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The evaluation of the effect of strain limits on the physical properties of Magnetorheological Elastomers subjected to uniaxial and biaxial cyclic testing

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ABSTRACT

Magnetorheological Elastomers (MREs) are "smart" materials whose physical properties are altered by the application of magnetic fields. In a previous study by the authors, variations in the physical properties of MREs have been evaluated when subjected to a range of magnetic field strengths for both uniaxial and biaxial cyclic tests. By applying the same magnetic field to similar samples, this paper investigates the effect of both the upper strain limit and the strain amplitude on the properties of MREs subjected to cyclic fatigue testing. As the magnetorheological (MR) effect is due to the dipole-dipole interactions of the magnetic particles in an MRE, it is expected that the larger the upper strain limit, the lower the overall MR effect will be. This is investigated by varying the upper strain limit between tests while keeping the magnetic field applied during testing at selected cycles constant between tests. To investigate if the MR effect is only dependent on the upper strain limit and the magnitude of the applied magnetic field during cyclic testing, the tests are repeated with the same upper strain limits and applied fields but with reduced strain amplitude.

1. Introduction

Magnetorheological Elastomers (MREs) are classified as smart materials that undergo changes in their physical properties which are observed as an increase in modulus when a magnetic field is applied to an MRE [1]. The increase in the modulus (Youngs modulus) is caused by the ferromagnetic particles which are added to the elastomer during the curing process, tending to align with the applied magnetic field. The alignment occurs due to the applied field causing dipole-dipole interactions between the particles which move to screen each other from the field and adopt a minimum energy configuration [2].

MREs can be described as either isotropic or anisotropic depending on whether a magnetic field was applied during the curing process. Isotropic MREs have an homogeneous distribution of magnetic particles and are cured without the presence of a magnetic field, whereas anisotropic MREs contain aligned particle chains formed by the alignment of the magnetic particles with an external magnetic field applied during the curing process [3]. While anisotropic MREs provide greater MR properties when the magnetic field is applied parallel to the particle chains [3], the presence of the magnetic field during the curing process introduces an extra variable into the experimental results obtained from cyclic testing. For this reason isotropic MRE samples were used in the tests to ensure that any measured changes in their properties can be fully attributed to changes in test conditions and not changes in the sample particle distribution due to variations in the magnetic field applied during the curing process [4].

While the influence of the applied magnetic field on the MR effect of MREs has been presented in many reports [1–3,5–11] there is a lack of comparable data for similar MRE samples tested under different strain conditions using the same applied magnetic fields. In particular, experimental results do not exist for MREs cycled at high strain for both uniaxial and biaxial conditions [4,11].

The focus of this research is to investigate the influence of strain limits on the MR effect for MREs under cyclic uniaxial and biaxial loading. This is achieved by testing MREs under both uniaxial and biaxial loading conditions with similar strain limits and with the same applied magnetic field. The tests were repeated with the same maximum strain but lower strain amplitudes. As the effective strain in biaxial tension for a specific strain limit is much higher than in the uniaxial case, a direct comparison of the properties (modulus) is impossible but trends can be compared [4].

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As the MR effect is due to the interaction of magnetic particles [2] and this interaction is inversely proportional to the square of the distance between the particles [12], it would be expected that the upper or maximum strain rather than the strain amplitude would predominantly govern the MR effect with respect to applied strain conditions.

2. Apparatus and materials

2.1. Magnetorheological Elastomers

The MRE samples used in all tests reported in this paper are carbon black filled (1.65% volume per volume) natural rubber (NR) based isotropic MREs with 18.3% (volume per volume) iron particles from the same sample batch used to investigate the effect of magnetic flux density on the MR effect in an earlier study [4]. A number of previous studies by other researchers [7–9], focused on natural rubber based MREs. NR was chosen due to its superior physical (modulus) and a fatigue property, which is important for isolating the MR effect as with softer rubbers, such as silicone or urethane, the change from cycle to cycle may be attributable to fatigue effects in the matrix material [4,7–9].

The test method is described in the previous study by the authors [4] with the same sample dimension for both the uniaxial 70 mm × 20 mm × 1 mm strain applied along the 70 mm dimension and biaxial tests 1 mm thickness 50 mm diameter discs being used.

2.2. The magnetic field

Flux density values generated by the electromagnetic array are given for the centre point of the array without the presence of a magnetic sample. For the uniaxial tests this value has a maximum deviation of 15% of the stated value at a displacement of 20 mm from the centre point. For the biaxial bubble inflation tests, the variation in the flux density over the area in which the vision system records the stress strain data is 5% of the stated flux density value. The deviations reported are inevitably a characteristic of magnetic fields in air due to the $1/r^2$ relationship [13]. All magnetic fields applied in this study to both the uniaxial and biaxial tests were generated by the same electromagnetic array used and outlined in a previous study by the authors [4]. The electromagnetic array consisted of 4 1500 turn electromagnets and iscabable of supplying a flux density of 200 mT at its centre point and field maps are provided in a previous study [4].

3. Testing methods

3.1. Uniaxial tensile fatigue tests

Uniaxial tensile fatigue tests were performed on the isotropic NR MREs with the strain and magnetic flux density applied in the same directions as the previous study by the same authors which investigated the MR response of the material samples of 70 mm × 20 mm × 1 mm under different applied magnetic flux densities [4].

As with the previous investigation into the effect of the applied magnetic flux density on the overall MR effect [4], the magnetic fields where cycled between the off and on positions every 50 cycles starting with no flux applied for the first 50 cycles then flux applied for the next 50 consecutive cycles this was repeated until the test ended with the flux density applied for cycles 450–500. However, the flux densities applied in all uniaxial fatigue tests in this paper were constant between tests with the applied strain conditions being varied for each testAll tests carried out were constant strain amplitude tests. The stress was calculated as true stress from the load cell output. $\sigma_{true} = \frac{F\lambda}{A}$ where σ_{true} is the true (Cauchy) stress, F is the force on the load cell, A is the initial cross sectional area of the sample, and λ is the stretch ratio (strain + 1). All modulus values reported in this study are for $E_{true} = \frac{\sigma_{true}}{\varepsilon}$ where ε is the strain.

3.2. Equi-biaxial bubble inflation tests

The bubble inflation tests were carried out on the DYNAMET equibiaxial bubble inflation test machine developed in the Dublin Institute of Technology by Murphy et al. [14,15] and further developed by Johnson et al. [16,17].

As with the uniaxial tests, the magnetic field was cycled between its on and off positions every 20 cycles at the same cycle numbers as the previous investigation (off for cycles 70–89, on for cycles 90–109) [4]. The flux density was held constant for all bubble inflation tests in this paper however, the strain conditions where varied between the different bubble inflation tests.

For the bubble inflation tests both stress (using the pressure, radius of curvature and strain) and strain are recorded directly using a vision system. Modulus is calculated in the same manner as in the uniaxial tests where $E_{true} = \frac{\sigma_{true}}{\varepsilon}$.

The focus of this study is to determine the effect of altering strain limits on the MR effect.

4. Results

4.1. Uniaxial tensile test results

All tests on MREs reported in this study were for cyclic loading between fixed strain limits (ΔL). The MR effect was calculated as the increase in the average modulus for a block of 50 cycles using the final 200 cycles of a uniaxial test. The later cycles of the test where chosen for analysis of the MR effect as the early cycles show diminishing maximum stress values due to the Mullins effect [18]. It was observed that the material properties had stabilized by the latter stages of the tests and therefore any change in properties of the material was due to the applied magnetic flux density. The error bars represent the standard error (mathematical error on the mean due to sample size). The stepped increase in modulus, visible at the 360th cycle on the red line (average modulus) on the x-axis in Fig. 1, is from 1.325 MPa to 1.413 MPa. This is an increase of approximately 6.5% in the average modulus of the 50 cycle block. This corresponds with the field being switched on at cycle 360. The blue line shows the average modulus calculated for each individual cycle and the average of these are is the red line.

The results presented in Fig. 2 are for a similar test to this shown in Fig. 1 but with higher strain amplitude applied (0.04–0.57). From the data presented in Fig. 2, the increase in the block

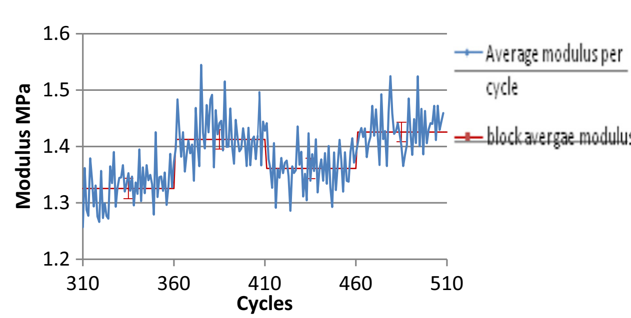

Fig. 1. Average Modulus v Cycles in uniaxial testing at a flux density of 206 mT for a strain amplitude of 0.04–0.08.