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Test method

An efficient method for obtaining the hyperelastic properties of filled elastomers in finite strain applications

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ABSTRACT

An efficient methodology for obtaining hyperelastic material parameters for filled elastomers utilizing unloading curves in uniaxial tension, pure shear and the inflation of a rubber membrane is presented. Experimental results from biaxial extension are crucial when fitting hyperelastic material parameters, and the bubble inflation technique is an excellent method of obtaining this data when specialized test equipment is unavailable. Moreover, filled elastomers have considerable hysteresis, and the hysteresis grows with increasing strain amplitudes. Therefore, the loading curve is in general comprised of both elastic and inelastic contributions, even at very low strain rates. Consequently, it is deemed more accurate to use experimental data from the unloading curve to describe the elastic behavior of the material. The presented methodology enables obtainment of parameters related to both the first and second strain invariant, which is required for a good fit between measurement and simulation results. Finally, it is essential that a chosen material model is accurate in all deformation modes when designing components subjected to a complex, multi-axial load history. An accurate material model enables more concepts and geometries of a component to be studied before a physical prototype is available.

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1. Introduction

Rubber has characteristics that make it indispensable in many engineering applications due to the materials' unique combination of high extensibility, fatigue resistance and damping. It is used in vibration and shock absorbers, tires, conveyor belts and seals, to name just a few. With the increase in computational power over recent decades, commercial finite element (FE) software is now used early in the design phase to study the stresses and strains in components with complex geometries. However, the design engineer must be confident that the material parameters, and indeed the chosen material model, are sufficiently accurate to ensure reliable simulation over the expected range of frequencies, strain amplitudes and temperatures.

For unfilled, vulcanized elastomers displaying negligible hysteresis and having a weak frequency dependency, the mechanical behavior is successfully described by statistical and continuum mechanics [1–4]. Moreover, the material can often be assumed to be incompressible in industrial applications where the component has a sufficiently large unbounded area. In this paper, the phenomenological approach to incompressible rubber is employed, with the aim of describing the observed elastic properties of a material in a mathematical framework. For many applications, the elastic properties are sufficient to characterize filled elastomers.

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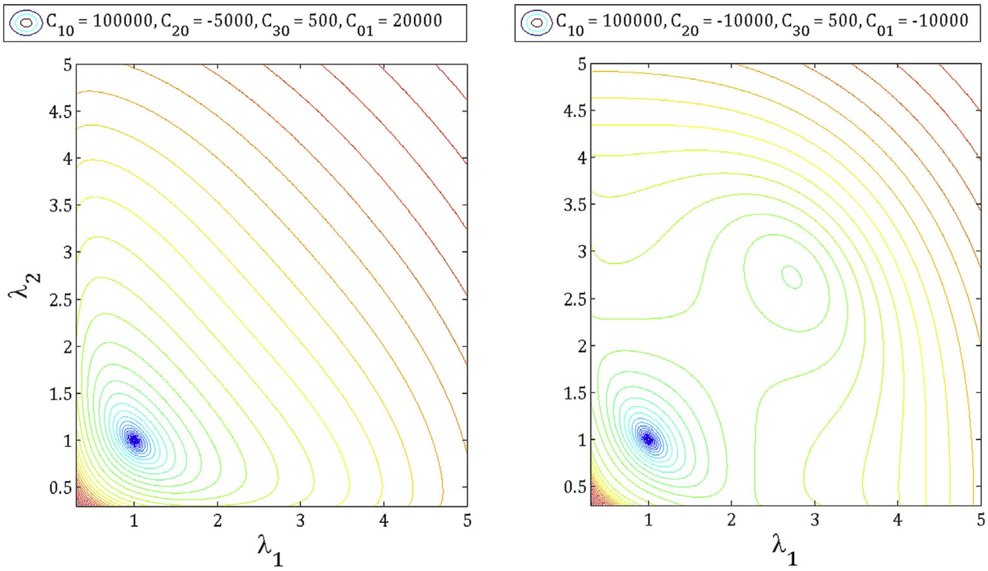

Fig. 1. Contour plot of strain energy density function for two different incompressible Biderman materials with units in Pa. Left: Physically admissible material parameters. Right: Bi-stable set of material parameters.

Phenomenological material models of rubber elasticity utilize a scalar valued strain energy density function to derive the non-linear, elastic relation between stress and strain. For materials with negligible hysteresis, there are several methods available to compare and choose an accurate model for the expected range of strain amplitudes. See for instance Ogden et al. [5] and Marckmann and Verron [6] and references therein. However, filled elastomers often show hysteresis at very low strain rates [7–10], even although the test specimens have been preconditioned to remove the initial stress softening, i.e. the Mullins effect [11]. Furthermore, several measurements in literature, where both the loading and unloading curves are presented, clearly demonstrate that the hysteresis grows with increasing strain amplitude [8,12,13]. Therefore, the loading curve of filled elastomers can be expected to be comprised of both inelastic and elastic contributions. This is supported by the fact that several models utilizing a plasticity framework are successful in capturing the mechanical behavior of filled elastomers [8,9,13]. The difference between loading and unloading can be substantial [8,13] and the design engineer must make the choice when solely the elastic contribution is sufficient to describe the material at hand in a satisfactory way. Otherwise, more advanced material models are necessary. Therefore, it is important to report both loading and unloading curves from experiments together with the response from simulations with the fitted material model [14]. Nevertheless, the unloading curve is deemed more suitable for fitting material parameters when the elastic properties of the material are of interest.

In order to obtain material parameters for elastomers, filled and unfilled, experiments in different deformation modes, e.g. uniaxial tension (UT), pure shear (PS) and equibiaxial tension (ET) should be performed [2,5,15,16]. If only UT experiments are conducted, and material parameters are fitted to this data, simulations in other deformation modes will yield erroneous results [2,5]. Therefore, experimental data from several deformation modes is crucial when studying the elastic properties of filled

Table 1
Strain invariants of the right Cauchy-Green tensor for three deformation modes in an incompressible material, where λ is the maximal principle stretch ratio.

Strain invariant	UT	ET	PS
I_1	$\lambda^2 + 2\lambda^{-1}$	$2\lambda^2 + \lambda^{-4}$	$\lambda^2 + \lambda^{-2} + 1$
I_2	$2\lambda + \lambda^{-2}$	$\lambda^4 + 2\lambda^{-2}$	$\lambda^2 + \lambda^{-2} + 1$
I_3	1	1	1

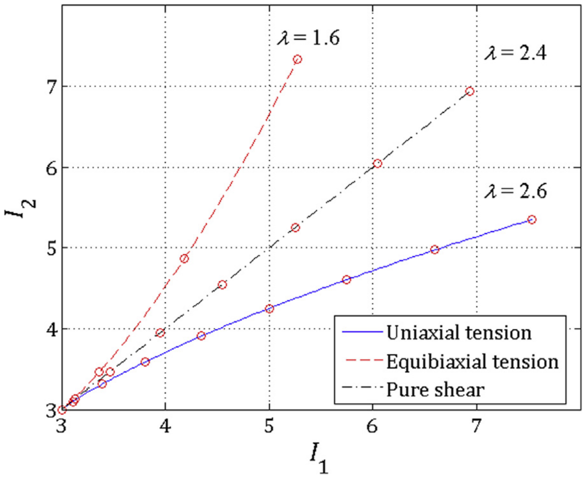

Fig. 2. I_1 and I_2 for different deformation modes in an incompressible material. For each deformation mode, the maximum plotted stretch ratio is given, together with equidistant markers 0.2 in stretch ratio apart.

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