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Experimental methods to validate modeling of fiber reinforced materials

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Micro Abstract
This contribution provides insight to some methods that provide an experimental data basis for modeling of material constituents on microscopic scale and their interaction. This covers the use of versatile full-field methods to improve the cross-validation, to obtain fiber dispersion, topology and orientation, the use of micromechanical techniques and application of in-situ methods to analyze damage progression as function of external load

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Introduction

In the past century, material modeling methods have been established for homogenous isotropic materials. Developments of the last 50 years then extended their applicability to homogenous anisotropic materials, followed by activities in the last 20 years to consider heterogeneity and hierarchy of materials. For fiber reinforced polymers (FRP), this needs to consider the distribution and orientation of the filaments and rovings, that cause the anisotropy and heterogeneity within the material. Much of these approaches have approximated the material microstructure as perfectly symmetric by introducing representative volume elements or by using material homogenization techniques on artificial sub-structures as in textile architectures. Despite of the significant advances this added to the fields of structural modeling, process modeling and alike, some of the modeling attempts are prone to fail if the real microstructure of the material is not sufficiently considered. This may happen whenever the approach involves materials with pronounced heterogeneity (as seen e.g. for tape-based thermoplastic materials or metal/FRP hybrids) or gradient sub-structures (e.g. due to filler particles with preferred dispersion). In addition, this may easily happen for modeling attempts trying to capture the dynamics of fracture processes, or trying to describe the interaction of internal substructures with wave-fields. The aim of this contribution to GACM 2017 is to highlight some of the latest experimental developments that help to validate associated modeling work.

Computed tomography

One powerful experimental approach is the use of computed tomography for quantitative measurement of the 3-dimensional inner structure of materials with unprecedented accuracy. Meanwhile, even commercial systems allow voxel resolutions below one micrometer, sufficient to analyze the orientation of single fiber filaments (cf. Figure 1-a). At synchrotron facilities, full 3D images of fiber reinforced materials can now be recorded in the sub-seconds range [12]. Several software packages are readily available to perform automated analysis of fiber orientation and their size distributions. Still this is an active field of research, as quantitative results are influenced by the particular algorithm, the raw data quality and averaging effects. Nevertheless, direct mapping of fiber orientation extracted from volume images is getting a standard for modeling the directivity effects and material mixtures on the microscale by importing this information into modeling programs. Another recent approach is the extraction of internal

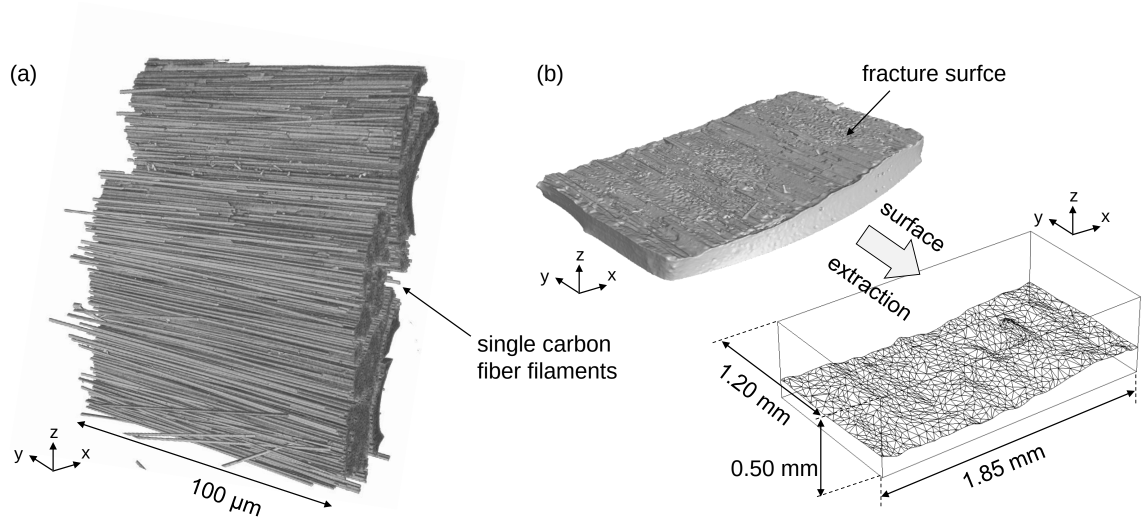

Figure 1. Example for high-resolution details of an carbon fiber reinforced polymer (a) and extraction of fracture surface resulting from normal load into mesh (b).

topologies for modeling work. Figure 1-b. shows an example of an extracted crack surface used for a finite-element-modeling (FEM) approach. For the purpose of comparison to crack modeling techniques, concise knowledge of the true crack topology in the material is crucial. In addition, in modeling of nondestructive testing methods, a detailed description of the interaction between such defects and the incident wave-field is important to turn from qualitative modeling to quantitative modeling [8, 13].

Full-field methods

For the purpose of thermomechanical modelling of materials it has already become a standard to use image correlation measurements on macroscopic scale [8, 11]. The tracking of subsets of stochastic patterns provide a discrete representation of displacement fields and strain fields on the surface of the material. This is not limited to the macroscopic scale as seen in the same approach applied to an image series recorded in 3-point bending of a fiber reinforced thermoplastic material. In this case, the stochastic fiber distribution acts as natural pattern, used for an image correlation step. In addition, the incorporation of this fiber distribution into an FEM program and application of the experimental displacement constraints then allows for numerically reproducing the same inhomogeneity of the strain field as recorded experimentally (cf. Figure 2). Meanwhile, several groups reported the successful use of the inner material structure to perform digital volume correlation [1, 2, 11]. With the same idea and the availability of volumetric correlation algorithms, this allows extraction of volumetric displacement fields and strain fields to compare to corresponding modeling work.

Micromechanics

For modeling on the microscale, several material properties of the matrix material and the reinforcement fibers, as well as their interaction is required. For process modeling, it is important to consider, that the presence of the fibers may lead to changes of the matrix chemical structure in the vicinity, so macroscopically determined properties may not necessarily be applicable. However, peak force quantitative nanomechanics (PFQNM) mapping techniques of local stiffness values may add to understand such changes [6]. However, some reinforcement fibers themselves are anisotropic, yet measurement of their full stiffness tensor is still not accessible by experimental means. In a related field, the quantification of the adhesion between fiber and matrix is still challenging. To respect all influence due to the fabrication process, the single fiber push-out

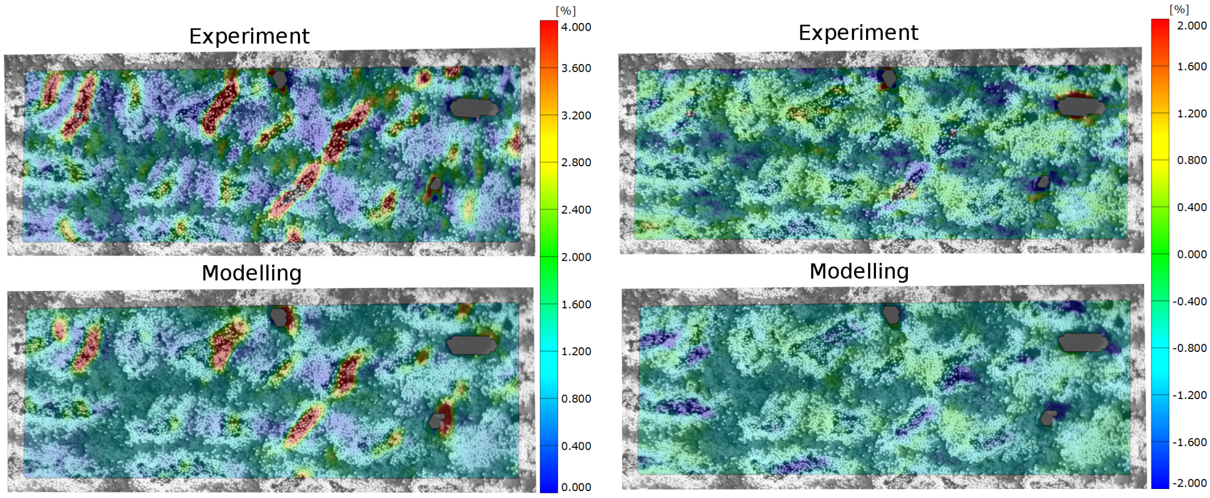

Figure 2. Inhomogeneities due to presence of porosity seen in the strain field in x- and y-direction and comparison to corresponding modeling work.

technique uses a small slice of a fiber reinforced material to evaluate the quality of the bonding. With a modified, cyclic load profile it became possible measuring the mode II interfacial fracture toughness [3, 4, 7]. This can be used for numerical modeling of this experiment setting and thus cross-validate the experimentally used data reduction [4] and to visualize the crack growth as function of load, taking into account residual thermal stresses and the presence of surrounding fibers (cf. Figure 3.).

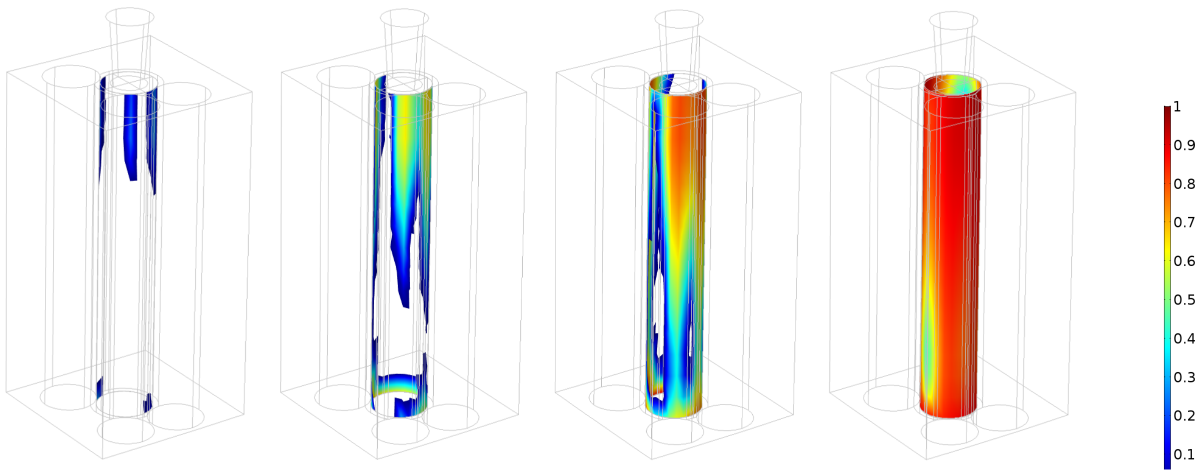

Figure 3. False-colour representation of interface decohesion (blue colour at initiation, red colour corresponds to completely debonded) as computed with cohesive zone model including influence of surrounding fibers for push-out displacements of $0.3\,\mu m$, $0.5\,\mu m$, $0.65\,\mu m$ and $0.85\,\mu m$

In-situ methods

In-situ observation for material modeling is valuable for micromechanical modeling, but certainly not limited to this field. Especially for structural modeling of fiber reinforced materials under load, the use of full-field methods, such as digital image correlation is well known for validation of FEM modeling of materials, but also used for structural components. Other methods, such as acoustic emission add further information obtained in-situ during application of the load. Recording the transient acoustic waves due to crack initiation and progression allows tracking the birth and growth of damage inside the material. Using signal classification procedures this can be assigned to particular failure mechanisms [8–10]. With the aid of sensor networks, this also allows to localize the position of the crack in the material [5,8]. The mapping of this information to the structure as function of load can be compared to prediction of failure mechanisms from analytical or numerical models. A simple example for such a comparison shows the calculated first onset of inter-fiber failure and fiber failure using Puck's failure criteria and the acoustic emission result for several laminate configurations in Figure 4.

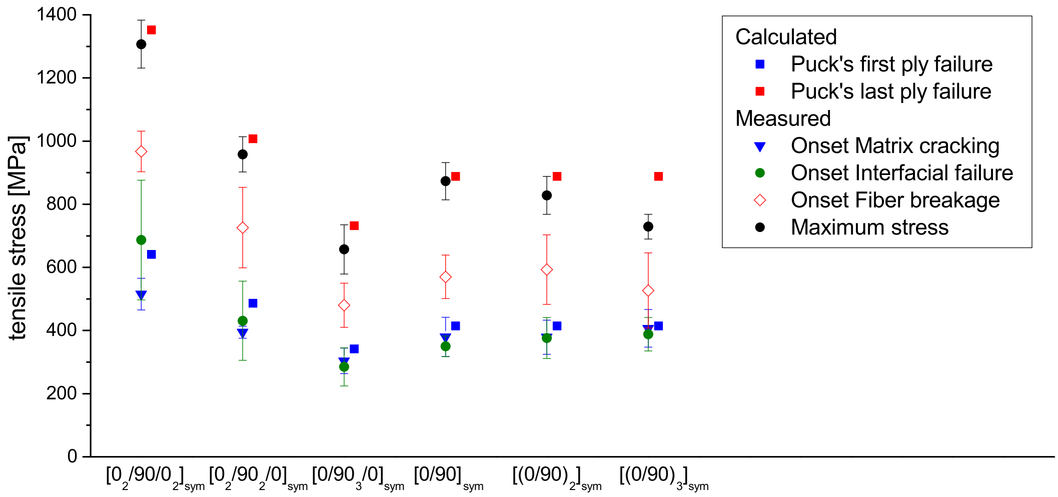

Figure 4. Comparison of Puck's failure criteria vs. acoustic emission measurement results for several different laminate configurations.

Conclusions

Modern experimental approaches allow validating modelling techniques for fiber reinforced materials in several aspects. They can provide details of the volumetric material structure of the material and allow full-field comparison of calculated quantities with measured quantities. Dedicated micromechanical experiments have been designed to test for the interaction between fiber and matrix materials and to measure the material properties required for fracture mechanics approaches on the microscale. Even for macroscopic test situations, in-situ methods can be used to access full-field displacement and strain information, but also to register and localize formation of damage.

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