

Phase transforming cellular materials



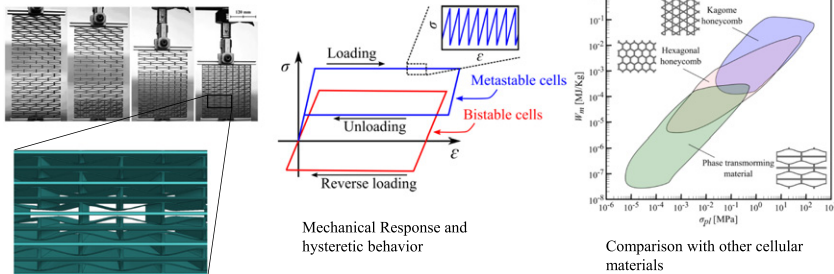
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GRAPHICAL ABSTRACT

Phase Transforming Cellular Material (PXCM)



HIGHLIGHTS

- We extend the notion of phase transformations to cellular materials (CMs).
- Phase transformations in CMs are due to changes in the unit cell configuration.
- Each stable configuration of a unit cell corresponds to a distinct PXCM phase.
- Phase transformations associated with snapbacks allow PXCMs to exhibit hysteresis.
- Energy dissipation in PXCMs occurs in the elastic regime of the base material.

ARTICLE INFO

Article history:

Received 22 May 2015

Received in revised form 10 August 2015

Accepted 10 August 2015

Available online 13 August 2015

Keywords:

Cellular materials

Phase transformation

ABSTRACT

We extend the notion of phase transformations to periodic cellular materials by introducing materials whose unit cells have multiple stable configurations. Each stable configuration of the unit cell corresponds to a stable phase, and transitions between these phases are regarded as phase transformations of the cellular material. We present a cellular material that exhibits phase transformation, identify key elements of the unit cell geometry that yield its mechanical behavior and introduce an analytical model that describes its constitutive behavior. Cellular materials that exhibit phase transformations show hysteresis and their response is characterized by a long serrated loading and unloading plateaus, making these materials attractive for energy absorption applications. While these phase

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Energy absorption
Compliant bistable/metastable mechanism

transforming cellular materials offer an energy absorption performance that is comparable to metal and polymeric honeycombs, the key difference is that the deformation on these materials is fully recoverable.

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1. Introduction

Active materials like shape memory, ferroelectric and magnetostrictive alloys obtain their characteristic properties due to phase transformations [1–4]. In these materials, phase transformations occur by changing the packing arrangement of the atoms in a process that resembles multistable mechanisms switching between stable configurations [5,6]. A similar behavior has been observed in folded proteins in which phase transformations (i.e. the change from folded to unfolded configuration) provide the mechanisms through which biological materials obtain remarkable properties like combinations of strength and toughness, superelasticity, shock energy dissipation, among others [7–10].

In this work, we extend the notion of phase transforming materials to cellular materials whose base material does not necessarily exhibit phase transformations at the atomic level. To this end, we define a phase transformation in a cellular material as the change in geometry of its unit cell from one stable configuration to another stable (or metastable) configuration while keeping its original topology. The capability of a cellular material to undergo phase transformation is attained mainly by a proper choice of an elastic base material and, the topological and geometrical design of the unit cell in order to allow the elastic reversibility of the transformation. We present a phase transforming cellular material (PXCM) whose unit cells comprise compliant bistable or metastable mechanisms (see the schematic representations in Fig. 1(a)–(b)). Such mechanisms exhibit a force–displacement behavior characterized by two limit points $((d_I, F_I)$ and $(d_{II}, F_{II}))$ that lead to three regimes in their mechanical response: Regimes I and III are characterized by a positive stiffness as they represent the deformation of stable configurations of the unit cell. These configurations correspond to local minima in the potential energy response of the mechanism. Regime II is characterized by a negative stiffness and corresponds to a transition of the mechanism from one limit point to another [11,12]. In the case of a metastable mechanism, the second stable configuration corresponds to a special case of stability in which a sufficiently large disturbance along a specific direction can cause the mechanism to revert to its first stable configuration, which has a lower potential energy (Fig. 1(b)) [13]. A metastable mechanism in the unit cell of a PXCM allows the material to undergo large deformations and return to its original configuration once the load is released. This behavior is similar to the pseudo-elasticity exhibited by superelastic shape memory alloys. On the other hand, a material with a bistable mechanism unit cell exhibits two stable phases. A region of the PXCM is said to be in phase 1 when all its cells are in

the first stable/metastable configuration; and similarly for phase 2.

The outline of the rest of this article is as follows: We introduce a PXCM design and analyze its mechanical behavior in Section 2. The experimental validation of the PXCM design is presented in Section 3, followed by an analysis of the energy dissipation characteristics of PXCMs in Section 4. Some concluding remarks and potential future applications are given in Section 5.

2. Phase transforming cellular material (PXCM)

In this paper we focus our analysis on the PXCM shown in Fig. 2(a), whose unit cell is formed by two sinusoidal beams with the shape given by: $y = (A/2)[1 - \sin(2\pi(x - \lambda/4)/\lambda)]$, thickness t , depth b , wavelength λ and amplitude (peak to valley) A that are connected by stiffening walls of thickness $1.5t$. One half of the symmetric unit cell is shown in Fig. 2(b). Each sinusoidal beam acts as a compliant bistable/metastable mechanism while the stiffening walls provide local support to prevent transverse displacement at the ends of the sinusoidal beams. A characteristic stress ($\sigma = F/(w \cdot b)$)–strain ($\varepsilon = \delta/L$) response for a PXCM specimen is shown in Fig. 2(c) in dash-dotted line, where F is the total force applied on the specimen and δ is the corresponding displacement of the specimen. The PXCM exhibits a linear stress–strain response until the first row of sinusoidal beams collapses at a peak stress, and switches to the other stable configuration; this corresponds to a phase transformation for this row. The subsequent collapse of each row of sinusoidal beams leads to a serrated stress–strain path that is characterized by an average plateau stress σ_{pl} [14–16]. The progressive collapse nature of this process, as shown in Fig. 2(d), is due to a distribution of small imperfections that trigger the rows at slightly different values of (but close to) σ_{max} . A similar behavior occurs under unloading, but now the initiation of phase transformation occurs at σ_{min} . σ_{min} is positive for a unit cell with a metastable mechanism and is negative for a unit cell with a bistable mechanism. The serrated behavior is caused by the softening of the material response, when one row of cells is undergoing phase transformation, and the subsequent hardening, once the phase transformation is completed. It should be mentioned that, while the PXCM shown in Fig. 2(a) is a 2D cellular material, phase transformations takes place only for loads in the y -direction. We regard this as a 1D PXCM material and the current investigation is focused on the mechanical behavior in the y -direction.

For the PXCM design presented in this paper, we employ only one base material and postulate that the unit cell can be tailored to exhibit either bistable or metastable

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