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An anisotropic hyperelastic constitutive model for short glass fiber-reinforced polyamide

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ABSTRACT

The present paper describes the development of a unified hyperelastic constitutive model based on anisotropic hyperelastic material with families of fibers approach and integrating both; pure isotropic matrix of polyamide-6.6 and anisotropic materials induced by the short glass fiber reinforcement (SGFR), into one framework. The material model is implemented in a four-node shell element. The model is used to predict the mechanical behavior of SGFR polyamide-6.6. Material parameters are identified using experimental data from tensile tests on unreinforced and 10, 20, and 30% wt reinforced, polyamide-6.6. The proposed model is validated with two points bending experimental results. Experimental and finite elements results are compared. Numerical results prove the good performances of the developed model to predict the anisotropic behavior of SGFR polyamide-6.6.

1. Introduction

Short fiber reinforced thermoplastic composites are used more and more in various industrial sector. Their good mechanical proprieties and lighter weight allow them to be a good substitute to metallic material. However they are inhomogeneous and anisotropic therefore their mechanical behavior and structure are quit complexes. Knowledge of their behavior is necessary in order to optimize the use of such materials.

Up to now, several studies have been done to determine the mechanical properties of short glass fiber reinforced polyamide-66 (PA66-GF) witch result from the combination of the properties of the matrix, glass fibers and the interface matrix/glass fiber. The effect of variables as the diameter, the length, the orientation and the quantity of glass fibers was studied in Thomason (1999) and O'Regan, Akay, and Meenan (1999). The mechanical properties depend also on the injection conditions: speed and pressure of injection and temperature of the mold (Güllü, Özdemir, & Özdemir, 2006) and on the speed of deformation, temperature of test, hygotermal (Benaceur, Othman, Guegan, Dhieb, & Damek, 2008; Ghorbel, Saintier, Dhiab, & Dammak, 2011; Mouhmid, Imad, Benseddiq, Benmedakhène, & Maazouz, 2006; Ramazani, Morshed, & Ghane, 2011). Moreover, a central parameter which can affect the static and fatigue behavior of short glass fiber reinforced polyamide is the fiber orientation with respect to flow direction; see e.g. Bernasconi, Davoli, Basile, and Filippi (2007), Brunbauer, Mösenbacher, Guster, and Pinter (2014), Zhou and Mallick (2006) and Benaarbia, Chrysochoos, and Robert (2015). Results showed decreasing of elastic modulus, ultimate tensile stress and fatigue strength with increasing of the specimen orientation angle with respect to flow direction. This orientation dependent of mechanical properties of short glass fiber reinforced polyamide-66 make it an anisotropic materials. In Nouri, Meraghni, and Lory (2009), the author developed a phenomenological fatigue-damage model for injection-molded short glass fibre reinforced polyamide, PA66-GF30, based on

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the work of Ladevèze and Le Dantec (1992) and Sedrakian (2004). The free energy function is defined for a linear elastic orthotropic material by making the assumption of the thin or moderately thick structures. In Launay, Maitournam, Marco, and Raoult (2013), viscoelastic-anisotropic elastoplastic constitutive equations are used to predict the mechanical response, monotonic and cyclic, of PA66-GF35. Fourth-order linear anisotropic elastic tensor is used as the instantaneous elasticity.

In addition to the anisotropic behavior of the fiber reinforced polyamide-6.6, studied and discussed above, experimental evidence illustrate that thermoplastic subjected to axial tension stress have a non linear response even in the elastic stage. This behavior requires the introduction of a hyperelastic approach. For extensive discussions of constitutive models derived from this theory; see e.g., Holzapfel (2000) and Boyce and Arruda (2000) among others.

In this paper short glass fiber reinforced polyamide is considered as an isotropic solid matrix, PA66, reinforced by one family of fibers. Such material anisotropy is called transversely isotropic. This approach, based on a hyperelasticity theory, is first developed by Spenser (1984). Various authors have successfully used this approach typically to simulate the behavior of ligaments and tendons; for example, Calvo, Pena, Martinez, and Doblaré (2007), Gasser, Ogden, and Holzapfel (2006), Holzapfel, Gasser, and Ogden (2000), Weiss, Maker, and Govindjee (1996), and Girard, Downs, Burgoyne, and Suh (2009) among others.

In the case of fiber-reinforced composites or elastomers where matrix and fiber behaviors are considered isotropic hyperelastic, the only known bound for the effective homogenized stored energy function is the Voigt upper bound; Ogden, (1978). deBotton, Hariton, and Socolsky (2006) used the homogenization approaches to estimate the effective stored-energy function for fiber-reinforced elastomers with incompressible Neo-Hookean phases. Agoras, Lopez-Pamies, and Ponte Castaneda (2009) propose a more general constitutive model for the effective response of fiber-reinforced elastomers. The matrix and fiber phases are assumed to be incompressible, isotropic, hyperelastic solids. The model is derived by means of the "second-order" homogenization theory. Peng, Guo, Zia-Ur-Rehman, and Harrison (2010) developed an anisotropic hyperelastic constitutive model to characterize the nonlinear material behaviour of woven composite fabrics under large deformation during forming. Fereidoonnezhad, Naghdabadi, and Arghavani (2013) characterize the hyperelastic behavior of transversely isotropic incompressible fiber-reinforced rubbers.

The common anisotropic hyperelastic models suggested in the literature are three dimensional. In the case of membrane or shell like structures, we find the work of Reese, Raible, and Wriggers (2001) who developed an orthotropic model to describe the behavior of pneumatic membranes reinforced with roven-woven fibers. A solid-shell brick finite element is used. In Balzani, Gruttmann, and chröder (2008), the authors propose the simulation of anisotropic hyperelastic thin shells on the basis of polyconvex strain energy functions. The zero normal stress condition is iteratively enforced using 3D-constitutive laws. Prot, Skallerud, and Holzapfel (2007) propose the implementation of a transversely isotropic hyperelastic membrane material model where the plane stress and incompressibility conditions are accounted for directly. In parallel, Dammak, Regaieg, Kallel, and Dhieb (2007) derived the general explicit expressions for the stresses and the fourth-order elasticity tensor for exactly incompressible transversely isotropic membranes with plane stress condition. This last development is extended in Abdessalem, Kammoun-Kallel, and Fakhreddine (2011) for orthotropic membranes. Kroon and Holzapfel (2009) propose an inverse method for estimating the distributions of the nonlinear elastic properties of inhomogeneous and anisotropic vascular membranes.

The objective of this paper is to fully characterize and validate the mechanical behaviour of polyamide and short glass fiber reinforced polyamide for weight fractions from 0 wt% to 30 wt%. To cover all this cases, the chosen mechanical behavior model, have to be anisotropic and nonlinear. Thus, this paper considers the development of an anisotropic incompressible hyperelastic constitutive model.

The paper is organized as follows. We begin in Section 2 with a description of the anisotropic hyperelasticity constitutive equations. Material and experimental procedures are presented in Section 3. Identification of the constitutive behavior of short fiber reinforced polyamide-6.6 is given in Section 4. In Section 5, a beam bending apparatus is developed and served as validation test to demonstrate the ability of the identified constitutive model, developed in Section 4 to reproduce acceptable results in the case of bending test. Finally, Section 6 summarizes the conclusions of the paper.

2. Anisotropic hyperelastic constitutive equations

Let us consider the movement of deformation defined by the function $\varphi(\mathbf{X}, t)$: $B \times R \to R^3$ and $\mathbf{F}(\mathbf{X}, t)$ be the deformation gradient. Here, $\mathbf{X} \in R^3$ indicate the position of a particle in the reference configuration.

$$\mathbf{F} = \frac{\partial \varphi}{\partial \mathbf{X}}, \quad J = \det(\mathbf{F}) \tag{1}$$

where $J > 0$ is the local volume ratio. The hyperelasticity implies the existence of an energy function dependent on the right Cauchy–Green tensors $\mathbf{C}$ expressed as

$$\mathbf{C} = \mathbf{F}^T\mathbf{F} \tag{2}$$

Rule of mixtures is a fundamental theory to integrate the mechanical properties of each constituent of a fiber-reinforced composite material. Thus, the free energy, which is considered as the thermodynamic potential, can be decomposed in two terms as follows

$$\psi = \psi_m + \psi_f(c) \tag{3}$$