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Developing an Analytical Model for Viscoelastic Anisotropic Dielectric Elastomer and Investigating the Rate Dependent Electromechanical Behavior

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ABSTRACT: The studies on the behavior of dielectric elastomers, as one of the electroactive polymers, often focus on their hyperelastic and dielectric properties. However, the expansion of the use of these materials as actuators depend on a better understanding of the factors affecting their behavior, including viscoelasticity, as well as the possibility of adding new features such as anisotropy. In this work, a nonlinear coupled model was presented to describe the behavior of anisotropic hyper viscoelastic materials with dielectric properties using the development of fundamental relations in continuum mechanics and the study of governing equations. First, the proposed model was evaluated by stepwise comparing the results of the presented model with the experimental results reported in the available literature. The acceptable agreement between the results indicates the model's accuracy in describing the material's behavior. Next, using the comprehensive form of the model, the effect of loading rate and electric field on the behavior of fiber-reinforced elastomers at various orientations has been studied. The results from applying the model to a sample problem show that increasing the angle of the fibers relative to the horizon reduces the stress range and increases the impact of the loading rate and electric field.

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1- Introduction

Initial models to describe the electromechanical behavior of dielectric elastomers introduced the Maxwell stress as a function of the permittivity of the material and the applied electric field. Electromechanical energy density was also used to describe the material's behavior for strains greater than 20% [1]. While confirming the application of anisotropy as a method to increase the stability of the material, Yong et al. [2] showed that the actuation characteristics of a fiber-reinforced dielectric elastomer depend on the orientation, layout, density, and type of fibers. Another study focused on the time-dependent behavior of dielectric elastomers and used time-dependent coefficients for strain energy function [3]

This research presents a constitutive model to consider all the desired characteristics and provide the possibility to study their effect on the behavior of dielectric elastomers. The model is utilized to examine the behavior of a fiber-reinforced dielectric elastomer sample under different loading rates and electric fields and final results are reported.

2- Model Development and Calibration

Due to large deformations, dielectric elastomers actuated by electric voltages show nonlinear behavior. Therefore, to calculate the stress of these materials, the strain energy function is needed. The model should include terms to describe all the material's features.

The Mooney-Rivlin model (function of the right Cauchy-Green tensor's invariants I_1, I_2) [4] and Holzapfel model (function of anisotropy invariants I_4, I_6) [5] are used to describe the hyperelastic behavior of the matrix, $\overline{W}^{hyper}$, and anisotropic effect of two fibers families, W^{aniso}, respectively. Some other terms are used to describe the effect of incompressibility [6], W^{vol}, viscoelasticity [7], $\overline{W}^{visco}$, and electroactivity [8], W^{elec}.

$$W = \overline{W}^{hyper} + W^{vol} + W^{aniso} + W^{elec} + \overline{W}^{visco} \tag{1}$$

Then, to extract the second Piola-Kirchhoff stress tensor, one needs to take the derivative of the strain energy function with respect to C and $\dot{C}$.

$$S = 2\left(\frac{\partial(\overline{W}^{hyper} + W^{vol} + W^{aniso} + W^{elec})}{\partial C} + \frac{\partial \overline{W}^{visco}}{\partial \dot{C}}\right) \tag{2}$$

Pushing the second Piola-Kirchhoff tensor forward leads to the Cauchy stress tensor, σ :

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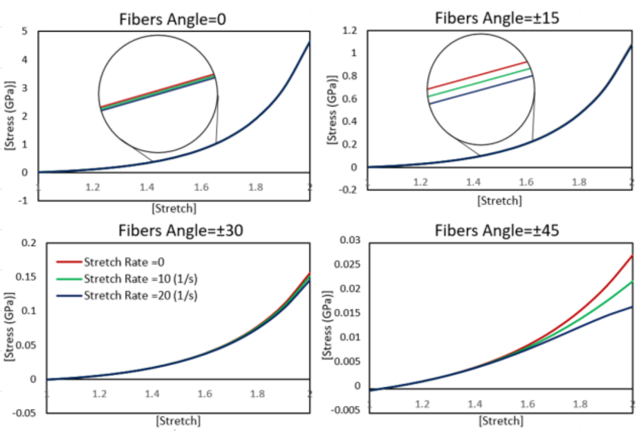

Fig. 1. Stretch rate effect for fibers at different orientations

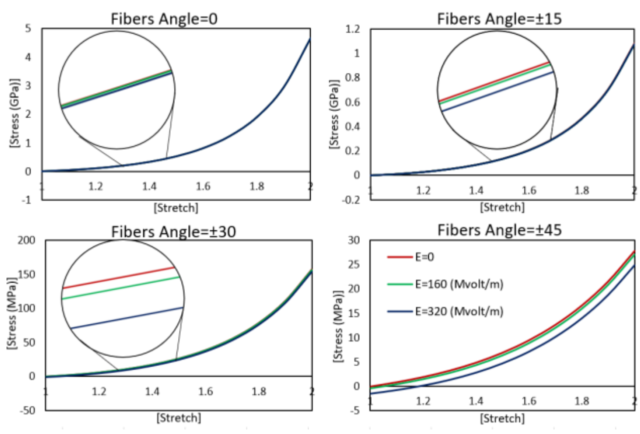

Fig. 2. Electric field effect for fibers at different orientations, group 1

$$\sigma_{mn} = \frac{1}{J} F_{mi} F_{nj} S_{ij} \tag{3}$$

The proposed model for the second Piola-Kirchhoff tensor, as the nominal stress, is evaluated in predicting hyperelastic and anisotropic behavior, viscoelastic feature, and dielectric property using experimental test results reported in [7, 9, 10], respectively. Then, experimental results available in [9, 11-13] are used to extract the required constants of a silicon rubber matrix reinforced with two families of fibers using a curve fitting process.

3- Results and Discussion

Fig. 1 displays stress-stretch results of uniaxial tensile loading for different fiber orientations (0, ±15, ±30, and ±45°) and different stretch rates (0, 10, and 20 (1/s)). According to the results, the effect of stretch rate on fibers parallel to the tension axis (0°) is negligible. As the fiber angle grows, stress ranges decrease, and the stretch rate effect becomes more significant. Furthermore, for fibers at ±30 and ±45°, it is possible to observe slope decline if the stretch is large enough.

To explore the effects of the electric field, the stretch rate is assumed to be 1(1/s). Stretch-stress results are categorized into two groups with different electric field ranges. Based on Figs. 2 and 3, the reverse relationship between stress range and fiber angle is detectable for both groups. Moreover, as the electric field increase, the y-intercept hits bigger amounts since electric stress contributes more to the final Cauchy stress. Despite the positive slope in all the results of group one, in group two, the slope initiates to decrease for big enough fiber angles (±30 and ±45°).

According to Figs. 1 to 3, as the fiber angles grow, stretch rate and electric field affect stress-stretch results more. When fibers are parallel to the stretch axis (at 0°), a significant

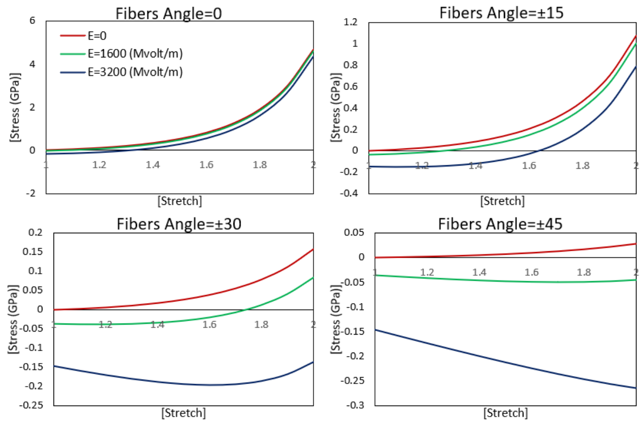

Fig. 3. Electric field effect for fibers at different orientations, group 2

portion of stress is carried by them. Since dielectric and time-dependent were not considered for fibers, it is not possible to observe the electric field and stretch rate effect when they are carrying the bigger portion of stress. As the fiber angles increase, the matrix, which is assumed to be a time-dependent dielectric elastomer, contributes more to transmitting the stress; consequently, the effects of the electric field and stretch rate rise.

4- Conclusions

In this study, a model is presented to describe the behavior of hyper-viscoelastic dielectric material reinforced with two fiber families. Comparing the analytical results obtained from different parts of the model with the available experimental results in the research literature for desired characteristics indicates the accuracy of the proposed model in describing the behavior of the material. On the other hand, the comprehensive form of the proposed model can predict Cauchy stress as a function of stretch. Obtained Cauchy stress for a uniaxial tensile test confirms the model's ability to capture the effect of the electric field, anisotropy, and rate-dependency features. According to the findings, as the fiber angles grow, the stress ranges decrease. It also leads to less sensitivity to the effects of loading rate and electric field.

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