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# Magnetorheological Elastomers: Experiments and Modeling

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**Résumé** — Magnetorheological elastomers (MREs) are ferromagnetic particle impregnated elastomers whose mechanical properties are altered by the application of external magnetic fields. Due to their magnetoelastic coupling response MREs are finding an increasing number of engineering applications. The objective of this work is : (a) the experimental study of transversely isotropic MREs (i.e., the particles form chains along a certain direction) that are subjected to prestressing and arbitrary magnetic fields and (b), the phenomenological modeling of these materials using transversely isotropic energy functions.

**Mots clés** — magneto-mechanics, multi-physics, elastomers.

## 1 Introduction

Devices made of magneto-rheological elastomers (MREs) have been proposed for a number of engineering applications due to the potentially controllable nature of their mechanical properties [1]. Although there has been a substantial effort in theoretical descriptions of these types of solids (e.g. [2], [3] and [4]), there have not been many studies—to the best knowledge of the authors—dealing with the constitutive modeling and characterization of MREs. Material models for other magnetoelastic solids, however, have been presented in the literature. For example, [5] gave the first characterization of Terfenol-D. In this regard, due to the absence of adequate constitutive description for MREs, it has been difficult to quantify the extent of benefits that a MRE device could offer. The objective of this work is twofold ; first, we present experiments of iron-particle-filled elastomers subjected to prestressing and arbitrary magnetic fields and second, we carry out a phenomenological modeling of these materials.

## 2 Experiments and modeling

Experiments are carried out for MREs comprising 25% of iron particles of sizes ranging from  $0.5\mu\text{m}$  to  $5\mu\text{m}$  cured in a 0.5T magnetic field. The application of a magnetic field during the curing process leads to formation of particle chains aligned with the curing field direction. The experiments involve three different setups ; (a) uniaxial stress tests in the direction of a magnetic field which is aligned with the particle chains, (b) uniaxial stress tests in the direction of a magnetic field which is perpendicular to the particle chains and (c) simple shear tests where the particle chains are initially aligned with the applied magnetic field, as shown in Fig. 1.

The second part of this work pertains in finding an energy density function  $\hat{\Psi}$  that best fits the experiments reported above. As already pointed out, the material under investigation is a transversely isotropic composite since the iron particles form chains along a certain direction. This implies that the free energy density  $\hat{\Psi}$  should also depend on the unit vector  $\mathbf{N}$  (see Fig. 1), which defines the initial orientation of the particle chains. Thus,

$$\hat{\Psi} = \hat{\Psi}(\mathbf{C}, \mathbf{N}, \mathbf{M}), \quad \mathbf{C} = \mathbf{F}^T \bullet \mathbf{F}, \quad \mathbf{N} \bullet \mathbf{N} = 1, \quad (1)$$

where  $\mathbf{F}$  is the material's deformation gradient ( $\mathbf{F}^T$  denotes its transpose),  $\mathbf{C}$  denotes the right "Cauchy-Green" tensor and  $\mathbf{M}$  the specific magnetization. Following [4] (c.f. relations (2.42) and (2.44) in that reference), we obtain the following expressions for the total Cauchy stress  $\boldsymbol{\sigma}$  and the magnetic field  $\mathbf{h}$

$$\boldsymbol{\sigma} = \rho \left[ 2\mathbf{F} \bullet \frac{\partial \hat{\Psi}}{\partial \mathbf{C}} \bullet \mathbf{F}^T + \mu_0 (\mathbf{M}\mathbf{h} + \mathbf{h}\mathbf{M}) \right] + \mu_0 \left[ \mathbf{h}\mathbf{h} - \frac{1}{2}(\mathbf{h} \bullet \mathbf{h})\mathbf{I} \right], \quad \mu_0 \mathbf{h} = \frac{\partial \hat{\Psi}}{\partial \mathbf{M}}, \quad (2)$$

where  $\rho$  is the current material density. Note that in vacuum ( $\rho = 0$ ), the total stress is non-zero and equals the Maxwell stress  $\mu_0[\mathbf{h}\mathbf{h} - (1/2)(\mathbf{h} \cdot \mathbf{h})\mathbf{I}]$ .

Theoretical predictions, based on the energy density of equation (1) are compared to experimental results in the case of a simple shear test, shown in the bottom of Fig. 1.

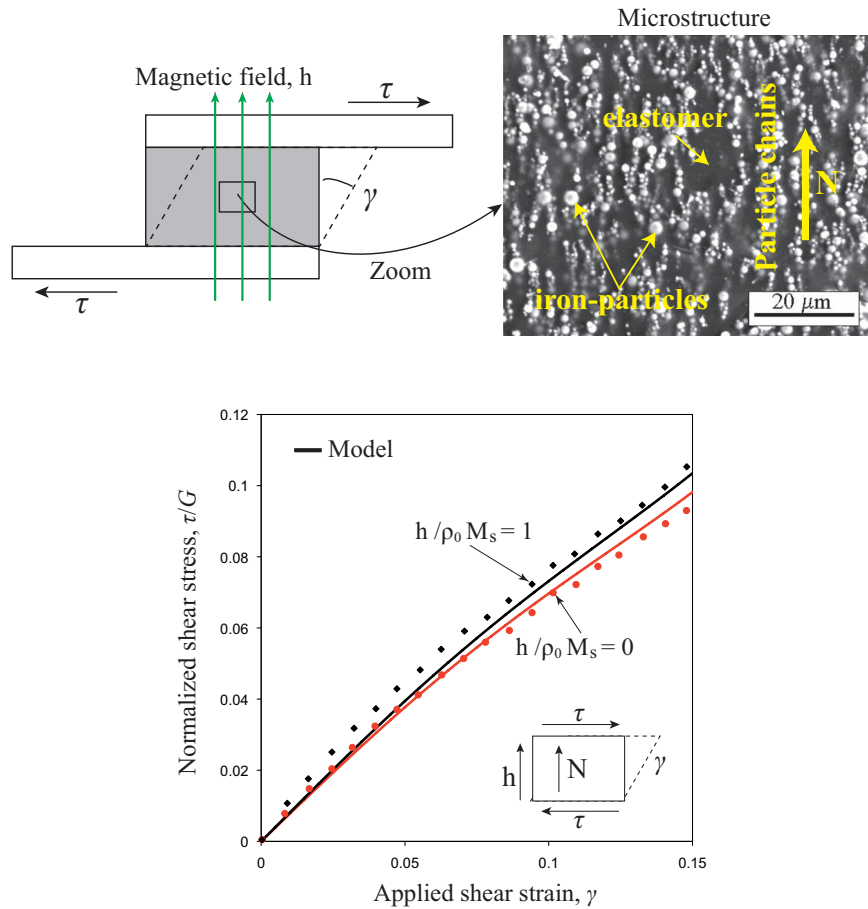


FIGURE 1 – Top left, shows the schematics of a specimen subjected to simple shear in the presence of a magnetic field. Top right shows an electron micrograph (from [1]) of a MRE comprising 25% of iron particles of sizes ranging from  $0.5\mu\text{m}$  to  $5\mu\text{m}$  cured in a 0.5T magnetic field. The application of a magnetic field during the curing process leads to formation of particle chains aligned with the curing field direction. In the bottom figure are experimental (discrete marks) and theoretical (solid lines) results showing the influence of the magnetic field on the MRE's simple shear response with  $G$  denoting the shear modulus.

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