Dynamic Characterization and Modeling of Magneto-Rheological Elastomers Under Compressive Loadings

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Abstract. The primary goal of this paper is to characterize and model the compression properties of Magneto-Rheological Elastomers (MREs). MRE samples were fabricated by curing a two component elastomer resin with 30 % content of 10 µm sized iron particles by volume. In order to vary the magnetic field during compressive testing, a test fixture was designed and fabricated in which two permanent magnets could be variably positioned on either side of the specimen. By changing the distance between the magnets, the fixture allowed for varying the magnetic field that passes uniformly through the sample. Using this test setup and a dynamic test frame, a series of compression tests of MRE samples was performed by varying the magnetic field and frequency of loading. The results show the MR effect (percent increase in the materials “stiffness”) increases as the magnetic field increases and loading frequency increases within the range of the magnetic field and input frequency considered in this study. Furthermore, a phenomenological model was developed to capture the dynamic behaviours of the MREs under compression loadings.

1. Introduction

Magneto-Rheological Elastomers (MREs) are a class of smart materials whose elastic modulus or stiffness can be varied depending on the magnitude of an applied magnetic field. As controllable stiffness elements, MREs can offer innovative engineering solutions to various engineering challenges. For the application of MRE materials, it is essential to understand and model the dynamic characteristics of the materials under various conditions. A number of researchers have investigated the shear properties of MRE materials over the past decade [1]. However, limited research has been performed in characterizing the compression properties of MREs [2]. Compression-tension type combined loadings are realistic loading conditions for various mechanical and structural systems, such as base isolation mounts, and it is imperative that the dynamic behavior of MREs be well understood. Therefore, this study investigates the dynamic characteristics of Magneto-Rheological Elastomers (MREs) under compressive loadings. In particular, it focuses on the stress-strain relationship associated with an MRE’s deformation under various input loading conditions. These characteristics can serve as key merits of performance for MRE-based actuators.
2. MRE Sample Preparation

MRE samples were fabricated by curing a two component elastomer (silicone rubber) resin with 30% content of 10 µm sized iron particles by volume. The shape and dimensions of the samples followed the ASTM standard for compression testing. The cylindrical shape samples are 9.5 mm (3/8 in.) high and 19 mm (¾ in.) in diameter. The silicone rubber contributes elastic properties to the cured sample. The iron particles allow the samples to be influenced by application of a magnetic field. Figure 1 (a) shows an MRE sample with the mold, and an SEM image of the cross section of the sample, which shows the uniformly distributed iron particles in the sample (Figure 1(b)).

![Figure 1](image1.png)

(a) MRE sample and mold (b) SEM image of an MRE sample

3. Experimental Setup

For dynamic compression testing of MREs, it is tricky to change the magnetic field in the axial direction and measure the mechanical properties (i.e., stress) in the same direction. In this study, in order to vary the magnetic field during compressive testing, a high-stiffness fixture was designed and fabricated in which two permanent high-strength magnets could be variably positioned on either side of the specimen. By changing the distance between the magnets, the fixture allowed for varying the magnetic field that passes uniformly through the sample. Figure 2 (a) shows the test fixture installed in a material testing frame. Using this test setup and a dynamic test frame, a series of compression tests of MRE samples was performed by varying the magnetic field and frequency of loading.

![Figure 2](image2.png)

(a) Compression Experimental Setup, (b) Contour Plot of Magnetic Fields (c) Magnetic Field Variation Across the Specimen at the Center (Transverse Direction)
The selection of the magnet was done by using Finite Element Method Magnetics (FEMM). Figure 2 (b) shows the contour plot of magnetic fields when two magnets are the distance of the MRE sample’s height away. In order to ensure the uniformity of the magnetic fields across the sample, a magnetic field distribution is measured over the width of the sample, across the center. As shown in Figure 2 (c), the strength of the magnetic field only dropped by about 8% from the center to the edges, which is an acceptable amount of variation. Based on the FEMM analysis, a 38.1 mm (1.5 in.) diameter, N52 magnetic was chosen which is rated at 0.6985 Tesla at the surface.

4. Experimental Results
In all compression tests, the MRE samples were axially pre-compressed by 5% and cycled between +/- 5% strain from the pre-compressed state. To investigate the effect of a varying magnetic field, the magnitude of the field was varied from 0 T to 0.6 T at increments of 0.1 T. Moreover, the input frequency was varied between 0.1 Hz and 1 Hz at each value of the magnetic field to study the effects of loading frequency.

Figure 3 (a) shows the stress-strain variation of an MRE sample with varying magnetic fields at 0.1 Hz harmonic loading frequency. It shows that the stress increases as the magnetic field increases. Moreover, the area of the loop increases as the magnetic field increases, indicating the damping of the material also increases.

In order to quantitatively characterize the dynamic performance of MRE samples under compressive loadings, an MR effect is used, which is defined as the ratio of the maximum stress with a magnetic field to the maximum stress with the absence of a magnetic field (equation 1). It indicates the percent increase in materials stress.

\[
MR \text{ Effect} \% = \frac{\sigma_{\text{max}}B - \sigma_{\text{max}}B=0}{\sigma_{\text{max}}B=0} \times 100
\]  

(1)

Figure 3 (b) shows the MR effect variation of MRE sample with varying magnetic field at two different loading frequencies (0.1 Hz and 1 Hz). Within the loading frequencies considered in this study, the MR effect increases as the loading frequency increases. Moreover, the MR effect increases linearly at low magnetic fields (i.e. less than 0.4 T). However, the MR effects jumped from 0.5 T to 0.6 T. It is anticipated the MR effect would “exponentially” increase at higher magnetic fields before it saturates.
5. Dynamic Modeling of MREs
In order to capture the dynamic behaviour of the MREs under compressive loadings, the MRE element can be modeled using a combination of a linear damping element and a nonlinear spring element (see Figure 4 (a)). In this model, the MRE element’s force can be represented as

\[ F = c_0 \cdot \dot{x} + f_\lambda (x) \]

where \( c_0 = c_{0a} + c_{0b} \cdot B \), \( f_\lambda (x) = k_0 \cdot x^2 + k_1 \cdot x \cdot \lambda \), \( k_0 = k_{0a} + k_{0b} \cdot B \), \( k_1 = k_{1a} + k_{1b} \cdot B \), and \( B \) = magnetic flux density.

To demonstrate an example of modelling, experimental results for the 0.1Hz loading frequency with \( B = 0.1 \) T are compared with the results of the numerical modeling. Figure 4 (b) and (c) compares the time history of the stress, and the stress-strain behaviour of the MRE with the simulation models, respectively. The values of the model parameters used in the simulation are summarised in Table 1.

![Figure 4.](image-url)

(a) MRE element model (b) Comparison of the Stress Time History and Model Simulation (c) Comparison of the Stress-Strain and Model Simulation

| Parameters | Values |
|------------|--------|
| \( c_{0a} \) | 0.8342 |
| \( c_{0b} \) | 0.2670 |
| \( k_{0a} \) | 4.1072 |
| \( k_{0b} \) | 1.2435 |
| \( k_{1a} \) | 0.1677 |
| \( k_{1b} \) | 0.0002 |

6. Conclusions
This study focused on the dynamic characteristics of Magneto-Rheological Elastomers (MREs) under compressive loadings. Cylindrical shape MRE samples were fabricated by curing silicon based rubber resin with the 30 % content of 10 µm iron powers by volume. A test fixture was designed such that two permanent magnets uniformly pass the magnetic fields through the sample. Using this setup, a series of compression tests of MRE samples was performed by varying the magnetic field and frequency of loading. The results show that the mechanical stress of the MRE sample increases nearly 40 % with 0.6 T at 1 Hz loading frequency. Moreover, a phenomenological model that captures their dynamic response characteristics is developed.

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