Parameter identification for constitutive models of innovative textile composite materials using digital image correlation

Justin Felix Hofmann1,* , Claudia von Boyneburg2, Sophie Tunger1, Hans-Peter Heim2, and Detlef Kuhl1

1 Institute of Mechanics and Dynamics, University of Kassel, Mönchebergstraße 7, 34109 Kassel, Germany
2 Institute of Material Engineering, Polymer Engineering, University of Kassel, Mönchebergstraße 3, 34125 Kassel, Germany

This contribution focuses on an innovative composite material consisting of textile layers made from continuous wooden fibers embedded in a thermoplastic matrix. A finite element simulation of potential use-cases is planned to support the development process and to study the suitability of the material in an architectural context. The simulation is based on a constitutive model assuming homogenous orthotropic elastic behavior and will be expanded to include multiscale modeling in future research. The material parameters used in such models can often be determined based on a small number of local measurements during experiments like tensile tests, which assume classical one dimensional load scenaria at least in parts of the specimen. However, this is not sufficient for non-homogeneous materials, especially when dealing with non-isotropic materials in off-axis configurations and the need for full-field measurements like digital image correlation (DIC) arises. Experimental results of uniaxial on- and off-axis tensile tests using DIC are presented and used in the identification of the material parameters of the given model. Results of simulations and experiments are compared and the suitability of the material model is discussed.

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1 Motivation

Standardized testing methods for the determination of elastic material parameters often focus on isotropic mechanical behavior. They require specific specimen geometries to generate homogeneous strain states during testing, which in turn require only a small number of local measurements to be fully captured. However, nonisotropic materials demand more sophisticated techniques. The parameter identification method presented here is based on finite element model updating and processes full-field displacement measurements gained during uniaxial tensile tests (Fig. 1). Rectangular specimens (Fig. 2) were tested in on and off-axis configurations, but the method could be applied to other forms of testing and specimen geometries as well [1].

The method is applied to a composite material based on woven fabrics made from continuous wooden fibers and thin polypropylene films containing 5 wt% of a coupling agent (maleic anhydride). The composite is produced in a high precision hot compaction process. It is expected that the material behavior is orthotropic.

2 Experiment

To enable independent stress-strain states during the tests, the specimens were cut from the base material at various angles (0°/22.5°/45°/67.5°/90°) with respect to the warp direction of the textile layers. A stochastic pattern was applied to the surface of each specimen prior to testing. Pictures of the specimens surfaces were taken at regular intervals during the experiments using a two-camera setup and converted into displacement data \( u_{\text{exp}} \) using digital image correlation (Fig. 4). The transformation between camera and specimen coordinate systems was acquired during a calibration step. Corresponding force measurement were taken using a load cell.

The results have demonstrated highly inhomogeneous displacement fields due to the inhomogeneity of the composite.

3 FE-simulation

A finite element model reproducing the test setup was created for each specimen and load step. Each model includes the specimen geometry (width, thickness, effective length between clamps), the orientation of the material with regard to the specimen coordinate system, as well as the boundary conditions applied during the campaign (clamps, force). The specimens were discretized using a finite element mesh consisting of bilinear quadrilateral elements (Fig. 3). The initial material parameters \( p_0 \) for an orthotropic linear elastic material model were chosen arbitrarily.

* Corresponding author: e-mail hofmann@uni-kassel.de, phone +49 561 804 2341

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4 Parameter identification

The parameter identification algorithm follows the idea of finite element model updating (Fig. 5). Experimental and numerical results are compared on the strain level at each gauss point in the area of interest using error function

$$e(p_n) = \sum_{j=1}^{N} |\epsilon_{j}^{\text{num}}(p_n) - \epsilon_{j}^{\text{exp}}|^2$$

The error is subsequently minimized using the gradient descent method to find a set of optimal material parameters. Prior to solving this inverse optimization problem, the experimental displacement data $u_{i}^{\text{exp}}$ is converted into strain data $\epsilon_{j}^{\text{exp}}$ at the gauss points of the finite element mesh by solving a local element-wise optimization problem described in [2] for each element containing sufficient corresponding measurements. To compute an update step of the material parameters, the experimental strain data of all specimens and load steps is compared simultaneously to the corresponding numerical strains $\epsilon_{j}^{\text{num}}$ generated using the finite element model. To save computation time, the first and second analytical derivatives of the error function with regard to the material parameters were used in the gradient descent algorithm, as opposed to a numerical approach.

Given reasonable starting values, the identification algorithm fully converged after approximately 8 to 10 iterations (Fig. 6 and 7). The converged solution was independent of $p_0$ and in agreement with the expected range of values, based on previously determined material parameters of the individual material components and the theory of mixtures of composites.

5 Conclusion and outlook

An inverse method for the identification of the elastic material parameters of orthotropic materials has been presented. The method is based on finite-element-model updating. Displacement measurements taken during tensile tests were compared to the results of a finite element simulation using a strain based error function which is subsequently minimized via the gradient descent method. It could be shown that the method converges against a solution for the orthotropic material parameters which is independent of the chosen starting values and that the results agree with predicted values based on prior knowledge. However, validation of the method is still pending.

The experimental results show a strong material inhomogeneity, which can’t be reproduced by the material model used in this work. Consequently, the parameter identification method will be applied to multiscale modeling in future research.

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