A phenomenological constitutive model for the viscoelastic deformation of elastomers including the Mullins effect

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Introduction

Elastomers are utilised in a range of industrial applications including dampers and seals to name a few. Constitutive models are used in the design process to simulate the complex behavior exhibited by these products during their life cycle. Hence there is a need for the development of a model capable of accurately predicting the complex viscoelastic and stress-softening phenomena exhibited by these materials.

Objectives and Methodology

A method of analysing the complex material phenomena, as presented by De Focatiis et al. [1], is to extract the elastic and viscous contributions (Fig. 1a). In their study, they observed a viscous 'master curve' with stretch once the permanent set has been accounted for. The focus of this study is to develop a mechanical model based on this experimental evidence.

In [1] EPDM specimen were subjected to four uniaxial tensile cycles to a specified maximum stretch. The experimental data in [1] was employed in this study. A significant difference in the stress-strain behavior is noted between the initial loading (pre-deformation) and subsequent loops as illustrated by Fig 1a, this softening is characteristic of the Mullins effect. To remove the influence of the Mullins effect only the third loop (3rd unloading – 4th loading) has been considered in this study, see Fig. 1a. Furthermore, transients have been accounted for by discarding a portion of the data as shown on Fig. 1a.

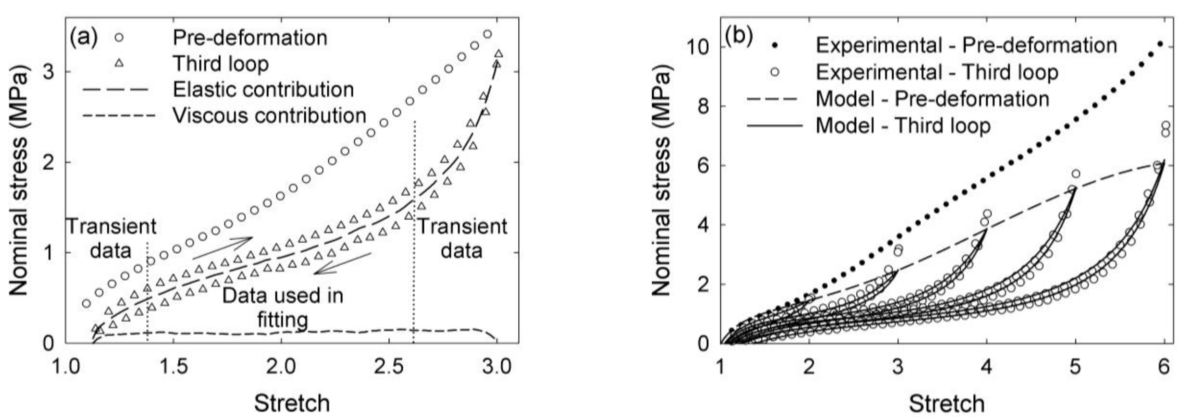

Fig. 1. (a) Extraction of elastic and viscous contribution from a stress-strain loop. (b) A comparison of the experimental and model pre-deformation and third loop behavior. The third loop behavior has been shown for five pre-deformation $\lambda_{\max}$ increments between 2 and 6, inclusive.

Edward-Vilgis (EV) [2] function was fitted to the elastic contribution, this function was chosen as it is physically motivated. Alongside the cross-link density N_C, slip-link density N_S, chain inextensibility α and slip-link mobility, permanent set stretch λ_{set} was added as a further parameter to accommodate for the permanent deformation. These parameters evolve with increasing pre-deformation $\lambda_{\max}$, the evolution of α is shown on Fig. 2a. The viscosity was computed from the viscous contribution, the resulting 'master curve' with effective stretch λ_{eff} is illustrated on Fig. 2b. The general form of functions describing the evolution of α and η are shown on Fig. 2a and 2b, respectively.

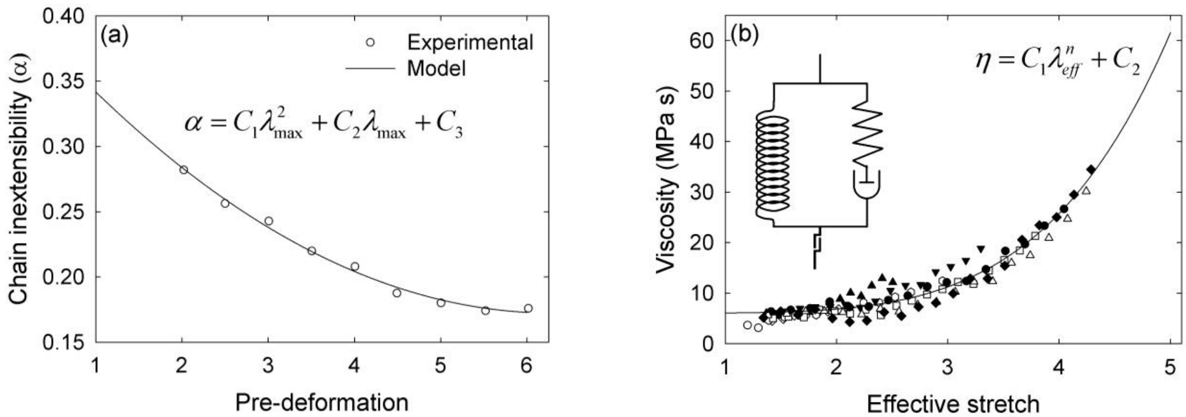

Fig. 2. (a) Evolution of α with increasing uniaxial pre-deformation and the general form of the function describing the evolution. (b) Evolution of η with increasing effective stretch, the general form of the function describing the evolution and a schematic of the model utilised in this study. The experimental viscosity was determined for different pre-deformation levels (third loop), represented by different symbols. The model is represented by a line.

The proposed model is a modified standard linear solid (SLS) model in series with a slider. The modified SLS model consists of an EV spring in parallel with a modified Maxwell model, where the linear dashpot is replaced with a non-linear variant whose viscosity evolves with stretch as shown on Fig. 2b. The elements in the model account for different features observed in an elastomeric material; the slider for permanent set, the EV spring for the underlying rubbery behaviour and the modified Maxwell element for the underlying viscoelasticity. The modulus of the linear spring was determined by comparing the experimental and model small strain behaviour.

Results and analysis

The model is capable of predicting the stress-strain response of the third loop to a good accuracy as shown on Fig. 1b. Although the characteristic stress-softening observed by elastomeric materials is present, the initial loading is underestimated by the model, see Fig. 1b. The missing stress on initial loading is associated with the Mullins phenomena as this additional stress is not present on pre-conditioned specimen as shown by an accurate prediction of the third loop. This model is therefore ideal for predicting the stress-strain response of scragged materials.

References

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[2] S. F. Edwards and T. Vilgis, "The effect of entanglements in rubber elasticity," *Polymer (Guildf).*, vol. 27, no. 4, pp. 483–492, Apr. 1986.