

INTEGRATED NONLINEAR MULTI-SCALE MATERIAL MODELLING OF FIBER REINFORCED PLASTICS WITH DIGIMAT: APPLICATION TO SHORT AND CONTINUOUS FIBER COMPOSITES

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Abstract. The simulation of composites has to address several challenges: anisotropic behavior following the local microstructure, nonlinear behaviors (plasticity, damage, ...), strain rate and temperature dependences, various failure mechanisms, These behaviors can be observed for all important performances – stiffness, failure, high cycle fatigue, creep... It is found for short as well as continuous type of fiber reinforcement, for glass as well as for carbon fibers.

FE analysis seeks to describe composite designs in complex load scenarios which require the usage of advanced temperature or strain rate dependent material and failure models. To model the local anisotropic behavior, the analyses must take into account the real material microstructure as predicted by process modeling software (for examples injection or compression molding for short fiber reinforcement; draping in the case of UD or woven composites). All this must be available in a smooth and effective workflow and cover various types of scenarios and question, from simple stress analysis over the investigation of crash behavior towards full life time prediction for the plastic composite part.

Digmat aims at bridging the gap between process and structural modeling by building nonlinear multi-scale material models, using the local material microstructure, in order to predict different kind of performances. The technology developed in Digimat (see for example [1,2,3,4]) as well as representative applications will be covered in the paper.

1 INTRODUCTION

Lightweight design becomes more and more important to the Automotive and Aerospace industry. Such designed parts can very well be produced based on plastic composites. Plastics can individually be tailored for different applications and exhibit a large freedom of design. Both, thermoplastic as well as thermoset matrices can be combined with various fiber reinforcements, be it short, long or continuous glass or carbon fibers.

The blessing can become a real challenge though when it turns to finding the optimum design of a composite part for a given application. A full range of performances have to be tested on parts exhibiting highly complex properties. It is absolutely necessary to understand the stiffness and failure behavior under static and dynamic loads. Increasing demand arises to also cover the prediction of fatigue lifetime.

The basic challenge is to understand the influence of the microstructure and constituents' properties (induced or partially induced by the process) over the composite performance. For the best possible design for a specific performance under the given constraints such as e.g. the overall weight, it is important to go through optimization cycles for the processing step, the structural design and even of the material itself. The final performance of the part will depend on all three of them at the same time. Today it is possible to set up complex multi-scale simulations. All three influences are fully coupled and thus can be investigated in one unique approach.

The paper gives an overview over recent micromechanical approaches to tackle stiffness and failure of plastic composite materials. The goal is to use such material models efficiently with an industrial usage in mind.

2 MULTI-SCALE APPROACH

2.1 Micromechanical Material Modelling

Composite properties can be predicted based on micromechanical modelling. Several methodologies can be used to predict material behavior across scales i.e. mean-field homogenization, full-field finite element homogenization, asymptotic methods, methods of cells,... Amongst these, mean-field homogenization methods like Mori-Tanaka (MT), using Eshelby's solution, can be used effectively both for material and structural engineering of composites. Even if the former formulation of such methods was focusing on linear material properties, as well as aligned and straight ellipsoidal inclusions, various extension were performed in order to target nonlinear performance as well as different type of material microstructure (short fibers, long fibers, UD, woven, ... see for example [1,3]).

In Digimat [4] in order to model the fiber distribution of short fiber reinforced material, a decomposition of the inclusions into "pseudo grains" is performed (see Figure 1). Each grain represents a class of inclusions which share the same orientation. In each grain, a homogenization procedure is carried out to obtain its material properties on the composite level. Hence, for each pseudo grain the mean stress response is known. In the second step of homogenization, Voigt averaging is used over all pseudo grains to derive the final properties of the material on the macroscopic level.

The level of the pseudo-grains is especially interesting when it comes to the implementation of advanced material models. That is, for the description of failure of short fiber reinforced composites as well as for the setup of fatigue models resulting in anisotropic Wöhler curves. In

general various stages give access, during the homogenization process, to the material state (stress, strain, history variables), and thus allow to compute failure indicators (see figure 2).

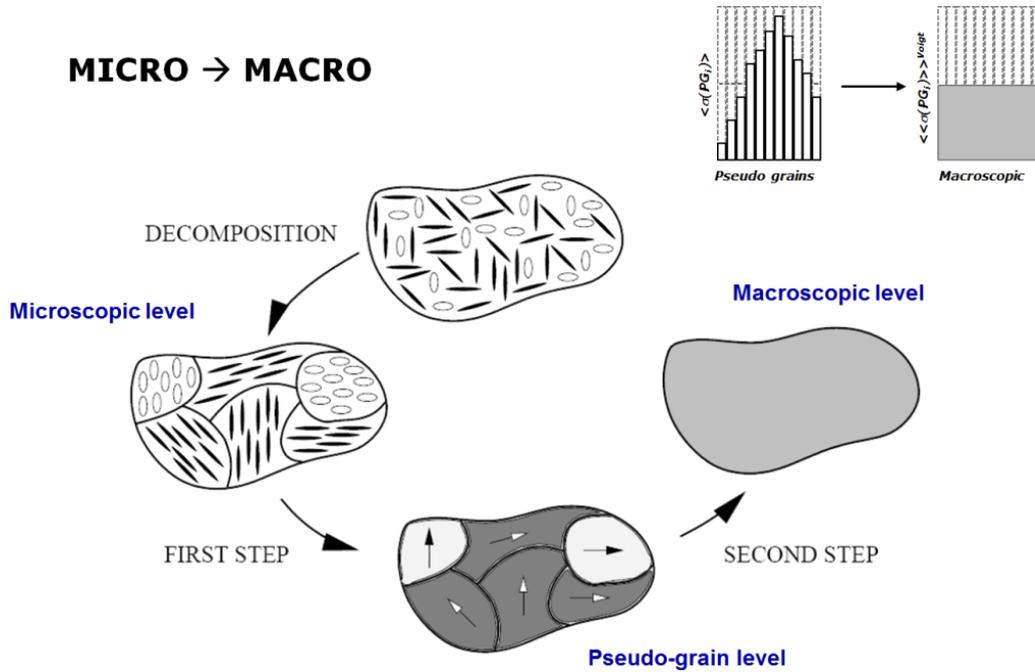


Figure 1. Homogenization technology derives macroscopic composite properties for materials defined on the microscopic scale. Three subsequent steps are involved. First, a decomposition of the randomly oriented inclusions in the material matrix into so called “pseudo grains” is performed. Each pseudo grain represents a class of inclusions sharing the same orientation in space. For each pseudo grain, Mori-Tanaka homogenization is carried out to obtain material properties on the composite level. After this step for each pseudo grain the average stress response is known. In the final step Voigt averaging is used over all pseudo grains to derive the final properties of the material on the macroscopic level.

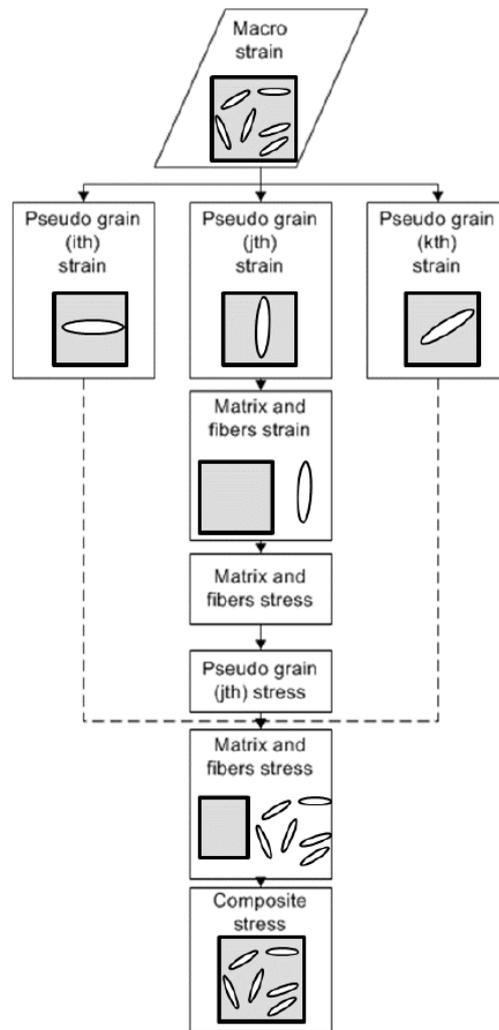


Figure 2: Levels at which failure indicators can be computed during a mean-field homogenization step.

MT homogenization can be extended to describe nonlinear material response. Typically, nonlinearity arises from properties defined in the material matrix, fibers being described via linear elastic models in most case (isotropic in the case of glass and transversely isotropic for carbon fibers). A broad range of material models are available amongst which:

- (Thermo-) Elasticity
- (Thermo-) Elastoplasticity
- (Thermo-) Viscoelasticity
- (Thermo-) Elasto-Viscoplasticity
- (Thermo) Hyperelastic
- Electrical conductivity
- Thermal conductivity
- Damage and Progressive failure

All material models become fully anisotropic at composite level and the microstructure (fiber orientation, fiber content, aspect ratio, existence of clusters, ...). Thermal dependency means that indeed all parameters of the model can be expressed as a function of temperature and the coefficient of thermal expansion is included. In strain rate dependency, differentiation is made between creep and dynamic behavior on a short time scale. Both effects can be covered, also in combination with temperature dependencies.

2.2 Integrative Approach to Simulation

Processing of the composite material will influence the local microstructure in the final design. As a consequence, material properties are not homogeneous over the part but must be described via a distribution of local properties. Integrative simulations take all this into account in an overall approach (see figure 3). Processing technologies can be for example injection or compression molding for short fibers and draping or fiber placement for continuous fiber reinforced plastics.

Anisotropic material models based on micromechanics are used to bridge the gap between the influence of processing and the performance of the final part in simulation. The material model itself plays the central role (see also figure 4). Once it has been parameterized in sufficient quality, best via reverse engineering to some experimental data obtained on the composite level of the material, it can be coupled to the output of processing simulation.

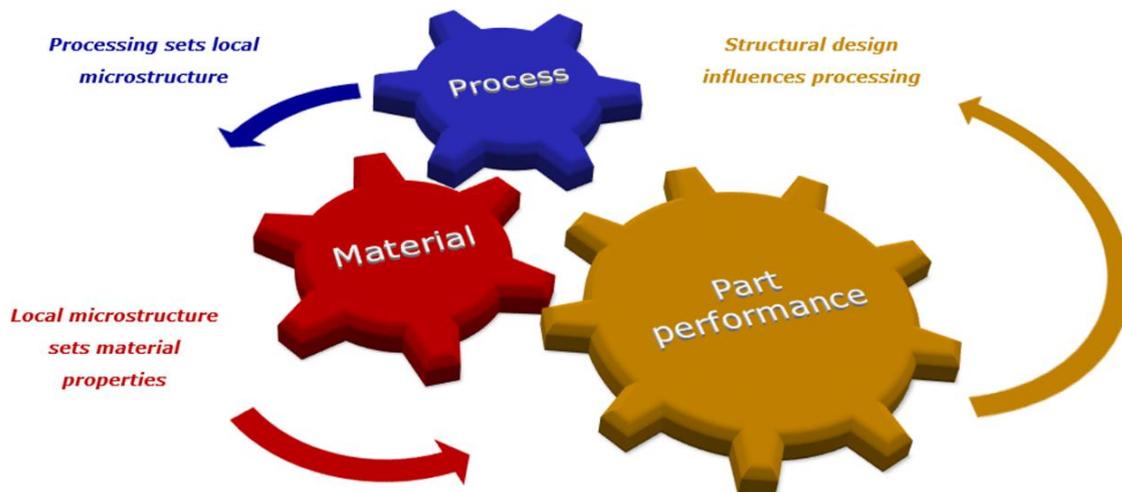


Figure 3. Coupling of processing simulation, micromechanical modelling and simulation of the part performance in the integrative approach.

3 SHORT FIBER REINFORCED PLASTICS

3.1 Workflow of coupled analyses

Figure 4 illustrates the coupled approach for short fiber reinforced plastics. The results from an injection molding simulation (orientation tensors given per element) are mapped onto the structural FEA mesh. During this procedure, results are usually transferred from elements to the integration points. As usually the structural mesh is much coarser than the one used for injection molding, in the end each material point bears its individual microstructure. The micromechanical model is used by FEA solvers via user defined subroutines. Each time material information is required the information is computed by the material modelling software. The base of this computation of local material properties is the mapped microstructure information from the processing simulation.

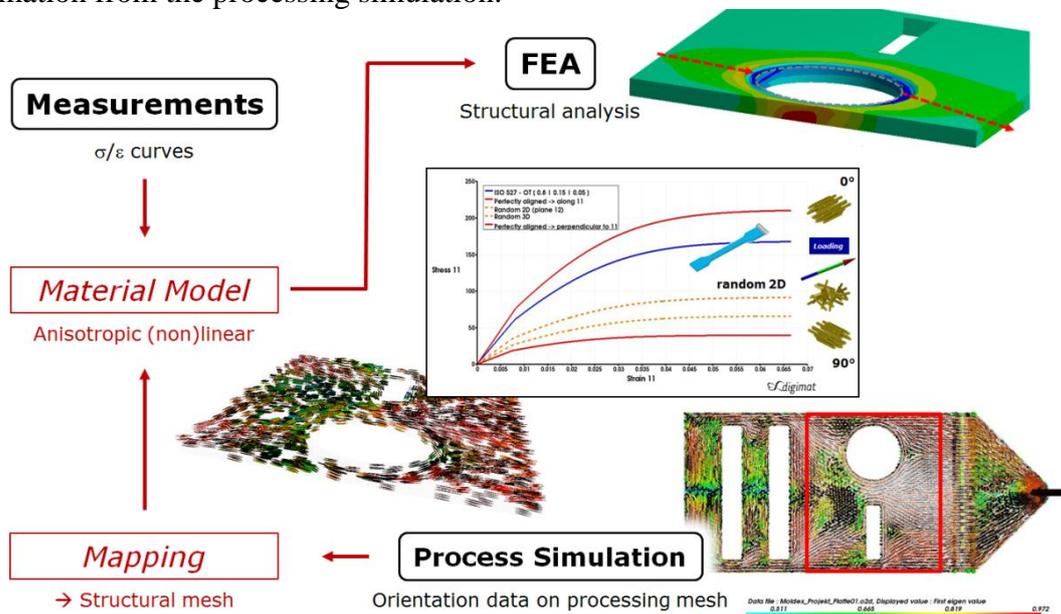


Figure 4. In the coupling of processing simulation with Finite Element Analysis (here shown for injection molded plastic parts) the micromechanical material model plays the central role.

3.2 Solution technology for explicit analyses

Stiffness and failure of SFRP are especially difficult to cover in impact and crash scenarios. The above described stepwise homogenization procedure is key to high quality material models. Failure of SFRP is implemented on the pseudo grain level of this procedure.

Impact and crash naturally involve the usage of explicit solvers. With the above described solution of computing material properties on-the-fly, the so-called MICRO solution, for larger models the user will run into CPU demanding analysis. For some typical example of an impact as depicted in figure 5, the explicit MICRO solution takes 9 days to solve on three CPUs. During the procedures, in each layer of an element, for each integration point in each step of the

analysis, material properties are computed including full communication between the FE solver and the material modelling software. Also all material properties, on the microscopic as well as macroscopic level are communicated.

Another way of dealing with the communication of material data is used in the HYBRID solution method. With HYBRID, properties are pre-computed, thus substantial computational time is saved during the coupled analysis. Furthermore, in the communication with the FE solver, only macroscopic results are transferred by the material modelling software. With the HYBRID technology, the macroscopic response of the composite still leads to good results. This can be seen in the comparison of local as well as global data between the MICRO and HYBRID methods (figure 5). The immediate benefit in terms of CPU can also be derived from the presented model: with HYBRID, the same analysis now runs in one day on only one CPU. With parallel computation on 3 CPUs time would further reduce to about 8 hours. Following this example clearly shows that with HYBRID technology, coupled solutions are ready to be used in everyday design procedures for composite structures.

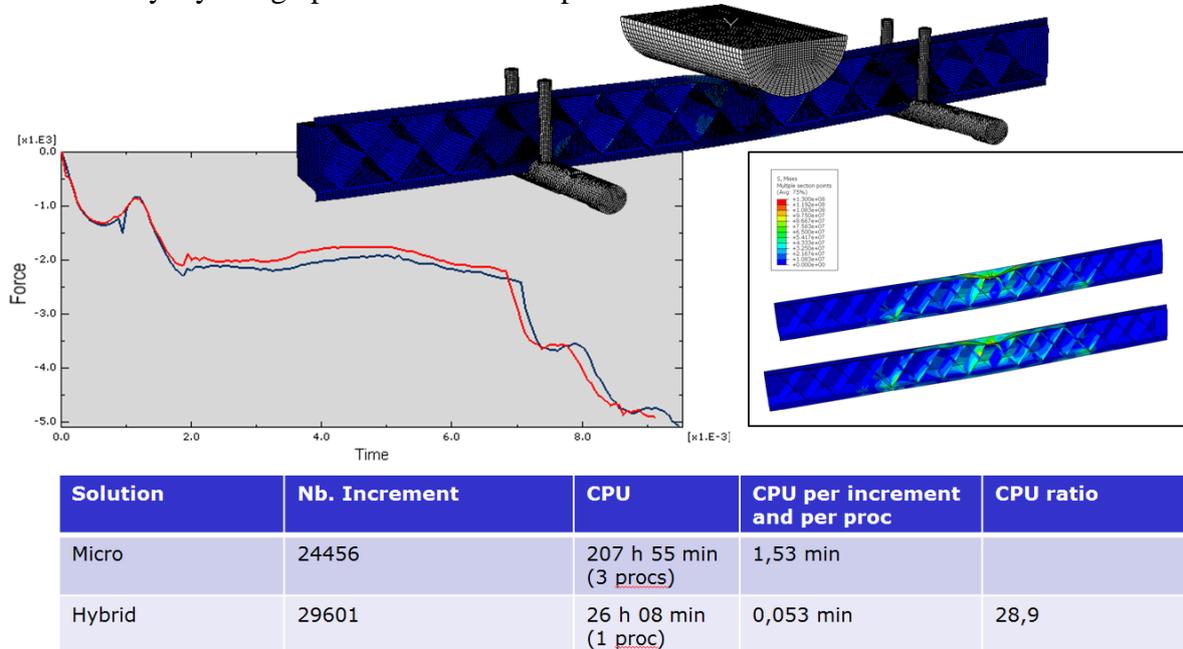


Figure 5. The HYBRID solution method offers great speed-up for explicit solutions of coupled analyses. Whereas the local and global response of the composite design remains the same in comparison to the on-the-fly computation of material properties (MICRO solution), at least a factor of 20 can be saved in terms of CPU time by using HYBRID.

3.3 Modelling of failure of short fiber reinforced plastics

The realistic description of failure for SFRP is part both of the MICRO and HYBRID solution strategies. It is implemented via the so called FPGF (First Pseudo Grain Failure) model. In this Ansatz, all advantages of the pseudo grain level are used. For each pseudo grain, the individual stress history is known. Furthermore, the orientation of the fiber in each grain clearly determines the orientation of the local coordinate system in the material. As in one grain all fiber share the

same orientation, this axis system can be used to express failure. There exists a broad range of failure indicators for classical composite materials with well-known performances and applications (e.g. Tsai-Hill, Tsai-Wu, ...). In principle all of these can be included in the here described procedures.

Figure 6 shows some example where a Tsai-Hill 3D transversely isotropic criterion has been used on the composite level of the pseudo grains to define failure in an HYBRID computation. To assure a realistic failure of SFRP, for sure the use of a fully three-dimensional criterion per grain is mandatory. In practice however, the parameterization of failure based on such an indicator can become quite a nightmare. A large number of parameters have to be identified. The here used solution takes advantage from the fact that each pseudo-grain bears transversely isotropic symmetry by definition. Thus also some transversely isotropic criterion can be used to describe failure in the grain.

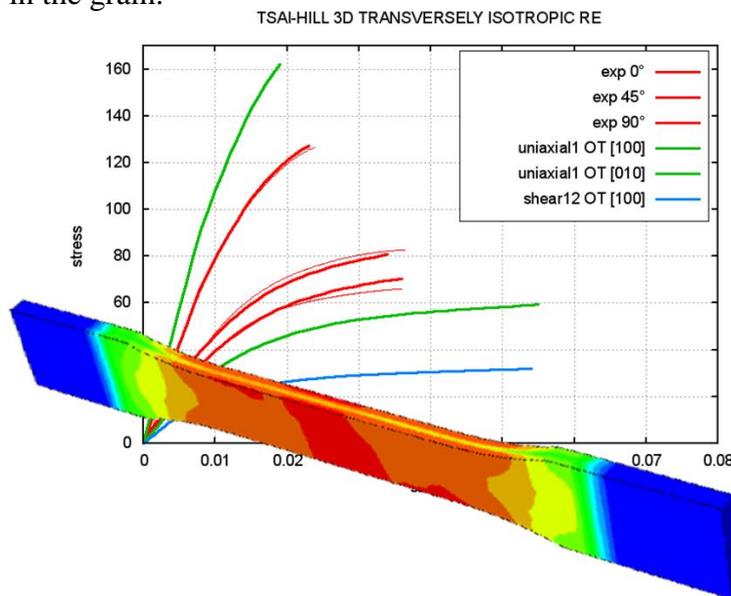


Figure 6. Failure of short fiber reinforced plastics. Results of the parameterized model are shown in comparison with experimental stress/strain curves and the response in a dumbbell cut out from an injection molded plate. Both stiffness and failure behavior of the experimental curves are very well mirrored by the model (red curves). In addition, the pure response along fiber, perpendicular to the fiber and the shear response are shown (green and blue curves). In the dumbbell, the expected skin-core effect is nicely observed.

4. UD & WOVEN COMPOSITES

4.1 Workflow of coupled analyses

For continuous type of reinforcement the overall approach to coupling is highly similar to the above described (see figure 7). In contrary though, now draping or fiber placement simulations deliver some local information about the microstructure of the continuous fiber composite (fiber orientation, ply thickness...). For stacked composites, a warp angle is exchanged. In the case

of woven materials, warp and weft angles are transferred. Usually no mapping step is required as most draping type of analyses directly work on the mesh of the structural simulation.

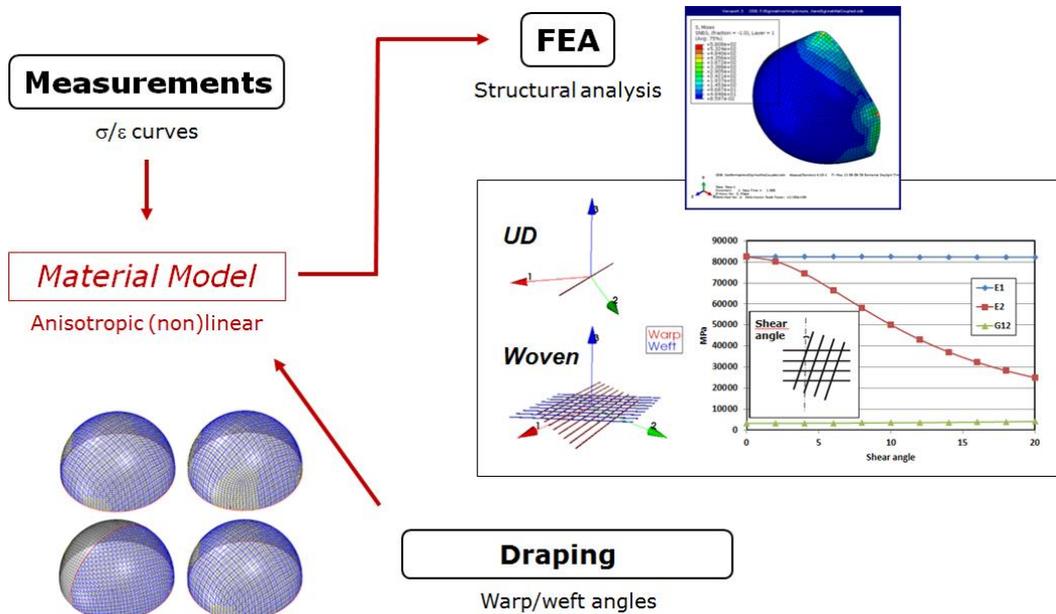


Figure 7. In the coupling of processing simulation with Finite Element Analysis (here shown based on a draping analysis) the micromechanical material model plays the central role.

4.2 Nonlinear stiffness response of organosheets

For woven composites basically the same micromechanical models are applied as for short fibers. Via an increased aspect ratio definition of the ellipsoidal representation continuous fibers can be expressed and superpositioning of these fibers leads to a basic model for woven composites that can fed with information about local warp and weft as given by draping simulations.

The existing models are well able to cover the nonlinear response of the material. For woven composites this becomes especially interesting when describing organosheets, for which the matrix is based on thermoplastic materials. Whereas in this case the material response aligned with the fibers is still linear elastic, directions deviating from this strict alignment can exhibit nonlinear stress strain curves (see figure 8).

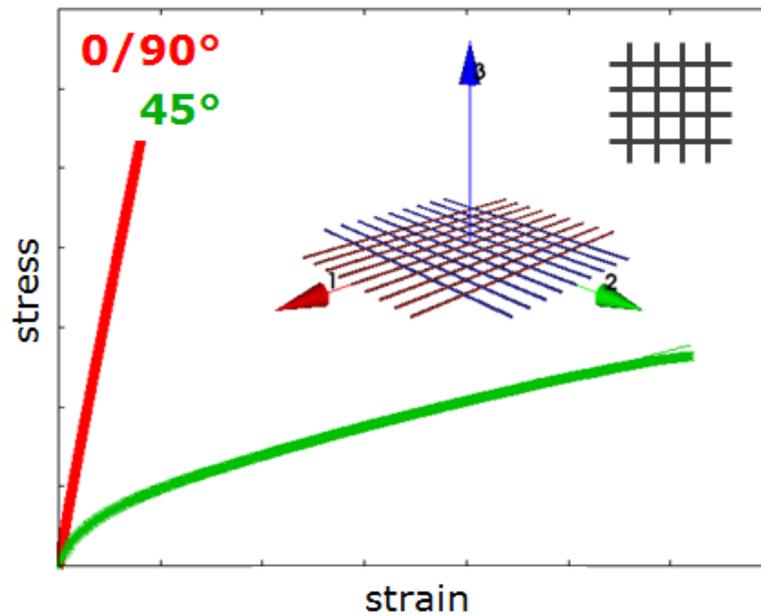


Figure 8. Nonlinear micromechanical model parameterized matching the global stress-strain response, for different loading directions, of an organosheet with $0^\circ/90^\circ$ weave pattern.

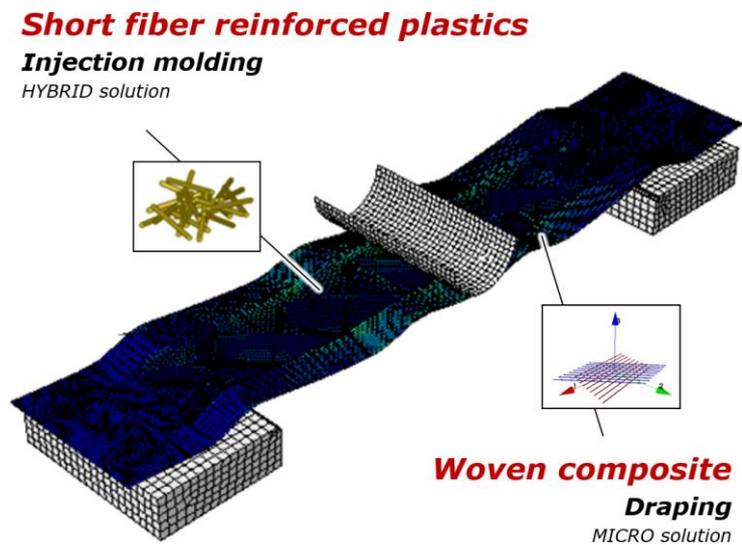


Figure 9. Hybrid design in computer simulation. Whereas the injection molded ribs are described with local material properties based on injection molding simulations, the model for the woven composite is built based on warp and weft information derived from draping analysis.

5. HYBRID DESIGNS

5.1 Comparative study between classical injection molded and over molded hybrid design

In the final, coupled simulation both types of material models are combined to describe the local material properties in the composite part. The short fiber model reads local fiber orientations from an injection molding simulation whereas the model for the woven is taking account results from a draping step (see figure 9).

The study consists of the comparison between a classical design purely based on injection molding as processing technology and the new, hybrid design which combines the benefits of continuous and short fiber reinforcement (see figure 10). It becomes obvious that the higher stiffness of the continuous fibers can be used efficiently to tweak the response of the part with respect to force-displacement. In the bending test the hybrid part exhibits about twice the stiffness of the purely injection molded variant.

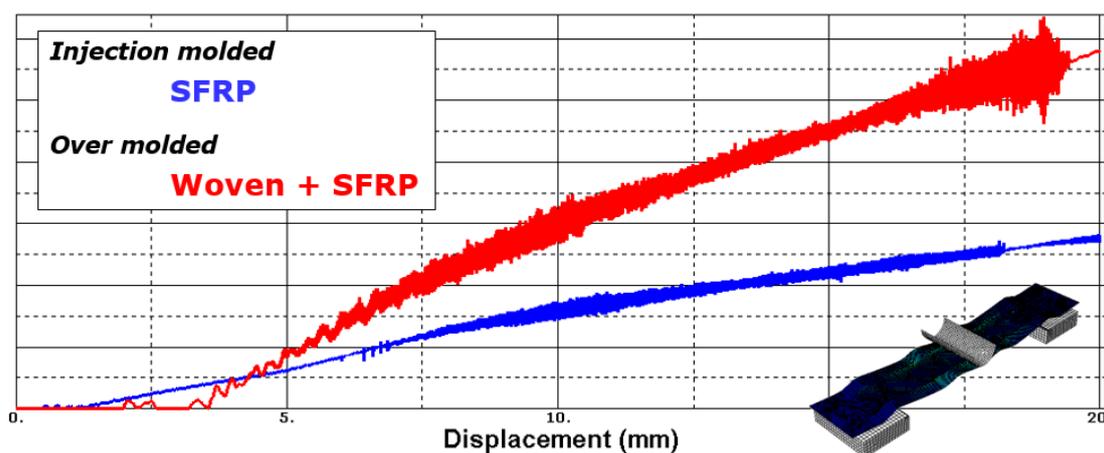


Figure 10. Force-displacement curves comparing a classical, purely injection molded design (blue) with a hybrid design combining continuous and short fibre reinforcement (red). The hybrid design is about twice as stiff as the injection moulded part.

Such results open the doors for improved lightweight design. As the material as well as the process have become direct design variables in the computer analysis, a larger design space can be covered in a few variations. By changing the geometry, material and processing conditions of the part at the same time, an optimum design can be found more easily than by using classical FEA alone. In its complete workflow the integrative approach thus can give really systematic answers to the important key questions:

- Is the part producible?
- What is the best performing (and cheapest) material that can be used in the design?

- Will the final design perform well in its working environment?

For this reason it is believed that in future more and more designs will be based on the idea of coupled simulations in virtual analyses. This method, which today is mostly used in the late stage of design, will certainly shift more and more to a usage in the early stages.

6. CONCLUSIONS

The paper has exposed the ability of mean-field homogenization methodologies to:

- Target multiple materials systems and their specific microstructures.
- Be part of an integrative process-material-structure methodology.
- Target different processes.
- Model multiple material performance.
- Be CAE environment agnostic (usable together with Nastran, Marc, Abaqus, Ansys, LS-Dyna, Moldflow, Moldex, Simulayt, ...).

Such multi-scale methodology enables to compute and predict the influence of various process, microstructural and material properties over the final structural performance, thus giving new improvements opportunities to part design.

REFERENCES

- [1] Doghri I., Brassart L., Adam L., Gérard G-S, "*A second-order incremental formulation for the mean-field homogenization of elasto-plastic composites*", International Journal of Plasticity, (2009).
- [2] Selmi A., Doghri I., Adam L., "*Micromechanical simulation of biaxial yield, hardening and plastic flow in short Glass fiber reinforced Polyamide*", Composites Science and Technology, (2009).
- [3] Doghri I., Adam L., Bilger N., "*Mean-field homogenization of elasto-viscoplastic composites based on a general incrementally affine linearization method*", International Journal of Plasticity, vol.26, (2010), pp.219-238.
- [4] Digimat, "*The nonlinear multiscale material and structure platform*", Users' manuel, v5.0, (2014)