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Research paper

Stiffening by fiber reinforcement in soft materials: A hyperelastic theory at large strains and its application

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ABSTRACT

This work defines an incompressible, hyperelastic theory of anisotropic soft materials at finite strains, which is tested by application to the experimental response of fiber-reinforced rubber materials. The experimental characterization is performed using a uniaxial testing device with optical measures of the deformation, using two different reinforcing materials on a ground rubber matrix. In order to avoid non-physical responses of the underlying structural components of the material, the kinematics of the deformation are described using a novel deformation tensor, which ensures physical consistency at large strains. A constitutive relation for incompressible fiber-reinforced materials is presented, while issues of stability and ellipticity for the hyperelastic solution are considered to impose necessary restrictions on the constitutive parameters. The theoretical predictions of the proposed model are compared with the anisotropic experimental responses, showing high fitting accuracy in determining the mechanical parameters of the model. The constitutive theory is suitable to account for the anisotropic response at large compressive strains, opening perspectives for many applications in tissue engineering and biomechanics.

1. Introduction

Several biomechanical studies have been carried out concerning the mathematical representation of the anisotropic behavior of soft materials undergoing finite strains. Numerous formulations have been recently proposed for the modeling of fiber-reinforced tissues such as skin (Xu et al., 2008), arteries (Holzapfel and Ogden, 2010), esophagus (Natali et al., 2009) and abdominal organs (Ciarletta et al., 2009).

Classical constitutive equations in soft tissue biomechanics are based on a phenomenological approach, which is concerned mainly with fitting the constitutive equations to experimental data (Fung et al., 1979; Chuong and Fung, 1983). As discussed by Holzapfel et al. (2002), these models predict qualitatively reasonable responses for restricted geometry and loadings, but the physical meaning of the proposed mechanical parameters is difficult to interpret, while restrictions on their values are needed to ensure convexity and, consequently, to avoid material instabilities. Even if a lack

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