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Research paper

A probabilistic elasticity model for long fiber reinforced thermoplastics with uncertain microstructure

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ABSTRACT

The present study deals with uncertainties in the material response of long fiber reinfoced thermoplastics (LFT). In an experimental study, the mechanical response of the material is investigated in direction longitudinal and perpendicular to the fiber preference orientation. Using an optical grey-scale correlation system, local strain measurements on the surface of regular tensile specimens are performed. From the results, local stress-strain curves and material parameters are derived. The results reveal a distinct local variability of the mechanical response of the material due to the variability in the local fiber orientation and fiber density. Based on the experimental observations, a probabilistic elasticity model for LFT materials is proposed. This model allows a numerically efficient virtual prediction of the effect of microstructural disorder of LFT materials on the macroscopic response of structures and structural components.

1. Introduction

Long fiber reinforced thermoplastic (LFT) materials with disordered fiber orientation are important materials in many fields of modern lightweight construction. Being processed by standard processes for polymeric materials such as injection or press molding, long fiber reinforced thermoplastics are especially suitable for industrial scale production ((Bijsterbosch and Gaymans, 1995; Henning et al., 2005). Due to their increased fiber length, typically in the range up to 25, …, 50 mm, they feature superior characteristics compared to standard short fiber composites, however, due to the use of well established standard polymer processing methods, they are less expensive than unidirectionally fiber reinforced polymers (Thomason, 2002). Furthermore, they can easily be processed to much more complex shapes than unidirectionally fiber reinforced materials. Hence, long fiber reinforced thermoplastic materials are well suited for industrial scale lightweight construction with limited expenses, suitable for all applications, where high, but not extremely high performance materials are required.

One of the major shortcomings of LFT materials is their random disordered microstructure leading to a distinct variability of their macroscopic material properties. Furthermore, since their preferred fiber direction is process dependent, their material properties depend on the flow direction and the completed flow path. Consequently, in a study on the microstructure of injection molded long glass fiber reinforced PA6, Bijsterbosch and Gaymans (1995) found a distinct variability in local fiber orientation distribution. For compression molded LFT, based on computed X-ray tomography, Fliegener et al. (2014) report similar findings. Considering the effect that in a small control volume different fiber orientations and lengths will be present, a number of LFT material models using ensemble averaging techniques have been proposed in the literature. In this context, Taya and Chou (1982) published an analysis of the stress-strain response of short fiber composites based on Eshelby (1957) method, accounting for different fiber orientations based on assumed fiber orientations. A similar analysis, however based on the Mori–Tanaka (Mori and Tanaka, 1973) method and directed to the damage response has been provided by Nguyen and Khaleel (2004). Garesci and Fliegener (2013) proposed an analytical model for LFT materials with disordered microstructure, based on the Halpin–Tsai (Halpin and Kardos, 1976) fiber model, forming a simplified for of Hill's (Hill, 1965) self-consistent approach. The LFT model accounts for the fiber orientation distribution, however, the study still provides a deterministic model. In another recent study, Phelps et al. (2013) proposed a model for attrition of fibers during the molding process. Here, a distinct variability of the fiber length is found in the final product even for initially constant fiber lengths due to breakages during processing. Other studies on the effective material response of long fiber reinforced thermoplastics with uncertain microstructure using ensemble averaging techniques are due to Dunn et al. (1996), Fu and Lauke Fu and Lauke (1996) or Kunc et al. Kunc et al. (2015). In a recent contribution, Sharma et al. Sharma et al. (a), Sharma et al. (b) analyzed the fiber length

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distribution of carbon fiber based LFT materials using microsectining in conjunction with optical methods. Based thereon, the elastic constants are determined using the Mori–Tanaka (Mori and Tanaka, 1973) method.

Although they might be based on stochastic considerations regarding the fiber orientations at a specific material point, all LFT material models mentioned above are deterministic material models providing identical material properties for identical input data, i.e. by using ensemble averaging. To deal with the problem of unknown local properties, probabilistic models treat selected or all microstructural parameters as stochastic variables, provided with an appropriate probability distribution. A general review on the uncertainties in fiber reinforced materials resulting from processing such as draping, impregnation or solidification has been provided by Mesogitis et al. (2014). In an experimental approach, Thieme et al. (2014) deal with probabilistic effects on the strength of fiber reinforced thermoplastic materials with knitted fiber reinforcement. In a recent contribution, Bednarcyk et al. (2014) provided a probabilistic model for infinite fiber reinforced materials dealing with scatter effects caused by uncertain fiber misalignment. A review on application of stochastic approaches to modelling of fiber reinforced composites has been provided by Sriramula and Chryssanthopoulos (2009).

Especially in the recent years, a number of contributions with special interest directed to short and long fiber reinforced materials has been provided. Lee and Jasiuk (2013) deal with the numerical prediction of the elastic constants for non-infiltrated long fiber networks with disordered microstructure using a probabilistic numerical approach based on a substructure technique. A similar problem is addressed by Dirrenberger et al. (2014) using the multiple analysis of testing volume elements with randomly generated microstructure. A numerical prediction of the elastic constants for random short fiber composites has been provided by Lusti et al. Lusti et al. (2002) using the probabilistic analysis of a multi-fiber representative volume element. Rahman and Chakraborty (2007) used the Mori–Tanaka (Mori and Tanaka, 1973) method in conjunction with probabilistic analysis based on the Karhunen–Loève expansion whereas Ma et al. (2014) employed the equivalent inclusion method coupled with the random factor method. Altendorf et al. (2014) are concerned with modelling of the elastic and thermal response of long fiber reinforced materials using a fast Fourier transform technique considering the uncertain fiber length, orientation, radius and curvature. The assessment of the resulting uncertainties in the effective material response is performed in terms of the basic stochastic moments. Probabilistic methods and models for using the predicted (or experimentally determined) uncertain material data in structural analyses on the macroscopic level have been provided e.g. by Soize (2006) or Sakata and Torigoe (2015) using a perturbation based approach. The essential base for probabilistic structural analyses using these methods is the availability of a stochastic material model which is able to predict the uncertainty in the effective material properties as well as all correlations between the different properties. In order to be able to provide the information on the correlations in a correct manner, the number of random variables in the model need to reduced to the essential minimum.

The objective of the present study is an experimental investigation and numerical modelling of uncertainty effects in long fiber reinforced thermoplastic materials deriving from variations in the local fiber orientation and fiber content. In an experimental approach, the scatter in the local (microscopic) strain state in macroscopic specimens under tensile and compressive loads is investigated using a digital image correlation system. The investigation is performed on a glass fiber reinforced polyamide matrix composite as a material example. In a second step, a probabilistic elasticity model is derived. In a similar manner as in a preceding study (Hohe et al., 2015), the model is based on the classical rules of mixture in conjunction with an ensemble averaging technique. In contrast to the earlier model, the local fiber volume fraction and both, the fiber angle within the flow plane of the material and the out-of-plane fiber angle are treated as random variables. The model is validated against the experimental data base. In parametric studies, the effects of the uncertainties in the three-dimensional fiber orientation and the local fiber content on the effective material response are demonstrated.

2. Preliminary experimental investigation

2.1. Material

As a base for development of the probabilistic elasticity model for long fiber reinforced thermoplastics in Section 3, a preliminary experimental investigation has been performed. The objective of this investigation was to study the effects of the microstructural uncertainties on the scatter to be expected in the macroscopic “effective” material properties and to provide a data base for validation of the numerical predictions. The model material system considered is a glass fiber reinforced polyamide 6.6 material (PA66-GF40). With the matrix and fiber densities of $\rho_{PA66} = 1.14\,\mathrm{g/cm^3}$ and $\rho_{GF} = 2.50\,\mathrm{g/cm^3}$, the fiber content of 40 wt% coincides with an average fiber volume fraction of $\rho_f = 23.3\%$.

The material has been processed by Fraunhofer ICT at Pfinztal in compression molding using the direct LFT (LFT-D) process (Henning et al., 2005). This process consists of a multi-stage procedure. In a first step, the polyamide matrix granulate is compounded in a twin screw extruder. In a second extrusion step, the fibers are added by inserting continuous rovings into a second extruder. The fibers are cut during the second extrusion step in the mixing extruder. As a result, a strand of the raw material is obtained. The LFT-strand is placed into the open mold. By closing the mold, the raw materials is pressed into the cavity to form the final product.

For the present investigation, the material has been provided as plane plate with an average thickness of 2.9 mm. An asymmetric inlay position located at one end of the plate has been used in order to obtain a range with distinct flow path and thus a pronounced fiber re-orientation in the flow range used for the specimen extraction at the opposite end of the plate (see Fig. 1).

2.2. Mechanical testing

From the received plates, plane tensile test specimens were machined. The specimen geometry is presented in Fig. 2. Two series of specimens were extracted. For the first series, the test direction coincided with the flow direction (labelled 0°-direction in the following), whereas for the second series (90°-direction), the specimen axis was oriented perpendicular to the flow direction. The specimens were tested in an Instron 1342 testing machine under displacement control in a quasi-static loading mode till failure. The cross-head velocity was chosen such that an engineering strain rate in the range from $d\varepsilon_{eng}/dt = 0.0002\,\mathrm{s^{-1}}$ and $0.00037\,\mathrm{s^{-1}}$ were obtained. During the tests, the resulting force was continuously recorded using the internal load cell. The local strain measurement was performed by optical means using the ARAMIS grey-scale correlation system. Both, the longitudinal and the transverse strains were determined. The facets for the local strain measurements, their size and position are sketched in Fig. 2. For the basic local assessment, facets with dimensions of $0.9\,\mathrm{mm} \times 0.9\,\mathrm{mm}$ were used. Since the local uncertainty is related to the size of the evaluation area, additional evaluations of the local strains on larger facets with dimensions of $1.8\,\mathrm{mm} \times 1.8\,\mathrm{mm}$ and $3.6\,\mathrm{mm} \times 3.6\,\mathrm{mm}$ were performed by taking the average of 2×2 and 4×4 arrays of the original $0.9\,\mathrm{mm} \times 0.9\,\mathrm{mm}$ facets (see Fig. 2). Furthermore, a global engineering strain was determined as the length variation of an initially 10 mm long line in the center of the specimens.

The results for the engineering stress-strain curves on the macroscopic level are presented in Fig. 3(a). As expected, distinct differences between the results for the two testing directions are obtained. For the