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Modeling of uncertainties in long fiber reinforced thermoplastics

Jörg Hohe *, Carla Beckmann, Hanna Paul

Fraunhofer-Institut für Werkstoffmechanik IWM, Wöhlerstr. 11, 79108 Freiburg, Germany

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ABSTRACT

The present study is concerned with a numerical scheme for the prediction of the uncertainty of the effective elastic properties of long fiber reinforced composites with thermoplastic matrix (LFT) produced by standard injection or press molding technologies based on the uncertainty of the microstructural geometry and topology. The scheme is based on a simple analysis of the single-fiber problem using the rules of mixture. The transition to the multi-fiber problem with different fiber orientations is made by the formulation of an ensemble average with defined probability distributions for the fiber angles. In the result, the standard deviations of the local fiber angles together with the local fiber content are treated as stochastic variables. The corresponding probability distributions for the effective elastic constants are determined in a numerically efficient manner by a discretization of the space of the random variables and the analysis of predefined cases within this space.

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1. Introduction

Long fiber reinforced composite materials with thermoplastic matrix are a new class of material combining the advantages of short fiber reinforced plastics and infinite fiber reinforced materials. Due to the limited fiber length, they can be processed using standard processing technologies for thermoplastic materials such as injection or press molding. On the other hand, compared to standard short fiber reinforced materials, the increased fiber length results in superior properties especially in terms of the effective strength. Major disadvantages of long fiber reinforced materials are their process-dependent microstructures (see Fig. 1) leading to spatial variations in the fiber mean orientation and thus the local effective properties as pointed out, among others, by Skourlis et al. [1] or Teixeira et al. [2] or Seelig et al. [3]. The latter study reports an example of a molded component consisting of glass fiber reinforced polypropylene which exhibits strong effects of the local fiber distribution. Their simulation results with and without consideration reveal that without consideration of the actual local fiber orientation, no useful results can be obtained.

In addition to the local variation of the effective material properties due to the molding process, the disordered irregular microstructure of LFT materials (see, e.g. tomographic investigations reported by Garesci and Fliegener [4]) causes a distinct non-negligible uncertainty in their local effective properties even for known means of the fiber orientation. This uncertainty is a physical uncertainty deriving from the fact that the orientation of individual fibers cannot be predicted in a deterministically exact manner [5]. Hence, the local fiber orientation at any specific position is subject to a variability causing an uncertainty in the local effective material properties at the respective spatial point. Consequently, experimental data for the effective material parameters is usually subject to a distinct scatter as, e.g. reported by Seelig et al. [3] for specimens taken from the flow range (see Fig. 2).

The numerical prediction of the effective properties for short and long fiber reinforced materials accounting for uncertainty effects caused by their disordered microstructure is a challenging task. Appropriate models have to account for the possibility of multiple fiber orientations occurring in limited spatial ranges. For this purpose, a number of advanced material models and simulation strategies have been developed in literature. Taya and Chou [6] have provided a model for the elastic moduli for short fiber composites with random fiber orientation using an ellipsoidal fiber model based on Eshelby's tensor accounting for different fiber orientations based on assumed fiber orientations. In a similar manner, Nguyen and Khaleel [7] used a Mori–Tanaka analysis in conjunction with an averaging procedure to account for different possible fiber orientations. Garesci and Fliegener [4] have provided an analytical model for LFT materials with, based on the Halpin–Tsai fiber model to account for the non-even fiber orientation distribution. An experimental characterization of short fiber composites together with a simplified analytical model based thereon, accounting for the fiber orientation distribution has been provided by Dunn et al. [8]. In a similar manner, Fu and Lauke [9] have considered the probability functions for fiber length and orientation

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* Corresponding author. Tel: +49 761 5142 340; fax: +49 761 5142 510.
E-mail address: joerg.hohe@iwm.fraunhofer.de (J. Hohe).

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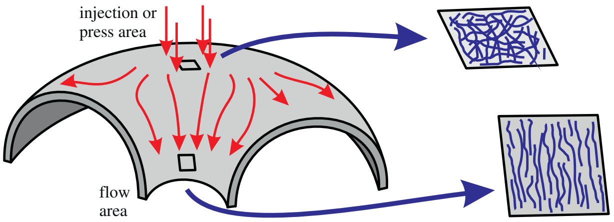

Fig. 1. Fiber orientation in structures consisting of long fiber reinforced materials.

and developed simplified formulae for average fiber stress and strength.

Although the microstructural disorder is accounted for in terms of probability distributions for fiber orientation and length, all previous models are still of the deterministic type since they provide deterministic values for the effective material properties in terms of averages. On the other hand, among others, Bijsterbosch and Gaymans [10] have shown that distinct spatial variabilities in the local fiber orientation distributions may develop during the manufacture of long glass fiber reinforced polyamide (PA) 6 materials using injection molding. As a result, a distinct local variability in local fiber orientation distribution and – as a consequence – a distinct variability in local failure strength and strain as well as the local impact toughness is obtained. In a more recent contribution, Phelps et al. [11] have shown that the attrition of fibers during the molding process causes a distinct variability of fiber length distribution of the final product even for initially constant fiber length due to breakages. Hence, a probabilistic analysis rather than a classical deterministic approach is necessary for an appropriate prediction of the material response of short and long fiber reinforced materials.

Comprehensive reviews on the application of stochastic approaches to the modeling of fiber reinforced composites as well as the mentioned and other effects causing uncertainties in the effective material behavior of fiber reinforced polymeric materials have been provided by Sriramula and Chryssanthopoulos [12] or, recently, by Mesogitis et al. [13]. Although the necessity for probabilistic approaches, only few studies providing such models for short and long fiber composites are available in literature. The variability in the elastic response of short fiber composites has been analyzed by Lusti et al. [14] considering a multi-fiber representative volume element in conjunction with a probabilistic evaluation. The prediction of the elastic constants of – although non-infiltrated – networks of long fibers has been considered by Lee and Jasiuk [15] using a probabilistic numerical approach based on a substructure technique for a large-scale representative volume element. An analysis of a similar problem has been provided by Dirrenberger et al. [16] using an alternative analysis technique consisting of the multiple analysis of smaller testing volume elements in conjunction with a stochastic evaluation. Rahman and Chakraborty [17] have provided a stochastic analysis of particle and short fiber composite using a Mori–Tanaka estimate in conjunction with a Karhunen–Loève expansion of the results to be used as input parameters for a macroscopic elasticity model such as, e.g. the model provided by Soize [18].

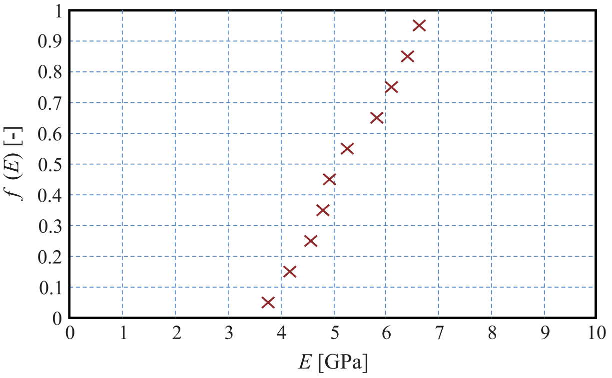

Fig. 2. Probability distribution of the secant modulus for LFT material (data by Seelig et al. [3]).

Aim of the present study is the determination of a simplified analytical scheme for prediction of the uncertainty in the effective elastic properties of structures and components consisting of long fiber reinforced thermoplastic materials. The scheme is based on a micromechanical consideration of the single fiber problem using the standard rules of mixture. Using the local fiber orientation distributions, the elastic properties of the multi-fiber material are obtained as an ensemble average. The material model allows the prediction of local elastic properties for the structure based on the local flow direction, fiber content and fiber orientation distribution.

Since both, the local fiber content and the local orientation distribution are uncertain due to process variabilities, the fiber volume fraction and the standard deviation of the fiber angle distribution are considered as random variables provided with probability density distributions. Adopting a numerical scheme proposed previously by the authors for the analysis of the effective properties of two- and three-dimensional solid foams [19], a repeated determination of the elastic properties for predefined sets of the random variables is performed. Considering the individual probability of occurrence for the analyzed cases in the (hyper) space of the random variables, the probability distributions for the macroscopic elastic properties are obtained as a function of the microstructural uncertainties.

2. Numerical procedure

2.1. Material model

The material model proposed for the prediction of the effective elastic properties of long fiber reinforced thermoplastic materials is defined in three steps. In the first step, the case of a single fiber oriented arbitrarily in space is considered. In the second step, a solution for the multi-fiber problem is derived, based on the solution for the single-fiber problem. In the third step, a probabilistic enhancement of the deterministic approach defined in the first two steps is defined.

For the analysis of the single-fiber problem, a local microscopic Cartesian coordinate system x'_i according to Fig. 3 is introduced. In the microscopic system, the x'_1-direction as usual coincides with the fiber direction whereas the x'_2- and x'_3-axes are oriented normally to the fiber direction. The microscopic fiber coordinate system is obtained from the macroscopic Cartesian system x_i by a rotation with respect to the x_3-axis by an angle φ. The macroscopic system x_i is oriented such that the x_1–x_2-plane coincides with the reference surface of the thin-walled LFT-structure with the x_1-direction as the flow (or otherwise preferred) direction of the manufacturing process. The possible misorientation of the fibers with respect to the reference surface of the thin-walled structure (i.e. an orientation out of the x_1–x_2-plane) is neglected since the average fiber length for LFT materials with maximum lengths in the range of 25 mm up to 50 mm is in the same order of magnitude for typical wall thicknesses and beyond. Notice that due to possible curvatures of the structure and process-dependent local changes of the flow direction (see Fig. 1), the macroscopic system x_i also has a local character.

In the analysis of the single-fiber problem, it is assumed that the fiber length – although finite – is large compared to the fiber diameter. The fibers may be curved, however, it is assumed that the curvature radii are large compared to the fiber diameter. For standard LFT materials, both conditions are usually satisfied. In this case,

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