Hysterons and pathways in mechanical metamaterials

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SUMMARY

Mechanical metamaterials are carefully engineered materials whose properties are controlled by their structure, not by their composition. This allows to design materials with practically beneficial features that may not be found in nature, but also allows to create metamaterials to study and control physical effects in detail.

In this thesis, we develop metamaterials to study the sequential, complex response of frustrated materials that are cyclically driven. In many cases, it is possible to model such complex systems as collections of so-called hysterons. These bistable elements flip their internal state s from '0' to '1' when the local driving exceeds an upper switching field ε^+, and flip from '1' to '0' when the driving falls below the lower switching field ε^-. Crucially, we take $\varepsilon^- < \varepsilon^+$, so that there is a hysteretic region, whose history-dependent state encodes memory effects.

In this thesis, we present two strategies to create hysterons in 'holar metamaterials', i.e., quasi-two dimensional metamaterials that are patterned with regular arrays of circular holes. First, we create hysterons by using the frustration between local defects and holar structures, and second, we use the frustration between competing deformations of holar metamaterials.

In Chapter 2 of this thesis, we demonstrate the strategy of creating hysterons by placing defect beams into a biholey metamaterial. Due to a competition between the initial curvature of the defect beam and the global

(rotational) deformation of the biholey array, the defect beam can either curve to the right or curve to the left under increased compression, and is able to hysteretically switch between these two states under cyclical compression. Hence, the defect beam acts as a hysteron, and we show how to control the snapping and unsnapping strains (= upper and lower switching fields) of these defect-based hysterons.

In Chapter 3, we study the states, transitions, and pathways of metamaterials that contain three defect-based hysterons, both experimentally and numerically. We map the evolution of the hysterons to transition graphs that fully encode the pathways of a given sample under cyclic compression. We tune the transition graphs by appropriate design of the defect beams. We then show that by tilting one of the boundaries, which produces spatial gradients in the degree of compression, we can tune the t-graph of a single sample. Finally, we evidence subtle friction effects that further tune the pathways, which reveal additional degrees of freedom. Together, our work presents the first example of rationally controlled, mechanical hysteron-based pathways that are observed experimentally.

In Chapter 4, we introduce a strategy of creating emergent hysterons in frustrated materials. In particular, we use the competition between two distinct, symmetry related deformation patterns (patterns A and B) in biholey metamaterials. This competition has been used in the past to realize a programmable mechanical response by clamping the material in the horizontal direction, and compressing it in the vertical. Here we use similar clamping to create systems with two and three emergent hysterons. We focus on samples with two hysterons and show that we can tune the pathways over a wide range of possibilities by tuning the clamp sizes and tilting the boundary conditions. Our pathways evidence significant interactions between the hysterons, and by measuring the precise switching fields, we are able to measure some of the interaction coefficients precisely. These interactions lead to avalanches where multiple hysterons change state (near) simultaneously. We briefly explore a larger sample in which we can embed three hysterons, and provide evidence that such samples can exhibit a wide variety of non-trivial pathways.

In Chapter 5, we explore the evolution of monoholar metamaterials under compression. We use computer simulations to accurately determine the first unstable mode of these samples under compression, and find that the parity (even/odd) of the number of rows and columns of holes strongly influences the instability — even rows and or columns generally produce competing patches of mode A and B, separated by a domain wall. By breaking the symmetry between mode A and B, using locally smaller or larger holes, we can control the seeding of mode A or B. Using multiple defect holes, we can thus control the frustration in the sample, which we show has a significant effect on its mechanical properties, and can lead to instabilities and snapping.

Together, the work in this thesis opens new routes to study the complex pathways in frustrated materials by using rationally designed, frustrated metamaterials.