Micromechanics of Electro- and Magneto-active Soft Composites

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We study the coupled behavior in soft active microstructured materials undergoing large deformations in the presence of an external electric or magnetic field. We focus on the role of the microstructures on the coupled behavior, and examine the phenomenon in the composites with (a) periodic composites with rectangular and hexagonal periodic unit cells, and (b) in composites with the random distributions of active particles embedded in a soft matrix. We show that for these similar microstructures exhibit very different responses in terms of the actuation, and the coupling phenomenon. Next, we consider the macroscopic and microscopic instabilities in the active composites. We show that the external field has a significant influence of the instability phenomena, and can stabilize or destabilize the composites depending on the direction relative to composite geometry.

In our work, we study the behavior of dielectric elastomer composites (DEC) [1] and, mathematically analogous, magnetoactive elastomers (MAE) [2] undergoing finite deformations in the presence of external electric or magnetic fields. A typical actuation of dielectric elastomers by an external electric field is schematically illustrated in Fig. 1 (note that the actuation setting is typically different in the magnetically active materials, leading to a different type of boundary conditions). We analyze the role of the microstructures in the overall performance and stability of the soft active composites. More specifically,

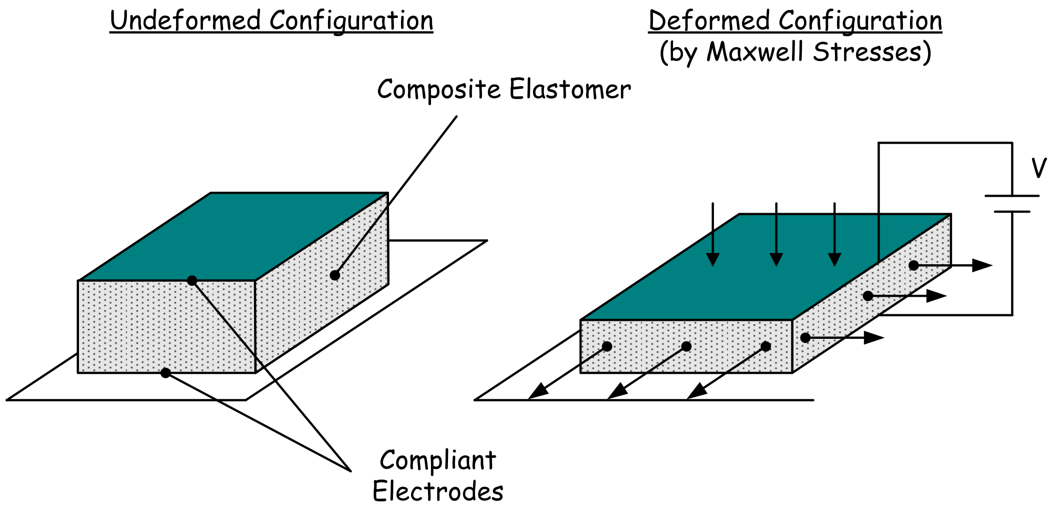

Fig. 1: A schematic illustration of a dielectric elastomer composite actuator. The composite material is actuated by an electric field induced by the charged electrodes placed on the top and the bottom sides of the composite active material. The undeformed state – left; the actuated deformed state – right.

we examine the coupled behavior of the active composites with (i) periodically and (ii) randomly distributed active particles embedded in soft matrix [3, 4], as well as (iii) periodic laminate composites and anisotropically structured composites with chain like structures [5]. We derive analytical solutions and estimates for the coupled behavior of the active composites, and compare these with finite element simulations of corresponding microstructures. These results assist us in identifying the key parameters governing the electro- and magneto- mechanical couplings. Moreover, we find advantageous microstructures that give rise to significant enhancement of the coupling and actuation of the active materials [3]. Furthermore, we show that even very similar microstructures, such as periodic composites with hexagonal and rectangular representative volume elements (RVE), exhibit very different behavior both in terms of actuation, and effective properties [4]. An example of the tunability of the coupled active composites by the internal geometry is illustrated in Fig. 2 for the periodic dielectric elastomer composites with the contrast ratio in the shear moduli $\mu^{(2)}/\mu^{(1)} = 10$, and the contrast in dielectric $\epsilon^{(2)}/\epsilon^{(1)} = 100$ for various initial inclination angles at a fixed volume fraction and aspect ratio of the active inclusion. We report the actuation strain as a function of the initial inclusion inclination angle. We observe that the actuation strain increases with an increase in the initial inclination angle, and the actuation achieves the maximum level at the inclination angle $\theta = \pi/2$. The snapshots illustrate the

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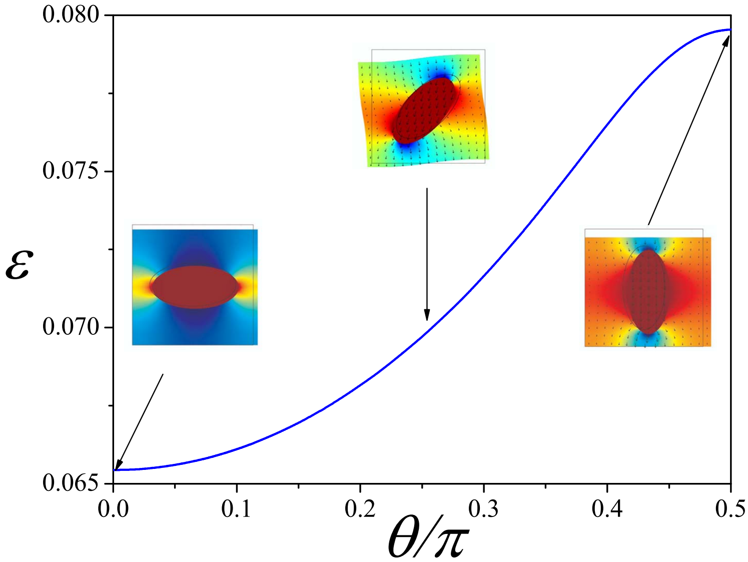

Fig. 2: Actuation strain vs initial inclination angle of an elliptical active inclusion embedded in a soft matrix. The results are calculated for DE composites with the contrast ratio in the shear moduli $\mu^{(2)}/\mu^{(1)} = 10$, and the contrast in dielectric $\mu^{(2)}/\mu^{(1)} = 100$; the ratio between the the first Lame coefficients and the shear modulus is $\Lambda^{(2)}/\mu^{(2)} = \Lambda^{(1)}/\mu^{(1)} = 50$.

evolution of the microstructure of the periodic dielectric elastomer composites in the deformed state for $\theta = 0$, $\pi/4$, and $\pi/2$. Clearly, for the non-aligned case, we observe the rotation mechanism of the inclusion resulting in the shear deformation of the unit cell. This behavior is not observed for the aligned cases $\theta = 0$, and $\pi/2$.

Next, we investigate the crucial aspect of the active composites' behavior, namely, the coupled electro- and magneto-elastic instabilities in DEC [6–8] and MAE [5]. These instabilities may occur at different wave lengths and may lead to a catastrophic failure. However, they may be also exploited to achieve new functionalities such as tunable band-gaps in elastic wave propagation [9–12]. We explore the role of the external electric and magnetic fields, microstructure parameters, and consentient properties on the onset of both microscopic and macroscopic instabilities. We present the multiscale instability analysis for a particular class of periodic microstructures, namely, multilayered active composites. To determine the response of the multilayered structure to coupled loadings, an analytical solution is derived for finitely deformed laminated in the presence of an external field [5, 6, 8]. The determined from the exact solution local fields are used in the superimposed Bloch-Floquet analysis to predict the onset of microscopic instabilities [8]. The onset of macroscopic instabilities is identified by analyzing the homogenized tensor of electro- or magneto-elastic moduli [5, 6, 13]. The results for global bifurcation modes agree with these of the limit of long wavelengths in the microscopic instability analysis.

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