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Model of the mechanical response of short flax fiber reinforced polymer matrix composites

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Abstract

Natural-fiber-reinforced short-fiber composites are finding more applications lately, therefore there is a need for estimation of the mechanical properties of such composites based on the properties of the constituents. The fibers themselves also possess complicated internal structure, resulting in anisotropy of their properties. Taking into account the internal structure of bast fiber, we evaluate the elastic properties of a composite unit cell, consisting of a fiber of average length and matrix according to the fiber volume fraction in the composite. The unit cell properties are used to estimate the stiffness of a misaligned short-fiber composite by means of orientation averaging. The results obtained are compared with the experimental stress-strain diagrams of short flax fiber/polypropylene matrix composite. Usually the mechanical response of short-fiber/polymer matrix composite is non-linear due to the inelastic matrix behavior. Accounting for the non-linear deformation of the matrix in the unit cell by modeling it as an elastic-plastic material, we also estimate its non-linear response under uniaxial loading.

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Keywords: flax fiber; short-fiber composite; non-linear deformation

1. Introduction

Natural fibers are being used as a substitute of, e.g., glass fibers for reinforcing polymer matrix, to produce composite materials. In a variety of applications, the reinforcement is in the form of short misoriented fibers. Stiffness of such composites can be evaluated by models of differing complexity and accuracy, ranging from numerical simulations, usually by finite element method (FEM), of the response

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of a representative volume element (RVE) [1-3] to the elementary rule-of-mixture estimations. Orientation averaging of the stiffness tensor of a unidirectionally reinforced (UD) short-fiber composite or its unit cell (UC) provides relatively straightforward and accurate modeling approach for elasticity characteristics [3]. Bast fibers, such as flax, have complex internal structure [4] that results in anisotropic elastic properties [5]. Such features of the fibers can also be allowed for in the orientation averaging approach [6].

Strain at the onset of non-linear deformation of short-fiber-reinforced polymer matrix composites may be rather low, commensurate with that of the matrix. The non-linear response of the composite can also be modeled by FEM using a RVE, but such models can yet incorporate only a relatively low number of fibers due to high computational requirements [3]. As a computationally less demanding alternative, UC models incorporating only one fiber have been proposed, see e.g. [7, 8]. To account for complex loading experienced by misoriented UCs under axial tension of the composite material, either UCs with different orientation with respect to loading direction [7] or UCs under respective complex stress [8] are considered, and the obtained UC deformation diagrams suitably averaged to yield the composite response. Mechanical properties needed for calculations comprise elasticity parameters of the fibers and the characteristics of non-linear deformation model of the matrix material.

In the case of natural fibers, the imperfect adhesion of the fibers to most thermoplastic polymers has to be reflected in the models. It has been argued that the apparent adhesion is mainly due to static friction [9]. Fiber-matrix slippage is unlikely in the low strain region, with linear elastic material response, so perfect bonding may be assumed when estimating the elastic properties of a UC. When evaluating the non-linear UC response at higher strains, imperfect interface needs to be allowed for.

In this study, stress-strain response of short flax fiber/polypropylene (PP) composites at several fiber volume fractions is characterized experimentally. Stiffness of the composite materials is evaluated by orientation averaging of the UC properties, obtained by FEM. Development of a UC for prediction of the non-linear response of the composite is considered.

2. Experimental

2.1. Materials

Two types of thermoplastic matrices were used in this study: 1) Adstif 770 ADXP Basell polypropylene; 2) PP+MAPP: a mixture of the PP and maleic anhydride grafted PP (noted as PPM). The thermoplastic was delivered in a granulated form. Flax fibers were delivered in a form of roving by FinFlax (Oulu, Finland).

2.2. Sample preparation

Flat composite samples with constant thickness were obtained from FF/PP compound. In order to manufacture the samples, the compound was heated to 190 – 200 ˚C and pressed in a press (pressure of 15 – 25 tons, temperature of the press ≈40 ˚C) under stiff profile. The compound was produced by co-extrusion of PP and flax fibers in a twin screw extruder (Krupp Werner & Pfleiderer ZSK 25 WLE). The temperature of the extruder at the entrance was 180 ˚C and it was raised to 190–200 ˚C along the length of extruder.

Composites with three different weight fractions of fibers (20%, 30% and 40%) were made, with both, PP and PPM matrices. Respective fiber volume fractions, v_f, were evaluated using constituent densities. Contrary to the expectations of random fiber orientation in the composite, optical microscopy [10] clearly indicated the presence of a slight preferential alignment of fibers along the specimen lengthwise direction.

2.3. Tensile tests

Samples for tensile tests were rectangular in shape with the following approximate dimensions (length L and width W): L = 250 mm; W = 25 mm. The actual width and thickness of each individual specimen were measured separately so as to obtain exact cross-section area for calculation of stress. In order to reduce stress concentration in the clamping area, a very fine metal mesh was applied on the specimen ends (approximately 50 mm on each end). The Instron 1272 tensile machine with a 25 kN load cell was used to perform testing. All experiments were carried out in displacement controlled mode with the loading rate of 2 mm/min. The axial strain was measured by an extensometer with 50 mm long base, whereas lateral strain was obtained by using strain gage (length of the gage approximately 10 mm). The lateral strain was measured only for the composite with 40wt% of fibers. The output data (including time, axial and lateral strains, axial displacement and load) was acquired with sampling frequency 10 pts/s and stored on computer for further processing.

Specimens were loaded until failure and the maximum load was used to calculate strength of the material. Although this composite did show non-linear behavior (see Fig. 1), a clear yield point on the stress-strain curve, which is normally seen for neat PP, was not detected. At least five specimens for each material were tested.

3. Model

3.1. Geometry of unit cell

The unit cell was build as a rectangular parallelepiped with a single fiber embedded. The amount of matrix was related to the fiber volume fraction. The unit cell geometry was chosen so that the surfaces of the unit cell were in same distance from fiber surface [6, 8].

3.2. Estimation of elastic properties

The elastic properties of a composite reinforced by short randomly oriented fibers can be estimated using averaging method proposed in, e.g., [11]. Stiffness tensor components C_{ijkl} of the composite are then calculated using formula:

$$C_{ijkl} = \iint C^*_{ijkl}(\alpha,\beta)p(\alpha,\beta)\sin\alpha\, d\alpha\, d\beta \tag{1}$$

where C^*_{ijkl} are stiffness tensor components of the unit cell, $p(\alpha,\beta)$ – distribution density of fiber orientation, α and β – the elevation and azimuthal angles of a fiber.

C^*_{ijkl} was determined using engineering constants of elasticity which were obtained by a FEM model of the UC via strain energy of the UC under selected loading modes [6]. Since the UC was considered to be transversally isotropic, five independent constants were determined.

3.3. Modeling of inelastic response

Inelastic response of composite material due to non-linear behavior of the matrix, and due to imperfect bonding of the fibers and matrix was modeled. Fully bonded fiber/matrix interface, as well as unbonded interface with frictional load transfer between fiber and matrix in the UC was considered. To describe matrix non-linearity, the Ramberg-Osgood material model of deformation plasticity was applied, linking strain ε and stress σ of the matrix material in tension via Young's modulus E and parameters a, n, σ_0:

$$\varepsilon = \frac{\sigma}{E}\left(1 + a\left(\frac{\sigma}{\sigma_0}\right)^{n-1}\right) \quad (2)$$

Stress-strain diagrams of the UC were obtained by the FEM model for two loading modes – longitudinal tension (i.e. in the fiber direction) and transverse tension. The fiber was modeled as a linear elastic anisotropic composite body [6].

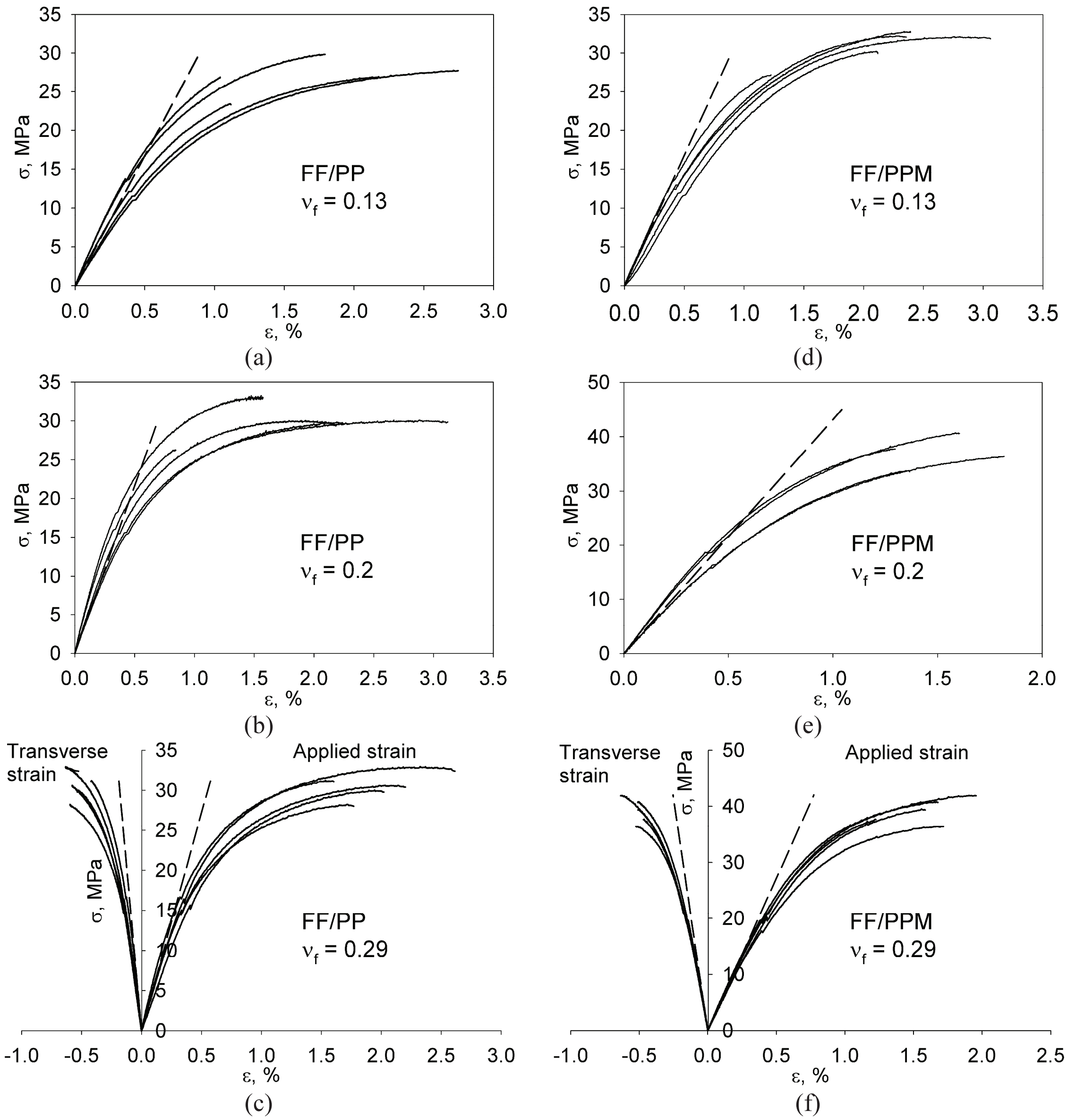

Fig. 1. Composites with PP matrix: fiber volume fraction $\nu_f = 0.13$ (a), $\nu_f = 0.2$ (b), $\nu_f = 0.29$ (c); composites with PPM matrix: $\nu_f = 0.13$ (d), $\nu_f = 0.2$ (e), $\nu_f = 0.29$(f). Note that for $\nu_f = 0.29$, both longitudinal (positive) and transverse (negative) strains are plotted.

4. Results and discussion

Finite element modeling of the mechanical response of the UC was performed using FEM software package ABAQUS. Standart 20-node quadratic brick elements C3D20 were used.

Linear elastic UC model was built using FinFlax fiber and PP matrix properties [6] as follows. Axial Young's modulus of fiber was 69 GPa, and fiber length of 1.21 mm was chosen as the experimentally determined average fiber length in the composite. The internal structure of the fiber was also reproduced [6]. Elastic modulus of the PP matrix was 1.6 GPa, Poisson's ratio 0.4. Several loading scenarios were selected to obtain the elastic properties of the UC, assumed as transversely isotropic. Further, by averaging UC stiffness according to Eq. (1), elastic properties of flax/polypropylene composite were obtained. The predicted elastic response is shown by dashed lines in Fig. 1 together with test results. A good agreement of the theoretical and experimental elastic modulus is seen. However, the linear elastic approximation is applicable only for low strains (less than 0.4 %).

If prediction of the response of composite at higher strains is of interest, then non-linearity of matrix behavior should be allowed for in the UC. For this purpose, the nonlinear behavior of PP matrix, described by Ramberg-Osgood rule Eq. (2) with the following parameters: E = 1.6 GPa, σ_0 = 16 MPa, a = 0.0663, n = 8.34, was introduced in the UC, but fiber deformation was still retained as linear elastic. Only loading in the longitudinal and transverse directions of the UC was considered. Periodic boundary conditions were applied for these calculations. In addition to fully bonded matrix and fiber, models without bond and with different levels of friction between fiber and matrix were studied. The predicted deformation diagrams for a selected v_f value are shown in Fig. 2 together with the scatter range of the experimental diagrams of FF/PP, plotted by dashed curves. Note that qualitatively similar results, not shown here, were obtained also for the rest of fiber volume fractions considered above.

It is seen in Fig. 2 that in the case of no bonding between the fiber and matrix in the UC, the predicted tensile stress-strain curves are below the lower limit of the experimental data of misaligned fiber composite with the same fiber volume fraction. Higher coefficients of friction lead to a rather limited increase in longitudinal stiffness of the UC, as seen in Fig. 2a, leveling off at around μ = 0.5. By contrast, perfect fiber/matrix bonding results in an almost linear UC response in the fiber direction, with a rather high modulus, as expected for aligned reinforcement. The compressive residual stresses, neglected in the present model, would lead to more efficient interfacial stress transfer via friction, and therefore higher apparent stiffness of the UC.

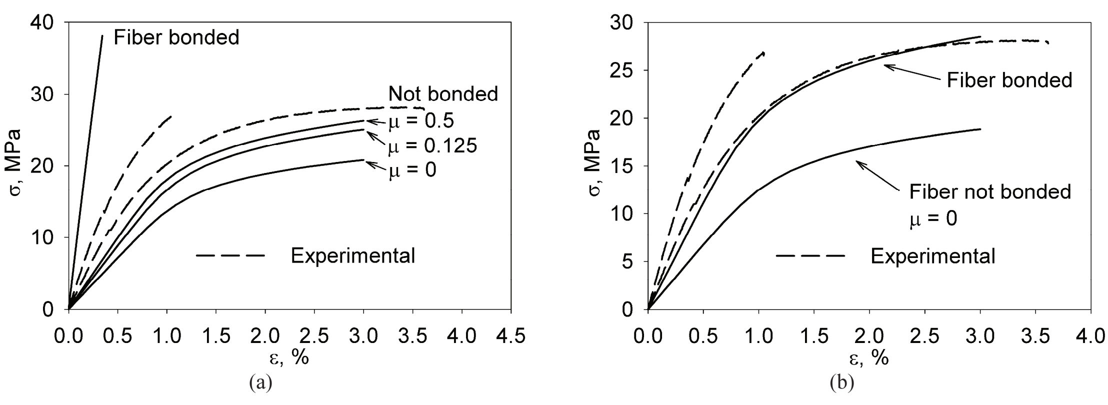

Fig. 2. Predicted inelastic behavior of a UC in tension for fiber volume fraction v_f = 0.13. Dashed lines indicate the scatter band of the experimental diagrams of misaligned FF/PP composite while solid lines show the predicted response of the UC in longitudinal tension (a) and transverse tension (b) with different fiber/matrix bonding conditions, characterized by the coefficient of friction μ.

In order to efficiently implement a frictional interface in the UD, estimates of both residual stress at the interface and the coefficient of friction of the interface are needed. While the former can be evaluated by an appropriate micromechanical model, the latter may be related to the apparent interfacial shear strength as discussed in [9].

5. Conclusions

Application of orientation averaging of a unit cell response for prediction of the deformation of misaligned-short-flax-fiber reinforced polymer matrix composite has been studied. Allowing for the anisotropy and perfect bonding of flax fiber in a linear elastic unit cell was shown to yield accurate prediction of the stress-strain relations in tension of flax/polypropylene composites with different fiber volume fractions up to ca. 0.4% strain. In order to model inelastic response at higher strains, elastic-plastic matrix behavior as well imperfect bonding characterized by interfacial friction, have to be incorporated in the unit cell.

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