BUCKLING-INDUCED CHIRALITY IN CELLULAR STRUCTURES

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Summary Here we exploit mechanical instabilities to predictively understand new classes of centrosymmetric structures that can be rapidly and reversibly switched between achiral and chiral configurations with single handedness over a wide range of length scales and over large areas, as required for many applications such as optical filters and sensors. Using a combination of analysis and experiments, we uncover the underlying mechanical principles and provide predictive descriptions. Traditionally, mechanical instabilities have been viewed as an inconvenience, with research focusing on how to avoid them; our results transform this prospective and demonstrate that they can be exploited to create materials with novel, switchable functionalities. Buckling allows the switching between achiral and chiral configurations to be fast, reversible and the mechanism is strong, robust and works over a wide range of length scales.

INTRODUCTION

Chirality is important in understanding and controlling the behavior of living and non-living systems because the presence or absence of chirality in the material plays important roles in its interactions with molecules [1], mechanical stress [2], and light [3]. These characteristics are irreversible and there is no known example that chirality can be dynamically switchable depending on the stimuli. Moreover, processes that induce chirality have been extensively studied at the molecular and macroscopic scales, but they have been relatively unexplored at the mesoscale whose length scale is relevant for optical applications. We are going to investigate possible approaches for making dynamic chiral structures, opening avenues for the fabrication of novel optical metamaterials.

Materials with significant porosity, generally termed cellular solids, exhibit properties that differ from those of their solid counterparts. Lattice structures may significantly change their architecture in response to diverse stimuli as a result of mechanical instabilities [4]. Beyond the instability threshold, rapid and dramatic changes of the structural geometry occur [5] and the interconnectivity provided by the micro-structures allow an effective transmission of the local patterns induced by buckling to their neighboring cells, thus potentially yielding uniformly patterned structures. For elastic materials the geometric reorganization occurring at instability is both reversible and repeatable and it occurs over a narrow range of the applied load, so that it can be exploited to design materials with switchable functionalities.

We are going to exploit mechanical instabilities to predicatively understand new classes of centrosymmetric structures that can be rapidly and reversibly switched between achiral and chiral configurations with single handedness over a wide range of length scales and over large areas, as required for many applications such as optical filters and sensors. Using a combination of analysis and experiments, we will investigate the underlying mechanical principles and provide predictive descriptions. Traditionally, mechanical instabilities have been viewed as an inconvenience, with research focusing on how to avoid them; our results will transform this prospective and demonstrate that they can be exploited to create materials with novel, switchable functionalities. Buckling allows the switching between achiral and chiral configurations to be fast, reversible and the mechanism is strong, robust and works over a wide range of length scales.

SURFACE-ATTACHED CELLULAR STRUCTURES

We focus on elastic 2D surface-attached cellular structures and use swelling to trigger the instability (Fig. 1). Because of the constraint provided from the substrate, the plates forming the cellular structure will buckle above a critical level of swelling, leading to a cooperative buckling cascade and resulting in either chiral or racemic configurations with single handedness over large areas. We identify the underlying mechanical principles based on analytical predictions and finite element simulations, fabricate structures based on the modeling, and characterize their properties.

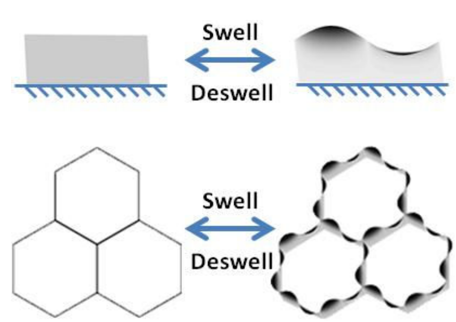

Figure 1 Schematic of the swelling-induced pattern formation. (Top) Side view showing the buckling of a single cell wall. (Bottom) Top view showing the critical mode of a surface-attached honeycomb.

By rational design based on modeling, we experimentally demonstrate the controlled reversible switching between achiral and chiral configurations using swelling/de-swelling of surface-attached cellular structures. Importantly, the buckling patterns and the associated symmetry reduction of the initially achiral centrosymmetric structures could be tuned, simply by changing their dimensions. This approach opens the way to deterministically select to select the appearance of either mixed (racemic) or chiral phases. In the case of chiral transformations, spontaneous symmetry breaking resulted in the formation of large uniform areas of structures of single handedness. The fundamental understanding of this process provides a general route to designing deterministically deformable structures with dynamically switchable mechanical and/or optical properties.

2D FREE-STANDING CELLULAR STRUCTURES

We also investigate the response of free-standing periodic porous elastomeric structures and find that two periodic patterns exist for which planar chirality induced by buckling is observed. Beyond the critical load, the thin ligaments between two adjacent voids buckle leading to a cooperative buckling cascade within the 2-D plate. Both micro-scale swelling experiments and finite element simulations are used to explore the underlying mechanics in detail and to show a proof of concept of the proposed structures. During swelling, the initial non-chiral pattern of the circular voids is transformed to a deformed pattern which exhibits planar chirality through buckling-induced symmetry breaking. In order to explore the effect of planar chirality, we perform an acoustic band structure calculation at different level of deformation. The planar chirality is found to strongly affect the in-plane phononic band gaps, providing opportunities for tunable phononic band structures.

CONCLUSIONS

We report a general approach in which loading controls the reversible switching between achiral and chiral structures by a buckling instability. Using surface-attached cellular structures and 2D porous plate structures as a model cellular structures, we show that one can control buckling-induced pattern formation by changing the aspect-ratio of walls and the pores arrangement, respectively. The underlying principle is scalable and it can be applied to various material systems as there is no characteristic length scale and the loading is the only parameter that triggers pattern transformation. Our findings can provide a new way of dynamically switching mechanical and/or optical properties depending on stimuli by inducing structure transformation and can be potentially utilized for applications such as controlled wetting , phononic switching, and tunable optical grating .

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