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A thermo-viscoelastic-damage constitutive model for cyclically loaded rubbers. Part I: Model formulation and numerical examples

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Abstract
Cyclically loaded rubbers exhibit a complex history-dependent response characterized by fatigue-induced stress-softening and hysteresis along with dissipative heating. The coupling between these different inelastic effects usually appearing together is far from being fully established. In this Part I of two-part paper, we present a new thermo-viscoelastic-damage approach, in accordance with the thermodynamic principles, for the prediction of this set of inelastic fatigue phenomena. An interpretation of the underlying physical mechanisms is proposed in which two types of dissipative network rearrangements are considered, i.e. recoverable rearrangements inducing viscoelasticity and unrecoverable rearrangements inducing damage. The recoverable viscoelastic rearrangements are assumed to be induced by the move of entangled and non-entangled free chains superimposed on a purely elastic perfect rubber network. Each population of free chains is considered to be the main source of one aspect of the history-dependent mechanical cyclic features, i.e. stress-softening and hysteresis, respectively. The thermo-mechanical coupling is defined by postulating the existence of a free energy in which two internal state variables are introduced to account for the two types of dissipative network rearrangements. Network thermal kinetics, induced by the dissipative heating, as well as network damage kinetics, induced by the fatigue damage, are defined and used to alter the cyclically loaded perfect rubber network. The proposed constitutive model is implemented into a finite element program and a parametric study is presented via numerical applications on rubber structures in order to analyze the effects of key model parameters on the rubber inelastic fatigue response. A focus is especially made on the respective influence of temperature, viscoelasticity and damage on the rubber softening.
Keywords: Thermo-viscoelastic-damage coupling, fatigue, dissipative heating, rubbers.

1. Introduction

Rubbers used in engineering applications are often cyclically loaded and exhibit a complex history-dependent fatigue response characterized by fatigue-induced stress-softening and hysteresis along with dissipative heating. Establishing the coupling between these different inelastic fatigue phenomena, usually appearing together during the cyclic loading history, is an open issue to be addressed.

The physical essence of the fatigue-induced stress-softening is generally attributed to the network degradation, interpreted as an accumulation of the damage effects within the rubber medium (Bouasse and Carrière, 1903; Mullins, 1948; Houwink, 1956; Bueche, 1960; Kraus et al., 1966; Simo, 1987; Govindjee and Simo, 1991; Wineman and Huntley, 1994; Miehe, 1995a; Ogden and Roxburgh, 1999; Drozdov and Dorfmann, 2001; Marckmann et al., 2002; Laiarinandrasana et al., 2003; Chagnon et al., 2004, 2006; Goktepe and Miehe, 2005; Hanson