ON THE PROBLEM OF GENERATING RELIABLE MATERIAL DATA OF SFRPS FOR STRUCTURAL SIMULATIONS

K. Kose[1*], A. Zeiser[1]

[1]*inpro Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der Fahrzeugindustrie mbH, Berlin, Germany*
**kim.kose@inpro.de*

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Abstract

Virtual development and testing is a standard in the development of new parts and devices. The aim to provide reliable simulations leads to the need for reliable material data as a basis. For FE- calculations of short fiber reinforced polymers locally defined material behavior is needed to identify problematic regions successfully. Current test specimens are usually not suited for the determination of material as well as fatigue life data of highly oriented material in different loading directions.

This paper presents a test specimen to overcome this problem and an algorithm to deduct reliable material data for construction purposes.

1 Introduction

Virtual development and testing is a necessity in the development of new parts and devices. Through the advancements made in the development of short fiber reinforced polymers (SFRPs) this material class is now considered for a large range of semi-structural as well as fatigue loaded parts in the automotive industry.

The aim to provide reliable simulations not only for the structural behavior but also for the determination of the fatigue life leads to the need for reliable material data as a basis of the simulations. This need is enhanced by the imperative to avoid prototypes as much as possible even for fatigue prone parts.

The use of SFRPs leads to an anisotropic material with considerable differences of the material behavior through thickness as well as in all locations of a part. This is also true for test specimens used to determine material characteristics. Hence material characteristics are always the result of measurements which are integral at least in the through-thickness direction. This is contrary to the need of locally defined material behavior which is needed for FE-calculations. Especially for fatigue calculations even small deviations e.g. arising out of different fiber orientations in the stress results may add up to large deviations in the computed fatigue life.

To overcome this problem it is proposed to analyze experimental results with the help of coupled structural and molding simulations (although these may give sometimes erroneous results for the fiber orientations, see [7]). In this way it is possible to determine the material specific properties which do not depend on the actual fiber orientation of the test specimens.

2 The task

Standard data supplied by a polymer manufacturer or compounder does usually provide only a medium linear stiffness of the material. For a real part the stress-strain relationship is dependent on the strain, the strain rate, the fiber orientation and further manufacturing parameters like holding pressure and time. This again is the basis for the fatigue life calculation. In this paper we deal with the determination of the correct nonlinear stress-strain-relations based on a injection molding simulation. To accomplish this task we have developed a new test specimen as well as an accompanying software to determine the material parameters using simulations. The main feature of this cylindrical test specimen is its single-curved section in the middle (see Figure 1) which makes it a three dimensional version of a standard tension test specimen. Due to this geometry the fibers have a high orientation in the direction of the cylinder-axis.

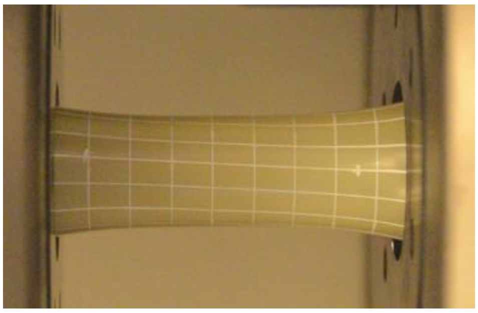

Figure 1. Test specimen on test rig

The material parameters are used to determine the stress state in the object considered. Due to the nonlinear nature of the stress-strain curves the stress state in a real object will not be linear to the loading.

Numerically, material parameters as well as fatigue life curves are determined using well defined test specimens. The fiber orientations are however only well known for the standard tensile test specimen. For all other test specimens, e.g. cut-outs of a plate, the fiber orientations have to be determined numerically. The same is true for the stress-strain relationship. In Figure 2 the force over tension and the moment over torsion angle for the test specimen are shown. In the curves with injection molding simulation the linear stiffness tensor was computed by that program.

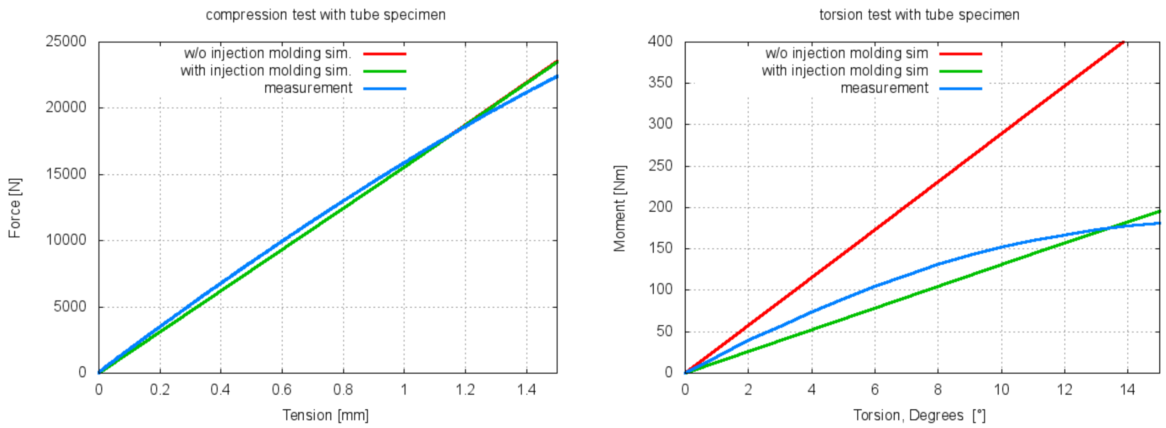

Figure 2. Force over compression (left) and moment over torsion (right), measured (blue) in comparison to computed values without (red) and on the basis of an injection molding simulation (green)

The differences in the torsion stiffness are considerable, although the calculations agree relatively good with the measurement in the tension and pressure tests. In order to avoid faulty designs it is necessary to have a better accordance between measurement and calculation.

2 Proposed approach

The overall aim is to obtain a material model which is parameterized by the local fiber orientation distribution and additional global constants, depending only on the material itself. The material parameters are determined in the following way. For each fiber reinforced material the designed test specimen is produced through injection molding and a molding simulation is performed to predict the fiber orientation distribution. Then tension, compression and torsion experiments are performed on the specimen. Now the material parameters are adjusted to reproduce the experiments in the best possible way. The latter task is performed by coupling the structural simulation and an optimization software.

2.1 Material modeling

As a material model we propose using a homogenization method [4]. Ideally the material behavior can be expressed through the material models of its constituents, allowing literature values to be used. These parameters may be thought of as a first guess and have to be fitted to the present situation. However the fitting may be limited to a few important parameters. In the following we present a simple material model which is based on modeling the matrix phase with the help of a Ramberg-Osgood material model and the fibers as linear elastic, see also [10].

Consider a two phase composite consisting of matrix and fibers, where the matrix phase and the fiber occupies the volumes V_m and V_f, respectively, of the representing volume element V. Define the volume fraction v_f of the fibers as $v_f = V_f / V$. We assume that the fibers have the shape of rotated ellipsoids with aspect ratio l/d and are distributed according to an orientation distribution function (ODF).

In the first step we assume that all fibers are aligned in a given direction p, $\|p\| = 1$, and that the matrix and the fibers exhibit isotropic linear elastic behavior. The corresponding stiffness tensors are denoted by C_m and C_f. Using the mean-field homogenization of Mori-Tanaka [9] based on the Eshelby tensor [6], the average strains can be expressed as by using the strain concentration tensors $H_{m,\mathrm{UD}}$ and $H_{f,\mathrm{UD}}$:

$$\langle \varepsilon \rangle_f = H_{f,\mathrm{UD}}(C_m, C_f, l/d, v_f, p)\langle \varepsilon \rangle, \ \langle \varepsilon \rangle_m = H_{m,\mathrm{UD}}(C_m, C_f, l/d, v_f, p)\langle \varepsilon \rangle \tag{1}$$

Here the average strain in the whole reference domain $\langle \varepsilon \rangle$ and the strains in each phase, i.e $\langle \varepsilon \rangle_m$ and $\langle \varepsilon \rangle_f$ for the matrix and fibers, resp., are given by

$$\langle \varepsilon \rangle = \frac{1}{V} \int_V \varepsilon(x) \mathrm{d}V \ , \ \langle \varepsilon \rangle_{m/f} = \frac{1}{V_{m/f}} \int_{V_{m/f}} \varepsilon(x) \mathrm{d}V \ .$$

The average stress can then be computed by

$$\langle \sigma \rangle = C_{\mathrm{UD}} \langle \varepsilon \rangle, \ C_{\mathrm{UD}} = C_m + v_f (C_f - C_m) H_{f,\mathrm{UD}} \ .$$

In a second step we treat the orientation distribution of the fibers. In this case one obtains the stiffness C of the composite through averaging C_{UD} with respect to the given ODF. This can be achieved using the fiber orientation tensors of second and fourth order of the ODF [1]. Usually only the second order tensor is available such that the fourth order tensor has to be approximated using a closure approximation, see [5] for a evaluation of different approximations. In the present work we use the multiplicative closure. Analogously, the non-symmetric tensors $H_{f,\mathrm{UD}}$ and $H_{m,\mathrm{UD}}$ can be averaged with a slight modifying the procedure.

Finally we treat the case of nonlinear material behavior of the matrix phase. For rate independent materials we approximate the stress-strain-relation in terms of stress and strain rates, i.e.

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle\sigma\rangle_m(t) = C_m^t(t)\frac{\mathrm{d}}{\mathrm{d}t}\langle\varepsilon\rangle_m \tag{2}$$

for a uniform tangential stiffness tensor of the matrix $C_m^t(t)$ [3]. More specifically we use a Ramberg-Osgood model depending on the average stress and strain of the matrix phase. We interpret the one-dimensional relation

$$\varepsilon = \varepsilon^e + \varepsilon^p = \frac{\sigma}{E} + \left(\frac{\sigma}{\sigma_0}\right)^n$$

as a decomposition into an elastic strain ε^e and a plastic strain ε^p. The elasto-plastic tangent modulus E^t is then given by

$$E^t = \frac{E}{1 + n(\sigma/\sigma_0)^{n-1}}.$$

For the calculation of the tangent modulus E_m^t of the matrix we plug the equivalent Mises stress of the average stress $\langle\sigma\rangle_m$ of the matrix phase into the last equation. In addition to E_m^t the original Poisson ration ν_m is used for the calculation of the tangent stiffness $C_m^t(t_n)$.

In the simplest case the differential equation (2) may be discretized by a forward Euler scheme. The resulting tangent stiffness tensor may then be plugged into the strain concentration tensors (1). Finally we arrive at the following procedure: Given a macroscopic strain increment $\Delta\varepsilon$ in the time interval $[t_n, t_{n+1}]$ evaluate the tangential stiffness $C_m^t(t_n)$ using the average stress $\langle\sigma\rangle_m$ in the matrix phase. Now plug this tensor into the definition of the strain concentration tensor $H_f(t_n)$ and calculate the stiffness $C(t_n)$ of the composite. The stress increment of the composite is given by $\langle\Delta\sigma\rangle = C(t_n)\Delta\varepsilon$, and that of the matrix phase as $\langle\Delta\sigma\rangle_m = C_m^t(t_n)\langle\Delta\varepsilon\rangle_m$, $\langle\Delta\varepsilon\rangle_m = H_m(t_n)\Delta\varepsilon$.

The material model has been implemented as a user defined material into the Abaqus FE simulation package.

2.2 Parameter determination

The performed tests may now be simulated using the material model described above. The structural simulation depends on the calculated fiber orientation distribution and the global material parameters. The simulation is automated such that it can be coupled to an optimizer which alters the material parameters of the constituents systematically. The objective is to reproduce the experimental results, i.e. displacement force curves, as good as possible. Performing a sensitivity study the most important material parameters can be determined.

3 Preliminary results

The approach has been applied to Polyamide 6 with 30%wt short glass fibers on the basis of preliminary measurements. In Figure 3 the results of the parameter optimization process are displayed. In the case of compression the force displacement curve is reproduced quite well. However the tension test shows a significant difference in the initial slope of the curve. This applies to both the linear and the proposed model since they rely on the same homogenization principle. It is to note that a scaled version of the new model agrees well with the measurements.

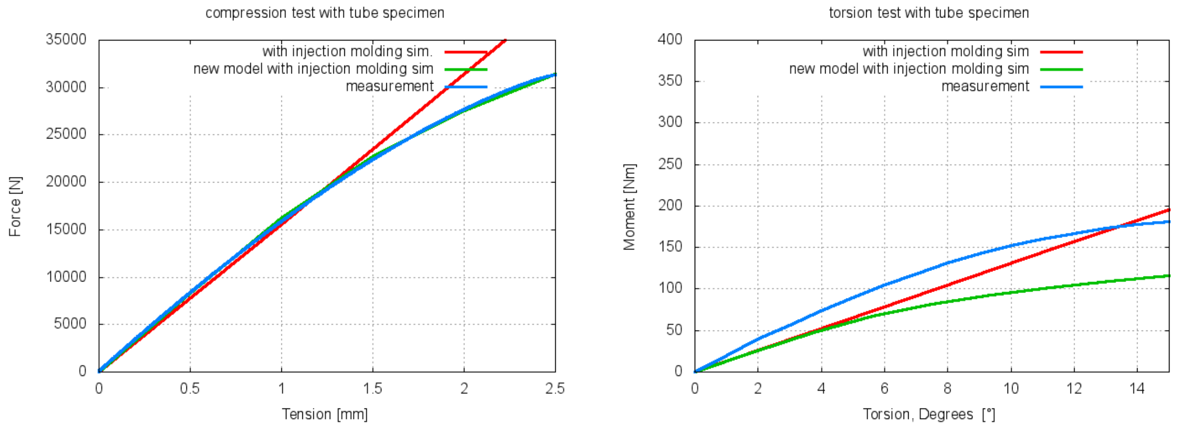

Figure 3. Force over compression (left) and moment over torsion (right), measured (blue) in comparison to values with a linear model (red) and the proposed non-linear model (green)

4 Open tasks

The proposed incremental Mori-Tanaka scheme based on the Ramberg-Osgood model is one of the simplest material models. It should be thought of as a first step to describe the material behavior of composites. In order to model the unloading behavior more sophisticated material models for the constituents have to be considered, see [4]. This results in an implicit discretization which leads to a coupled system of nonlinear equations.

The anisotropic behavior of pure thermoplastic material (see [8]) poses an additional challenge which should also be tackled.

In a second phase of this project the stress states determined here will be correlated with fatigue life measurements. The result will be single- and multiaxial fatigue life curves for well defined fibre orientations.

Acknowledgements

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