2021-2022 Grand Challenge Award Final Report

Awardee: **Chad M. Landis, Professor**
Aerospace Engineering & Engineering Mechanics

Research Award Title: **Computational Modeling of the Deformation and Failure of Soft Materials**

Research Summary The details of the research carried out under this award differed from the originally proposed work, but did focus on the computational models of the behavior of soft materials and fracture mechanics. The first problem that was studied was on the instabilities that can occur in a dielectric elastomer film bonded to a stiff substrate. Electromechanical instability has been recognized as a mode of failure for dielectric elastomer membranes subject to increasing voltage, which limits the amount of energy conversion by dielectric elastomers in practical applications. Experimental observations on pre-stretched dielectric elastomeric layers bonded to stiff substrates and subject to a voltage difference across top and bottom conducting surfaces reveal that the uniformity of the layers gives way to localized creasing-like instabilities as the voltage difference is increased. The numerical analysis of the finite strain creasing solution is challenging for several reasons, especially because the wavelength of the wrinkling mode is indeterminate and the solution path from the uniform state to the creased state is highly nonlinear and unstable. This work addresses these issues in the investigation of the competition between wrinkling and creasing. Figure 1 shows the basic geometry of the dielectric elastomer film in (a) the unstretched configuration, which can be pre-stretched (b) prior to an applied electrical voltage, which then can induce (c) wrinkling, or (d) creasing.

The reference configuration of a dielectric elastomer film of thickness h_0, prior to the application of pre-stretch or electrical loading is shown in Figure A.

Figure B shows homogeneous deformation by an equi-biaxial pre-stretch λ_0. After the film is pre-stretched, it is then bonded to a rigid conducting substrate such that upon application of electrical loading it is constrained from lateral expansion/contraction along the bottom surface.

During electrical loading a voltage drop V is applied across the top and bottom conducting surfaces of the film, and a resulting charge Q is exchanged. Above a critical electromechanical loading, the homogeneous deformation becomes unstable and bifurcation takes place to form either (Figure C) periodic surface wrinkles or (Figure D) periodic creases.

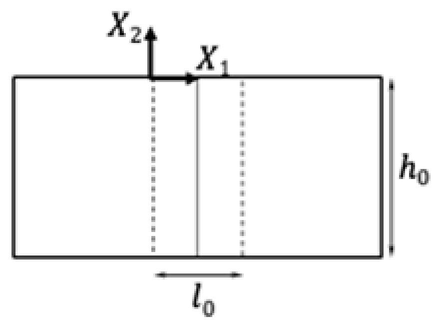

Figure A

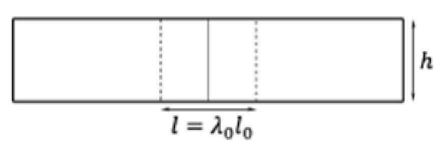

Figure B

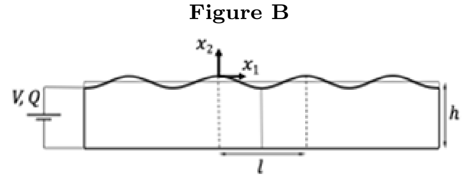

Figure C

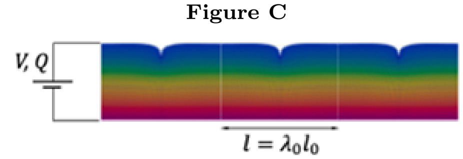

Figure D

The analysis of these phenomena included both linear perturbation analysis to determine the critical voltage for wrinkling, as well as the implementation of finite element methods for the simulation of the large deformation response of the post-instability creasing behavior of the dielectric elastomer film. The two major findings of the work were that (a) the critical voltage for creasing is able to explain the experimental measurements, which is not possible from the linear perturbation analysis for wrinkling, and (b) the creasing instability is most likely triggered at electrically conducting defects on or near the surface of the film.

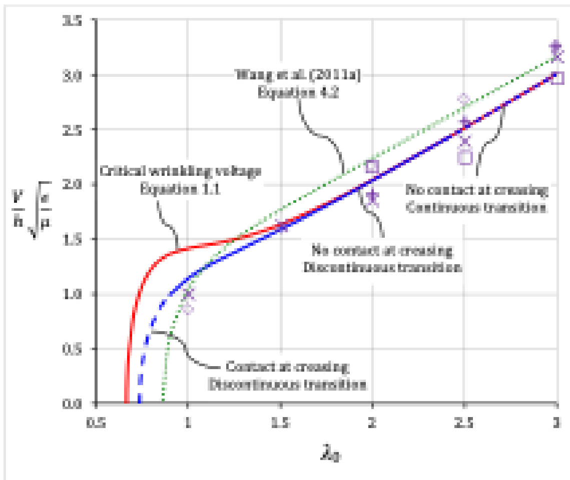

Figure 2

Figure 2: The critical voltages for wrinkling (red curve), creasing (blue curve), The green dotted line and experimental measurements (purple markers) are from Wang et al. (2011a). The curve for the creasing voltage is divided into three regions. For $0.736 < \lambda_0 < 0.9$ the transition to creasing results in self-contact. This region also has a jump in the transition from the flat to the creased state. For $0.9 < \lambda_0 < 2.4$ the initial transition to creasing does not result in self-contact, but the transition to creasing is discontinuous. Finally, for $\lambda_0 > 2.4$ the transition does not result in self-contact and is continuous

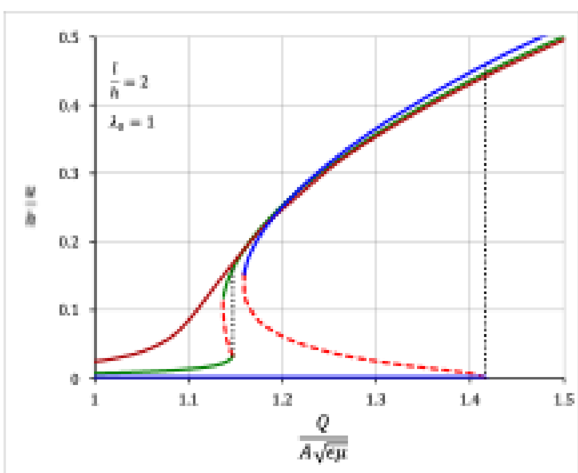

Figure 3

Figure 3: Crease displacement-charge behaviors for the dielectric elastomer film with no pre-stretch ($\lambda_0 = 1$) and a small conducting defect. The green curves (with red dashed unstable branch) are for a conducting channel depth of $\frac{a}{h} = \frac{1}{120}$ and the crimson curves are for a depth of $\frac{a}{h} = \frac{1}{48}$. The results with no defect are also shown for comparison.

The second topic that was studied under this award was on the computational modeling of fracture. Predicting the failure of materials and structures due to crack nucleation and propagation is critical for many engineering applications. As a result, several numerical approaches have been developed to capture complex fracture phenomena. This work has focused on the phase-field approach to fracture and specifically in extending that approach for the analysis of large structures while maintaining strength-based nucleation of failure near smooth defects. The significant contribution of this work was on the introduction of a new failure degradation function within the theory and the demonstration that this function can be tailored to decouple the physical length scale associated with fracture, l_p, which is usually very small (on the order of microns), from the phase-field length scale, l_0, associated with the numerical model. Figure 4 illustrates the result that this decoupling of length scales can be extended to extremely large structure sizes with at most modest increases in numerical mesh densities.

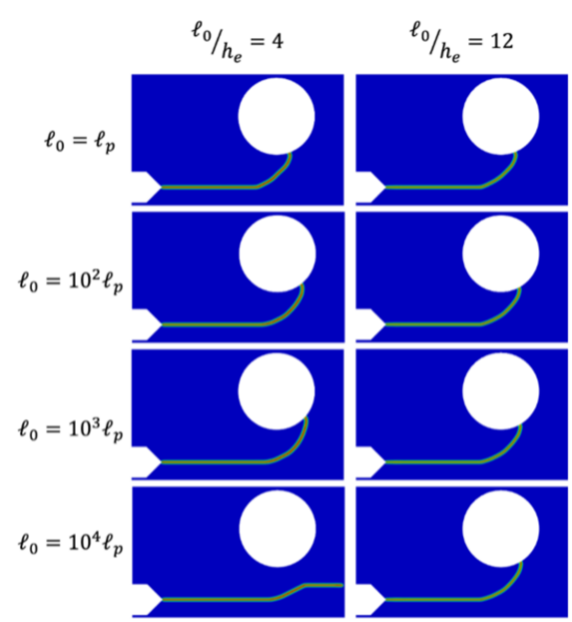

Figure 4

Publications

- C.M. Landis, R. Huang, and J.W. Hutchinson, 2022, "Formation of surface wrinkles and creases in constrained dielectric elastomers subject to electromechanical loading." Journal of the Mechanics and Physics of Solids 167 105023.
- J.W. Hutchinson, R. Huang, and C.M. Landis, 2022, "Errata: Surface instabilities of constrained elastomeric layers subject to electro-static stressing." Journal of the Mechanics and Physics of Solids 160 10409.

- Y.S. Lo, T.J.R. Hughes, and C.M. Landis, 2023, "Phase-field fracture modeling for large structures." Journal of the Mechanics and Physics of Solids 171 105118.

Presentations made

- C.M. Landis, R. Huang and J.W. Hutchinson, "Formation of Surface Wrinkles and Creases in Constrained Dielectric Elastomers Subject to Electromechanical Loading", 19th U.S. National Congress on Theoretical and Applied Mechanics, Austin, TX, 6/20/2022.

Invited lectures

- C.M. Landis, Y.S. Lo, and T.J.R. Hughes, "Phase-field Fracture Modeling for Large Structures", Society for Engineering Science Annual Conference, College Station, TX, 10/19/2022. (Keynote)

Awards or Recognitions Received

- Elected as Fellow of the Society of Engineering Science – 2022

Service

I would like to acknowledge that this Moncrief Grand Challenge Award also allowed me to devote time to two essential and impactful service activities. The first was in Chairing the 19th U.S. National Congress on Theoretical and Applied Mechanics which was held on campus in June of 2022. The Congress is held every four years and is a major conference for the applied mechanics community. The Congress was widely viewed as a success, bringing over 800 researchers to Austin towards the end of the COVID pandemic. The Congress brought positive visibility to the University of Texas at Austin and to the Oden Institute. The second activity that I devoted time to was on leading the ABET Accreditation review for both the Aerospace Engineering program and our new Computational Engineering program. Both programs passed the review with positive comments and feedback. It is notable that the reviewers were particularly impressed with the Computational Engineering undergraduate program, and asked questions with an eye towards developing a similar program at their own universities.