Experiment-Informed Finite-Strain Inverse Design of Spinodal Metamaterials

Prakash Thakolkaran*[1], Michael Espinal[2], Somayajulu Dhulipala[2], Carlos M. Portela†[2], and Siddhant Kumar‡[1]

[1]Delft University of Technology, Department of Materials Science and Engineering – Netherlands
[2]Massachusetts Institute of Technology, Department of Mechanical Engineering – United States

Abstract

Spinodal metamaterials, with architectures inspired by natural phase-separation processes, have presented a significant alternative to periodic and symmetric morphologies when designing mechanical metamaterials with extreme performance. While their elastic mechanical properties have been systematically determined, their large-deformation, nonlinear responses have been challenging to predict and design, in part due to limited data sets and the need for complex nonlinear simulations. This work presents a novel physics-enhanced machine learning (ML) and optimization framework tailored to address the challenges of designing intricate spinodal metamaterials with customized mechanical properties in large-deformation scenarios where computational modeling is restrictive and experimental data is sparse. By utilizing large-deformation experimental data directly, this approach facilitates the inverse design of spinodal structures with precise finite-strain mechanical responses. The framework sheds light on instability-induced pattern formation in spinodal metamaterials—observed experimentally and in selected nonlinear simulations—leveraging physics-based inductive biases in the form of nonconvex energetic potentials. Altogether, this combined ML, experimental, and computational effort provides a route for efficient and accurate design of complex spinodal metamaterials for large-deformation scenarios where energy absorption and prediction of nonlinear failure mechanisms is essential.

*Speaker
†Corresponding author: cportela@mit.edu
‡Corresponding author: Sid.Kumar@tudelft.nl

sciencesconf.org:esmc2025:592928