Polymer Testing 46 (2015) 134–143

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Property modelling

Creep loading response and complete loading–unloading investigation of industrial anti-vibration systems

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ARTICLE INFO

Article history:
Received 17 June 2015
Accepted 27 July 2015
Available online 29 July 2015

Keywords:
Creep
Rebound energy
Hyperelasticity
Rubber unloading
Design

ABSTRACT

This article presents engineering approaches to evaluate creep loading response and a complete loading–unloading procedure for rubber components used as anti-vibration applications. A damage function for creep loading and a rebound resilience function for mechanical unloading are introduced into hyperelastic models independently. Hence, a hyperelastic model can be extended for both creep and unloading evaluations. A typical rubber product and a dumbbell specimen were selected to validate the proposed approaches. It has been demonstrated that the predictions offered by the new models are consistent with the experimental data. In addition, a loading procedure using the same final value, with and without involving unloading, prior to a creep test can produce different results. The proposed approach can capture this phenomenon which was observed in the literature. The proposed approach can also be easily incorporated into commercial finite element software (e.g., Abaqus). It is demonstrated that the proposed method may be used for anti-vibration products at an appropriate design stage.

1. Introduction

Rubber springs are widely used in industry as anti-vibration components and typically provide many years of service. When a constant stress is imposed on a rubber spring, the resulting deformation increases continuously with time; this is known as creep, drift [1] or strain relaxation [2].

The creep of vulcanized rubbers is usually classified into two processes: primary creep, which is due to the physical rearrangement of molecular positions in the final stages of the approach to equilibrium; and secondary creep, which is chiefly due to oxidization. Primary creep dominates at the beginning of the loading time, while secondary creep becomes evident and eventually dominates after a significant length of time (e.g. in years) has elapsed [1,3]. Sometimes, a third or tertiary stage is referred to as creep failure occurring at an increasing rate and terminating in fracture [4]. It is known that the relatively poor creep resistance of rubbers is unfavourable to their application as structural materials. Creep of rubbers easily exceeds structural limitations, and fracture due to creep often occurs due to long-term loading. Because long-term creep tests are very expensive and time-consuming, many accelerated methods for creep tests on polymers have been developed to predict long-term creep behaviour based on short-term experiments. Based on the fact that higher stresses increase the creep or relaxation rate of viscoelastic materials, which is similar to the effect of higher temperatures, several time–temperature–stress superposition principles (TTSSP) have been proposed using Boltzmann's superposition principle and its modified forms; these principles have predicted creep for longer periods based on shorter-period tests [5–8]. Similarly, Starkova et al. [9] applied time–stress superposition (TSS) to construct smooth master curves by considering the nonlinearity of viscoelastic behaviour and by introducing a stress reduction function into an exponential creep kernel. Gupta and Raghavan [10] and Achereiner et al. [11] used the time-temperature-superposition principle (TTSP) to obtain master creep curves for a time period beyond the experimental time window. In Kolarik and Pegoretti [12,13], a concept was adopted so that the non-linearity of tensile creep is primarily caused by the strain-induced increment of the free volume. Consequently, the traditional stress–strain linearity range can be viewed as an artificial limit related to the limited accuracy of

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http://dx.doi.org/10.1016/j.polymertesting.2015.07.009
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measurements at low stresses and strains. The internal time-tensile compliance superposition of non-linear creep data was applied to construct creep master curves, which corresponded to a pseudo-iso-free-volume state; a Boltzmann-like superposition principle for multistep nonlinear tensile creep was used with three types of polypropylene. For alternative methods to the Boltzmann superposition principle, statistical analyses have been performed for creep prediction. Gnip et al. [14] built long-term creep curves using the data obtained in direct experiments with a duration of 122–183 and 1100–1432 days, and demonstrated that creep compliance could be approximated by power and exponential regression equations.

A number of factors affecting polymer creep have been investigated in previous studies. To ensure that the equipment settings were correct for the creep experiment, some improvements were made. Nitta and Maeda [15], for example, designed a creep apparatus in which the external load was controlled by the transient data of the cross-sectional area of the deformed specimen to make sure that a constant stress level was maintained. Tomlins et al. [16] obtained tensile creep data for vinyl chloride at a number of temperatures ranging from 21.5 to 58 °C. It was shown that neither the ageing rate nor the shape of the distribution of retardation times was affected by temperature. Further studies (e.g., Dean [17]) found that errors in long-term properties derived from the application of TTS could arise unless changes in creep behaviour caused by physical ageing were considered. Printer et al. [18] found that times to failure increase continuously with the age of the solutions on the degradation of the surface's active environment. Creep failure could also be predicted based on a thermally activated rate process where the creep rate reaches its minimum value [19]. The effect of temperature may also be important and is probably different for secondary creep. Additionally, oxidation is probably diffusion-controlled at certain temperatures. Attempts to study long-term creep behaviour by accelerated tests on small samples require, therefore, careful study to avoid false conclusions [3]. In parallel with above methods mentioned, viscoelasticity models were also developed to predict polymer creep. The theoretical background of the framework of viscoelasticity for polymer creep behaviour has been well documented [4,20–22].

Mechanical loading–unloading processes strongly affect rubber's creep behaviour. Drozdov [23] demonstrated that the loading process significantly influences rubber creep due to unloading. In his experiments, specimens were subjected to stretching up to various maximum strains followed by retraction to various smaller strains, creep tests were then performed and it was found that the creep curves were strongly affected by the unloading increments. Additionally, Khan and Yeakle [24] found that a loading history prior to the creep test consisting of loading to a maximum stress or strain followed by partial unloading to a target stress could significantly modify strain–time behaviour, which was consistent with the findings from Omans and Nagode [25]. It was established that unloading the specimen between two different stress levels had a substantial influence on creep results.

For mechanical loadings on anti-vibration components, rubbers are widely modelled as hyperelastic materials based on strain energy density [22,26,27] (e.g., the Mooney-Rivlin, Ogden and Yeoh models). These models are generally used to predict the loading response and fatigue life of rubber products used in industry (Luo et al. [28–34] and Zerrin and Fatemi [35]). However, these models can only be used for the loading portion of a loading–unloading cycle. To include unloading effects on the hyperelastic models, a single additional (i.e., softening) variable was added to model a complete loading–unloading process (Ogden and Roxburgh [36,37] and Luo et al. [38–40]). Additionally, two more variables were used in the energy function so that it captured the observed softening and residual strain response (Dorfmann and Ogden [41] and Luo et al. [42,43]). Despite the progress described above, current hyperelastic models cannot be used for creep response because these models are not referenced to the elapsed loading time.

Rubber creep as a time dependent deformation is one of the critical factors when considering engineering design and applications for rubber springs. An important requirement is to control a rubber product to not exceed its structural limitation and to avoid early failure due to creep over its required service life. In industry, reliable prediction of creep for rubber structures over their entire service lives is essential at the design stage. For many anti-vibration applications, rubber components must be checked at specified time periods for safety issues; for example, rubber suspension systems used in rail vehicles must be inspected and adjusted during their operating service life.

In this study, we introduce a damage concept into hyperelastic models to predict creep for rubber materials. In addition, a dissipating function is added to capture the observed stress softening response for unloading during a cyclic loading process. Consequently, hyperelastic models based on strain energy potential can be extended to predict rubber unloading and creep performance.

The remainder of this article is outlined as follows. Experimental results for a rubber spring and a concept for rebound energy as well as its measurement are presented in Section 2. The hyperelastic models including unloading and creep effects with necessary equations are contained in Section 3. Next, simulation and validation results are demonstrated in Section 4. Finally, findings from this investigation are summarized in Section 5.

2. Experiment on rubber anti-vibration product

In engineering design and applications, rubber structures are usually loaded under compression and shear conditions. A typical industrial product (Metacone type spring) was selected for experiment and validation. Two experiments (i.e., mechanical loading and creep loading) were performed. The rubber compound used was a filled synthetic high cis polyisoprene with a shear modulus 1.2 MPa.

2.1. Mechanical loading experiment

Mechanical loading was performed before each creep experiment began to ensure that the product was compliant with real engineering applications and had the correct material properties. This component, which measured maximum 230 mm in diameter

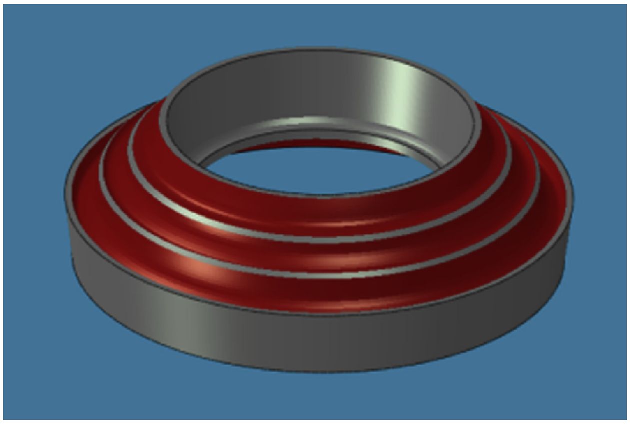

Fig. 1. A Metacone spring.