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A micro-mechanical model of the elastic properties of a short fibre reinforced polyamide

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Abstract

The elastic moduli of short fibre polyamide reinforced with different contents of glass fibres were computed by means of a numerical model. The analyses were based on the reconstructions of the internal fibre structure obtained by micro tomography using synchrotron light. The reconstructed volumes were used in a Cell Method micro-mechanical model in order to simulate the local tensile behaviour of the specimens.

Keywords: Micromechanical models, Cell Method, short fibre, reinforced composites, mechanical properties

1. Introduction

It is well known that the mechanical properties of short fibre reinforced polyamide (SFRP) depend on fibre content, fibre dimensions and fibre orientation distributions, since the local spatial arrangement of reinforcement and consequent local strain values influence the global mechanical behaviour [1,2]. In particular, the strain field in the cross section of a notched specimen can be affected by local variations in the fibre pattern within the matrix which result in local changes in stiffness [3]. Since it is practically impossible to perform a direct numerical simulation of a macroscopic engineering structure consisting of a heterogeneous material at the microstructural level, a commonly followed approach considers the actual properties obtained from a statistically representative volume of material. The results of this homogenization process can be later used for the analysis of the macroscopic structure.

Two approaches are possible for the estimation of local mechanical properties of heterogeneous...
materials: analytical or numerical models. For example, an analytical micromechanical model considering the effects of fibre length distribution and fibre orientation distribution on SFRP elastic modulus has been proposed in [4]. On the other side, the development of acquisition techniques such as phase-contrast micro-CT (micro-computed tomography) allows accurate volumetric acquisitions of samples with resolutions in the order of a few microns. This enables the implementation of computational methods for the assessment of mechanical properties derived directly from micro-architecture identification.

The Cell Method (CM) [5] is a numerical method that is particularly suitable in the presence of heterogeneities, or discontinuities in general. Applications of the Cell Method to the modeling of sintered alloys, metal matrix composites and biological materials such as trabecular bone have already produced results in good agreement with experimental data [6-9]. In this work, a numerical micro-model based on the Cell Method has been used to assess the local elastic properties of different grades of short fibre reinforced polyamide.

2. Materials and methods

2.1. Data acquisition

Three ISO 527-2 specimens of polyamide 6 reinforced with different contents of type E short glass fibre, respectively 10%, 20% and 30% by weight - indicated as GF10, GF20 and GF30 respectively in the following -, were used in this work. Nominal diameter of fibres is 11 microns. From each specimen, one sample was cut in the position shown in Figure 1. Each sample is a prism of 3mm x 4 mm x 10 mm.

![Fig. 1. (a) Specimen and position of the sample (b) location of VOIs within the sample; (c) VOIs nomenclature](image)
Each sample was subjected to phase-contrast micro-CT at the SYRMEP beamline of Elettra, the synchrotron radiation facility in Trieste (Italy), and the 3D reconstructions of the fibre patterns within the matrix were thus obtained. Data acquisition was performed according to the procedures described in detail in [10-12]. The Volume Of Interest (VOI) defines the cubic volume for the micro-mechanical analysis. The VOIs, consisting of \(80\times80\times80 \text{ voxel}^3\), corresponding to \(720\times720\times720 \text{ micron}^3\), were extracted from the micro-CT reconstructions of each sample in the positions shown in Figure 1(b). The nomenclature of the VOIs is the same for all the samples and is depicted in Figure 1(c). Examples of 3D reconstructions of the VOIs micro-architecture are shown in Figure 2.

2.2. Cell Method

A numerical model based on the Cell Method was used to simulate a tensile test on each VOI in order to assess the structure apparent elastic moduli, \(E_x, E_y, E_z\), along the three coordinate axes shown in Figure 1. A detailed description of the CM is beyond the purpose of this paper and can be found in [13-15]; it will be sufficient to point out that the method, not based on a differential formulation of physical laws, is particularly suitable for modeling heterogeneous materials. The numerical model had been originally developed for the analysis of trabecular bone structures and is described in detail in [8, 9]. Each VOI was modeled with a mesh of 812905 tetrahedral cells and 141982 nodes and the mechanical properties of each cell were assigned according to the matrix/fibre distribution derived from the corresponding micro-CT reconstruction, resulting in a different fibre pattern for each VOI. Elastic, homogeneous and isotropic constitutive laws were used, with a Young’s modulus of 2 GPa for matrix and of 70 GPa for glass fibre. Computations took 0.5 h for the three axes on a i7 CPU 6 GB RAM notebook.

3. Results

A morphological analysis, as described in [10, 11], was performed on all VOIs and confirmed that the principal directions of fibre orientation are coincident with the coordinate frame. The largest elastic modulus computed with the CM model is always to be found in the preferred fibre orientation direction as determined by morphological analysis and is coincident with the direction of the injection moulding flow in the specimen, axis \(y\). The trend of \(E_y\) is shown in Figures 3 to 5, for the three different fibre contents. These values appear to be in general agreement with those of axial tests performed on similar specimens: 4.64 GPa, 6.59 GPa and 9.03 GPa for GF10, GF20 and GF30 respectively in [16]. In Figures 6 to 8, the local elastic moduli in the transverse plane, \(E_x\) and \(E_z\), are depicted.
Fig. 3. Elastic modulus $E_y$ for the VOIs in the sample with 10% glass fibre reinforcement, min and max values highlighted.

Fig. 4. Elastic modulus $E_y$ for the VOIs in the sample with 20% glass fibre reinforcement, min and max values highlighted.

Fig. 5. Elastic modulus $E_y$ for the VOIs in the sample with 30% glass fibre reinforcement, min and max values highlighted.
Fig. 6. Computed elastic modulus in the $x$ and $z$ directions for the VOIs in the sample with 10% glass fibre content by weight.

Fig. 7. Computed elastic modulus in the $x$ and $z$ directions for the VOIs in the sample with 20% glass fibre content by weight.

Fig. 8. Computed elastic modulus in the $x$ and $z$ directions for the VOIs in the sample with 30% glass fibre content by weight.

4. Discussion

Non-negligible local variations in the principal elastic modulus $E_y$ can be observed in each specimen (35%, 46%, 24% for GF10, GF20 and GF30 respectively) and in the transversal elastic moduli $E_x$ and $E_z$. Changes in stiffness, due to local variations in the fibre pattern - both in content and in orientation - can indeed affect the strain field in the cross section, and these phenomena are detectable even in the absence
of notches. These results complement the findings described in [3], where it was shown that fibre orientation effects influence the full cross section strain distribution in notched specimens.

Since these findings indicate that any numerical model of SFRP components should take into account the fibre orientation effects, the assessment technique based on micro-CT and MIL can provide an important validation tool for the software used in simulations.

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