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Hyperelasticity with rate-independent microsphere hysteresis model for rubberlike materials

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ABSTRACT

The mechanical behavior of elastomers strongly differs from one to another. Among these differences, hysteresis upon cyclic load can take place, and can be either rate-dependent or rate-independent. In the present paper, a microsphere model taking into account rate-independent hysteresis is proposed and applied to model filled silicone rubbers behavior. The hysteresis model is based on a combination of monodimensional constitutive equations distributed in space. The behavior of each direction is described by a collection of parallel spring slider elements. The sliders are Coulomb dampers with non-zero break-free force in tension. This model is tested on a filled silicone rubber by the way of uniaxial tensile and pure shear tests. The mechanical response of the material is well predicted for such tests. Finally, the constitutive equations are implemented in the finite element software ABAQUS. Calculation results highlight good performances of the proposed model.

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1. Introduction

The study and modeling of the mechanical behavior of rubberlike materials have been widely studied in last decades due to the increasing number of industrial applications, such as vibration isolators, tires or shock absorbers, non exhaustively. Classically, rubbers are filled by mineral fillers in order to improve their physical properties. The addition of fillers typically implies an increase of stiffness and a reinforcement of crack growth resistance [1,2]. However, it also induces numerous additional effects [1,2]. Among them, one can cite the stress softening, which mainly occurs between the first and second loads, and often called the Mullins effect [3] (which can rarely be observed in unfilled rubbers too [4]), the stress relaxation and the mechanical hysteresis (unload different from load).

The load and unload responses of filled rubber differ during cyclic tests. Even if this evolution is mainly due to the Mullins effect during the first cycle, a difference between load and unload responses is still observed once the material is softened, i.e. after the first cycle. This phenomenon, so-called hysteresis, can depend on the strain rate [5], the crosslinks density [6] or the temperature [7].

Several micromechanism-inspired approaches of the hysteresis phenomenon were proposed in the literature, based on different physical considerations. To the opinion of Bergström and Boyce [6], hysteresis is induced by the viscous reptation of elastically inactive macromolecules. This type of micromechanism has also motivated a micro-sphere approach [8], where hysteresis is considered to be due to the fillers entanglement. Some authors considered that a part of the broken cross-links can be re-formed upon unload [9]. More recently, the idea of a successive breakdown of filler clusters taking place during a load, and of a complete re-aggregation of the filler particles taking place during an unload was proposed [10]. This implies filler-induced hysteresis.

According to either the physical or the phenomenological approach used, different viscoelastic models with or without damage were proposed to take into account the hysteresis (for example [11–13]). A classical hypothesis of the proposed constitutive models is the multiplicative split of the deformation gradient into elastic and inelastic parts [6,14–17]. Other approaches used a history dependent function to account for the hysteresis [18].

Even though most of the papers focused on the viscoelastic behavior of the material, some of them studied the rate-independent hysteresis [9,11,18,19]. To distinguish stress-softening and hysteresis, most of the authors removed the Mullins effect from the material behavior by carrying out beforehand several loading cycles [6,15].

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This paper focuses on the quasi-static modeling (i.e. the rate independent behavior) of hysteresis effect after stress-softening. The aim of this work is to propose a directional method able to represent the difference between load and unload, easily extendable to anisotropy and well-adapted to the implementation in a finite element code.

The different mechanical tests carried out on a filled silicone rubber and the results obtained are presented in Section 2. The theoritical background to model hysteresis is introduced in Section 3. In Section 4, experimental data are compared with simulations and results are discussed. Section 5 presents model implementation in a finite element code with calculation results obtained in case of heterogeneous test and capacities of the model. Finally, concluding remarks close the paper.

2. Experimental setup

2.1. Materials

The material considered here is a filled silicone rubber (Bluestar RTV 3428). Its mechanical properties were previously investigated [7,20,21] and it was shown that this material exhibits stress-softening, occurring mainly during the first load, hysteresis and temperature dependent behavior.

2.2. Loading conditions

Two types of classical tests are carried out, uniaxial tensile tests and pure shear tests. These tests are performed using a Gabo Eplexor 500 N. For the uniaxial tensile tests, the length, width and thickness of the specimens are 12, 2 and 2 mm, respectively and a 25 N load cell is used. For the pure shear tests, the length, width and thickness of the specimens are 2, 40 and 2 mm, respectively and a 500 N load cell is used. Several tests were carried out at different strain rates on the considered material, and it was observed that no significant difference can be observed for strain rates lower than $\dot{\lambda} = 1.67 \times 10^{-3}\ \mathrm{s}^{-1}$. As a consequence, to assume quasi-static conditions, the tests of this paper are performed at a low strain rate, i.e. $\dot{\lambda} = 1.67 \times 10^{-3}\ \mathrm{s}^{-1}$.

In order to distinguish mechanical hysteresis from Mullins effect, a preconditioning test is carried out on each specimen to remove the stress softening from the mechanical behavior. This procedure is classically applied in the literature to ensure test repeatability [6,15,22]. In the present study, preconditioning consists in performing 5 cycles of load unload to a stretch of $\lambda = 3$. Results of uniaxial tensile tests are presented in Fig. 1(a), in terms of the nominal stress versus the stretch λ. Fig. 1(b) shows that there is no more stress softening between the 4th and 5th cycles proving that 5 cycles are sufficient to remove the Mullins effect from the mechanical behavior of the silicone rubber. The results are quite similar for planar tensile tests and are not reported here.

2.3. Experimental results

Uniaxial tensile test is first carried out with increasing load cycles. These cycles are performed to $\lambda = 1.5, 2$ and 2.5 (see histogram in Fig. 2). It can be observed in Fig. 2(a) that there is a difference between loads and unloads, and that this phenomenon increases with increasing stretch. It is worth noting that there is still a very few residual strain.

A similar planar tensile test is performed, with three cycles to $\lambda = 1.5, 2$ and 2.5. The results of this test are presented in Fig. 2(b). The curve is quite similar as for the uniaxial tensile test, the only difference is the stress level that is higher for the planar tensile test.

Two additional non-classical uniaxial tensile and planar tensile tests are performed to study the hysteresis phenomenon. The first test (called 'nc1' in the following) is a load–unload major loop with two hysteresis loops during the load and the unload. The second test ('nc2') is also a load–unload tensile test with a hysteresis sub-loop inside a first loop during the load. Fig. 3 presents the histograms and results of these tests. Once again, it can be seen that the stress level is higher for planar tensile tests. In the 'nc2' test, the size of the hysteresis sub-loop is smaller than the size of the hysteresis loop, whereas for the 'nc1' test the four hysteresis loops seem to have the same size.

3. Theory

3.1. Motivation

As mentioned above, hysteresis is a phenomenon whose physical mechanisms are still not clearly understood. Similarly to the other elastomers, silica filled silicone rubbers exhibit a hysteresis loop in terms of the stress–strain relationship [7]. The hysteresis loop is not observed when the silicone rubber is unfilled [7],

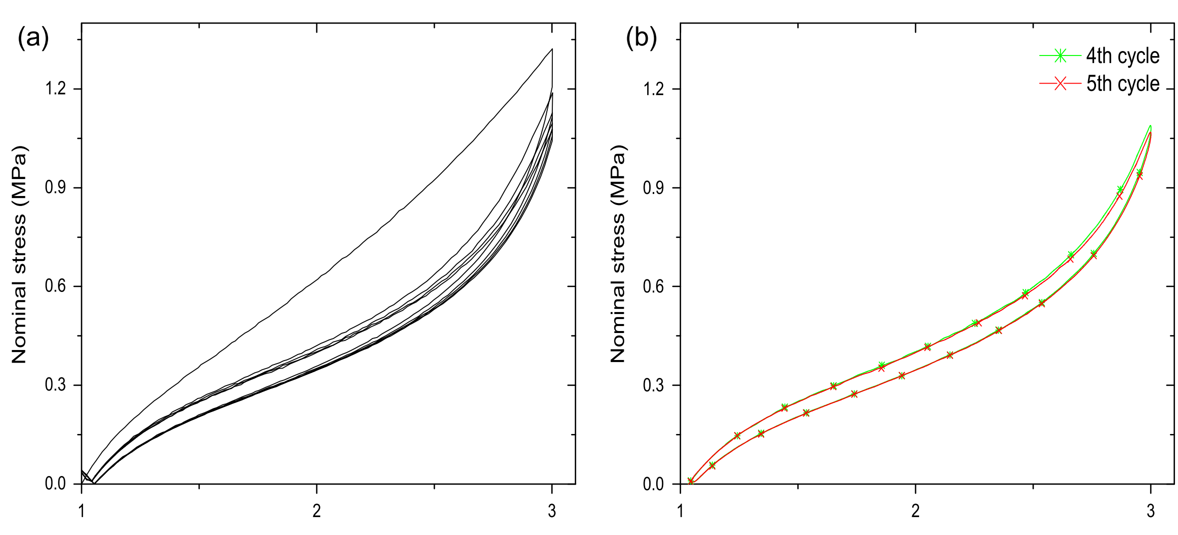

Fig. 1. Preconditioning test to remove the stress softening during an uniaxial tensile test, with (a) the five first cycles and (b) the fourth and fifth cycle, at a stretch of $\lambda = 3$.

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