A COMPUTATIONAL FRAMEWORK FOR MODELING ELECTRIC BREAKDOWN IN ELECTROACTIVE POLYMERS

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1. Introduction

Electroactive polymers (EAPs) are considered a promising emerging class of smart materials, which have received an extensive consideration among researchers. EAPs are an active class of materials with the ability to undergo large deformations when they are subjected to external electric stimuli. Therefore, various applications have been proposed in the literature including artificial muscles, medical devices and soft biomemetic applications ([2],[1]).

A typical actuator consists of a thin film of dielectric elastomer, which on its major surfaces, two flexible electrodes are smeared, and an electric potential difference between the electrodes is applied. Despite the high-level of actuation performances enabled by EAPs, their extensive use is conditioned by a high driving electric fields. Thus, the applied electric field may cause an electric breakdown. As the electric breakdown in solid dielectrics takes place, tubular conductive channels evolve, and they do not recover when the voltage is discharged.

In this work, a computational model, which is able to predict possible electric breakdown while accounting for the electromechanical coupling is presented. Moreover, a finite element formulation with various nodal degrees of freedom is introduced.

2. Governing equations

In this paper, we consider a body, which occupies a $\mathcal{B}_0$ at reference configuration. The body is subjected to mechanical body forces, mechanical surface tractions on the boundary $\partial\mathcal{B}_0^{\mathbf{T}}$, and electric charges on the boundary $\partial\mathcal{B}_0^{\mathrm{Q}}$, as shown in Fig. 1.

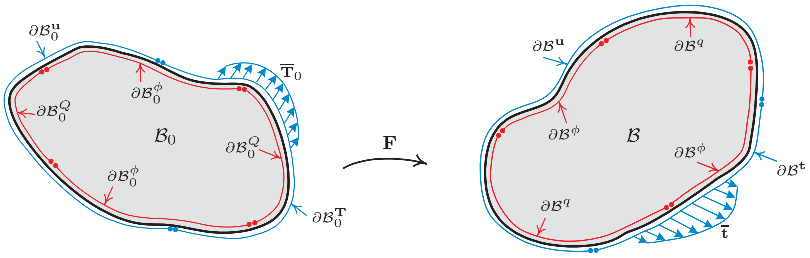

Figure 1: Sketch of the deforming body.

Let $\mathbf{X}$ denotes the location of a material point in the reference configuration, $\mathbf{x}$ denotes the location of the same material point in the present configuration, and $\mathbf{F} = \partial\mathbf{x}/\partial\mathbf{X}$ denotes the deformation gradient, which maps the reference configuration to present configuration with the constraint $J = \det(\mathbf{F}) > 0$. Also, let $\{\boldsymbol{E}, \boldsymbol{D}\}$ be the reference electric field vector and reference electric displacement vector, respectively. In the case of electrostatics and in the absence of free currents and free electric charges, Maxwell's balance equations become,

$$\text{(1)} \qquad \mathrm{Div}\,(\boldsymbol{D}) = 0, \quad \mathrm{Curl}\,(\boldsymbol{E}) = \mathbf{0}$$

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Next, the equilibrium equations, which are derived from the linear momentum balance in the local form for nonlinear electroelasticity are written in reference configuration such as

$$\text{Div}\,(\mathbf{FS}) + \mathbf{f} = \mathbf{0}, \tag{2}$$

with $\mathbf{S}$ being the total second Piola-Kirchhoff stress tensor consists of all contributions. $\mathbf{f}$ is the reference mechanical body forces (force by unit reference volume). In order to derive the constitutive laws, a strain energy function (per unit volume), is assumed. Specifically, the strain energy function reads

$$W\left(\mathbf{C},\, \boldsymbol{E},\, \mathbf{A}_1, ..., \mathbf{A}_n, s\right) = \rho_0 \psi \left(\mathbf{C},\, \boldsymbol{E},\, \mathbf{A}_1, ..., \mathbf{A}_n, s\right) - \frac{1}{2} J \varepsilon_0 \mathbf{C}^{-1} \colon \left(\boldsymbol{E} \otimes \boldsymbol{E}\right). \tag{3}$$

where $\{\mathbf{A}_1, ..., \mathbf{A}_n\}$ are the strain like internal variables, $\mathbf{C}$ is the right Cauchy-Green deformation tensor, n represents the number of the viscus Maxwell branches, ρ_0 is reference density, and ψ is free energy function. As well, $s\left(\mathbf{X}, t\right)$ is a phase scalar, which varies from $s = 0$ indicating the totally damaged state to $s = 1$ indicating the virgin state.

3. Finite element

For providing a numerical tool, a finite element formulation has been developed. The nodal degrees of freedom are the displacements in the three dimensional space, the electric potential, and the phase field scalar, as shown in Fig. 2.

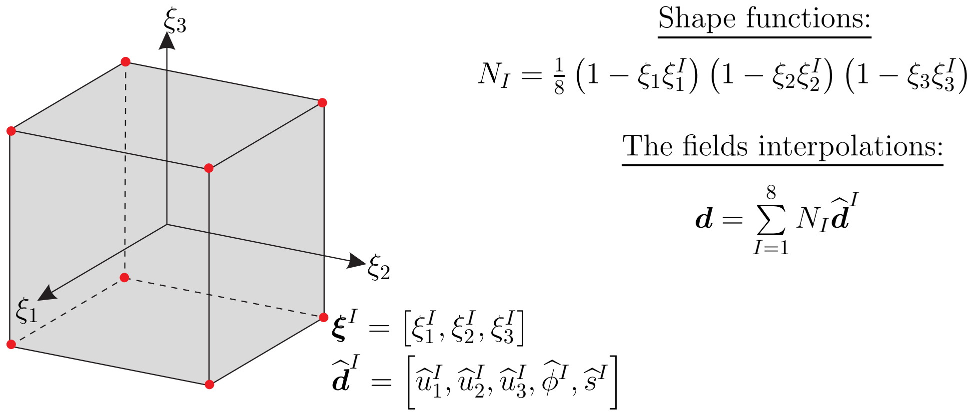

Figure 2: Sketch of an element in the isoparametric space.

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