Numerical verification of three point bending experiment of magnetorheological elastomer (MRE) in magnetic field

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Abstract. In the article a method of numerical verification of experimental results for magnetorheological elastomer samples (MRE) is presented. The samples were shaped into cylinders with diameter of 8 mm and height of 20 mm with various carbonyl iron volume shares (1.5%, 11.5% and 33%). The diameter of soft ferromagnetic substance particles ranged from 6 to 9 µm. During the experiment, initially bended samples were exposed to the magnetic field with intensity levels at 0.1T, 0.3T, 0.5T, 0.7 and 1T. The reaction of the sample to the field action was measured as a displacement of a specimen. Numerical calculation was carried out with the MSC Patran/Marc computer code. For the purpose of numerical analysis the orthotropic material model with the material properties of magnetorheological elastomer along the iron chains, and of the pure elastomer along other directions, was applied. The material properties were obtained from the experimental tests. During the numerical analysis, the initial mechanical load resulting from cylinder deflection was set. Then, the equivalent external force, that was set on the basis of analytical calculations of intermolecular reaction within iron chains in the specific magnetic field, was put on the bended sample. Correspondence of such numerical model with results of the experiment was verified. Similar results of the experiments and both theoretical and FEM analysis indicates that macroscopic modeling of magnetorheological elastomer mechanical properties as orthotropic material delivers accurate enough description of the material’s behavior.

1. Introduction
Magnetorheological elastomers (MREs) are materials with rheological properties which can be changed in a continuous way, rapidly and reversibly by the applied magnetic field. They are the solid analogues of magnetorheological fluids (MRFs), consisting of magnetically permeable particles (such as iron) added to a viscoelastic polymeric material prior to crosslinking. Before the curing process of the polymer a strong external magnetic field is applied. The field induces dipole moments within the particles, which seek minimum energy states. The chains of particles with collinear dipole moments are formed and curing of the polymeric matrix material locks the chains in place. In this orientation, the particles can form separate chains in the three-dimensional simple lattice structures or even more complicated structures, where particles have multiple interaction points [4].

The microstructure of MRE is shown in figure 1.
1 filled with 11.5 vol. % of carbonyl-iron particles, cured under magnetic field of: a) 100mT, b) 300mT [1].

2. Experimental results
The experiments have been conducted to evaluate the magnetorheological material response to the applied magnetic field. An electromagnet has been used to produce the magnetic field. The field strength has been constantly monitored using the Hall-probe method. The cylindrical samples ($\phi=8\text{mm}$, $h=18\text{mm}$) have been used for the experiments. The experimental setup is shown in figure 2.

The experiment objective was to measure the response of samples to a deflection under the magnetic field. The samples were placed parallel to the magnetic field lines and deflected before the application of a magnetic field. A deflection, which is analogous to a three point bending, was applied to change the orientation of the particles chains in the material. After the application of the magnetic field the samples tend to straighten which was measured by a deflection sensor. The magnetic field within the range of 0-0.9 T has been applied. The samples response became stronger with rising intensity of the field in all the cases. A deflection value was changing depending on the content of iron in a sample. The highest deflection was observed for samples with 11.5% of iron particles. The lower deflection of samples with 33 vol. % Fe may be caused by a higher stiffness of samples with a greater amount of particles [2].

3. Numerical model and analysis
A numerical model was developed to verify the results the experiment described above. The model was based on the assumption that MRE behaves like an orthotropic material with the material properties of MRE on the direction along the iron chains - and of a pure elastomer - on the other directions. Such an assumption can be made for the small deformations of a sample, what took place in the considered experiment.

The material properties, especially the Young modulus were taken from previous experiments [1] and were presented in figure 3. The assumed value of Poisson ratio was 0.46.

The FE analysis consisted of the two stages: the first one was to initially deflect a cylindrical sample ($\phi=8\text{mm}$, $h=18\text{mm}$) by a nodal force to the deflection value taken from the experiment described before. Then the deflected sample was stretched by the external force simulating the

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1 PU 80/20 – a polyurethane elastomer made of 80% of an initial polymer and 20% of a hardener
influence of the mass forces appearing in the iron chains under the magnetic field. A scheme of the numerical experiment stages is presented in figure 4.

Figure 3. Influence of the iron volume fraction on the Young’s module of the magneorheological elastomer (a). An increase in the Young’s modulus value in comparison with a pure elastomer (b).

A numerical analysis was carried out for the MRE sample with 11.5 vol. % Fe and the iron chains parallel to the sample axis. The considered magnetic fields were 0.1, 0.3, 0.5, 0.7 and 1T. The number of Fe dipoles in 1 mm$^3$ was about 273058.

A static FE analysis was accomplished with MSC Patran/Marc computer code.

4. Analytical calculations

The external stretching force, which simulated the action of magnetic field on Fe chains, was calculated according to the equation describing a dipole interaction force in iron chains along the sample axes. The equation is as follows [5]:

$$F_0 = \left(\frac{3\mu_0}{4\pi}\right) \cdot (m^2) \cdot (5 \cos^2 \alpha - 1) \cdot \left(\frac{1}{r^2}\right)$$ (1)

where: $\alpha$ - angle between the external magnetic field and the dipoles chain axes, $\mu_0=4\pi \times 10^{-7}$ H/m – a magnetic permeability of a void, $r=12$ $\mu$m – the distance between two interacting dipoles, $m$ – magnetic momentum of MRE, considered in accordance to the volume iron share and magnetic field intensity (taken from previous researches). The resulted value describes the force per 1 gram of the elastomer – iron composite. For FE analysis the force $F_0$ value was multiply by the value of the sample mass, what is given with the equation (2):

$$M = V \cdot (U \cdot \rho_{Fe} + (1-U)\rho_{elastomer})$$ (2)

where: $V$ – MRE volume, $U$ – volume share of iron particles in elastomer, $\rho_{Fe} = 7874$ kg/m$^3$ – iron density, $\rho_{elastomer} = 1030$ kg/m$^3$ – pure elastomer density.

5. FE analysis results

The response of the initially bended MRE sample to the external stretching force simulating the action of a magnetic field was analyzed. In agreement with the experiment during the FE analysis the sample should exhibit a complete return to the initial state. It means that the final deflection of the numerical sample first bended and then subjected to the external force simulating magnetic field action should approach zero. A comparison between the experimental and FE analyses is presented in Table 1. The values of the magnetic field intensity and of the initial deflection were taken from the experiment, the external force simulating the action of a magnetic field on the iron chains was calculated with the equation (1). The initially bending force and the sample response values are the results of the numerical analysis.
Table 1. Comparison of the results of the experimental and the FE analysis.

| Magnetic field (experiment) | Initially bending force (FE analysis) | Initial deflection (experiment) | External force simulating magnetic field action (analytical calculations) | Total final deflection (FE analysis) |
|-----------------------------|---------------------------------------|---------------------------------|--------------------------------------------------------------------------------|-------------------------------------|
| [T] | [N] | [mm] | [N/kg] | [mm] |
| 0,1 | 0,059 | 0,028 | 1,6 | 1,55·10^{-3} |
| 0,3 | 0,44 | 0,2085 | 4,4 | 1,87·10^{-3} |
| 0,5 | 0,59 | 0,279 | 6,3 | 1,61·10^{-3} |
| 0,7 | 0,63 | 0,295 | 10,1 | 1,44·10^{-3} |
| 1 | 0,72 | 0,34 | 12,7 | 1,39·10^{-3} |

It can be concluded that a response of the bended sample to a force simulating magnetic field action corresponds to the experimental findings that the sample should vanish. The values of the final deflection vary from zero by only about 0,15%, what means that the initial bending deflection almost disappeared.

6. Conclusions

The three point bending experiment of a MRE sample in a magnetic field was numerically simulated. The results of the applied modeling method of magnetorheological elastomers for small deformations agrees with experiments. The considered material model was orthotropic with the material properties of MRE in the direction along the iron chains and – of a pure elastomer – for the other directions. The FE modeling resulted in about 0,15% of correspondence between the numerical and experimental analyses. It also allows to consider the influence of the stiffer iron chains in elastomer. The model shows a distribution of the material properties in MRE. It takes into consideration a direction of Fe chains. It can be also modified if the tested MRE sample has iron chains directed not parallel to the sample axis (for example if an angle between axes and chains reached 45 degrees the orthotropic material properties local coordinate system are rotated in the same way – see fig. 5).

![Figure 5. Local axes of the orthotropic material properties](image)

The model can be used to predict a behavior of MRE working in a domain of small deformations. It is a simple way how to assess the influence of a magnetic field, a volume share of iron particles in an elastomer and a direction of Fe chains in a tested sample.

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