Programmable mechanical metamaterials

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Summary

Chapter 1

Metamaterials are artificially designed materials with properties that may not be found in nature. They derive these properties from their architecture rather than their composition, and are often constructed through a tiling of micro-structured unit cells. Metamaterials were first introduced in optics to create materials with a negative refractive index, which could be used to develop perfect lenses or invisibility cloacks.
The concept of obtaining extraordinary material properties by designing the micro-structure of a material is also applicable beyond optics. In mechanical metamaterials the materials response to a deformation is tuned by the precise design of the micro-structure. For example, materials with a negative Poisson's ratio (also known as auxetic or dilational materials) have been developed. These materials expand (contract) in the transverse direction when stretched (compressed) in the axial direction. An important limitation common to all these metamaterials is that each mechanical functionality requires a different structure. In this thesis, we present a novel strategy to overcome this limitation and create programmable mechanical metamaterials, where the response of a single structure is determined and can be changed by the amount of lateral confinement.

Chapter 2

The metamaterials described in this thesis are made from quasi 2D elastic sheets of rubber perforated by a square array of holes of two different, alternating, diameters. We call these samples biholar. Compressing this biholar patterned sheet will result in a pattern transformation, from spherical holes to orthogonal ellipses. The orientation of the ellipses in the compressed state depends on the direction of compression. When compressed in the x-direction (y-direction), the major axis of the large ellipses is orientated in the vertical (horizontal) direction. We call this pattern x-polarized (y-polarized). When compressing in both directions, there is a competition between x and y-polarized patterns which leads to nontrivial mechanics.
We first impose a confinement in the x-direction, using laser cut acrylic clamps, and then measure the force resulting from a uniaxial deformation in the y-direction. Furthermore the polarization of the holes is tracked using image analysis. Depending on the amount of lateral confinement we observe four different mechanical regimes: (*i*) For small lateral confinement, the applied vertical deformation force increases monotonically and the polarization smoothly grows from its initial negative value to positive values. (*ii*) For moderate confinement, the force becomes nonmonotonic and the increase in polarization gets focussed in the ”negative slope” regime but remains monotonic. (*iii*) For larger confinement, the force resulting from the vertical deformation exhibits a hysteretic transition with a corresponding hysteretic switch from x- to y-polarization. (*iv*) For high confinements, the material becomes increasingly strongly x-polarized for increasing vertical compression and does no longer switch to a y-polarized state, and the force is again smooth and monotonic. These four different mechanical regimes are also observed and studied in numerical simulations and in a simple theoretical model.

Chapter 3

In this chapter we describe the theoretical model in more detail. The mechanics of the biholar sheet is modeled by rigid rectangles connected by hinges at their corners. This simple model demonstrates a similar pattern transformation when compressed in the vertical or horizontal direction.

By adding a set of linear springs, a force resulting from a deformation in the vertical direction can be computed as function of lateral confinement, and we find the same four qualitatively different mechanical regimes as in chapter 2. Moreover, we understand these regimes by calculating the equilibrium branches, and stable and unstable paths, followed by this biholar mechanism when it is deformed.

Chapter 4

Here we study the role of geometry, both experimentally and numerically for the mechanics of biholar metamaterials. There is a range of horizontal confining strains for which the resistance to compression becomes non-monotonic or hysteretic - in a range of compressive vertical deformations. We show how the dimensionless geometrical parameters that characterize the wall thickness and size ratio of the holes that pattern these metamaterials can significantly tune these ranges of deformations where the non-trivial mechanics is present. For small biholarity, when all the holes are (almost) of equal size, there is hardly any competition between horizontal or vertical compression, and the transition between the four different regimes as function of lateral confinement is not present. For large biholarity, small holes appear to become irrelevant, and the regime transitions are absent. For small wall thickness, the ranges of strains required to observe the four regimes become small but finite. For large wall thickness, the required strains become so large that deformations become localized near the boundaries, and the regime transitions are lost. Programmability is optimal for moderate values of wall thickness and biholarity.

Chapter 5

In the final chapter we present a systematic study of the effect of clamping locations on the mechanical response and programmability of biholar metamaterials. We find that clamping leads to inhomogeneities in the materials polarization, which can cause sharp domain walls to form between x- and y-polarized patches. These domain walls can either propagate through the bulk or get trapped near the boundary, and this behavior can be controlled by the clamping conditions. This leads to a complete new “barcode” programmability of our biholar metamaterials, where the location or absence of clamps at certain locations can be used to strongly influence the mechanical response of our materials to uniaxial compression.