MODELS FOR ACTUATION, FAILURE AND TEARING OF ELECTROACTIVE MATERIALS

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Summary A consistent energetic formulation of boundary value problems for dielectric, electroactive materials is formulated, including the electrostatic stress. This formulation is utilized to develop computational models for the combined electrostatic and mechanical response of such materials. This method is used to simulate the actuation of components devised from these materials. The analysis includes consideration of those materials whose permittivity varies significantly during straining. Such computations are also used to address the failure of the material during actuation, perhaps caused by dielectric breakdown, associated with instabilities and bifurcations in the structural response. These simulations account for the effect of the finite compressibility of the polymer, which is found to have a significant effect on the response involved. The energy release rate for cracks or tears in electroactive materials is calculated and the J-integral for these systems obtained. The outcome is a comprehensive and consistent fracture mechanics for electroactive materials. The concepts are extended to address ferroelectrics and piezoelectrics, where different modes of electromechanical coupling are involved.

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Elastomers are heavily cross-linked polymers that sustain large elastic deformations without significant viscoelastic effects. Such large deformations induce preferential orientations of the polymeric chains constituting the material, and consequently induce changes in their physical properties. Upon deformation, the intrinsic polarizability of a monomer on the polymer backbone reorients with respect to the polymeric chain as well as with respect to other monomers from the same and neighboring chains. Furthermore, the intrinsic polarization of side groups will reorient as well, having an effect on the polymer chain polarizability, and on the macroscopic optical and dielectric properties of the material.

For the last decade, dielectric elastomers have been used in combination with highly compliant electrode materials to create systems capable of transforming electrical energy into mechanical work. These devices are known as dielectric elastomer actuators (DEA). A thin film elastomer coated with compliant electrodes on its top and bottom planes is the simplest example of this type of device. When an electric field is applied between the electrodes, it gives rise to electrostatic forces that compress the film parallel to its through thickness direction and stretches it in-plane. Materials with such characteristics are highly desirable for the development of high speed, lightweight, efficient actuators, *e.g.* silicone polymer (Dow Corning Sylgard) exhibits

thickness reductions of up to 32% due to electrostatic forces. This behavior is often modeled through the expression of the electrostatic forces as an *effective pressure* equal to the square of the electric field between the electrodes times the permittivity of the elastomer, assumed to be constant and isotropic. The *effective pressure* model provides an excellent qualitative description of the electrostriction of elastomers, but overestimates the magnitude of the resulting deformation. The discrepancy is often attributed to a reduction of the elastomer permittivity upon straining.

A theoretical analysis developed by Kuhn and Grün [1] expresses the polarizability tensor of a Gaussian chain molecule as a function of its end-to-end distance, the number of bonds along the chain and the individual polarizabilities of the bonds, with results based on the methods of statistical mechanics. We use the strain birefringence model developed by Kuhn and Grün [1] to obtain the dependence of permittivity on strain, and implement that relationship in the analysis of electro-active materials in the style of McMeeking, Landis and Jimenez [2]. The resulting constitutive law is used to analyze the behavior of actuators made from such materials, their stability limits and how their performance can be improved with avoidance of such instabilities and failures.

The formulation is developed through use of a free energy function for the material that depends on the dielectric energy coupled to the free energy of deformation as the material deforms. This formulation is extended to address the behavior of a variety of materials such as piezoelectrics and ferroelectrics that exhibit coupling between electrostatic and mechanical fields in a variety of ways. Such a formulation permits the assessment of the driving forces for fracture, rupture and tearing in the various materials studied. A feature of the approach is that the opening displacement of the crack or tear cannot be neglected and must be addresses during the formulation of the problem.

Computations are carried out for electroactive materials that are experiencing cracking, rupture of tearing in which the finite deformation of the flaw during material response is accounted for. The result is a set of consitent calculations assessing how cracks, ruptures and tears behave in electroactive materials, accounting for all effects which are important within these systems.

References

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[2] R.M. McMeeking, C.M. Landis and S.M.A. Jimenez, "A principle of virtual work for combined electrostatic and mechanical loading of materials," *International Journal of Non-Linear Mechanics*, **42**, pp. 831-838 (2007).