Harnessing Instabilities to Design Tunable Architected Cellular Materials

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Abstract

Mechanical instabilities are traditionally regarded as a route toward failure. However, they can also be exploited to design architected cellular materials with tunable functionality. In this review, we focus on three examples and show that mechanical instabilities in architected cellular materials can be harnessed (*a*) to design auxetic materials, (*b*) to control the propagation of elastic waves, and (*c*) to realize reusable energy-absorbing materials. Together, these examples highlight a new strategy to design tunable systems across a wide range of length scales.

INTRODUCTION

Architected cellular materials with well-defined periodicity are ubiquitous not only in nature, but also in synthetic structures and devices (1). These materials offer unique properties, including light weight (2), high-energy absorption (3), and the ability to control the propagation of waves (4). Although the study of the mechanical response of such materials has a long history (1), recent technical developments in both fabrication and analysis have opened exciting opportunities for the design and realization of architected materials with unprecedented properties. On one hand, advances in fabrication, including projection microstereolithography (5), two-photon lithography (6–8), and so-called pop-up strategies (9–15), are enabling fabrication of materials with intricate and precisely defined cellular architecture. On the other hand, the integration of finite element analysis capable of capturing the highly nonlinear response of such materials with new optimization algorithms is offering a systematic framework for navigating the design space (16).

Because the properties of architected materials are governed primarily by their geometry, an intriguing avenue is to incorporate internal mechanisms capable of altering the materials' spatial architecture in situ, therefore enabling the creation of materials that have tunable functionality. In particular, one recent finding is that buckling in elastic architected cellular materials may trigger dramatic homogeneous and reversible pattern transformations (17–20). For elastic materials, the geometric reorganization occurring at the onset of instability is both reversible and repeatable and occurs over a narrow range of applied load. Therefore, such reorganization provides new opportunities for design of materials having properties that can switch in a sudden but controlled manner.

Below, we provide three representative examples that illustrate how instabilities can be harnessed to design architected cellular materials with new functionality.

HARNESSING BUCKLING TO DESIGN AUXETIC ARCHITECTED CELLULAR MATERIALS

When materials are elastically compressed (stretched) along a particular axis, they are most commonly observed to expand (contract) in directions orthogonal to the applied load. The property that characterizes this behavior is the Poisson's ratio, which is defined as the ratio between the negative transverse and longitudinal strains. The majority of materials are characterized by a positive Poisson's ratio, which is approximately 0.5 for rubber and 0.3 for glass and steel. Counterintuitively, materials with a negative Poisson's ratio (also referred to as auxetic materials) will contract (expand) in the transverse direction when compressed (stretched).

The first reported example of an artificial auxetic material was a foam with reentrant cells that unfolded when stretched (21). Following this seminal work, a number of 2D geometries and mechanisms have been proposed to achieve macroscopic negative Poisson's ratio (21–26). In particular, networks of rigid units that rotate relative to each other result in auxetic behavior (27). This mechanism, in its most ideal form, may be constructed in 2D by using rigid polygons connected together through hinges at their vertices. Upon application of uniaxial compressive (tensile) loads, the rigid polygons rotate with respect to each other to form a more closed (open) structure, giving rise to a negative Poisson's ratio. Although this mechanism results in large negative values of the Poisson's ratio [networks made of squares and triangles have in-plane Poisson's ratios of -1 (27)], one drawback of these configurations in practical applications is that a large number of hinges and rotating elements is required to achieve the intended motion.

Recently, it has been shown that buckling in periodic cellular materials can be harnessed as a possible mechanism for realizing auxetic materials based on rotating units without use of rotating

hinges. The simplest example of a buckling-induced auxetic response is provided by a square array of circular holes embedded in an elastomeric sheet (19). When such a structure is uniaxially compressed, buckling triggers a sudden transformation of the holes to a periodic pattern of alternating, mutually orthogonal ellipses (17) (see **Figure 1*a***). Importantly, this transformation is also accompanied by synchronous rotation in opposite directions of the square domains defined by the holes. Such rotations result in a pronounced negative Poisson's ratio (19), which is retained over a wide range of applied strain (see **Figure 1*b***). Inspired by the rich behavior of this simple system, researchers have also discovered buckling-induced auxetic behavior in planar porous structures with rotating units of different shape [obtained either by changing the arrangements of the circular holes (28) or by altering the shape of the pores (29)] and in 3D structures with periodic architecture (30, 31).

These findings of buckling-induced auxetic behavior provide a fundamentally new way of generating materials with a negative Poisson's ratio and offer a range of advantages: (*a*) The auxetic behavior can be achieved in structures with simple geometry, (*b*) the proposed design can be applied to various length scales, and (*c*) the auxetic behavior is retained over a wide range of applied strain.

HARNESSING BUCKLING TO CONTROL THE DYNAMIC RESPONSE OF ARCHITECTED CELLULAR MATERIALS

In recent years, architected cellular materials have also received increasing interest because of their ability to control the propagation of elastic waves (32), opening avenues for a broad range of applications, such as wave guiding (33, 34), cloaking (35), noise reduction (36–38), and vibration control (39, 40). An important characteristic of these structured systems is their ability to tailor the propagation of elastic waves. An important characteristic of these structured systems is their ability to tailor the propagation of elastic waves through the existence of band gaps—frequency ranges of strong wave attenuation—which can be generated by either Bragg scattering (41) or localized resonance within the medium (42). Architected materials with band gaps generated by Bragg scattering are typically referred to as phononic crystals, whereas systems in which local resonance is exploited to attenuate the propagation of waves are referred to as locally resonant metamaterials.

Most of the proposed architected cellular materials designed to control the propagation of elastic waves operate in fixed ranges of frequencies that are impractical to tune and control after the assembly of the system (43–48). Although the dynamic responses of structures could be altered by mechanically deforming them (49–51), a large amount of loading is typically required to significantly affect the position and width of the band gaps.

Recent studies indicate that the tunability of phononic crystals and acoustic metamaterials can be significantly enhanced by triggering mechanical instabilities along the loading path. If we focus on the structure presented in **Figure 1** (i.e., a square array of circular holes in an elastomeric matrix), it has been numerically shown that the pattern transformations occurring at instability strongly affect the phononic band gaps of the material (52, 53). More specifically, in the postbuckling regime, some of the preexisting band gaps close, and new ones open (see **Figure 2**), opening avenues for the design of acoustic switches to filter sound in a controlled manner. The topological changes induced by the instability also significantly affect the wave directionality. In the undeformed (prebuckling) configuration, the structure is anisotropic, with larger wave speed along preferential directions corresponding to the maxima of the lobed pattern in **Figure 2*a***. In contrast, after buckling, the system behaves as an isotropic medium, and the group velocity becomes uniform with direction (53) (see **Figure 2*b***).

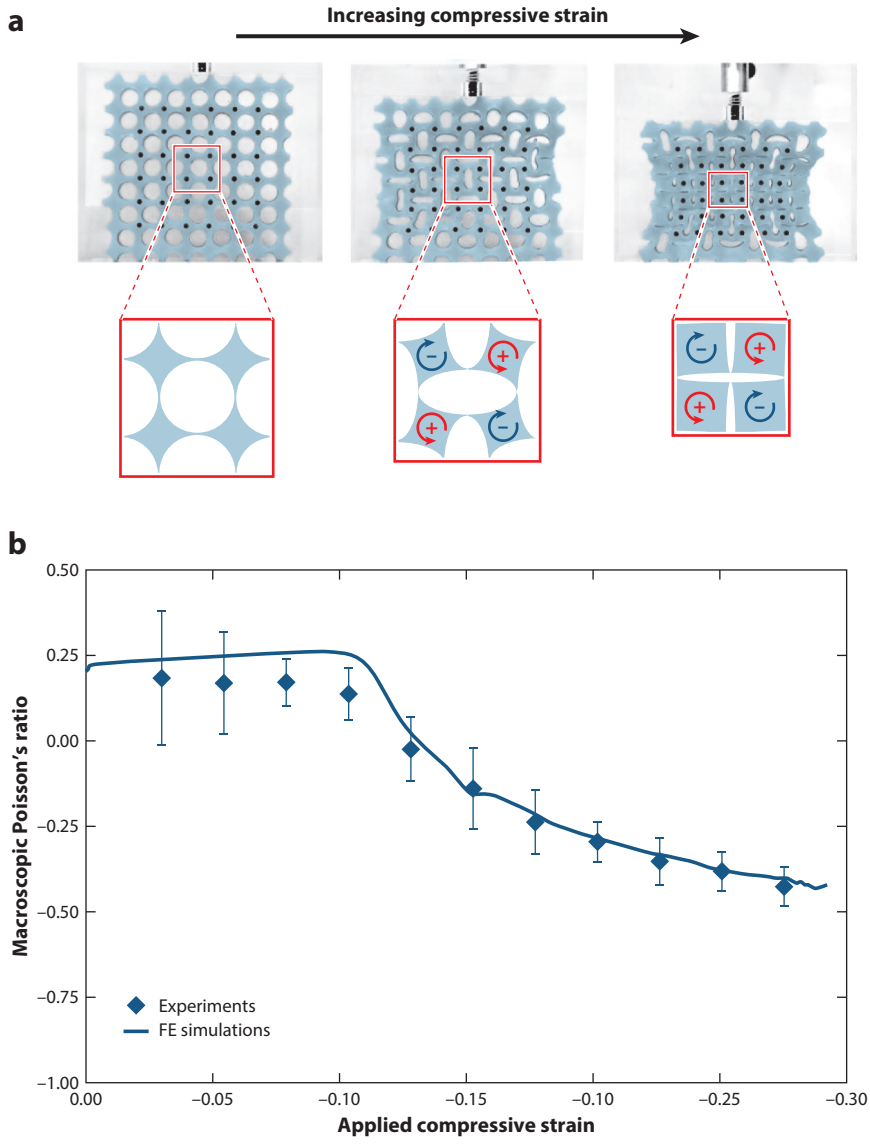

Figure 1

(*a*) Experimental images of an elastomeric structure (*colorized blue*) comprising a square array of circular holes for increasing values of the applied compressive strain. After instability, the lateral boundaries of the sample bend inward, a clear signature of negative-Poisson's-ratio behavior. Buckling is accompanied by synchronous rotation in opposite directions of the square domains defined by the holes. (*b*) Evolution of Poisson's ratio of the structure as a function of the applied compressive strain. FE denotes finite element. Adapted with permission from Reference 29.

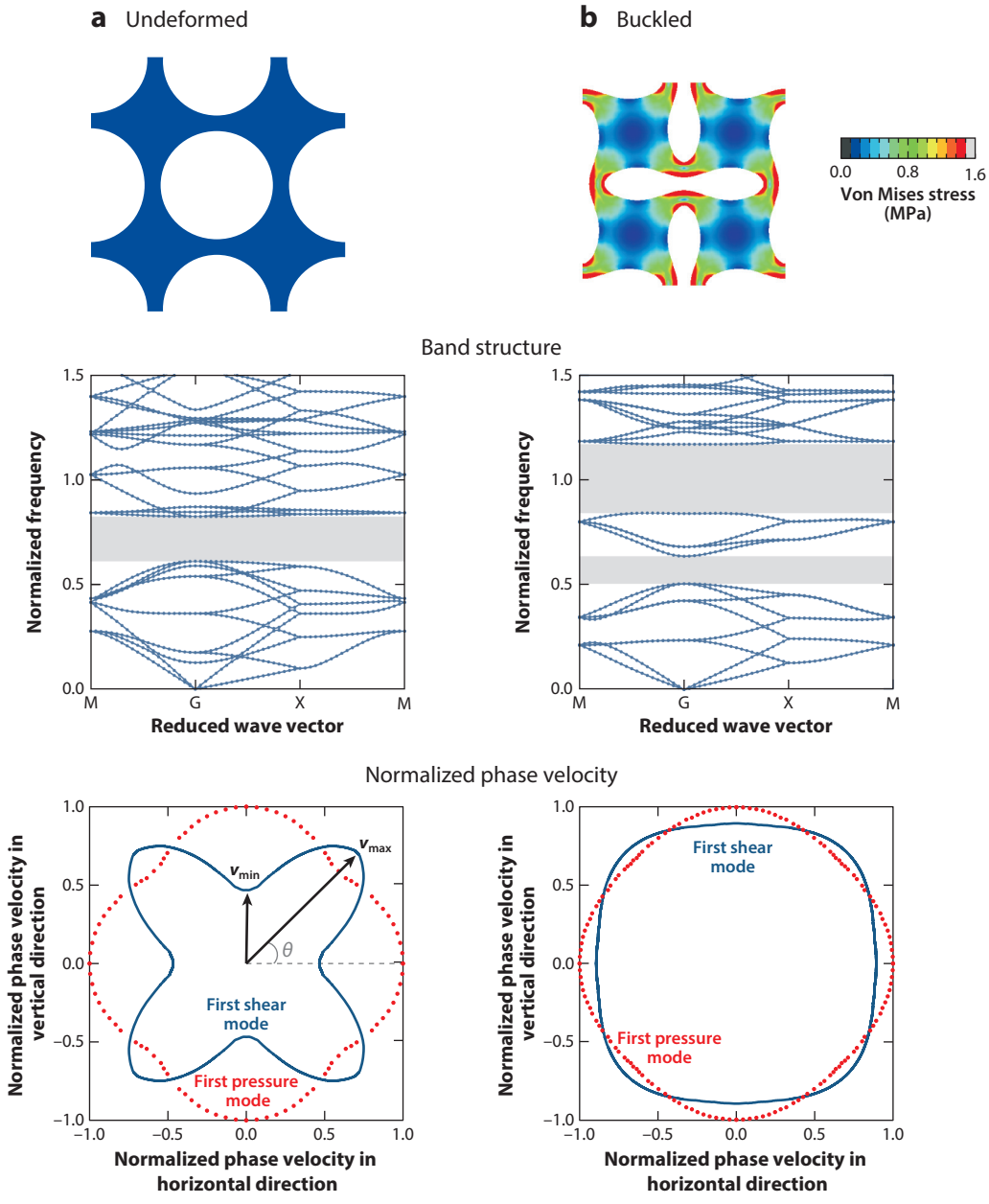

Figure 2

Phononic band structure and wave directionality for a square array of circular voids in an elastic matrix subjected to uniaxial compression (*a*) in the underformed configuration and (*b*) after buckling. v denotes normalized phase velocity. The direction of propagation is indicated by θ. Adapted with permission from Reference 53.

Although the effect of instabilities on the dynamic response of architected cellular materials was first demonstrated numerically for a square array of circular holes in an elastomeric matrix (52), the concept was recently extended to a number of systems, including hexagonal (54) and hierarchical (55) lattices; multilayers (56); locally resonant metamaterials (57); lattices with curling, soft, auxiliary microstructural elements (58); and 3D architectures (59). Moreover, the effect of buckling on the propagation of elastic waves has also been experimentally verified in both phononic crystals (60) and locally resonant metamaterials (57). Finally, because elastic instabilities persist to the submicrometer scale (18, 61), the changes in the architecture induced by the applied deformation can also be exploited to significantly alter the optical transmittance of photonic crystals (62).

HARNESSING BUCKLING AND BISTABILITY TO DESIGN REUSABLE ENERGY-ABSORBING ARCHITECTED MATERIALS

Energy-absorbing materials are widely deployed for personnel protection, for crash mitigation in automobiles and aircrafts, and for protective packaging of delicate components. Many strategies, including plastic deformation in metals (1, 63–65), fragmentation in ceramics (66), and rate-dependent viscous processes (1, 67, 68), have been investigated to create materials that efficiently dissipate mechanical energy. However, all these systems present challenges associated with either reusability or rate dependency. Architected cellular materials were recently fabricated in novel geometries to realize recoverable energy-absorbing behavior in elastic systems (6, 69–74), suggesting novel strategies for mechanical dissipation of energy.

On the one hand, ultralow-density, hollow metallic and ceramic microlattices can fully recover from large compressive strains while dissipating a considerable portion of the elastic strain energy (6, 71). This mechanism is related to coordinated local buckling of individual bars, which generally occurs in a layer-by-layer fashion. Upon macroscopic compression, individual lattice bars locally buckle (generally near the nodes) and subsequently undergo large rotations to accommodate the global lattice strain. This results in a nearly flat stress plateau from which the material can fully recover after unloading (see **Figure 3**). As such, the amount of energy dissipated by the microlattices during an entire cycle is given by the area within the hysteresis loop. Although hollow metallic microlattices can provide an excellent platform for vibration isolation, a drawback is that buckling-related damping, the unique and dominant damping mechanism used by hollow microlattices, requires relative densities well below 1%, limiting the strength, stiffness, and energy absorbed per unit volume that microlattices can achieve.

On the other hand, bistable elastic elements have been recently used to create fully elastic and reusable energy-trapping architected materials (72–74). In contrast to typical elastic units that

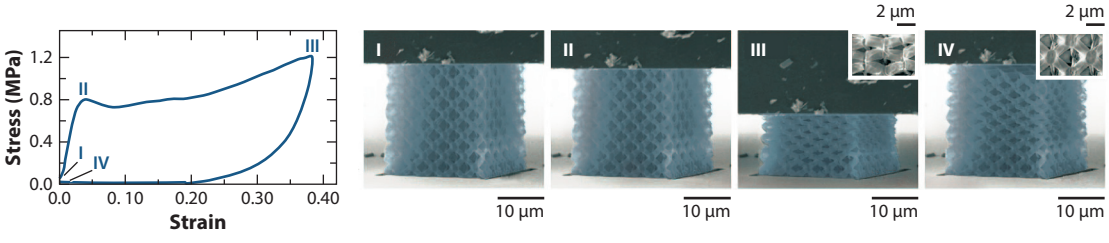

Figure 3

Mechanical data and still frames (*colorized blue*) from a compression test on a thin-walled nanolattice demonstrating the slow, ductile-like deformation, local shell buckling, and recovery of the structure after compression. Adapted with permission from Reference 6.

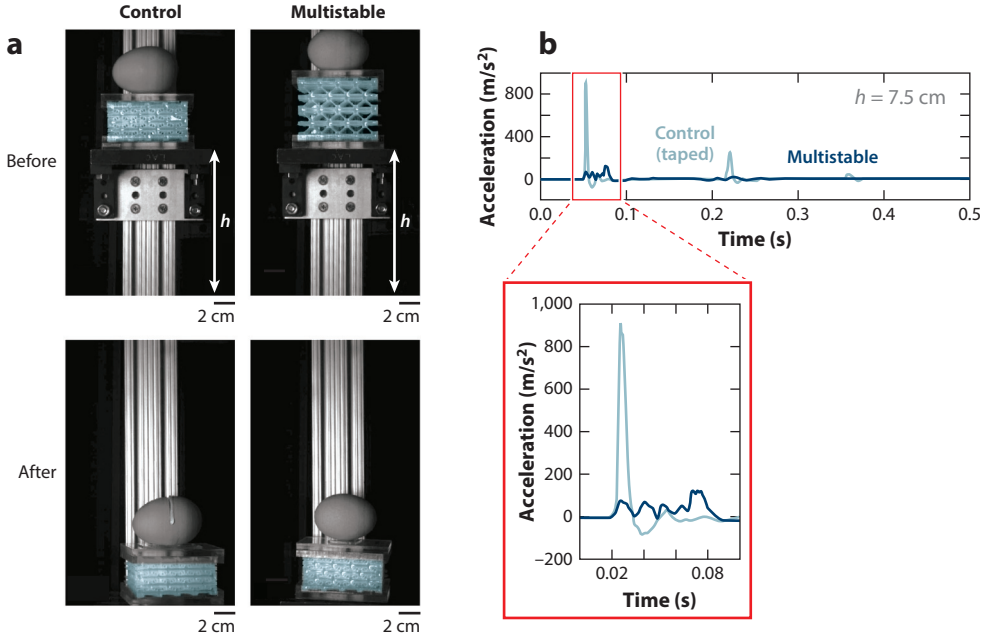

Figure 4

(*a*) Comparison of drops of multistable and control elastomeric samples (*colorized blue*). Controls consisted of the same structures, but taped to make all beams intentionally precollapsed prior to the drop test. Raw eggs attached to the top of the structures were dropped from $h = 12.5$ cm. The eggs attached to the multistable structures survived, whereas those on the control samples broke upon impact. (*b*) Acceleration-time curve for a multistable structure and the corresponding control sample dropped from $h = 7.5$ cm. Adapted with permission from Reference 72.

recover their initial shape when unloaded, bistable elements snap between two different stable configurations and retain their deformed shape after unloading. As such, they are capable of locking in most of the energy imparted into the system during loading and can therefore be used to realize energy-absorbing materials. The concept was first demonstrated with systems comprising arrays or bistable elastomeric beams (to achieve the required large deformation behavior without material failure; see **Figure 4**) (72, 73). This strategy offers several advantages, as it can be applied to structures with length scales from micro to macro, the loading process is fully reversible (allowing the structures to be consistently reused), and the energy absorption is unaffected by loading rate or history. However, the strategy results in architected materials that typically exhibit fairly low strength. To address this issue, systems comprising bistable triangular frames were recently proposed (74). The resulting multistable materials are orders of magnitude stronger than previously published concepts and can be realized in virtually any constituent (polymer, metal, ceramic, or composite).

CONCLUSIONS

In summary, mechanical instabilities of architected cellular materials have recently opened exciting new research directions. Although mechanical instabilities have been traditionally viewed as failure modes, the postbuckling regime allows for dramatic reconfigurations that can be exploited for function. Given the importance of the architecture in setting the properties, the underlying principles are scale independent and can be applied to design tunable architected materials over

a wide range of length scales, ranging from meter-scale architectures to nanoscale photonic systems. However, viscoelasticity, plasticity, fracture, and other phenomena can introduce additional timescales and length scales that may compromise the geometric universality of the buckling modes.

In the future, some of the exciting opportunities include coupling the mechanics of architected materials with other phenomena, such as adhesion, friction, and flow; incorporating sensing and control functionalities into architected systems to design materials capable of autonomously responding to changes in the surrounding environment; and developing architected materials for which topological properties bring new phenomena.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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