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On the numerical simulation of damage for the visco-hyperelastic anisotropic behavior of the biomaterials in cyclic loading: relationship of the Mullins effect and fibers reinforcement

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Abstract

This work is focused on the homogeneous macroscopic material level in order to provide a suitable formulation for structural finite element simulation. A reduction of the stiffness depending on loading, summarized as `damage phenomena', is considered. We present the modeling of visco-hyperelastic damage with the Mullins effect of fiber-reinforced biomaterials. We show that the Ogden-Roxburgh model is more realistic for a reproduction of the damage of hyperelastic materials. Analyzing the parameters set, compressibility and reinforcement (reinforcement contribution, fibers directions and their dispersion in the material) on the hysteresis phenomenon in the tensile cyclic deformation of these biomaterials is achieved

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1. Introduction

Nowadays, simulations of complex and highly nonlinear mechanics problems are conducted using the finite element method (FEM). FEM is also an ideal numerical tool to analyze viscoelastic rubber parts. Usually, these structures cannot be described analytically because of material nonlinearities and complex geometry. Often, time dependent and dissipative material behavior is observed simultaneously with load dependent stiffness reduction. For example, filled elastomers and biological tissues belong to this class of materials. Both phenomena, i.e. viscoelasticity and damage,

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are incorporated into a formulation of finite strain elasticity [1]. The phenomena can be used either together or one of the other features is suppressed by choosing appropriate material parameters.

The accurate prediction of the mechanical behavior of rubberlike materials remains an open issue [2]. These materials are used often under cyclic conditions, where large deformation viscoelasticity coupled with damage is relevant. Their mechanical behavior has been described first as hyperelastic, and several forms of strain energy density have been defined thus far, see for example Ref's. [3-6]. Later, the stress softening induced by the first loading cycle, known as the Mullins effect [7], was included in constitutive equations by including damage. An isotropic damage parameter, d, has been introduced often in order to modify the strain energy density by the multiplicative factor (1-d) [8-11]. In an alternative approach based on macromolecular models, and still assuming isotropy, it was proposed to account for damage by making the average length and volume fraction of the chains that support stress depend on the loading history[12]. Early experimental results have demonstrated the viscoelastic character of rubberlike materials [13-15]. For instance, the uploading and unloading responses differ during cyclic loadings. Many visco-hyperelastic constitutive models with or without damage have been proposed [16-19], among others. It has been reported as well that some anisotropy is induced by the Mullins effect [13].

In this paper, we present a theoretical study related to the parameters defining the dissipative behavior by Mullins effect. Then, we perform the numerical simulation of the biomaterials damage under cyclic loading. The influence of parameters such as: parameters set; compressibility and reinforcement of biomaterials is showing. The study models are implemented in finite element computer code "Abaqus®". We focus the study on the influence of anisotropy induced by the fibers directions. We consider the transverse anisotropy for the modeling of the biomaterial behavior. The influence of the fibers orientations on the biomaterial response; in the static loading (without regard to the Mullins effect), can be found in Ref. [20].

This paper is organized as follows: Section 2, the modeling techniques of the Mullins effect is briefly revised. In Section 3 the utilized models (model for Mullins effect and hyperelatic models) are reported. The numerical simulation results of the coupled problems (Mullins effect phenomena and hyperelastic anisotropic behavior) for biomaterials are presented and disputed in Section 4. Finally, Sections 5 includes conclusions and remarks.

2. Micromechanical motivation

The Mullins effect is less studied then the hyperelastic behavior of materials in order to set up behavioral laws. There are models that attempt to reproduce the Mullins effect and most do not provide explicit laws or 3D models (see [21]). The Govindjee-Simo micro-macro model is expressed by an exploitable behavior law in the structure computation [8, 22]. In the Mullins effect, it runs again into an old debate on the interactive nature of the matrix-fillers. Many studies try to predict this predominant phenomenon in the microstructural interaction [23, 24]. Two dissipation models are quoted: dissipation attached to the stress amplification caused by the fillers presence [14, 25] or dissipation related to the "bond rubber" [24, 26]. In this section, we present the two principal methods for modeling of Mullins effect.

The micro-physics method considers the damage in the chains networks. Thus the modeling in this case was based on the "bond rubber". The authors integrate a micro-dissociating behavior of chain network that suffer only the volumetric fillers presence and a second chain network that was interacting with these fillers. The damage carried only on the matrix part related to the fillers in the chains dissipation form that suffers an important elongation. At the larger elongations λ_i^m attached to directions u_i in the course of the history, the parameter damage is the scalar:

$$\mu = Max(\lambda_i^m) \tag{1}$$

So, it defines the damage as a scalar that characterizes an isotropy phenomenon. Now, a delicate detail is missing: the remnant deformation. This phenomenon is found considering that damage is anisotropic and attached to its direction [27]. In the principal axes, it seems natural to have rather:

$$\mu_i = Max(\lambda_i^m) \tag{2}$$

Hyperelastic laws for rubberlike materials based on sets of material directions have been proposed previously [28, 29]. In such models, which are able to account for anisotropy, the hyperelastic strain energy density is approximated