Cyclic viscoelastoplasticity and low-cycle fatigue of polymer composites

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1. Introduction

This paper is concerned with experimental investigation and constitutive modeling of the viscoelastoplastic behavior of polymer composites in cyclic tests with a stress-controlled program (ratcheting).

In the past 5 years, a number of studies have focused on experimental and theoretical analysis of the time-dependent response of polymers and polymer composites subjected to cyclic loading: Xia et al. (2005), Hizoum et al. (2006), Drozdov and Christiansen (2007), Yakimets et al. (2007), Sullivan (2008), Bles et al. (2009), Cantournet et al. (2009), Drozdov (2009), Mizuno and Sanomura (2009), Speickermann et al. (2009), Zrida et al. (2009), Ayoub et al. (2010), Bouchart et al. (2010), Buckley et al. (2010), Drozdov (2010a), Ramkumar et al. (2010), Silverstein and Boyce (2010) and Vandenbroucke et al. (2010). Constitutive equations developed in those works were confined, however, to the description of observations along the first cycle (loading–unloading) of a cyclic deformation program. Attempts to predict the mechanical behavior of polymers subjected to severe (at least, hundreds of cycles) deformations have recently been undertaken by Ayoub et al. (2011) and Drozdov (2011) for strain-controlled loading programs. Observations in cyclic tests with stress-controlled programs (ratcheting) on polymers and polymer composites were reported by Tao and Xia (2007), Liu et al. (2008) and Kang et al. (2009), to mention a few.

The objective of this study is three-fold:

1. To report observations in uniaxial tensile tests on a polymer composite (polyamide-6 reinforced with glass fibers) at ambient temperature. The experimental program involves (i) cyclic tests with a stress-controlled program (ratcheting with a fixed maximum stress $\sigma_{\text{max}}$ and various minimum stresses $\sigma_{\text{min}}$) up to breakage of samples, (ii) short-term relaxation tests at various strains, and (iii) short-term creep tests at various stresses.

2. To develop constitutive equations in cyclic viscoelastoplasticity of polymer composites, to find adjustable parameters in the stress–strain relations by fitting the observations, and to demonstrate that the model adequately predicts growth of maximum and minimum strains per cycle with number of cycles up to breakage of specimens.

3. To perform numerical simulation of the time-dependent response of polymer composite under cyclic deformation and to analyze the effects of (i) strain rate and (ii) minimum stress per cycle on number of cycles to failure $n_f$.

To describe the viscoelastoplastic behavior of polymer composites under cyclic deformation, a two-scale model is developed. At the micro-scale (an individual cycle of loading–unloading), a composite is treated as an equivalent transient network of chains bridged by junctions. A characteristic feature of the model is that the plastic strain tensor is split into the sum of two components that characterize irreversible deformations in crystalline and amorphous phases. Constitutive equations are derived by using the Clausius–Duhem inequality for an arbitrary three-dimensional deformation with small strains.

At the macro-scale (loading–unloading with a large number of cycles), kinetic equations are proposed to describe evolution of coefficients in the stress–strain relations with intensity of plastic strain at instants when the strain rate alters its sign. With reference to experimental data, it is presumed that after some transition period, most coefficients in the constitutive equations adopt...