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Non-uniform pneumatic actuation for programmable macroscopic stiffness and elastic-wave bandgaps in pattern-forming metamaterials

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Abstract

Pattern-forming elastomeric metamaterials exploit reversible buckling of microstructural ligaments to switch effective properties; in most designs, however, the macroscopic mechanical load both triggers buckling and implicitly selects the emerging pattern. We report two results showing that spatially non-uniform pneumatic actuation can serve as an additional control input that triggers unit-cell buckling and selects the post-buckled configuration, enabling reversible programming of macroscopic stiffness and elastic-wave bandgaps. First, we study a periodic square lattice of rectangular voids subjected to alternating inflation and suction in a checkerboard arrangement. A reduced geometrically nonlinear beam description condenses the ligament network to a minimal set of generalized coordinates, enabling an explicit energetic stability analysis and a closed-form estimate of the critical pressure difference for pattern onset. The model clarifies how pressure work associated with compartment volume changes competes with ligament bending and how the imposed pressure periodicity maps to the periodicity of the emerging pattern. Plane-strain finite-element simulations of hyperelastic RVEs corroborate the predicted bifurcation and quantify the associated reduction in homogenized tangent stiffness. Extending the reduced model to combined pneumatic actuation and external compression yields a "critical-state" boundary in pressure–load space that can be used to design actuation-first loading paths and maintain stability of the selected post-buckled mode during subsequent mechanical loading. Second, we transfer the control principle to honeycombs with hexagonal stacking of circular voids, which under mechanical loading exhibit three canonical patterns (shear, butterfly, flower-like) depending on loading biaxiality. We design non-uniform suction schemes—implemented as pressure ratios across selected rows/void groups—that pneumatically reproduce this family of patterns, including multiple orientations. Periodic RVE simulations track the evolution of the homogenized stiffness tensor during pattern formation and show that pneumatic pattern selection tunes not only stiffness level but also anisotropy, enabling direction-dependent stiffness contrasts. Bloch–Floquet analyses demonstrate that the pneumatically selected states also modify elastic-wave bandgaps, providing a route to dynamic filtering controlled by the same pneumatic input. Both concepts are validated experimentally on finite silicone-rubber samples fabricated in 3D-printed molds and actuated in a custom setup capable of applying different pressures to different rows of voids, demonstrating pneumatic pattern selection beyond ideal periodic RVEs and highlighting finite-size and boundary effects.

Keywords:

Mechanical metamaterials Non-uniform pneumatic actuation Pattern-forming instability Computational homogenization Elastic-wave bandgaps