Polymer Testing 52 (2016) 246–253

Contents lists available at ScienceDirect

Polymer Testing

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

Material Behaviour

Numerical prediction and experiment on rubber creep and stress relaxation using time-dependent hyperelastic approach

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
11 March 2016
Accepted 15 March 2016
Available online 29 April 2016

Keywords:
Rubber
Polymer
Creep
Stress relaxation
Time dependency
Hyperelasticity

ABSTRACT

Rubber is an excellent material for anti-vibration components in industry with a long term service. However, its time-dependent behaviour is undesirable in engineering applications. This article presents an engineering approach to evaluate the time-dependent responses, i.e., creep and stress relaxation, for rubber anti-vibration components. A time-dependent damage function was introduced into hyperelastic models. This function can be expressed in three forms. A typical rubber product and a dumbbell specimen were selected to validate the proposed approach. It has been shown that the predictions obtained from this method are consistent with the experimental data. It has also been established that the time-dependent response of industrial products can be predicted based on the responses from simple specimens, e.g., dumbbell specimen. In addition, it is possible to obtain a creep response based on a relaxation response and vice versa (by changing K value only) using the proposed approach, which has also been observed experimentally in the literature. The proposed function can also be easily incorporated into commercial finite element software (e.g., Abaqus). It has been demonstrated that the proposed method may be used at an appropriate design stage. Finally, the readers can select one of the three forms presented to perform assessments on the time-dependent responses evaluations for rubber anti-vibration products.

1. Introduction

Rubber material is an excellent option for anti-vibration components in industry with a long term service. However, its time-dependent behaviour is an undesirable issue in engineering applications. When a constant load is applied to a rubber spring, the deflection increases with time; this is known as creep [1,2]. On the other hand, when a constant deformation is held on a rubber spring, the stresses set up gradually decrease with time. This phenomenon is known as stress relaxation [2,3]. The time-dependent effect is one of the critical factors when considering engineering design and applications on anti-vibration systems. For example, an important requirement of rail vehicle design is to control rubber anti-vibration components not to exceed its structural limitation due to the creep effect and to avoid early failure over its service life required.

As long-term creep tests in real industrial products are very expensive and time-consuming, many accelerated methods for creep tests on polymers have been developed in order to predict the long-term creep response. Several methods based on TTSSP (time temperature stress superposition principles) were proposed using Boltzmann superposition principle and its modified forms. They predicted long-term creep based on the shorter period tests [4–7]. Similarly, Starkova et al. [8] applied TSS (time–stress superposition) to construct master curves by taking both nonlinearity of viscoelastic behaviour and by introducing a stress reduction function for creep calculation. Gupta and Raghavan [9], and Achereiner et al. [10] employed TTSP (time temperature superposition principle) to obtain master creep curves for a long-term period. A tensile creep curve was generated from a strain using an increment of a free volume by Kolarik and Pegoretti [11,12]. They utilized the Boltzmann-like superposition principle for three types of polypropylene. For alternative methods to the Boltzmann superposition principle, statistical evaluations have been carried out for creep prediction. Gnip et al. [13] built long-term creep curves using the short-term experiments and demonstrated that both exponential

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http://dx.doi.org/10.1016/j.polymertesting.2016.03.026

and power equations could be used for the creep compliance.

A number of factors, affecting polymer creep and stress relaxation, were investigated. To ensure that the equipment settings were correct for experiments, some improvements were made by Nitta and Maeda [14] who developed apparatus to maintain a correct creep load using the input data from the cross-sectional area of the specimen to keep constant stress values. Tomlins et al. [15] obtained tensile creep data at a number of temperature ranges. Their experimental data indicated that temperature had no influence on both ageing rate and the distribution shape of retardation times. Further studies from Dean [16] established that longer-term creep errors generated from short-term experiment could increase using TTS (time-temperature superposition) method if the influence from physical ageing was not properly considered. Printer et al. [17] demonstrated that the ageing of the solutions acting on the specimen's surface could delay the creep failure. The creep failure could also be obtained using a minimum value of the creep rate based on a thermal process [18]. Cautions should be taken when consider the effect of the test temperature. Otherwise, incorrect conclusions could be drawn for a long-term time-dependent response based on accelerated short-term experiments using small samples [1].

Viscoelasticity models were developed to predict the rubber creep and relaxation. Theories of the framework of viscoelasticity for polymer response were well elaborated [19–22]. Recently, Oman and Nagode [23] recognized that both creep and relaxation were from the same viscoelastic mechanism and one could be predicted based on the others' results. Fernandes and Focatiis [24] observed that the stress relaxation was independent of both the applied strain and of the previous maximum strain after several loading-unloading cycles and explained the result using a viscoelastic model.

In contrast to viscoelastic studies on these time-dependent responses, a time-dependent hyperelastic approach is proposed to investigate both creep and relaxation performance of rubber material. We assume that the strain energy potential or strain energy density stored in loaded rubber material changes with both strain and elapsed time. Luo et al. [25–29] have used the rebound energy approach to predict the Mullins effect [30] based on a damage concept. Furthermore, this concept has been combined with a time variable to predict rubber creep performance [31–33]. As both creep and relaxation are time-dependent results, this time-dependent hyperelastic approach, in addition to predicting creep response, could be extended to investigate stress relaxation and to evaluate their relationships.

The remainder of this article is outlined as follows. Experimental results for a simple standard dumbbell specimen and an industrial product are demonstrated in Section 2. Next, the constitutive models for this approach with necessary equations are contained in Section 3, followed by the simulation and validation results in Section 4. Finally, findings and discussions on this investigation are presented in Section 5.

2. Experiment

Simple standard rubber specimens are usually utilized to obtain basic material properties. On the other hand, rubber components are complex parts and are usually loaded under compression and shear conditions in engineering applications. To cover the characteristics from both sides, two types of rubber specimens were selected. The first one was a type of simple standard dumbbell specimen (BS ISO 37:2011) [34], shown in Fig. 1. The other one was a typical industrial anti-vibration product (a seven layers circular mount), shown in Fig. 2. For both components, initial mechanical loadings were performed followed by a creep loading and a stress relaxation loading.

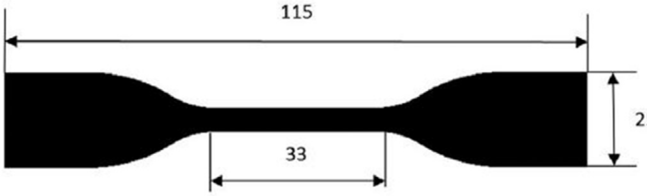

Fig. 1. The dumbbell specimen and main dimensions.

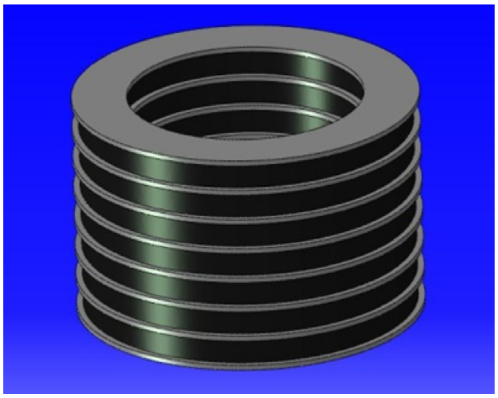

Fig. 2. The 7 layers circular spring. (a) Experimental load-deflection history of the dumbbell specimen. (b) Experimental creep history of the dumbbell specimen. (c) Experimental relaxation history of the dumbbell specimen.

2.1. Experiment on dumbbell specimen

The nominal thickness of the dumbbell specimen was 2 mm. The rubber compound was synthetic high cis polyisoprene with shear modulus 0.6 MPa. Consecutive seven tensile loading cycles were applied to the specimen to remove the Mullins effect. The maximum load is approximately 30 N. Fig. 3(a) shows the load-deflection result of this rubber specimen up to approximately 105 mm deformation after the seven loading cycles. The shape of the load-deflection curve is a typical loading response (S form) from rubber material. This loading experiment was also served as a benchmark for material properties used for later simulation (see “simulation with validation” section).

A creep experiment was followed after the initial mechanical loading procedure. The ambient temperature was maintained at 23° C. A constant load of approximately 30 N in tension was applied to the dumbbell specimen. The creep experiment lasted 1800 s. The creep history is plotted in Fig. 3(b). In the beginning, the slope of the curve was maximum in the creep response. After that period, the gradient of the creep curve changed gradually to a lower value as time progressed. The maximum value of the creep reached approximately 4.5% at 1800 s. Another time-dependent experiment, i.e., a stress relaxation experiment, was also performed in the laboratory. An approximately 105 mm constant deflection in tension was held over 1800 s. The response in load reduction with a maximum value of approximately 15% was recorded, as shown in Fig. 3(c). Comparing Fig. 3(c) with Fig. 3(b), (c) is like a reversed image of Fig. 3(b). It is indicated that the creep and the stress relaxation have similar characteristics. This phenomenon will be discussed further in section “Discussions”.

2.2. Experiment on circular mount

This rubber spring in Fig. 2, which measured maximum 260 mm in diameter and 170 mm in height, is used in vehicle mounts. Seven