Predeformation and frequency-dependence : Experiment and FE analysis

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ABSTRACT

Elastomers show significant dependence on prestrain and frequency when they are loaded with large static predeformation superimposed by harmonic small amplitude dynamic excitations. In order to investigate these dependencies, quasi statics and dynamic experiments were carried out. Based on the experimental facts, we examined the capacity of the Simo viscoelastic model implemented in the FEA software Abaqus to simulate experimental data with good accuracy. The formulation is in the frequency domain. Therefore, the constitutive equations are linearized in the neighborhood of a predeformed configuration, with the assumption that the linear expression of stress governs the new configuration. Hence, the experimental data at different prestrain levels are compared to the simulation results.

Keywords: elastomers, dynamic material behavior, frequency-dependence, prestrain-dependence, abaqus frequency domain viscoelasticity.

1 INTRODUCTION

Because of their remarkable dissipative properties, elastomers are widely used as damping components in industry. Indeed, they can undergo severe mechanical loading conditions. The load-case of large static predeformation superimposed by small amplitude dynamic excitations can be found in many applications. Experimental investigations of rubber materials show lots of non linear effects. In order to design industrial components, it is of major importance to measure the sensitivity of the dynamic response to the influencing parameters, and be able to predict the impact of those effects on the products.

In the present paper, we examine the capacity of the Simo viscoelastic model implemented in Abaqus software to simulate experimental data with good accuracy, and with respect to the frequency and predeformation-dependence. Hence, the frequency domain viscoelastic model in Abaqus is explored. The input requirement of the model from dynamic tests at several frequencies is detailed. The model assumes that the input requirement to Abaqus is independent of the prestrain in the data. This assumption is examined for a filled rubber material. The material model is used to predict component level response in simulations performed at different prestrain levels for several frequencies. Experimental data at different prestrain levels are compared to the simulation results.

2 EXPERIMENTAL RESULTS

2.1 Static experiments

The experimental investigations are focused on the prestrain and frequency-dependent behaviour of a filled rubber. For this aim, some quasi-static experiments are carried out. To exclude the Mullins effect, which is known as a stress softening of virgin material in the first loading cycles [1], the specimens are preconditioned before testing. Monotonic tests were carried out with an Instron Table Model Testing Machine (model 3345). All tests were performed at room temperature under displacement control, and under the assumption of homogeneous deformations. Tensile tests were performed on H2 specimens. Shear tests were performed on quad-shear test simples [2]. Focusing on the equilibrium stress response, we make use of multistep experiments at different strains with holding time of ten minutes. The resulting stress responses are shown in Figure 1.

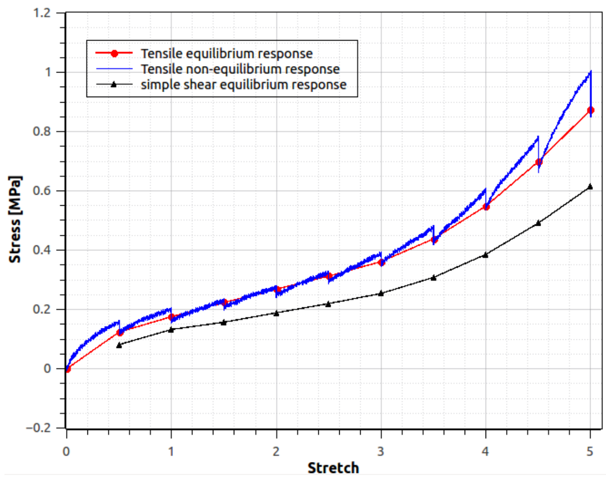

Figure1. Monotonic tests, loading conditions , equilibrium and non equilibrium stress response

2.2 Dynamic experiments

In this section, we discuss experimental observations on shear specimens. The specimens consist on an assembly of 3 stainless steel cylinders with 10 mm of diameter and 10 mm of length between which 2 rubber inserts, of about 2.4 mm thickness and indented from a rubber sheet furnished by the manufacturer, are glued. Dynamic properties were investigated by mean of a Metravib DMA 50N.

The experimental procedure consists in superimposing simple shear prestrain and a sinusoidal strain as:

$$\varepsilon(t) = \varepsilon_0 + \varepsilon_a \sin(\omega t) \tag{1}$$

were ε_0 denotes the prestrain, ε_0 denotes the strain amplitude, and ω is the angular frequency.

To consider the frequency-dependent materials behavior, frequency sweeps test with stepwise changing frequency from 0.1 Hz up to 40 Hz at constant predeformation and constant dynamic strain amplitude are used. In order to evaluate the materials response over a wide range of frequency, we used temperature-frequency shifting techniques and generate mastercurves [3][4]. Therefore, we have to investigate the temperature-dependence of the material behavior. The measuring temperature is varied between -100 °C and 100 °C and the reference temperature for the shifting process is set to 23.3 °C. On the basis of these conditions, we were able to shift the measured curves on the logarithmically scaled frequency axis.

The results were evaluated in terms of the shear storage modulus and the shear loss factor. The storage modulus determines that part of stress response which is in phase with the strain. The loss modulus that part of stress response which is in phase with the strain rate. The loss factor is the quotient of the loss modulus by the storage modulus. Figure 2 exhibits the frequency-dependent material behavior. The experimental data shows that the storage modulus increases significantly with increasing frequency. In comparison with this, the loss factor shows a broad maximum in the region of 1 e^{+04}Hz. In the region of lower or higher frequencies, this factor is significantly lowermost. Hence, the loss modulus increases with increasing frequency.

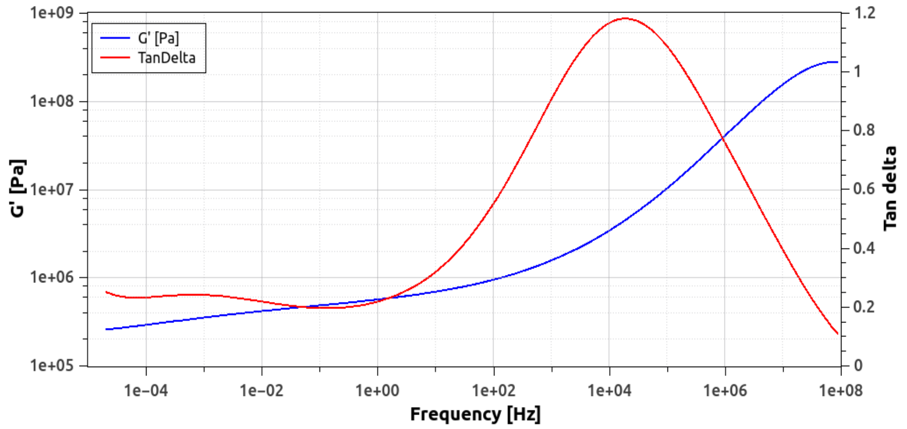

Figure 2. Material's frequency-dependent behavior , shear storage and loss factor

As mentioned before, and in order to determine the influence of the static prestrain on the dynamic materials behavior, frequency sweeps at different levels of static preload were carried out. The experimental curves show that increasing the static prestrain leads to a lower storage modulus and loss factor. Greater prestrain leads to a lower softening in term of shear storage modulus (Figure 3), the decrease between 0% of prestrain and 10% of prestrain is greater than that between 20% of prestrain and 30% of prestrain. Figure 4 exhibits the same phenomena for the loss factor. Therefore, the softening of the material is non linear.

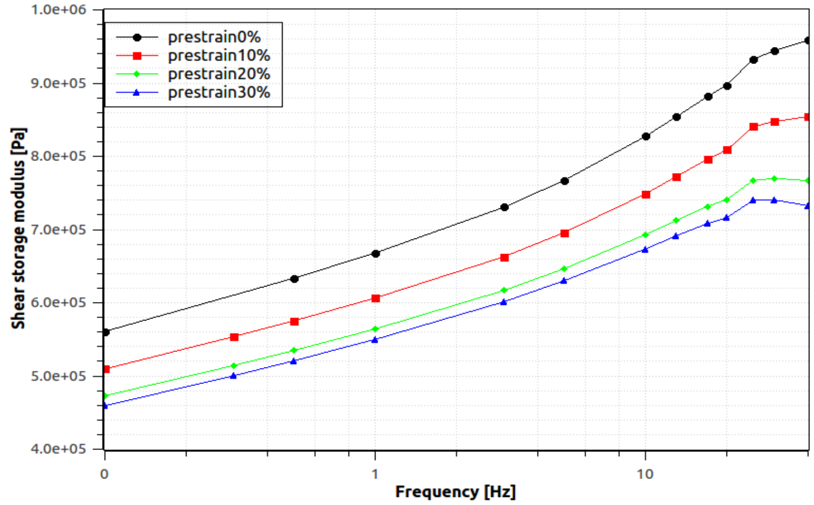

Figure 3. Shear storage modulus at different frequencies and prestrain levels

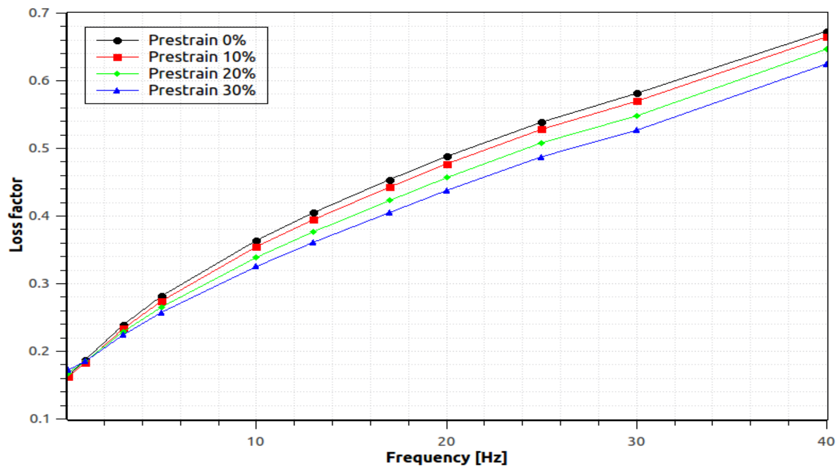

Figure 4. Loss factor at different frequencies and prestrain levels

3 FINITE ELEMENT ANALYSIS IN THE FREQUENCY DOMAIN

3.1 Abaqus FEA finite viscoelasticity model

We call $\boldsymbol{F}$ the deformation gradient it is defined as $\boldsymbol{F}=\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{x}}$ where $\boldsymbol{x}$ is the coordinate in the current configuration at $\boldsymbol{X}$ in the reference configuration. We call J its determinant $J=det\,\boldsymbol{F}$. When a solid is incompressible, every deformation is isochoric, so that: $J=1$.

The Abaqus FEA model is reminiscent of the Simo model [5]. The finite-strain viscoelasticity theory implemented in Abaqus is a time domain generalization of the hyperelastic constitutive model. Section 4.8.2 of the Abaqus Theory Manual version 6.13 [6] gives the following constitutive relations to model nonlinear viscoelastic effects :

$$\boldsymbol{\sigma}(t)=\boldsymbol{\sigma}_{\boldsymbol{0}}^{\boldsymbol{D}}(t)+dev\left[\int_0^t \dot{G}(s)\,\boldsymbol{F}_{\boldsymbol{t}}^{-\boldsymbol{1}}(t-s)\,\boldsymbol{\sigma}_{\boldsymbol{0}}^{\boldsymbol{D}}(t-s)\,\boldsymbol{F}_{\boldsymbol{t}}^{-\boldsymbol{T}}(t-s)\,ds\right]-p\boldsymbol{I} \tag{2}$$

where $dev(.)=(.)-\frac{1}{3}(.):\boldsymbol{I}$ is the deviatoric part of the bracketed term and $\boldsymbol{\sigma}_{\boldsymbol{0}}^{\boldsymbol{D}}$ is the instantaneous deviatoric Cauchy stress response (elastic response at very short times).
This constitutive relation is for incompressible solids. $-p\boldsymbol{I}$ is the hydrostatic term, and p is a Lagrange multiplier.
The time dependent shear relaxation function $G(t)$ is defined in terms of a series of exponentials known as the Prony series as:

$$G(t)=G_{\infty}+\sum_{i=1}^{n} G_i e^{\frac{-t}{\tau_i}} \tag{3}$$

where G_{∞} represents the long term shear modulus, G_i and τ_i are material constants.
Using Fourier transforms, the expression for the time dependent shear modulus can be written in the frequency domain as follows:

$$G_s(\omega)=G_0(1-\sum_0^n g_i)+G_0\sum_0^n \frac{g_i\tau_i^2\omega^2}{1+\tau_i^2\omega^2} \tag{4}$$

$$G_l(\omega)=G_0\sum_0^n \frac{g_i\tau_i\omega}{1+\tau_i^2\omega^2} \tag{5}$$

where $G_s(\omega)$ is the shear storage modulus, $G_l(\omega)$ is the shear loss modulus and ω is the angular frequency. g_i are dimensionless shear relaxation constants and are as:

$$g_i=\frac{G_i}{G_0} \tag{6}$$

The frequency domain viscoelasticity model in Abaqus is defined for a kinematically small perturbation about a predeformed state. The procedure consists on a linearised vibration solution associated with a long-term hyperelastic material behavior. This assumes that the linear expression for the shear stress still governs the system except that the long-term shear modulus G_∞ depends on the amount of the static prestrain γ_0 as:

$$G_\infty = G_\infty(\gamma_0) \tag{7}$$

Hence, this implies that the frequency-dependent part of the material's response is not affected by the static prestrain level.

3.2 Simulation results

In this section, the frequency domain viscoelastic model defined with the Abaqus step "Direct-solution steady-state dynamic analysis" [7] is studied in order to examine the capacity of the Simo viscoelastic model to simulate experimental data with good accuracy and with attention to frequency and prestrain dependences.
Harmonic excitation data at different prestrain and frequency levels are available. This data contains loss and storage modulus information. Long-term uniaxial data was used to calibrate an hyperelastic material model.

The simulation results for the equilibrium stress response are shown in Figure5. They reveal a very good matching between the experimental data and the simulated data for both uniaxial tension and pure shear tests.

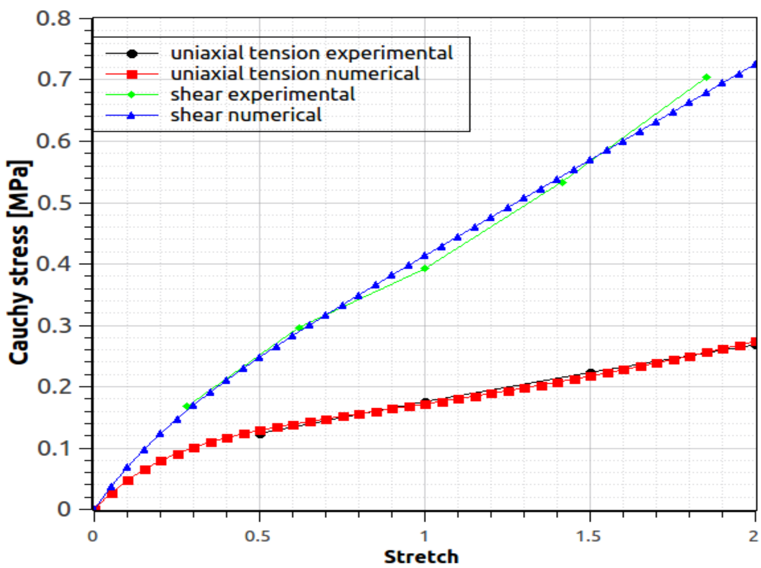

Figure 5. Experimental and simulated data for uniaxial and pure shear tests

With respect to the assumption of linearized vibration about prestrained configuration mentioned previously, harmonic data were introduced in the undeformed state. Hence, a small amplitude dynamic excitation was superimposed to a simulation of the nonlinear base state. Simulation results are graphically shown in Figure 6 and Figure 7. The frequency-dependent behavior is pronounced. Therefore, the results for the dynamic material response with respect to the prestrain-dependency are not accurate: the strain and frequency effects are separated. Thus, the basic assumption for the frequency domain viscoelasticity used in Abaqus is not reasonable for our investigated filled rubber.

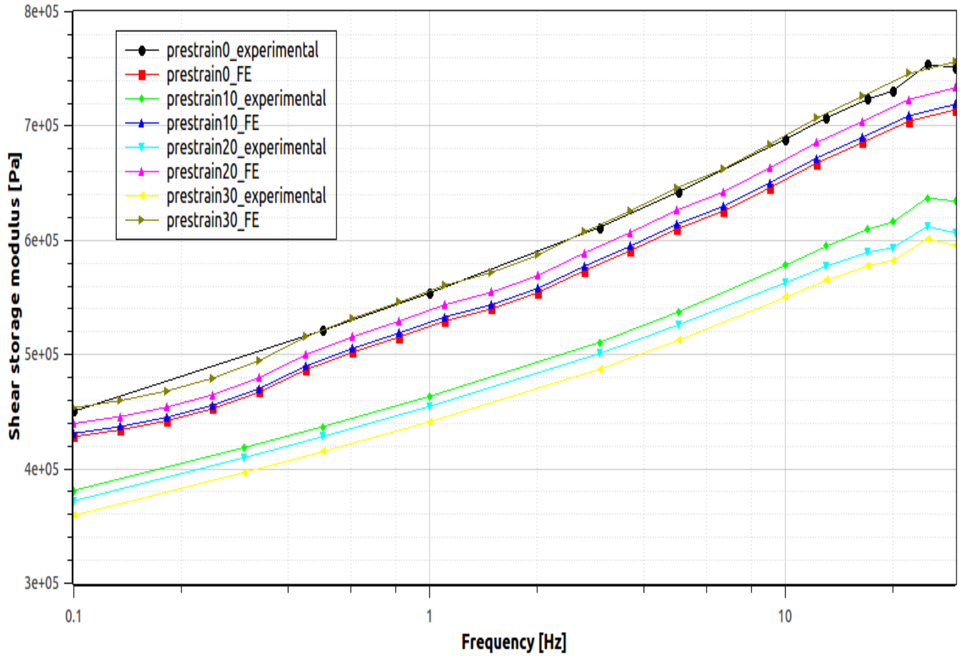

Figure 6. Experimental and simulated shear storage modulus at different frequencies and prestrain levels

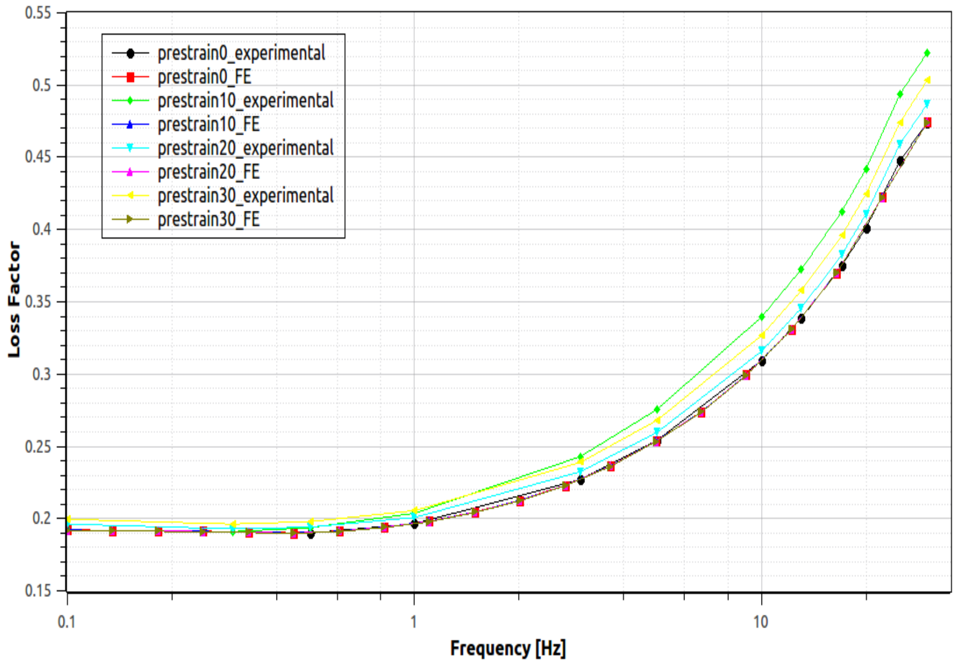

Figure 7. Experimental and simulated loss factor at different frequencies and prestrain levels

CONCLUSION

The experimental investigations of a filled rubber revealed a significant dependence on frequency and prestrain level. The frequency domain viscoelasticity in the FEA software Abaqus is used to simulate those dependencies and reproduce experimental results. This approach is based on the assumption of linearized harmonic excitation about a base state. Simulation results compared to experimental curves show that the frequency-dependent behavior is pronounced, but not the prestrain dependence. Thus, the strain and frequency effects are separated and the mentioned assumption above is non reasonable for the filled rubber material investigated in this paper.

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