Automatic Generation of Accurate Material Models for Long Fiber Reinforced Plastics in Crash Simulations

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Abstract Long fiber reinforced plastics (LFRPs) offer excellent mechanical properties and are widely used in automotive and aerospace industries. Accurately modeling the behavior of LFRPs under crash conditions is crucial for designing lightweight and safe structures. However, creating reliable material models for LFRPs is challenging due to their complex microstructure and anisotropic nature. This study presents an automatic method to generate highly accurate material models for LFRPs, specifically tailored for crash simulations.

The proposed approach employs virtual testing on representative volume elements (RVEs) that model the LFRP material with fibers and matrix separately. To ensure accuracy, a micro material model is applied, which is calibrated using real micro material experiments combined with computed tomography (CT) scans to obtain the actual fiber orientation distribution.

An anisotropic material card is then calibrated using the generated data. The influence of various factors, including strain rate, fiber orientation, fiber concentration, and stress state, is accurately described within the material model. The model's predictive capabilities are validated against a range of experimental tests, including tension, shear, and biaxial loading conditions.

The main advantage of this method is its efficiency and reduced experimental effort compared to established techniques. By leveraging virtual testing on RVEs and incorporating real micro material data, the proposed approach significantly reduces the time and resources required for material characterization. This enables quicker development and optimization of LFRP structures for crash applications, leading to improved safety and reduced time-to-market.

The presented automatic method for generating highly accurate material models for LFRPs offers a valuable tool for engineers and researchers involved in crash simulation and design optimization. Its ability to capture the intricate behavior of LFRPs under various loading conditions paves the way for enhanced structural analysis and lightweight design in numerous industries.

1 Introduction

Long fiber reinforced plastics (LFRPs) have gained widespread usage across industries due to their remarkable mechanical properties and low weight. Their intricate microstructure, characterized by anisotropic behavior, presents a formidable challenge for accurate material characterization, particularly for crash simulations. The complex material behavior arises from the interaction of fibers and matrix, their varying orientations, and the interplay between different phases. This complexity hampers straightforward material characterization, thereby impeding efficient simulation of LFRP structures subjected to dynamic loading conditions, such as crashes. Inaccurate material models can lead to flawed design decisions, compromising both safety and performance.

Various strategies have been proposed to characterize the behavior of LFRPs, for example the following. Schulenberg et al. (2017) proposed an anisotropic elasto-plastic model, incorporating local fiber orientation distributions to better capture the material's anisotropic response [1]. Reithofer et al. (2016) introduced the *MAT_4A_MICROMEC model, leveraging micro mechanics to describe the material behavior [2]. Nguyen et al. (2009) focused on predicting the elastic-plastic stress-strain response through experimental validation [3]. However, these approaches often demand a significant number of experiments, extensive material testing, and intricate modeling processes.

In contrast to established methodologies, our approach capitalizes on virtual testing on representative volume elements (RVEs) combined with real micro material experiments. This combination enables the separation of fiber and matrix phases, allowing us to optimize material parameters for both elasticity and plasticity. The micro material model, calibrated using real micro experiments and computed tomography (CT) scans, ensures fidelity to the true fiber orientation distribution. Furthermore, an automatic generation of a macroscopic material card is achieved, significantly minimizing the need for numerous physical tests.

The proposed method stands out for its efficiency and accuracy. By merging virtual testing and real micro material data, the material characterization process is streamlined, reducing the time and resources required. This not only enhances the speed of design and optimization but also maintains accuracy in predicting the complex anisotropic behavior of LFRPs under varying loading conditions.

Therefore this approach promises to revolutionize the field of material characterization for LFRPs. The subsequent chapters delve into the details of our methodology, its automation techniques, validation exercises, and the inherent advantages it offers over existing methods.

2 Material, Experiments, Virtual testing, and Models

The investigation focuses on a 30% glass fiber reinforced polypropylene (PP-GF30) provided by Sabic. The glass fibers have a diameter of 19 µm and a length of approximately 2 mm. Due to the fiber reinforcement, the elastic and plastic material behavior of the composite exhibits strong anisotropy. However, the degree of anisotropy varies locally within components or plates due to the fiber orientation achieved during the injection molding process. To accurately describe the material behavior, particularly at the onset of yielding, the stress state must also be considered. Additionally, the strain rate has a significant influence.

Unlike conventional characterization methods that involve a multitude of macroscopic tests at different stress states and strain rates, this study adopts a different approach. Instead, a limited number of micro-scale tensile tests were conducted, with samples having a cross-section of 0.5 × 0.5 mm² and a length of 6 mm. Computed tomography (CT) scans provided complete information about the fiber distribution within the samples. Strips were prepared using micro waterjet cutting, and five micro-samples were extracted from each strip. Prior to sample extraction, the strips were polished to achieve the desired thickness (see Fig.1:).

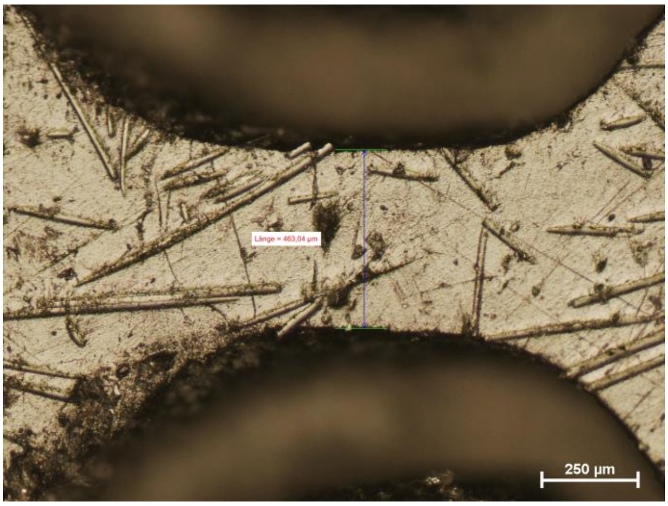

Fig.1: Micro-samples for tension tests characterizing the mechanical properties.

Based on the micro-scale tensile tests, a micro model was calibrated to perform subsequent virtual tests. These simulations on microscale were performed with GeoDict [4].The micro model represents the fibers and the matrix as two distinct phases. The real fiber distribution was incorporated into the model since the geometry was taken directly from the segmented CT scan (see Fig.2:). While the fibers were assumed to exhibit linear elastic behavior (E = 72 GPa, v = 0.22), the parameters governing the viscoplastic behavior of the matrix were iteratively adjusted, considering matrix damage, until a good agreement with the experimental measurements was achieved [5].

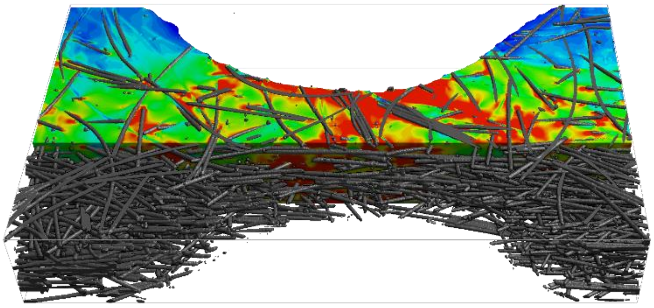

Fig.2: Segmented CT scan of a micro sample which was incorporated in the calibration of the micro model and an associated simulated strain field.

Representative volume elements (RVEs) were generated to conduct virtual tests for the automated creation of a macroscopic material card. Four parameters were varied to observe their influence on the material behavior. Firstly, the in-plane fiber alignment was varied by altering the A_{xx} component of the fiber orientation tensor, assuming five values ranging from 0.5 to 0.9. Secondly, fiber volume fractions of 11%, 12%, and 13% were considered. Thirdly, strain rates of 0.001/s, 10/s, and 200/s were applied. Finally, the anisotropy and stress state dependency were examined by subjecting the material to three deformations: uniaxial tension along the 0° and 90° fiber directions, and pure shear. The mean stress and strain from these virtual tests were utilized for the automated material characterization.

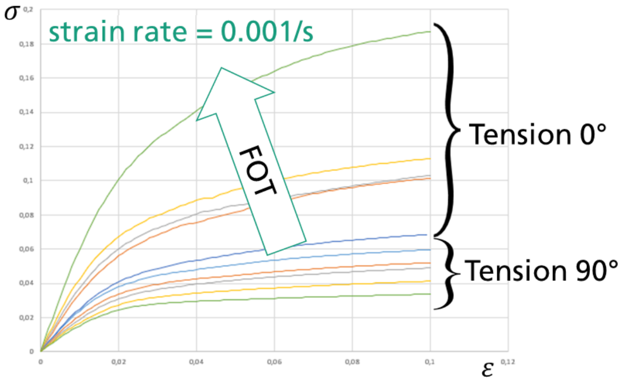

Fig.3: Stress strain curves of exemplary RVE simulations with the optimized micro model. Here tension in 0° and 90° are applied with a constant quasi-static strain rate whereby the fiber orientation is varied from A_{xx} =0.5 to 0.9.

For macroscopic crash simulations, the standard model **`*MAT_157`** or **`*MAT_ANISOTROPIC_ELASTIC_PLASTIC`** in LS-DYNA was employed. The model assumes transversely isotropic linear elasticity. The yield surface is described using Hill's criterion, incorporating an anisotropic yield initiation criterion dependent on the stress state. A flow curve can be defined independent of the loading direction, with each strain rate treated independently. In a preprocessing step, these parameters were assigned to individual elements within the component or sample based on their local fiber orientation and local fiber volume fraction obtained from an injection molding simulation.

3 Automatization Method

This chapter presents the methodology for automated adjustment of a complex material card, such as *MAT_157, based on the local fiber distribution obtained from the previously conducted virtual tests on

RVEs. The material parameters related to elasticity, yield initiation, and flow curve are optimized. In practice, it is not necessary to perform virtual tests for all possible combinations of influencing parameters. Instead, suitable assumptions can be made to interpolate the material properties for missing data points. Therefore, in addition to the fitting method applied to stress-strain curves, interpolation techniques are discussed in the following sections.

The stress-strain curves of PP-GF30 exhibit slight nonlinearity from the beginning and do not show a clear transition to plasticity. This complicates the determination of the elastic modulus (E). The point of maximum change in slope provides an estimate of the onset of yielding. The stiffness is then determined as the average slope up to the point of maximum change in slope.

For predicting the elasticity, widely accepted methods based on analytical homogenization exist. For instance, the transversely isotropic stiffness tensor proposed by Mori and Tanaka (1973) for ellipsoidal and unidirectional fibers, weighted by the fiber orientation according to Advani and Tucker (1987), was applied in this study. This approach allows the determination of the elastic modulus for each deformation, fiber orientation, and fiber volume fraction.

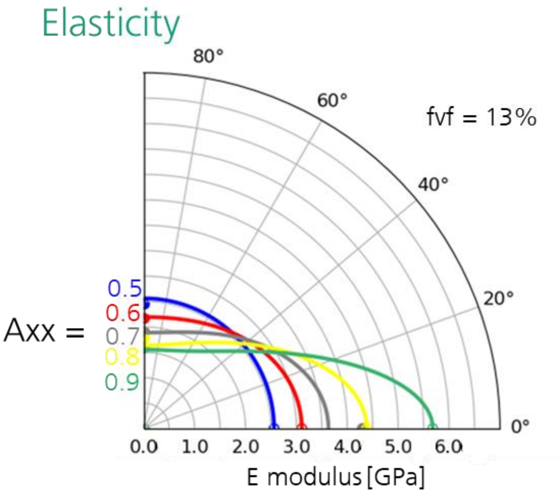

Fig.4: The anisotropic elasticity automatically determined from RVE simulation with varying fiber orientation at a fiber volume fraction of 13%.

Using the elastic modulus, the flow stress corresponding to the yield strength ($\mathrm{R}_{p0,2}$), where the material deviates by 0.2% strain from the linear behavior, was determined for each virtual test (see Fig.5:). By subtracting the elastic contribution from the total strain, the flow curves for the virtual tests were obtained. For most commonly used material models, a flow curve can be defined per strain rate, necessitating the adjustment of a representative curve for loading in the 0°, 90°, and shear directions. The flow curves were scaled to the same flow stress for this purpose (see Fig.6:).

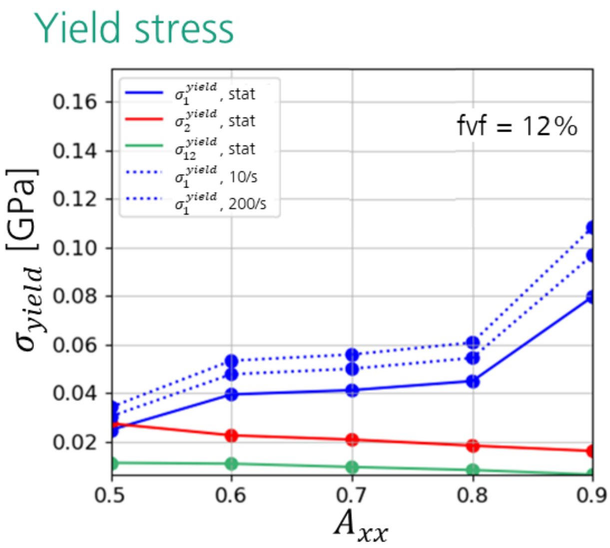

Fig.5: The anisotropic yield stress automatically determined from RVE simulation with varying fiber orientation and strain rate at a fiber volume fraction of 12%.

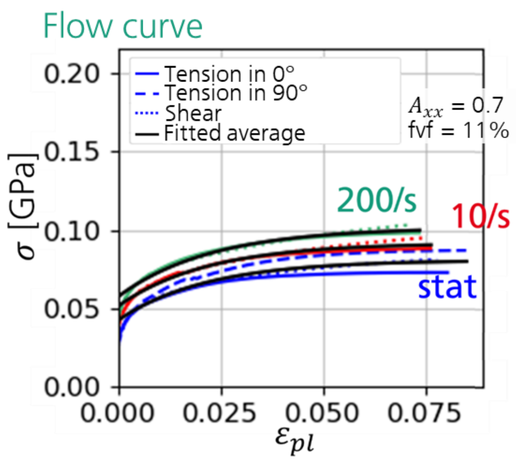

Fig.6: The strain rate dependent flow curves automatically determined from RVE simulation as an average over different loadings at a fiber orientation of A_{xx}= 0.7 and a fiber volume fraction of 11%.

In cases where data is missing, interpolation techniques can be employed to estimate the plastic behavior. Analytical homogenization approaches for nonlinear parameters are computationally expensive or unreliable. Hence, a linear interpolation method was adopted in this study. This allowed for the description of the complete yield surface and subsequent flow behavior at different strain rates and fiber distributions.

By automating the determination of material parameters, a complex and accurate macroscopic material card can be created without significant time expenditure, utilizing the information obtained from virtual tests.

4 Validation

Validation of the automatically generated macroscopic material card is conducted through a series of conventional characterization tests. To assess the accuracy of the material model, flat tensile tests are simulated at both 0° and 90° orientations, encompassing two distinct strain rates. The simulated results are meticulously compared with experimental data (see Fig.7:). Impressively, the simulation outcomes closely align with the experimental findings. Notably, the material model adeptly captures quasi-static behavior, demonstrating a robust prediction capacity. However, under dynamic loading conditions, the model exhibits a slight tendency to underestimate stiffness due to its singular representation of elasticity for a specific strain rate.

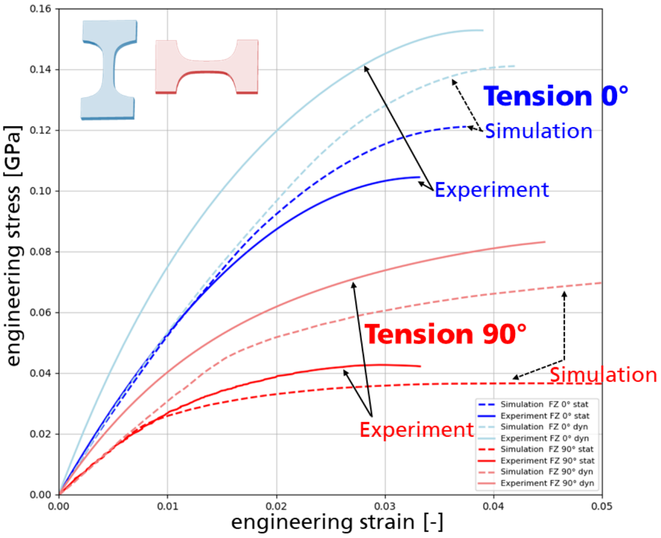

Fig.7: Comparison of simulation and experiment for macroscopic tension test in 0° and 90° for quasi-static and dynamic loadings for validation

The efficacy of the model's predictions is further showcased through biaxial stress state perforation tests (see Fig.8:). The model accurately characterizes material behavior up to the initiation of failure. Intriguingly, even beyond this critical point, a remarkable congruence is observed between the force-displacement curves obtained from experimental trials and those predicted by the simulation.

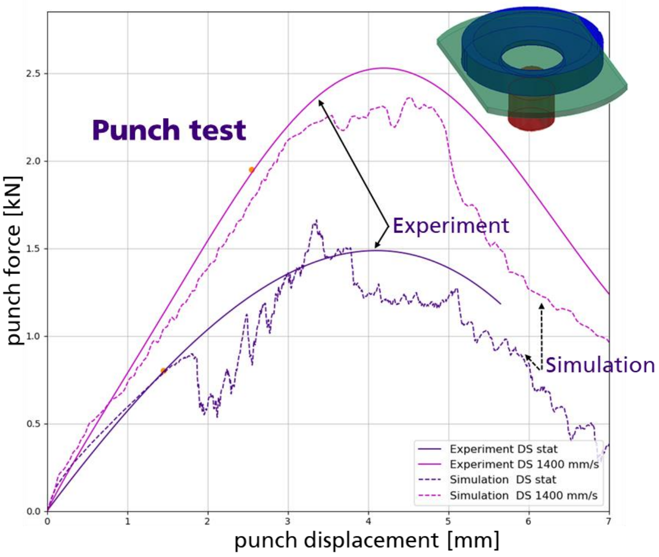

Fig.8: Comparison of simulation and experiment for biaxial test for quasi-static and dynamic loadings for validation

The validation procedures collectively underscore the fidelity of the generated material model in predicting intricate mechanical responses. While its prediction capabilities are evident in capturing static behavior, there exists potential for fine-tuning to enhance its accuracy in predicting dynamic responses. In summation, the notable concurrence between simulation and experimentation serves as a testament to the robustness and effectiveness of the proposed method in elucidating the nuanced behavior of long fiber reinforced plastics across diverse loading scenarios.

5 Conclusion

In this study, we embarked on a comprehensive exploration to address the challenges inherent in creating accurate material models for long fiber reinforced plastics (LFRPs) for crash simulations. Our goal was to develop a method that not only captures the intricate anisotropic behavior of LFRPs but also streamlines the material characterization process. Through a systematic approach, we succeeded in achieving these objectives, and the results presented herein showcase the efficacy of our approach.

We introduced a method that combines virtual testing on representative volume elements (RVEs) with real micro material experiments to create a highly accurate material model. By disentangling the fiber and matrix phases within the material, we could optimize parameters for both elasticity and plasticity. This method allowed us to automatically generate a macroscopic material card, thereby significantly reducing the requirement for extensive physical testing.

Validation of the proposed approach was undertaken using conventional mechanical tests. Tensile tests and biaxial loading perforation tests were simulated and compared with experimental data. The striking agreement observed between simulation and experiment underscores the reliability of the material model. Importantly, the model excelled in predicting static behavior, while also demonstrating potential for further refinements to enhance its accuracy under dynamic loading conditions.

The primary advantage of our method lies in its increased efficiency and reduced experimental demands compared to conventional techniques. By harnessing virtual testing and incorporating real micro material data, we expedite the material characterization process without compromising accuracy. This not only accelerates the development of lightweight structures for crash applications but also minimizes the associated time and resource expenditure.

In conclusion, this study introduces an innovative methodology that presents a paradigm shift in material characterization for long fiber reinforced plastics. The integration of virtual testing, real micro material experiments, and automated material model generation offers a powerful tool for engineers and researchers. As the automotive and aerospace industries continue to demand lightweight yet robust designs, our approach stands poised to revolutionize the field by providing an efficient and accurate means to tackle the challenges posed by complex material behaviors.

6 Literature

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