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On the dynamical behavior of filled rubbers at different temperatures: Experimental characterization and constitutive modeling

A. Delattre[a], S. Lejeunes[b,*], F. Lacroix[c], S. Méo[c]

[a] Airbus Helicopters, Marignane, France
[b] LMA, CNRS, UPR 7051, Aix-Marseille University, Centrale Marseille, F-13402 Marseille Cedex 20, France
[c] LMR, EA 2640, Université F. Rabelais de Tours, France

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ABSTRACT

This work focuses on the characterization and the modeling of the complex dynamical behavior of a butadiene rubber filled with carbon black. This material is used in helicopter rotors and submitted to severe operating conditions. In particular the effects of the environmental temperature, of the amplitudes and frequencies of cyclic loading are studied. A new constitutive model that takes into account the Payne effect, the frequency, temperature and pre-loading dependencies is proposed. A specific material parameter fitting strategy is also introduced.

1. Introduction

The architecture of modern helicopter rotors is based on several critical rubber parts. These parts are designed to transmit or to damp complex loadings and a precise knowledge of their behavior is required for an accurate simulation aided design of the structure. Operating conditions of these parts can be severe: a large range of ambient temperatures (−50 °C to +70 °C), mechanical loadings can be multiaxial and multi-frequencies with varying amplitudes. Obviously depending on the part design, rubber materials can vary in composition (matrix and fillers) or in grade (fillers and additives ratio). Therefore to cover a wide range of applications a general constitutive modeling of filled rubbers that can take into account complex loadings with an accurate response is needed.

In this paper, a butadiene rubber filled with carbon black is considered. The mechanical properties of the present material are very closed to materials used in the aforementioned applications. As many filled-rubber materials it exhibits typical phenomena (among others):

(a) Mullins effect: a softening phenomenon that occurs when the amplitude of loading is higher than the maximum previously seen amplitude.
(b) Self-heating: filled rubber exhibits a strong self-heating phenomenon when they are submitted to mechanical loadings.
(c) Thermal softening: far from the glass-transition temperature, an increase of the environmental temperature leads to a dynamical softening of the material behavior. *A contrario*, regarding only the response of the rubber gum (with a very low filler ratio or for small deformation rates) an increase of temperature (far from the glass-transition) leads to a stiffening behavior which is a fundamental characteristic of the entropic elasticity behavior of rubbers. Furthermore, the competition of this entropic elasticity and the thermal dilatation leads to the well-known effect of thermal inversion.
(d) Frequency dependency: when submitted to harmonic loadings with increasing frequency, the dissipated energy and the dynamical stiffness usually increase (nonlinear effect).
(e) Amplitude dependency or Payne effect: when submitted to harmonic loadings with increasing amplitude, the dissipated energy increases and the dynamical stiffness decreases (softening effect).
(f) Mean stress or static/dynamic effect: the dynamical stiffness can exhibit a nonlinear dependency on the pre-stress (preload) or mean-stress value.

In the present paper, we focus on the last four points. The Mullins effect and the self-heating phenomena are not considered for the modeling part. Concerning Mullins effect, experimental characterization has been done by applying a preconditioning to samples (“de-Mullinized”). Samples have been subjected to

* Corresponding author. Tel.: +33 484525597, +33 491054382; fax: +33 491054749.
E-mail address: lejeunes@lma.cnrs-mrs.fr (S. Lejeunes).

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several initial cycles with an amplitude that was higher than the maximum amplitude used for the dynamical characterization. The self-heating phenomenon or other thermo-mechanical coupling effects cannot be removed by a specific experimental procedure. These effects can be taken into account in the modeling part by a coupled thermo-mechanical approach (see for instance Meo et al. (2002); Reese and Govindjee (1997) for thermo-mechanical couplings with finite strain viscoelastic behaviors).

In the literature, many constitutive models has been proposed the last 25 years and at least three approaches can be distinguished to cover the aforementioned phenomena. The first one is the integral approach for which the viscous stress is described as a function of the whole history of strain (see for instance Coleman and Noll (1961); Morman (1988)). This approach can be used in the frequency or the time domain and gives generally very good results for covering a range of frequencies. Fractional derivatives can be introduced (see Wollscheid and Lion (2014) and reference therein) and Payne effect can also be represented (see for instance Lion and Kardelky (2004)). To the authors opinion, a disadvantage of this approach is that the link with the fundamental thermodynamical principles is not straightforward and can eventually lead to non-admissible models. The last two approaches share the same concept using the introduction of internal variables to describe inelastic effects. Behind these variables, the local (in time and in space) state hypothesis is used (see for instance Germain et al. (1983)) in the framework of the thermodynamics of irreversible processes. Approaches can be distinguished in the way that evolution equations are obtained. One can find micromechanically motivated models (see Linder et al. (2011); Reese (2003)), homogenization based model (see for instance Miehe and Göktepe (2005); Omnès et al. (2008)) and purely phenomenological models (see Rendek and Lion (2010) for Payne effect modeling within phenomenological models or Martinez et al. (2011) for a statistical representation of viscosity). In these approaches the link with fundamental thermodynamical principles is straightforward so as the numerical implementation in a finite element software.

The present model belongs to the last mentioned category. It constitutes an extension of a previously published model (see Delattre et al. (2014)). The starting point is to consider the rubber stress response as a sum of a nearly equilibrium response (which corresponds to the relaxed stress) and a finite number of non-equilibrium ones (which correspond to a discrete spectrum of viscous stress, each one is associated to a characteristic time of viscosity). The equilibrium response is assumed to follow a classical nearly incompressible visco-plastic behavior and the non-equilibrium ones are represented with an original isochoric viscous model that takes into account the dynamical softening due to Payne effect. The key points of the proposed approach are the introduction of tensorial viscosities and of damage like variables that represent the Payne effect. The tensorial viscous flow allows to take into account an effect of orientation of each viscous stresses relative to the global deformation. The characteristic times of viscosity are therefore not identical if one considers tension or shear. This approach allows a better phenomenological representation of multi-axial response and of mean stress (or preload) effect for cyclic harmonic tests (for these tests, the effect of the mean stress can be different in tension or shear). For Payne effect, it is considered isotropic internal variables which behave like damage variables. The Payne effect is commonly attributed to breakage of physically bonded filler network structure. The idea of a continuous breakage/reformation of the filler network during dynamical loading is at the origin of the so called Kraus model (Kraus et al. (1966)). The present evolution equations for damage like variables take into account characteristic times for Payne effect (dynamical softening can be found experimentally to not being instantaneous which is in contradiction with earlier approach of Kraus and coworkers) and is related to the maximal elastic strain energy seen during loading. A specific identification strategy is proposed to provide robust results with a relative cheap numerical cost. A temperature dependency of the mechanical material parameters is deduced from identification results. The present model exhibits very promising results at various temperatures, various frequencies and amplitudes of loading both in tension/compression and in simple shear.

2. Experimental characterization

2.1. DMA and DSC results

The studied material is a butatiene rubber filled with carbon black, however the precise chemical composition and the processing conditions are not given due to industrial confidentiality. The filler ratio in mass is near 45% of the total mass (determined with thermogravimetric analysis). Fig. 1 show differential scanning calorimetry and dynamical mechanical analysis results. The material homogeneity of the curing process has been checked in diabolo specimen by doing DSC analysis with two parts that were extracted from two different zones inside a diabolo: in the center and near an edge. It can be seen from Fig. 1(a) that the material is homogeneous inside the sample (the gap between both curves can be attributed to a difference of initial referential). It can be seen that the glass-transition temperature is located near −85 °C and that the frequency dependency is almost linear (in the range 1 to 100 Hz) in the linear regime of the material (*i.e.,* for an amplitude smaller than 1%).

2.2. Experimental setup in the non-linear regime

In the non-linear regime (for larger strain), the behavior is characterized from cyclic and monotonic (relaxation) tests that have been done on double-shear, diabolo and tension (H2) specimens. These tests have been done with electro-mechanic or hydraulic testing machines equipped with temperature controlled adiabatic chambers. Fig. 2 shows the geometry and the characteristic dimensions of each specimen.

The temperature of the samples is obviously not controlled and can evolve due to thermo-mechanical couplings (the temperature of the sample is not recorded). For cyclic tests, we consider that the self-heating phenomenon does not have sufficient time to develop significantly. For all tests, the samples are "De-Mullinized" by doing 20 cycles at a small strain rate and at a larger amplitude than the maximum amplitude seen by the material during characterization. Subsequent to this, a relaxation period is observed (30 min) to remove viscous effects before characterization tests. To check the experimental repeatability, each test has been run on two different specimens.

2.3. Equilibrium hysteresis

Fig. 3 show the equilibrium hysteresis in shear or tension at different temperatures. The equilibrium hysteresis (see for instance Lion (1996)) are obtained by interrupting a constant strain rate load and unload test with relaxation periods of 90 min. The equilibrium stresses obtained at the end of each relaxation period form an hysteresis loop. For this test, as a long relaxation period is observed it can be safely assumed that the temperature of the material at equilibrium (at the end of each relaxation) is strictly equal to the ambient temperature. If this hysteresis area is null or quasi null the behavior can be said to be perfectly viscoelastic (or perfectly thermo-elastic). A contrario, if the hysteresis area cannot be neglected the material exhibits more complex dissipative phenomena (crystallization, damage,…). For the studied material, the