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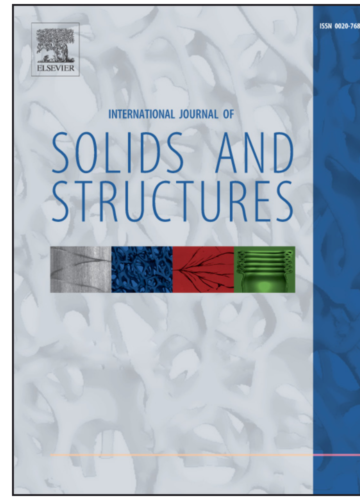

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S.Y. Ch'ng, A. Andriyana, M.S. Loo, E. Verron

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Constitutive modeling of strain-induced softening in swollen elastomers

S.Y. Ch'ng[a], A. Andriyana[a,*], M.S. Loo[a], E. Verron[b]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] LUNAM Université, École Centrale de Nantes, GeM, UMR CNRS 6183 BP 92101, 44321 Nantes, France

Abstract

Under cyclic loading, elastomeric material exhibits strong inelastic responses such as stress-softening due to Mullins effect, hysteresis and permanent set. The corresponding inelastic responses are observed in both dry and swollen rubbers. Moreover, it is observed that inelastic responses depend strongly on the swelling level. For engineering applications involving the interaction and contact between rubber components and solvent, the understanding and consideration of swelling are essential pre-requisites for durability analysis. In this paper, a simple phenomenological model describing Mullins effect in swollen rubbers under cyclic loading is proposed. More precisely, the proposed model adopts the concept of evolution of soft domain microstructure with deformation originally proposed by Mullins and Tobin. The swollen rubbers are obtained by immersing dry ones in solvent until desired degrees of swelling are achieved. Subsequently, their mechanical responses, in particular Mullins effect, under cyclic loading are investigated. These experimental data are used to assess the efficiency of the proposed model. Results show that the model agrees qualitatively well with experiments. Furthermore, the model captures well the fundamental features of strain-induced softening.

Keywords: Mullins effect, elastomer, swelling, constitutive modeling

1. Introduction

Many engineering applications involve the exposure of elastomeric components to aggressive solvent, e.g. gasket, seal, o-ring or drill packer. In these applications, two material degradations may occur: diffusion of solvent into elastomer leading to swelling and long term cyclic loading leading to fatigue [Ch'ng et al., 2013]. Therefore, the understanding and consideration of swelling are essential pre-requisites for durability and performance analysis of such components.

Similarly to dry elastomers, swollen elastomers show significant inelastic responses under cyclic loading: hysteresis, permanent set and stress-softening [Chai et al., 2013a]. The hysteresis corresponds to the amount of energy loss during a cycle and can be related to either viscoelasticity [Bergström and Boyce, 1998], viscoplasticity [Lion, 1997] or strain-induced crystallization [Trabelsi et al., 2003]. The permanent set refers to the residual extension remaining after a material sample is stretched and released while stress-softening is characterized by the difference between two successive cycles. Stress softening can be defined as a loss of stiffness of the elastomers and consequently affects the elastomers mechanical behaviour significantly. The stress-softening in dry rubbers was discovered by Bouasse and Carrière [1903] and was investigated intensively by Mullins [1948]. Hence, it is often referred to as the "Mullins effect". Detailed reviews on Mullins effect are provided in Harwood et al. [1967] and more recently in Diani et al. [2009]. The general features of Mullins effect can be summarized as below:

1. Stress-softening appears after the first loading at strain level lower than the previously maximum strain attained.

*Corresponding author. Fax: +60 3 79 67 53 17
Email address: andri.andriyana@um.edu.my (A. Andriyana)