Composite Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Composite Structures

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

Temperature dependent dynamic mechanical properties of Magnetorheological elastomers: Experiment and modeling

Yanxiang Wan[a,*], Yeping Xiong[a], Shengming Zhang[b]

[a] University of Southampton, UK
[b] Lloyd's Register, UK

A R T I C L E I N F O

Keywords:
Magnetorheological elastomer
Temperature effect
Dynamic mechanical analysis test
Viscoelasic modeling
Master curve

A B S T R A C T

Magnetorheological elastomers (MREs) are a group of smart composite materials which are composed of magnetic particles dispersed in an elastomeric matrix. The controllable dynamic properties of these materials rely on many factors, in which temperature is a significant influencing factor requiring further investigations. In this paper, the dynamic mechanical analysis (DMA) tests have been performed to determine the viscoelastic properties of MREs with different test conditions. Based on the experiment results, the dynamic properties of MREs is modelled respectively by fractional Maxwell model (FMM) and generalized Maxwell model (GMM), and then the master curve of complex modulus is constructed using the time–temperature superposition (TTS) principle. The results show that the transition behavior of the silicon rubber based MRE samples under uniaxial compression occurs at about 50 °C. The storage modulus exhibits two different trends with the temperature variation: It first decreases rapidly and then increases slightly or maintains a stable value with increasing temperature.

1. Introduction

Magnetorheological elastomers (MREs) are a group of smart composite materials which are composed of micron-sized ferromagnetic particles dispersed in an elastomeric matrix. The spatial distribution of the ferromagnetic powders in the elastomer can be either homogenous (isotropic) in the absence of external magnetic field or chain-like columnar (anisotropic) in the presence of external magnetic field during curing process. The viscoelastic properties of MREs normally varied instantly and reversibly because of the dipole interaction in the presence of magnetic field. In most cases, anisotropic MREs appear to be more sensitive to the applied magnetic field with slightly larger magnetorheological (MR) effect than isotropic MREs [1,2]. The material modulus rises with the increasing magnetic flux intensity until the magnetic saturation. The higher volume fraction of magnetic particles produces a higher MR effect, with an optimal volume fraction around 30% leading to the maximum of both MR effect and the long-term stability of MREs [3–5].

The controllable dynamic properties of MREs have attracted more and more attentions, gaining wide application prospects in dynamic vibration control, such as MRE based active-adaptive tuned vibration absorber and semi-active/passive variable stiffness and damping isolator [6–8]. MRE based devices are often operated in the wide range of load frequency and amplitude, magnetic field, and temperature. With respect to design and practical application, it is essential to investigate and model the dependent dynamic properties of MREs under various loading conditions. Among these influence factors, the temperature is one of most important factors and needs to be studied. The temperature changes in MREs and MRE based devices may be caused by the environmental temperature variations or/and internal temperature rise due to energy dissipation. The shear storage modulus of *cis*-polybutadiene (BR) rubber based MRE samples decreased linearly with the increasing test temperature, while the shear storage modulus of natural rubber (NR) based MRE samples first increased with the increment of temperature and then decreased when the testing temperature is elevated [9]. The internal temperature of the MRE isolator was generated by the electromagnetic coil and had a remarkable effect on the stiffness and damping of the MRE isolator [10].

In small amplitude excitation, the linear viscoelastic model may applied to describe the elastic and rheological properties of MREs under harmonic loads. Li et al. [11] proposed a four-parameter linear viscoelastic model by connecting the classical three-parameter standard viscoelastic solid model in parallel with a nonlinear spring representing the magnetic field induced stiffness. Zhu et al. [12] presented another type of four-parameter linear viscoelastic model which is composed of the fractional Kelvin-Voigt model, a dashpot, and a magnetic field

* Corresponding author.
E-mail addresses: yw8g12@soton.ac.uk (Y. Wan), Y.Xiong@soton.ac.uk (Y. Xiong), Shengming.Zhang@lr.org (S. Zhang).

https://doi.org/10.1016/j.compstruct.2018.04.010
Received 11 January 2018; Received in revised form 12 March 2018; Accepted 2 April 2018
0263-8223/

dependent spring in parallel. Norouzi et al. [13] developed a modified Kelvin-Voigt model to describe the nonlinear relationships between shear stress and shear strain of MREs under external magnetic field. The magnetic field dependent parameters in the proposed model were expressed by polynomial functions.

In order to investigate the effect of temperature on dynamic mechanical properties of MREs, the DMA tests have been performed for anisotropic MRE samples expose to vary temperatures and magnetic fields. Based on the achieved experiment results, the FMM and GMM are presented to describe the linear viscoelastic properties of MREs under uniaxial compression, after which the master curve of complex modulus is constructed using the time–temperature superposition principle. The model parameters are identified by minimizing the difference between the experimental data and predicted results of both storage modulus and loss modulus. The quality of the curve fit is discussed in detail by statistical analysis.

2. Experimental setup

The anisotropic MRE samples consisted of the silicone rubber (Wacker Chemie AG, Germany) and micron-sized iron particles (Sigma-Aldrich, US). The diameter of iron particles is 5–9 μm ≥99.5%. The synthesis of the MRE samples consist of three steps: Firstly, Elastosil A and Elastosil B were dispensed in a volume fraction of 10:1 and then the iron powders in a volume fraction of 30% were added. Secondly, the mixture was well blended and placed in a vacuum chamber for 20 min to reduce the air bubbles trapped inside the material during mixing progress. Finally, the mixture was put into the aluminum moulds and cured for 20 h under room temperature with an external magnetic field of about 300 mT produced by a pair of the cylindrical grade N42 neodymium permanent magnets (E-magnets, UK).

The DMA tests of the MRE samples were performed according to the BS ISO 4664-1:2011 by using Instron test machine (E1000 Electro plus) in the Transport Systems Research Laboratory. The influence of external magnetic field and test temperature on the dynamic properties of the MRE samples was achieved by a self-manufactured oven and a pair of permanent magnets as shown in Fig. 1. The oven consists of a thermo-detector, the aluminum shell with thermal insulation material, and the heating wire and its control panel. During DMA test, the MRE specimen temperature was monitored and controlled within the desired temperature range. The magnetic field was produced by pairs of the cylindrical grade N42 neodymium permanent magnets and the uniaxial harmonic compression strain was applied and controlled by Instron test machine (E1000 Electro plus).

The material properties of the samples were measured through DMA tests in a frequency range from 0 to 60 Hz, strain amplitudes from 0 to 1.5%, the temperatures from room temperature (about 25 °C) till 60 °C, and magnetic field intensities from 0 to 500 mT. Each set of tests was carried out with three pairs of MRE samples independently and every test was repeated twice for each pair of MRE samples.

3. Viscoelastic models

The linear viscoelastic relationships between stress and strain can be described by the fractional Maxwell element which consists of a spring and a springpot in series. The constitutive equation of the fractional Maxwell element can be expressed in the following form [14].

$$\sigma + \tau^{\alpha}\frac{d^{\alpha}\sigma}{dt^{\alpha}} = E\tau^{\alpha}\frac{d^{\alpha}\varepsilon}{dt^{\alpha}} \quad 0 < \alpha < 1 \tag{1}$$

in which E is the spring stiffness, η is the springpot viscosity, $\tau = \eta/E$ denotes relaxation time of fractional Maxwell element, and α is a fractional derivative. The springpot changes to a linear spring for the extreme case of $\alpha = 0$, and leads to the dashpot in the extreme case of $\alpha = 1$.

The complex modulus of the fractional Maxwell element can be expressed as follow by turning Eq. (1) into the frequency domain.

$$E^{*}(i\omega) = \frac{\sigma_0^{*}(i\omega)}{\varepsilon_0^{*}(i\omega)} = \frac{E(i\omega\tau)^{\alpha}}{1 + (i\omega\tau)^{\alpha}} \tag{2}$$

In order to obtain a good description of the linear viscoelastic behavior in a wide range of frequencies and time scales, the fractional Maxwell model (FMM) is often adopted which comprised of a spring and several fractional Maxwell elements in parallel as shown in Fig. 2(a). The complex modulus of the FMM can be obtained by summing the complex modulus of a spring and each fractional Maxwell element defined in Eq. (2).

$$E^{*}(i\omega) = E'(\omega) + iE''(\omega) \tag{3}$$

$$E'(\omega) = E_0 + \sum_{j=1}^{m} E_j\frac{(\omega\tau_j)^{2\alpha_j} + (\omega\tau_j)\cos\frac{\alpha_j\pi}{2}}{1 + (\omega\tau_j)^{2\alpha_j} + 2(\omega\tau_j)^{\alpha_j}\cos\frac{\alpha_j\pi}{2}} \tag{4}$$

$$E''(\omega) = \sum_{j=1}^{m}\frac{E_j(\omega\tau_j)^{\alpha_j}\sin\frac{\alpha_j\pi}{2}}{1 + (\omega\tau_j)^{2\alpha_j} + 2(\omega\tau_j)^{\alpha_j}\cos\frac{\alpha_j\pi}{2}} \tag{5}$$

where m is the number of fractional Maxwell elements, the model parameters: E_0, E_j, τ_j, and α_j are dependent on magnetic field and temperature, which can be identified according to the DMA test results.

For the extreme case of $\alpha_j = 1$, the fractional Maxwell elements in FMM in Fig. 2(a) are replaced by the Maxwell elements in the generalized Maxwell model (GMM) as shown in Fig. 2(b). The storage modulus and loss modulus of the GMM in Fig. 2(b) can be obtained by recalling Eqs. (4) and (5) in the extreme case of $\alpha_j = 1$.

$$E'(\omega) = E_0 + \sum_{j=1}^{m} E_j\frac{(\omega\tau_j)^2}{1 + (\omega\tau_j)^2} \tag{6}$$

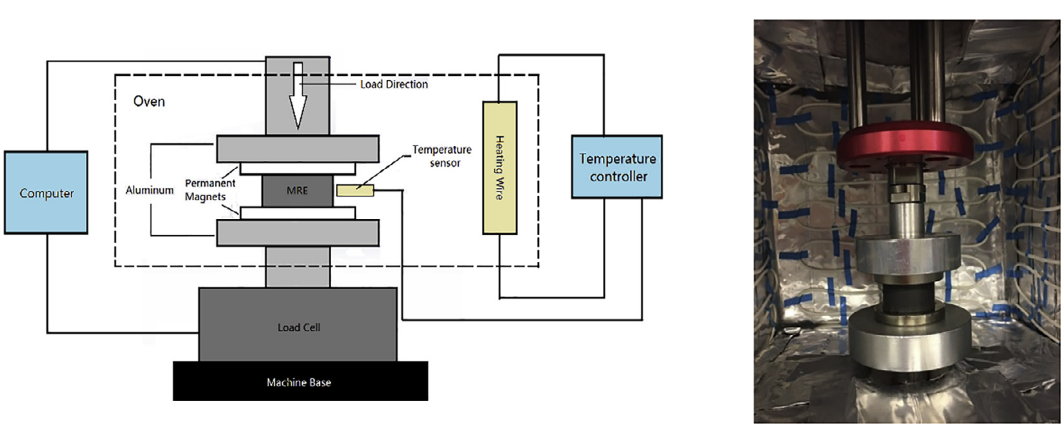

Fig. 1. Experiment setup for DMA test of MRE sample under uniaxial compression.