Electro- and magneto-active deformable composites

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Dielectric Elastomers (DE) are promising materials for developing soft machines (e.g., a human-made octopus). The principle of actuation has gained to DE the name "artificial muscles" since they can undergo large deformation when excited by an electric field. Another class of active materials that can be actuated by external field is Magnetoactive Elastomers (MAE). Although MAE and DE share mathematical similarities, the physics is different. Electric field can induce polarization in elastomers, and hence generate electrostatic stresses within the material. As a response to the electrically induced stresses, the material deforms. For

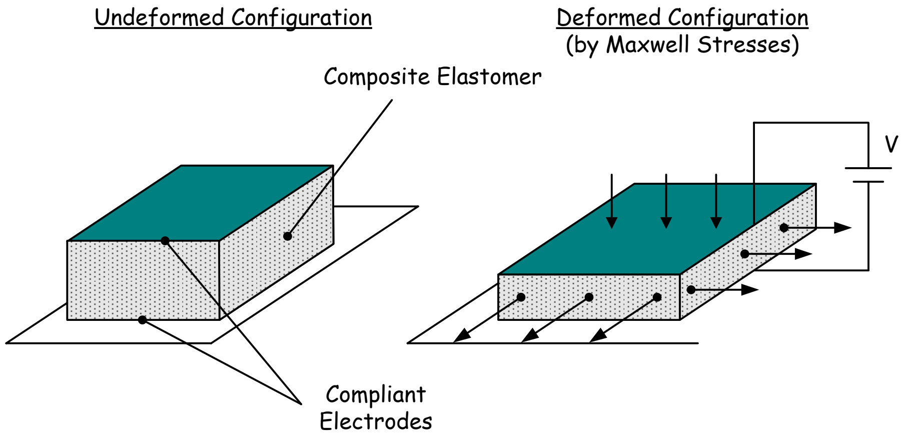

Figure 1: Schematics of Actuation of DE composites [1].

MAE the situation is different: elastomers are magnetically inactive, and a similar to DE effect is achieved by mixing the elastomer with magnetically active particles (e.g., carbonyl iron, nickel or Terfenol-D). Thus, due to the magnetic interaction of the particles embedded in a soft matrix, the composite can deform and modify overall stiffness as a response to a magnetic field. The performance of these composites can be further enhanced by optimizing microstructures. Indeed, a similar idea applies for designing DE composites with enhanced properties. These composites, once manufactured can solve the bottle-neck problem of DE technology - the need in extremely high electric fields for meaningful actuations, and potentially lead to a breakthrough in the technology.

• Composites for Better Performance

DE composites with random distribution of fillers showed a promising enhancement in electromechanical coupling [2]. According to theoretical and numerical studies, the enhancement is only a beginning, and DE composites with periodic microstructures will exceed the response of homogeneous materials (e.g., acrylic elastomer VHB 4910) by orders of magnitude [1]. In particular, Rudykh et al. [1] showed that neatly assembled layered materials (with sub-layered microstructures) benefits from existence of soft mode of deformation and local amplification of electrostatic stresses. This combination gives rise to the dramatic enhancement in the overall performance (see Fig. 2).

Thanks to the mathematical analogies between MAE and DE, these theoretical and numerical findings apply indeed for MAE. Recently, studies have begun exploring homogenized properties of the composites with random distribution of particles [3, 4]. Although, this type of composites is not competitive with the

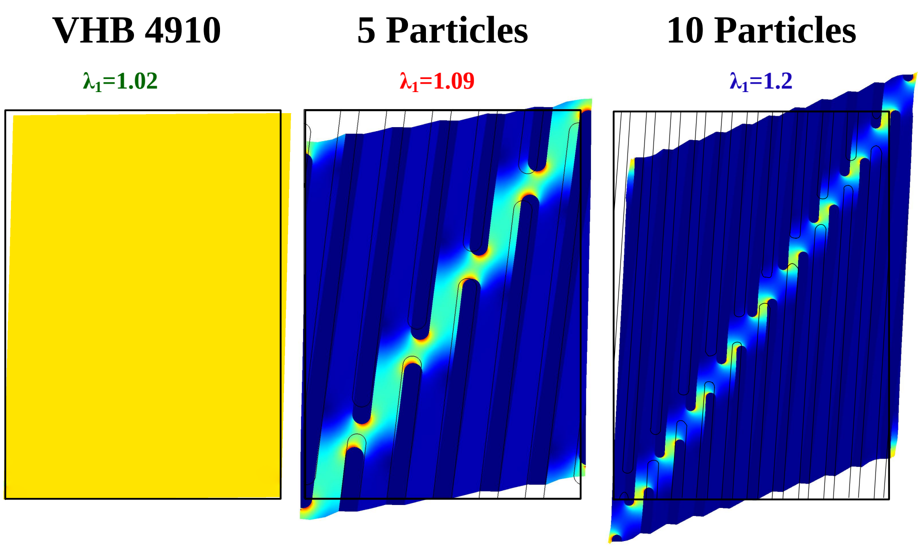

Figure 2: Enhanced actuation of composite DE. Responses of homogeneous material, and two types of composite materials with similar phases and volume fractions (from left to right) [1].

enhanced periodic composites, the random composites are easier to manufacture, and the models can provide useful insights for designing DE and MAE composites. An important feature of the active composites is the ability to modify their stiffness by external fields. Remarkably, the stiffening effect in MAEs with random distributions can be enhanced if the composite is prepared in the presence of a magnetic field. As a result, the particles form chain like structures resulting in an anisotropic behavior of the composite MAE. Rudykh and Bertoldi [5] have developed a micromechanical model for these anisotropic MAE and obtained a closed form expressions for modeling and optimizing these composites. Danas et al. derived a more complicated model and fitted the material parameters by using experimental data [6]. Cao and Zhao [7] analyzed layered structures and demonstrated a strong effect of the mesostructures on the stiffening effect in DE and MAEs.

- **Instabilities for New Functionalities**

Elastic instabilities[1] open the path for even more intriguing opportunities for controlling large variety of composite properties by triggering and controlling instability-induced microstructures (such as wrinkled interfaces in layered composites [8] , or periodically buckled porous materials [9]). These microstructure transformations can be used, for example, to manipulate wave propagation [10, 11]. This application was highlighted in previous discussions at *iMechanica* (e.g., http://imechanica.org/node/14431).

The presence of electric/magnetic fields significantly influences the stability of the composites. Depending on a particular microstructure, the role of the external stimuli may be either stabilizing or destabilizing. To analyze this phenomenon, Rudykh and deBotton [12] derived a general criterion for onset of macroscopic instabilities for a plane-strain settings. Rudykh and Bertoldi [5] extended the critical condition for fully 3D loading conditions. Bertoldi and Gei [14] explored microscopic and macroscopic instabilities in layered structures. These studies [5, 12, 14] formulated the analyses in terms of electrical displacement **D** as a primary field (magnetic induction **B**, in the magnetomechanical case). Although the use of electric displacement leads to a simpler mathematical problem, it is not natural from an experimental viewpoint. In experimental practice, it is significantly simpler to prescribe the electrostatic potential on a surface than to prescribe the exact charge distribution. Therefore, Rudykh et al. [13] formulated the problem in terms of

[1] more precisely, coupled electro- and magnetomechanical instabilities

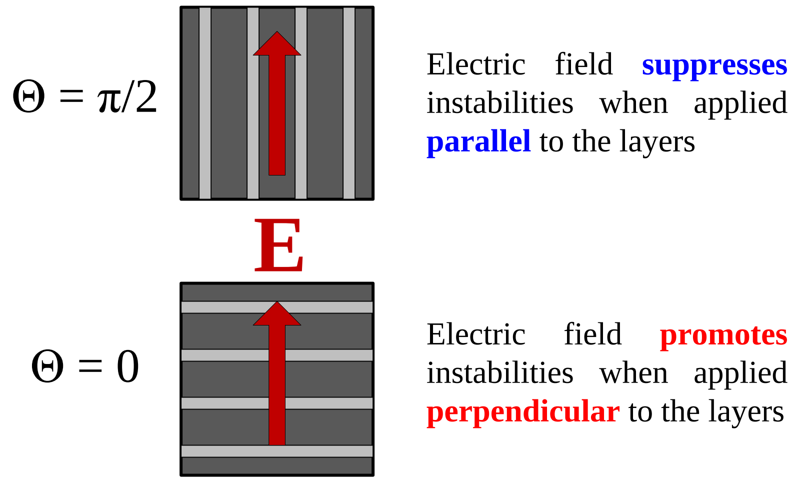

Figure 3: The role of electric field in stability of layered DE composites [12, 13].

electrostatic potential as the primary field variable. The study of electromechanical instability is direct since bifurcation criteria are prescribed in terms of the electric field. The study shows how different length-scale patterns can be induced by combinations of mechanical and electrical loadings.

These coupled multiphysics analyses are limited to a particular class of periodic composites, namely layered composites. Indeed, there is the whole world of various microstructures to explore, to discover new supereffective composites and fascinating microstructure transformations.

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