Journal of the Mechanics and Physics of Solids 69 (2014) 132–142

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

A nonlinear constitutive model of unidirectional natural fiber reinforced composites considering moisture absorption

Yihui Pan, Zheng Zhong*

School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, People's Republic of China

ARTICLE INFO

Article history:
Received 15 December 2013
Received in revised form
13 March 2014
Accepted 12 April 2014
Available online 21 April 2014

Keywords:
Natural fiber
Moisture absorption
Degradation
Thermodynamics
Energy dissipation

ABSTRACT

Moisture absorption in natural fiber reinforced composites causes remarkable degradation of mechanical properties. A nonlinear constitutive model is proposed to study the effect of the water uptake on the mechanical properties of unidirectional natural fiber reinforced composites. Accompanying the water absorption in the composites, there are several irreversible thermodynamic processes such as fiber degradation and interface damage. The energy dissipation induced by these processes is described by an internal variable, and two degradation parameters representing interface damage and fiber degradation are introduced to reflect the modulus reduction of the composite. Particularly, the model is used to derive the evolution of elastic moduli influenced by the moisture absorption. The predictions from the present model show a good agreement with experiment results of sisal fiber unidirectional reinforced composites.

1. Introduction

In recent decades, natural fiber (e.g., sisal or ramie) reinforced composites have attracted the attention of many researchers due to its excellent performances over conventional glass or carbon fiber reinforced composites, such as low cost, comparable specific tensile properties and superior biodegradability (Joshi et al., 2004). These composite materials are now applicable for aerospace, leisure, construction, sport, packaging and automotive industries (Cheung et al., 2009; Pandey et al., 2010). However, there are still some disadvantages for such composites, among which given as examples are the incompatibility in the interface between the fiber and the matrix (Li et al., 2007) and the degradation of material properties induced by the moisture absorption (Lu et al., 2003). When the composite is exposed to a humid environment, the moisture absorption inevitably takes place, causing swelling and mechanical degradation. Experimental observations showed that the moisture absorption strongly reduces the overall mechanical properties (Hu et al., 2010). More specifically, both the tensile modulus and strength undergo a catastrophic degradation. A large number of research have been conducted to study the effects of moisture absorption (Chow et al., 2007; Hu et al., 2010) and the methods of the surface treatment to improve the mechanical properties (Sgriccia et al., 2008; Song et al., 2011).

Numerous efforts have already been devoted to study the physical mechanism of the moisture absorption in natural fiber reinforced composites. Lu et al. (2003) found that the natural fiber has a porous structure capable of absorbing and storing large amounts of water. Espert et al. (2004) revealed three processes of moisture absorption in natural fiber reinforced composites. The main process is the diffusion of water molecules into the micropores between polymer chains of natural

* Corresponding author. Tel.: +86 21 65983998; fax: +86 21 65983267.
E-mail address: zhongk@tongji.edu.cn (Z. Zhong).

http://dx.doi.org/10.1016/j.jmps.2014.04.007

fibers, from which natural fibers swell dramatically and the mechanical properties of the fibers undergo significant degradation. The second process is the capillary transport into the gaps and flaws generating at the interfaces between the fibers and the polymer matrix due to incomplete wettability and impregnation. Hu et al. (2010) observed under scanning electron microscope that large amounts of microcracks appear on the interfaces during moisture absorption and the reserve of water in the cracks favored the interface debonding. This was further confirmed by a fiber pulling-out experiment (Sydenstricker et al., 2003), in which the saturated fiber was easier to extract than the intact one. The last process is the transport of water in microcracks of the matrix, which can be treated as a special swelling of the matrix. Dhakal et al. (2007) showed that the swelling of the matrix itself is much smaller compared to that of the whole composite and can be neglected in most cases.

Most of the available works of the moisture absorption and its effects on the mechanical properties of natural fiber reinforced composites stay in an empirical or semi-empirical description. Different from previous studies that treated the moisture absorption and the mechanical degradation as two separate processes, we deduce that these two processes are correlated, since the mechanical degradation largely depends on the water content in the composites. To our knowledge, rather few theoretical models have been proposed to correlate these two physical processes. The main difficulties may be quantitative description of both fiber and interface degradations, and invalidation of Fick's law to be applied in the last stage of moisture absorption (Espert et al., 2004).

In the present work, two parameters are introduced to characterize the fiber and interface degradations, and then a theoretical model based on non-equilibrium thermodynamics is presented to describe the process of moisture absorption and its effects on the mechanical properties. This paper is organized as follows: a general constitutive model considering moisture absorption in natural fiber reinforced composites is constructed in Section 2. Then, in Section 3 we particularize several specific forms of the Helmholtz free energies, as well as the dissipation energy. In Section 4 the present model is used to predict the evolution of five elastic coefficients of the unidirectional reinforced composite after moisture absorption. In Section 5, we compare the theoretical predictions with the experiment results of unidirectional sisal fiber reinforced composites. Finally, in Section 6, we make a conclusion.

2. General constitutive model

Consider a unidirectional continuous natural fiber reinforced composite material, whose macroscopic deformation can be described by the deformation gradient tensor, $\mathbf{F} = \partial\mathbf{x}/\partial\mathbf{X}$, where $\mathbf{X}$ is the position vector of a material particle in the initial undeformed and dry configuration and $\mathbf{x}$ is the corresponding position vector in the current deformed or swollen configuration. From the deformation gradient tensor, all other deformation information can be obtained. For example, the right and left Cauchy–Green deformation tensors are defined as $\mathbf{C} = \mathbf{F}^{\mathrm{T}} \cdot \mathbf{F}$ and $\mathbf{b} = \mathbf{F} \cdot \mathbf{F}^{\mathrm{T}}$, and the volume ratio is given as $J = \det \mathbf{F}$, where the superscript 'T' and the notation 'det' denote respectively the transpose and the determinant of a tensor.

The macroscopic deformation of a natural fiber reinforced composite can be further decomposed into two deformation modes, as shown in Fig. 1. One is the pure volume expansion caused by water uptake, which makes the composite evolve form the virgin state to the swollen state. Another is the mechanical loading induced isochoric deformation due to the incompressibility assumption for incompressible matrix composites (Holzapfel, 2000). Hence a multiplicative decomposition is made, namely,

$$\mathbf{F} = J^{1/3}\overline{\mathbf{F}}, \ \mathbf{C} = J^{2/3}\overline{\mathbf{C}}, \ \mathbf{b} = J^{2/3}\overline{\mathbf{b}} \tag{1}$$

where $\overline{\mathbf{F}}$, $\overline{\mathbf{C}}$ and $\overline{\mathbf{b}}$ are called the modified deformation gradient tensor, the modified right Cauchy–Green tensor and the modified left Cauchy–Green tensor, respectively. Furthermore, two principal invariants of modified right Cauchy–Green

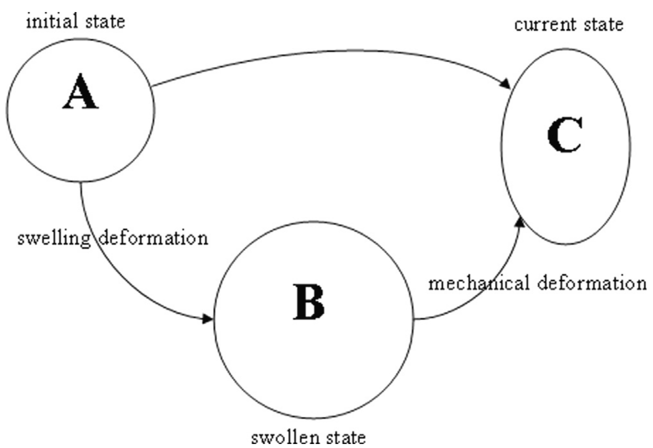

Fig. 1. Illustration of various configurations of the composite.