when a new car is purchased. To align the contradictory goals crashworthiness and lightweight design it is very promising to apply high-end compound materials due to their beneficial material characteristics (low density, high stiffness and very high energy dissipation rate [3]).

Question: Suppose you were to buy a car today, be it new or second hand, which factors, apart from the price, would make you lean towards one model over another?

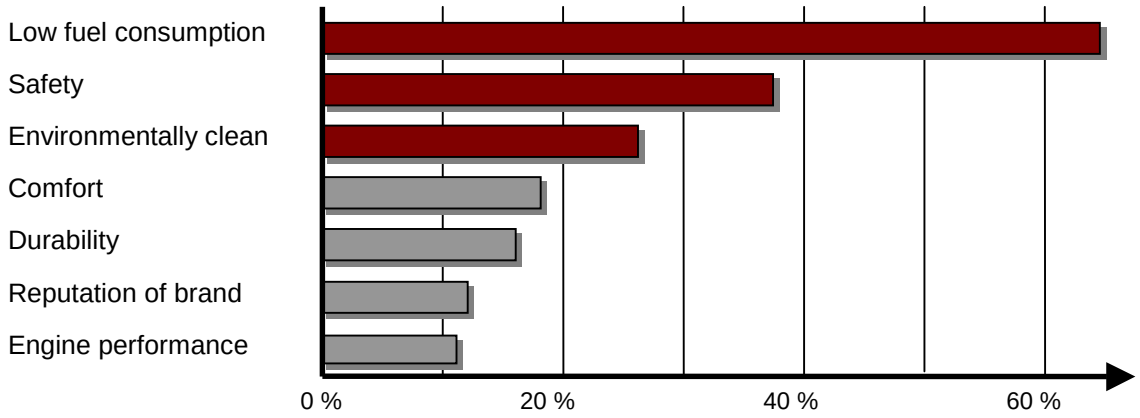

Figure 1. Aspects influencing the purchase decision. Excerpt TNS-survey: August 2008 [2]

Especially in the field of upcoming electric vehicles lightweight design has an emerging role due to current limitations in battery technology. To accomplish absolute lightweight design it is mandatory to already exploit the early phases adequately, as these steps offer the highest degree of freedom to the design engineer.

1.2 Objective

Within early design steps a first design proposal for the focused structural problem has to be determined. To reach an optimum design a lot of different geometric configurations and different materials have to be considered. Thereby the Finite Element Method is deployed to evaluate mechanical properties like crash performance.

An accurate Finite Element simulation of compound structures in early design steps is hardly practicable due to their complex material behavior. Within the present paper short fiber reinforced thermoplastic polymers should be focused exemplary, as especially these materials are characterized by lots of different material characteristics (nonlinearity, strain-rate dependency, anisotropy, etc.). Furthermore reinforced polymers are already deployed in the car body of series production vehicles (in form of local reinforcement elements) and lead to high crash-test ratings [4].

Since standard material models do not consider all these distinct material characteristics, third party tools are deployed for a detailed simulation [5], [6]. For first estimations usually simplified approaches are utilized to reduce the effort and safe time [7]. As within early design steps lots of different variants have to be focused, especially in this phase simplified approaches are deployed. Hereby the used material models are characterized by a low amount of input parameters which allows a quick calibration. However these simplified approaches being used in industrial practice neglect important material characteristics, only uncertain conclusions can be drawn. So the demanded adequate exploitation of early design steps (see section 1.1) is not fulfilled.

This leads to the research question of the paper, *how can the design engineer be supported adequately by simulation techniques in the context of early design steps.*

From this follows the objective to generate a way of modeling complex compound structures adjusted to the needs of the design engineer in early design phases. A middle course between drastically simplified and highly complex simulation approaches will be introduced. The basic idea of the new approach of material modeling is covering all important effects of the desired material by combining several *basic* material models. The combination of different material models in one finite element can be achieved by using layered elements [8]. The benefit of the approach is an accurate simulation of complex compound structures with reduced effort.

Before introducing the new approach the requirements for a material model for early design steps and the state of the art ways of modeling compound structures will be described. The explanation of the new approach of material modeling will be followed by its validation.

2. Requirements for a potential material description for early design phases

In the early design steps a variety of materials as well as various different geometrical configurations can be accounted for. This freedom of design has to be supported adequately by simulation techniques in order to exploit the early design steps effectively. Hence the following requirements for a potential material description are:

First of all a material model for early design steps has to be characterized by a manageable number and easy to determine input parameters to reduce the modeling effort. Appropriate calibration strategies must enable a quick adjustment of the input parameters. Due to the high amount of variants to be considered the material descriptions must allow for short calculation times and stable simulations. Ideally no additional software tools are necessary, so that the design engineer can stay in his familiar CAE-environment. To enable the demanded adequate exploitation of the early design steps, all significant effects of material

behavior have to be representable. Additionally more accurate simulation results (compared to common simplified methods) have to be accomplished.

In case of short fiber reinforced polymers special properties like nonlinear elastic-plastic stress-strain behavior, strain-rate dependency, tension-compression dependency and material anisotropy have to be taken into account [9]. The concrete constitution of the anisotropy has to be determined by a process simulation which should not be focused within the present paper. But regarding the anisotropy it should be emphasized that an alternating orientation of the fibers across the thickness of the part has to be presentable. Consequently a layer-based simulation approach is advisable. In the context of crash simulation a failure criterion is absolutely necessary to be able to determine the crash performance of the given structure. Figure 2 summarizes the significant material properties of short fiber reinforced polymers.

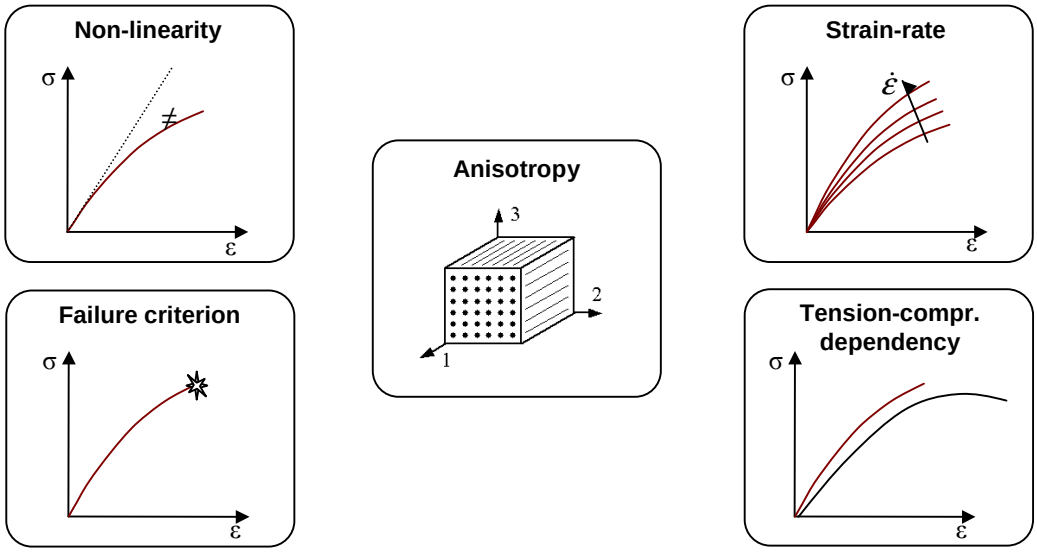

Figure 2. Characteristics of short fiber reinforced compound structures

3. State of the art

In general there are three different ways of describing the behavior of short fiber reinforced polymers within FE-simulations. These three methods will be discussed in the following at which their applicability for early design steps will be analyzed.

Simplification methods

The most suitable way of modeling the focused materials is based on making simplifying assumptions. Hereby effects that are difficult to express within the simulation (e.g. strain-rate, tension-compression dependency or anisotropy) are neglected entirely. To avoid overestimating the bearing strength, the assumed simplifications are taken into account by introducing global decreasing parameters for the mechanical properties like stiffness and strength. This procedure is very common in the context of anisotropy. Hereby a decreasing parameter of 0.8 is a standard value in industrial practice [10]. The great advantage of this way of material modeling is the fact that basic material models with a low calibration effort can be deployed (e.g. Mat_24). Furthermore the whole simulation can be performed within the standard well known CAE-environment (e.g. LS-Dyna + LS-PrePost). However this method is connected with noticeable inaccurate results. These uncertainties have to be considered by high safety factors respectively by the inverse decreasing parameters. So regarding the lightweight quality its deployment cannot be recommended. Despite its inaccuracy simplification methods are likely the most common way of modeling complex structures in early design phases due to their simplicity.

Complex material models

A more precise simulation can be obtained by using complex material descriptions which reproduce ideally all desired effects of material behavior. So in the following the available material models in LS-Dyna (approx. 195 [11]) will be checked for their ability to cover the material effects stated in section 2.

A quick look at the material reference table shows that over 85% of the available material models can be ruled out since they do not cover the important anisotropy. The great part of the remaining 28 material descriptions can be excluded as they can just be applied with distinct structures (beams, sandwiches, etc.). The residual material descriptions are mainly implemented for classical continuous filament compounds. As these materials are characterized by almost linear stress-strain behavior and a minor strain rate-dependency, nonlinearity and strain rate dependency are widely not covered. All in all just a few potential materials are left over (e.g. Mat_158). Since these materials need various input parameters they cannot be recommended for the focused early design steps. But despite their complexity these standard material models do not cover all the important characteristics of short fiber reinforced polymers on their own. Also the promising material description SAMP [12] has to be ruled since the important anisotropy is not covered yet. As current material models do not comprise all demanded effects of material behavior and are additionally connected with high calibration effort, the standard materials cannot be recommended to be deployed within early design steps.

Besides implemented standard materials also user defined materials can be generated. Concerning the stability of the calculation user defined materials cannot keep up with approved and within the years multiple revised standard material descriptions. Furthermore most of the user defined materials presented in research projects ([9], [13]) are not freely available. Since these material models are mainly implemented for final validation procedures they require extensive calibration measures which makes them less interesting for early design steps.

Third party tools

An accurate simulation of short fiber reinforced structures can be accomplished by using specialized third party tools. Usually these tools are not used within early design phases as they can be considered as time consuming and their operation is very complex. Furthermore the deployment of these tools is connected with further licensing costs which accumulate if lots different calculations have to be done (typical for early design steps).

In summary it can be stated that currently there are no ideal ways of modeling complex compound structures in the focused context of concept design. Either the deployment of the methods is too complex or their results are not accurate enough to realize the desired exploitation of early design steps.

4. Methodology of modeling compound structures within early design steps

Due to the lack of appropriate material models for simulating compound structures in the context of early design phases a new approach is presented in the following. The basic idea of this approach for a material description is combining several basic material models within one single finite element. The overall behavior of the new description should be able to characterize any desired target material. Since shell elements are less time consuming than brick elements and vehicle structures consist mainly of thin walled laminar structural members, shell elements will be focused in the following considerations.
This new approach for material modeling is based on the command **Part_Composite* which is available since V971 and is originally developed for modeling continuous filament composite structures [8]. The idea of this tool is to define parameters like thickness, orientation and material model individually for any integration point through the thickness in order to model the layers of a composite. But this idea can be extended to any kind of material since a lot of different material models can be combined within this user defined

integration rule. With the help of this approach materials can be modeled flexibly by combining already existing material models. On principle arbitrary material models can be put together as long as the overall behavior of the shell and the experimental results match. The methodology behind this reverse engineering based material superposition approach is summarized in figure 3 and will be explained explicitly in the following.

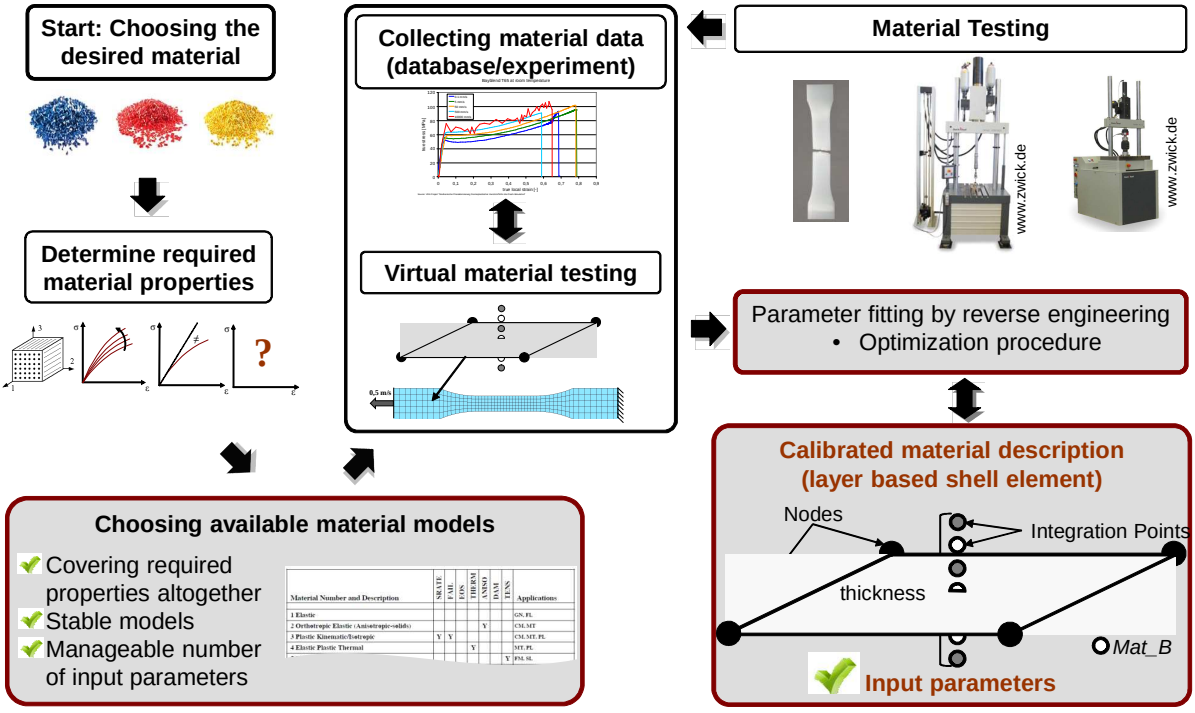

Figure 3. Methodology behind the reverse engineering based material superposition approach

In the beginning the material type of the structure to be analyzed has to be chosen. As already mentioned short fiber reinforced thermoplastic polymers will be the exemplary object of investigation. The specific properties of the material category have to be determined, which are in the present case:

- Anisotropy
- Nonlinear plastic stress-strain behavior
- Strain-rate dependency
- Specific failure criterion
- Alternating stress-strain behavior for compression and tension

The consideration of all possible phenomena of the material can soon lead to a too complex material representation for early design phases. That's why the alternating stress-strain behavior for tension and compression will be neglected in the following. In the context of early design steps this can be seen as a justifiable simplification. The next task is choosing existing and stable material models that have a manageable set of input parameters and cover in total all required material phenomena. Within the presented approach the first material model to be selected is the basic linear-elastic model for continuous filament compounds (Mat_54). It covers the anisotropic behavior by assigning distinct values for the young-modulus along (longitudinal) and orthogonal (transversal) to the fiber orientation. Optional an alternating failure criterion with respect to the alignment of the element coordinate system can be defined. However this material neither covers the required nonlinear plastic stress-strain behavior nor the necessary strain-rate dependency. These effects will be considered by the basic piecewise linear isotropic plastic model (Mat_24) which is the most widely used material description in the industrial application [6]. By replacing Mat_24 with MAT_187 (SAMP) also the tension-compression dependency can be

considered. Nevertheless Mat_24 will be chosen for the following considerations due to its simplicity. The deployment of a third material description should be avoided as this would make the determination of the input parameters very complex. In the given example there are basically six variables to vary the behavior of the resulting shell element description. In table 1 these parameters are listed in which factors like density and poisson's ratio are excluded as they cannot be varied arbitrary in order to obtain a realistic physical behavior.

Table 1. Parameters to be varied

Mat_24 Isotropic piecewise linear plastic	Mat_54 Anisotropic linear elastic
Young-modulus (isotropic)	Young-moduli ($E_{transversal}$ and $E_{longitudinal}$)
Yield stress	Shear-modulus
Yield curve	-

The next step of the work methodology is setting up virtual standard material tests. These tests will be modeled with shell elements assigning both of the selected materials to the given layers sequentially. Hereby a Belytschko-Tsay shell formulation [11] with five integration points through the thickness is chosen. The resulting stress-strain curves of the virtual tests have to be opposed to experimental results in order to determine the parameters stated in table 1. This reverse engineering procedure can be supported by parameterizing the unknown material parameters of the FE-model and employing an optimization code. Therefore no additional license costs are accumulating as in LS-Dyna the optimization software is already included (LS-Opt) [29]. In the presented example three virtual material tests (tensile, shear and bending test - see figure 4) are necessary to determine the unknown parameters.

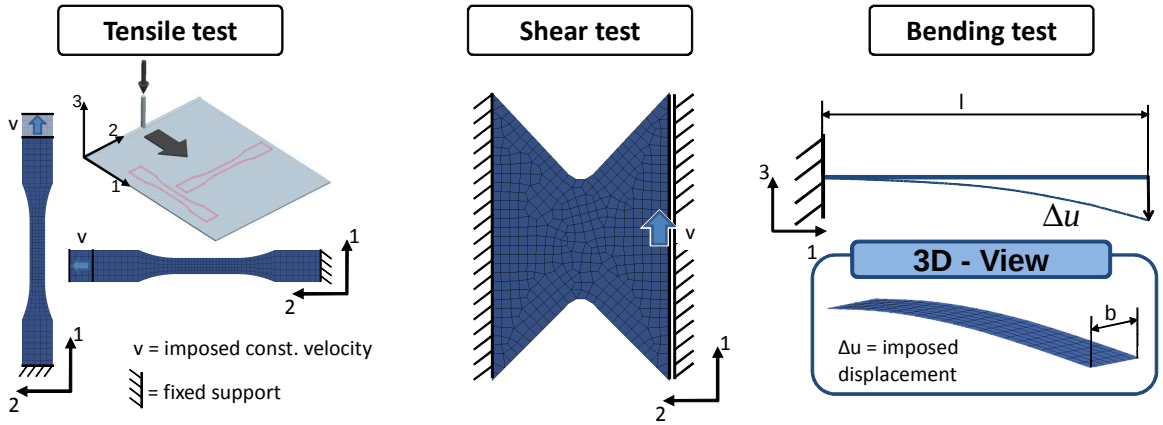

Figure 4. Types of virtual material tests

At first a tensile test along (longitudinal) and orthogonal (transversal) to the fiber orientation will be performed. Hereby the input parameters of Mat_24 as well as the young-moduli of Mat_54 (E_{trans} and E_{long}) will be defined. The shear behavior can be set by the shear-modulus of Mat_54. The distinct value is obtained by fitting the virtual shear test to experimental results. A variation of the shear-modulus does not affect the tensile behavior, which means tensile and shear properties can be chosen independently. However Mat_24 is influencing the tensile and the shear characteristics due to its isotropic nature. Consequently the values of Mat_24 have to be chosen appropriate for both fitting procedures. Finally the bending behavior is adjusted by adapting the layer thickness or the layer arrangement. If the virtual

test shows a minor bending stiffness compared to the experiment, layers with a high young-modulus have to be assigned to the outer shells or the thickness of stiff outer layers have to be increased. To avoid influencing the already fitted tensile and shear behavior an increasing of outer layers must be connected with an equivalent reduction of a central layer (see figure 5). The independent adjustment can only be performed under the precondition that the orientation and the material parameters of each chosen material model (Mat_24 respectively Mat_54) are identic. Furthermore symmetrical layer constitutions have to be selected to avoid influencing the mechanical behavior in the plane of the shell.

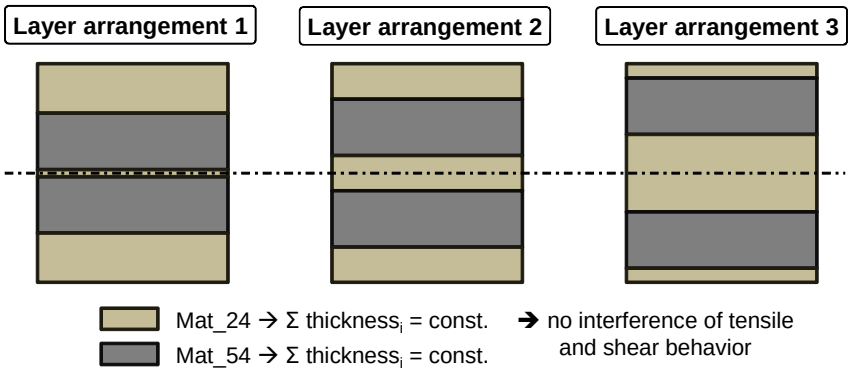

Figure 5. Alternating distribution of the layer thickness (element formulation with 5 layers)

5. Validation of the presented approach

To prove the legitimacy of the presented approach a validation will be performed in the following. It will be shown step by step that overlapping the basic materials Mat_54 and Mat_24 allows the consideration of all the specific material phenomena mentioned in the previous section. The virtual material tests are opposed to experimental results published by KRIVACHY [9]. As in [9] the strains are specified as engineering strain the virtual tests will also refer to engineering strain. In case no experimental data were accessible (e.g. strain-rate) only a qualitative validation can be performed. Within this first approach the fitting process will be executed manually.

5.1 Anisotropy and nonlinearity

The fitting of the anisotropic and the nonlinear behavior is performed with help of the tensile test longitudinal und transversal to the fiber orientation, starting with the transversal test. The anisotropy is covered by Mat_54 (E_{long} and E_{trans}) and the nonlinearity by Mat_24 (yield curve).

For the manual fitting at first the young-modulus E_{trans} of Mat_54 was set to a fictive fix value of *2 N/mm²*. The young-modulus E_{long} can be set to an arbitrary value as it hardly influences the transversal tensile test. By adjusting the young-modulus and the yield curve of Mat_24, the virtual transversal tensile test has to be approximated to the experimental data.

The stress-strain-curves in Figure 6 show that even with a manual fitting a sufficient approximation (maximum deviation <3 %) can be achieved. In strict sense the nonlinear behavior shown in the experiment cannot described with the use of the tabulated yield curve defined in Mat_24. By choosing an adequate high amount of interpolation points the multi-linear behavior of the simulation is satisfactory close to the nonlinear effects determined in the experiment. To reduce the effort of the manual fitting procedure only a coarse yield curve was defined.

The adjustment of the longitudinal behavior is carried out with help of the longitudinal tensile test. The parameters of Mat_24 determined in the previous virtual test must not be changed as this would influence the already fitted transversal behavior. So only the young-modulus E_{long} of Mat_54 remains as correcting variable. As the first tensile test showed a too stiff behavior in longitudinal direction, the value of E_{long} had to be reduced successively. With a

value of *2500 N/mm²* for E_{long} a sufficient first approximation could be achieved. As could be expected the deviation is noticeable bigger than obtained in transversal direction. However by using an optimization code a more suitable mean deviation for both directions can be achieved.

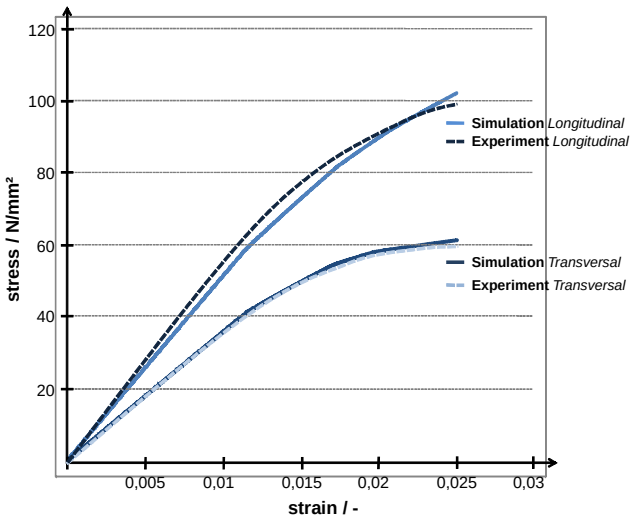

Figure 6. Anisotropy and nonlinearity: Experimental vs. virtual tensile test

5.2 Strain rate dependency

The possibility to consider strain-rate dependency is also validated on the basis of the tensile test. The influence of the strain-rate can be considered within Mat_24 by assigning an array of yield curves for distinct strain-rates. As no experimental data for varying strain-rates were available just a qualitatively validation can be performed.

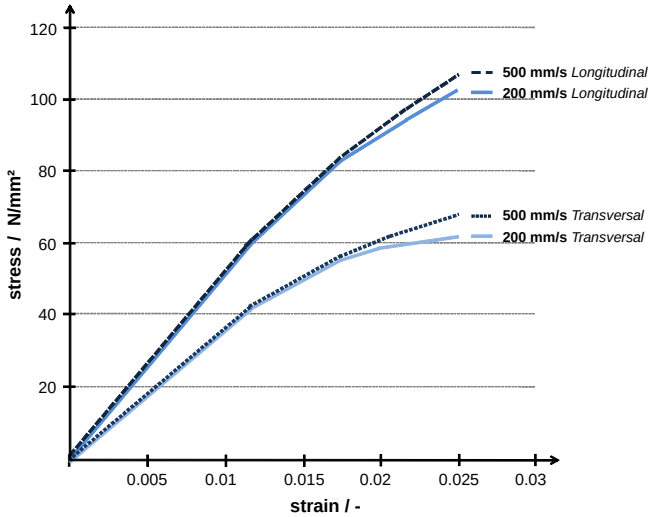

Figure 7. Strain-rate dependency: Virtual tensile test

Figure 7 shows the stress-strain curves in longitudinal and transversal direction for two different tension velocities (*200 mm/s* and *500 mm/s*). As the strain rate is influenced by the yield curves, this effect can only be represented from the beginning of the plastic area of Mat_24. At a strain value of approx. 0.013 a deviation between the curves occurs. Consequently this is the region where Mat_24 reaches its plastic share. By reducing the yield stress the beginning of the strain-rate dependent areas can be moved to minor strain thresholds.

5.3 Elastic Energy

Non reinforced polymers are characterized by a strong plastic behavior. By adding stiff elastic reinforcement fibers the plastic share is reduced in favor of the elastic share. Within the simulation the degree of remaining elastic energy can be influenced by adjusting the yield stress and the yield curve of Mat_24. To validate that the elastic share can be adapted arbitrary the virtual tensile test shown in figure 4 has to be modified. Instead of applying a constant velocity on the free end an increasing and afterwards decreasing force will be applied (see figure 8). The remaining deformation *u* gives information about the degree of the elastic energy.

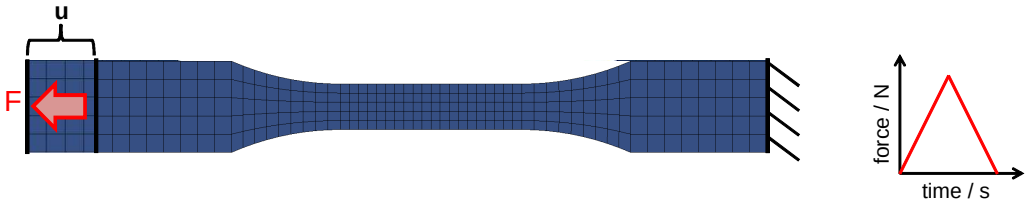

Figure 8. Test scenario for analyzing the share of elastic energy

As no experimental data are available it can only be shown qualitatively that the share of the elastic energy can be modified. Therefore three tensile tests according to the schematic shown in figure 8 are performed. In these tests the yield stress as well as the yield curve was varied (see figure 9a). The blue yield curve was generated in the fitting process of section 5.1. The alternating curves are obtained by shifting the initial yield curve in the positive y direction. Expectedly the yield point shown in figure 9b could be postponed by increasing the yield stress (see figure 9a). Furthermore the remaining plastic deformation can be increased by decreasing the input yield curve. Subject to the fiber content an appropriate elastic share has to be chosen. As the isotropic Mat_24 is influencing the overall material behavior, thoughts about the elastic share have to take place before the initial fitting procedure performed in section 5.1.

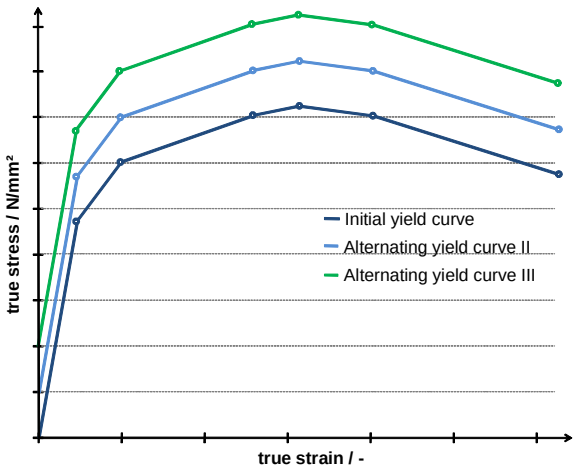

Figure 9a. Alternating input yield curves

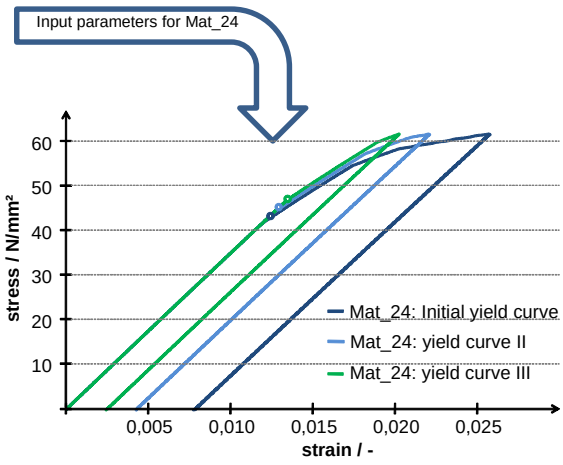

Figure 9b. Remaining el. energy: virtual tens. test

5.4 Shear behavior

Besides the tensile behavior briefly discussed in the previous sections, also the shear behavior has to be aligned with the results obtained by experiments. The shear properties are characterized by the shear-modulus *G*. For isotropic materials *G* can be derived based on the poisson's ratio *v* and the young-modulus *E* according to the equation

$$G = \frac{E}{2(1+\nu)}. \qquad \text{(Eq. 1)}$$

As Mat_24 is an isotropic material there is no possibility to vary the shear behavior independently. However Mat_54 as anisotropic material description offers parameters to adjust the shear properties. A shear-modulus for each plane (G_{12}, G_{23}, G_{13}, *see figure 4*) can be assigned. As shell elements are used, only the shear-modulus in the shell plane (G_{12}) will be focused. Consequently just one constant shear behavior can be set. This corresponds very well with the experimental results (see figure 10) which show an almost identical shear behavior in transversal and longitudinal direction.

For the fitting process the fibers of the shear specimen were oriented transversal to the direction of the load. The initial value of the shear-modulus was chosen arbitrary and set to 500 N/mm^2. Since the resulting shear behavior was too weak, G_{12} was increased gradually. A shear-modulus of 2700 N/mm^2 leads to a sufficient approximation of the experimental results. It could be verified within tensile tests that adjusting the shear modulus hardly affects the tensile properties.

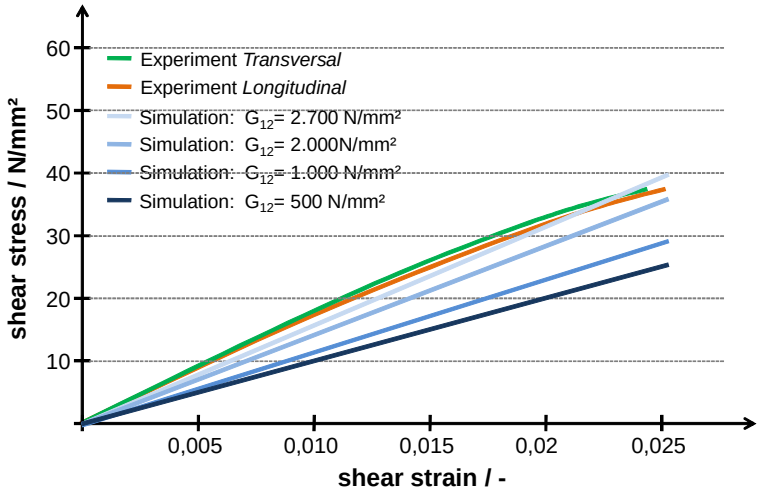

Figure 10. Shear behavior: Experimental vs. virtual tensile test (virtual tests: transversal)

The nonlinear characteristic as well as the differing behavior in longitudinal and transversal direction cannot be obtained in the simulation with the focused material models. Since these weak effects just lead to minor deviations, the presented approach still can be considered as promising for early design steps.

5.5 Failure

In the context of crash simulation the ability to consider failure is very important as usually the possible collapse of the target structure is investigated. Many of the material laws in LS-Dyna do not cover failure. The command **MAT_ADD_EROSION* provides a way to extend each material model (assigned to an under-integrated 2D shell element [11]) with a failure criterion. Although Mat_24 and Mat_54 have a failure criterion included **MAT_ADD_EROSION* is used as it's not bound to a distinct material description.

Since the presented reverse engineering approach primarily considers the global deformation progress of the analyzed structures, stress based failure criterions are not advisable. In **MAT_ADD_EROSION* the failure can be defined by the maximum principle strain. To identify the needed threshold a tensile test without a failure criterion is performed. At the point of time the failure occurs according to the engineering strain, the maximum principle strain has to be determined in the postprocessor. This value will be used as initial threshold for the failure criterion.

The experiment shows that short fiber reinforced polymers possess a major strain capacity in transversal direction due to a dominant influence of the polymer matrix (see figure 11). The simulation also displays a variation in the resulting strain capacity, but exactly the opposite way. In longitudinal direction the threshold of the chosen maximum strain is reached posterior in the progress of the deformation. Consequently the presented approach using the command **MAT_ADD_EROSION* does not lead to a satisfactory reproduction of the failure behavior. The results displayed in figure 11 were obtained with a mean value for the maximum principle strain. The deviations in longitudinal and transversal direction are approx. 7 % respectively 8 %.

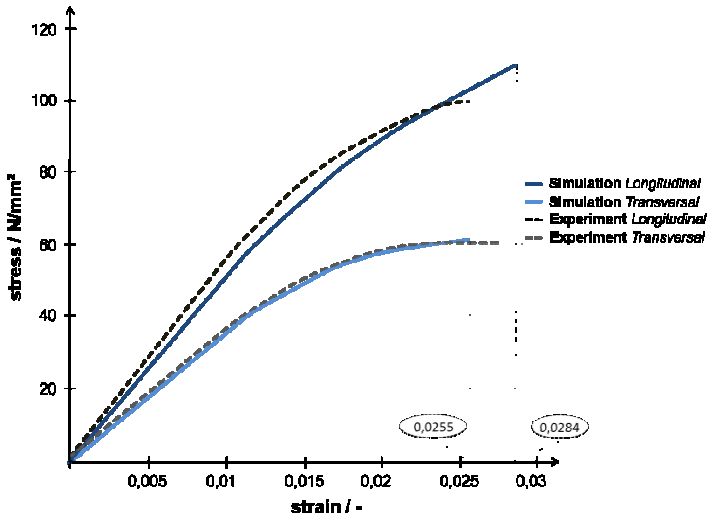

Figure 11. Failure behavior: Experimental vs. virtual tensile test

To enhance the capability to describe the failure behavior, anisotropic strain based failure criterions implemented in Mat_54 have to be evaluated. This will be the task of future considerations.

5.6 Bending behavior

Short fiber reinforced polymers are characterized by a heterogenic material constitution in through-thickness direction. Consequently the bending behavior cannot be deduced from mechanical properties in the plane. So finally the bending behavior of the simulation model has to be adjusted.

The bending properties cannot be set by using the material parameters of Mat_24 and Mat_54, since all available parameters were adjusted to describe the in plane behavior correctly. The bending stiffness can only be varied by changing the constitution and the thickness of the layers. Hereby the in plane behavior mustn't be modified (see section 3). The bending is analyzed with the help of a single edge supported flat bending beam. This test is not conform to standard material tests. As no experimental data were available for the fitting procedure this test configuration was chosen anyway due to its simplicity. Hereby the free end of the bending beam is loaded with an imposed displacement Δu. The bearing load in 3-direction will be analyzed to quantify the bending stiffness.

The material models are assigned to the five integration points of the shell formulation according to the order of figure 5. Simulations for three different ply thickness combinations were performed (see figure 5). Hereby the thickness of the Mat_54 layers was kept at a constant value. The thickness of the outer Mat_24 layers were reduced (from layer arrangement 1 to 3) while the central layer increased accordingly. As in the present case the Mat_24 layers possess the maximum stiffness, the arrangement 1 should show the maximum bending stiffness respectively arrangement 3 should have the weakest bending stiffness.

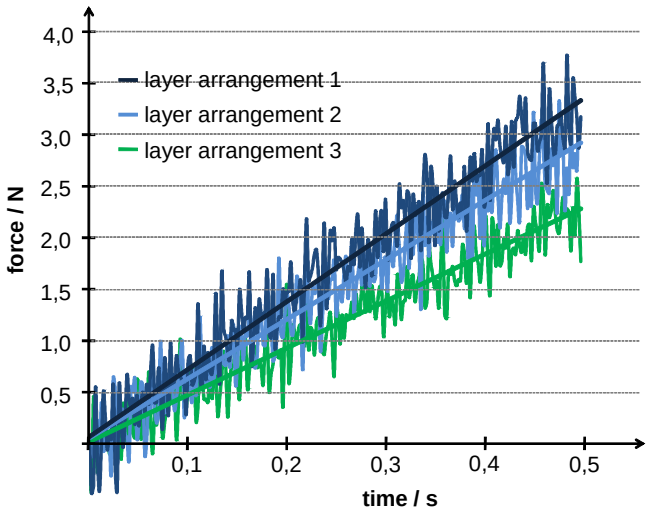

Figure 12. Bending stiffness: virtual bending test

The results of the simulation are displayed in figure 12. Due to the noisy character of the resulting curves, a trend line for each simulation is added. The oscillation of the time-force curve is not a result of the overlapped materials, as it occurs comparably for models with a single material model assigned to. The results prove the assumption that stiff outer shells increase the bending properties.

By varying the layer thickness the bending stiffness can be adjusted almost arbitrary. Furthermore the bending behavior can be affected by switching the order of the assigned materials. It could also be verified within tensile tests that the variation of the layers performed in this section does not influence the in-plane behavior as long a symmetric arrangement of the layers is kept.

6. Summary and discussion

In the present paper a reverse engineering based approach for simulating complex compound structures within early design steps was introduced. On the one hand the new approach should enable more accurate simulation results than common simplified methods usually deployed in early design steps. On the other hand more quick simulations (calculation and calibration time) have to be realized, compared to highly accurate simulation techniques normally applied within the final product validation. To meet with the specific requirements of the early design steps, a method of overlapping and adapting several basic material models within one shell formulation is presented. Hereby the superposition of Mat_24 and Mat_54 allows describing all relevant material characteristics of short fiber reinforced polymers. A final validation could prove the applicability of the method of material modeling.

The benefit of the presented approach is that basic material models (already implemented, low amount of input parameters) can be used to define almost any desired material behavior. So neither complex user defined material descriptions have to be programmed nor additional software tools have to be used. The validation could prove that all the desired effects of material behavior can be represented. Consequently more accurate simulations are enabled compared to common simplified approaches neglecting several material effects entirely. The focused material effects analyzed in section 5 can be described with a sufficient accuracy. Merely the precision of the failure criterion has to be enhanced within further considerations. The fact that effects like bending stiffness and shear behavior can be set almost independent of the tensile characteristics, can be seen as positive contribution of the presented approach. Also the demand for low calculation times can be fulfilled. The simulations performed in section 5 needed insignificant increased calculation times (approx. +2%) than similar models defined only by Mat_24.

The demanded appropriate calibration strategies to enable an efficient adjustment of the input parameters (see section 2) will be a major topic for further considerations. Furthermore the manual parameter fitting will be automated with help of an optimization code. To meet perfectly the concerns of early design steps also analytical methods to realize a quicker calibration will be investigated.

REFERENCES

[1] Stichling, J.: Im Idealfall rechnet sich Leichtbau in der Nutzungsphase. Lightweight Design, 2010, 01, pp. 16–18.

[2] TNS Market research: *Public Opinion survey on Energy Efficient Cars*, August 2008. http://www.foeeurope.org/cars/Poll/Results_by_country.pdf

[3] Stauber, R.; Vollrath, L.: *Plastics in Automotive Engineering - Exterior Applications*. Munich: Hanser-Verlag 2007.

[4] Short, P.; Tullo, A.: Bracing for 'K', Chemical & engineering news, 2007, 85(28), p. 26.

[5] Wartzack, S.: Versagensprognose bei der Crashsimulation von Kunststoff Türsystemen zur Erschließung des Leichtbaupotenzials in Fahrzeugen. In VDI-Bericht der Tagung SIMVEC, Baden Baden, 2008.

[6] Stelzmann, U.: Die große Materialvielfalt in LS-Dyna. In Ansys Conference & 27th CADFEM Users' Meeting, Leipzig, 2009.

[7] Gebhardt, C.: Praxisbuch FEM mit Ansys Workbench. Munich: Hanser-Verlag 2011.

[8] Chatiri, M.; Güll, T.; Matzenmiller, A.: An assessment of the new LS-DYNA layered solid element: basics, patch simulation and its potential for thick composite structure analysis. In 7th European LS-DYNA Conference, Salzburg, 2009.

[9] Krivachy, R. et. al.: Characterization and modeling of short fibre reinforced polymers for numerical simulation of a crash. *International Journal of Crashworthiness*, 2008, 13(5), pp. 559-566

[10] Schmachtenberg, E.; Brandt, M.: Wenn Kunststoffe Metall ersetzen. In *Plastverarbeiter*, 2008, 55(8), pp 52-53.

[11] Livermore Software Technology Corporation: LS-Dyna Keyword user's manual. LSTC, 2007.

[12] Haufe, A.; Du Bois, P. A., Kolling, S.; Feucht, M.: A semi-analytical model for polymers subjected to high strain rates, In 5th European LS-DYNA Users Conference, Birmingham, 2005.

[13] Peter, J.: Experimentelle und numerische Untersuchungen zum Crashverhalten von Strukturbauteilen aus kohlefaserverstärkten Kunststoffen. PhD Thesis. 2004 (Universität der Bundeswehr München).

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