Mechanical Investigation of Phase-Transforming Cellular and Origami Materials

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Abstract
Cellular materials, such as honeycombs and metallic foams, have attracted much attention due to their exceptional ability to absorb and diffuse mechanical energy. These materials have a wide range of applications, such as improving vehicle crash safety and helmet impact resistance. However, many of these materials are rendered unusable after one application because its energy absorption capacity is based mainly on the ability of the cellular material to dissipate energy by plastic deformation or damage. In contrast, Phase-transforming cellular materials (PXCMs) utilize bistable or metastable mechanism designed to remain in the elastic regime of its base material, as a means to dissipate energy from impact loads. In consequence, PXCMs have the added benefit over other cellular structures due to its reusability.

In this study, three PXCM designs are discussed and examined to determine their energy absorption capabilities: the common bending straw’s ribbed mechanism, the Kresling pattern cylinder, and a sinusoidal beam mechanism. These designs were tested under cyclic compression-tension loading and their force-displacement curves were examined. These tests showed that all three designs exhibit significant energy absorption behaviors. Each design shows promise, warranting further detailed study of their full properties.

Keywords
Phase transformation, cellular materials, energy absorption, origami.

1. Introduction

In the design of any building, safety equipment, or vehicle, the safety of the occupants is of the utmost importance. The invention of novel energy-absorbing materials and structures to improve the impact resistance of such objects is a subject that has been given a large amount of attention in recent years. Among them, Phase-Transforming Cellular Materials (PXCMs) have been designed to absorb energy by deforming under compression or tension while transforming between different stable configurations [1]. PXCMs have many of the energy-absorbing properties of other cellular materials with the added benefit of being reusable and reversible [1]. These PXCMs have applications ranging from improving upon vehicle crash safety to creating helmets with greater impact resistance.

Cellular materials consist of a foam, grid, lattice, or other structure which defines and separates individual geometric cells. These materials have been available for some time, but have only recently attracted attention due to advances in manufacturing technology improving upon the cost-effectiveness of their use [2]. These materials are known for possessing a variety of properties, the most relevant of which to this project is their superior ability to absorb and diffuse mechanical energy. This is accomplished by a combination of buckling within the material resulting in crumpling, friction between internal structural members, and viscous interaction between the material and the fluid filling its cells [3]. A significant amount of research has gone into determining optimal cell geometries and topologies [4-6], testing different component materials and manufacturing techniques [7-9], and developing new substructures and fillers for the material’s cells to optimize performance [10-12], as well as testing new applications for cellular materials [13,14]. In particular, hexagonal and kagome lattices are well-researched for their ease of production and exceptional performance [1,4]. However, many of these materials and solutions have the problem of being rendered unusable after one application. PXCMs solve this problem by directing load into
internal bistable or metastable mechanisms, which snap from one stable configuration to another, rather than buckling, crumpling, or performing any other plastic deformations [1]. If bistable mechanisms are used, once deformed, these materials can then simply be deformed in the opposite direction to return to their original state, since the material remains in a state of elastic deformation and never yields. If a metastable cell design is used, the cell will “bounce” back to its original state.

A recently-developed design described and tested by Restrepo, et al. consists of unit cells which direct one-dimensional forces applied to them through a sinusoidal beam [1]. Sinusoidal beams have been shown to exhibit bistable behavior even when not pre-stressed during fabrication, and have several parameters (such as wavelength, in-plane and out-of-plane thickness, and wave amplitude) which can be tweaked to modify a PXCM’s properties [15]. Since pre-stress is not necessary, this design of PXCM can easily be extruded, 3D printed, or cut in profile by a laser or water jet, and can be constructed from a variety of materials. However, only 3D printing plastics have so far been studied in PXCM applications, so further testing of sinusoidal PXCMs constructed from new materials is warranted. This sinusoidal design is one subject investigated by this study. However, this new sinusoidal cell design is not the only structure which exhibits bistable behavior. Other such cells could also be useful in the development of PXCMs. One such cells is the bistable rib mechanism found in common bending straws. The flexible portion of a straw consists of consecutive rows of ribs, which in turn consist of rings connected by webbing. The tensile deformation of a single rib is shown in Figure 1. The initial state is shown as state A, which is the mechanism’s stable compressed state. As load is applied, the material deforms elastically until the structure reaches state B, after which the interior webbing expands again until the mechanism achieves state C, the stable expanded configuration of the mechanism. The reaction force from the straw is a result of a combination of the compression of the interior webbing, the compression of the interior ring, and the expansion of the exterior ring. This mechanism not only allows for axial expansion and compression, but also for stable bending as well. This is accomplished when one side of a rib undergoes phase transformation while the opposite side of the rib’s diameter remains in the initial stage, resulting in a change in the angle between the planes of the interior and exterior rings. It should be noted that this bistable mechanism only works when both interior and exterior rings are intact; straws which have been cut in half along their axis do not exhibit any bistable behavior. In this paper, only the effects of axial tensile loading of straws is investigated, though this mechanism’s ability to absorb mechanical energy from bending scenarios should also be investigated in future studies.

Yet another cell design of note is the origami Kresling pattern cylinder. This structure consists of identical triangular panels arranged in a helical pattern. Each panel is connected to another along its hypotenuse and with the opposite orientation to form an element, and each cell of a Kresling cylinder
consists of any number of these elements connected and wrapped into a cylinder. The cell design most thoroughly explored by Cai et al. [16], and the design investigated by this paper, consists of six elements per cell which form a hexagonal column (see Figures 2 and 3). For this number of elements in a cell, bistable behavior becomes evident when each triangular panel has a ratio between the lengths of its sides of 2:3:4, among other possible ratios. The ends of each cell rotate relative to each other (for a 6 element cell, the ends rotate by roughly 60°), and as they rotate the hypotenuse of each triangle is compressed. This continues until a certain angle of rotation is reached, at which points the hypotenuse expands again and the cell achieves its second stable state. This is the design investigated in this study.

Figure 2: 6 element Kresling pattern. Thick lines represent folds which are concave into the page, and thin lines represent folds that are concave out of the page.

Figure 3: Two Kresling cylinder cells in a column

The goal of this study is to test the performance and behavior of the new sinusoidal beam PXCM design, as well as the general behaviors of the ribbed cell design in bending straws and the Kresling pattern cylinder. Each design was tested through cyclic compression-tension loading, and their resulting force-displacement relations are examined for energy absorption behavior. The desired result from each of these designs is shown in Figure 4. Each material should show a linearly elastic force-displacement or stress-strain behavior during loading which is divided by sharp decreases in reaction force as each cell snaps through from its first stable configuration to its second. While unloading, the materials should show a similar “serrated” force-displacement relationship but with lower reaction forces, as each cell snaps back into its original configuration. The integral between these two force-displacement curves represents energy dissipated by the material (for stress-strain plots, it represents energy dissipated per unit volume).

Figure 4: Ideal PXCM stress-strain behavior [1]

Figure 5: Aluminum test specimen

2. Sinusoidal Beam Design
The test specimen (Figure 5) was constructed from aluminum 6061 (E=68.9GPa, \(\sigma_{\text{yield}}=276\, \text{MPa}\)) via water jet machining from a larger block. It consisted of a 5x6 array of cells and was defined with the following parameters as shown by Figure 6:

- \(L = 34.1\, \text{cm}\)
- \(w = 74.6\, \text{cm}\)
- \(b = 2\, \text{cm}\)
The specimen was tested in an MTS Insight 300 kN load frame equipped with a 100 kN load cell, using MTS TestWorks software (see Figure 7). The specimen underwent a single compression-tension cycle with a displacement rate of 5 mm/min over a total one-way displacement of 180 mm.

During the loading portion of the test, the grips were unable to completely prevent in-plane rotation, resulting in the specimen rocking back and forth as only three cells per row transformed at a time, rather than the entire row as the design is supposed to. This decreased the reaction force provided by the material to roughly half of the expected value calculated by the equations derived by Restrepo, et al. [1]. The specimen also slightly buckled out of plane in the early stages of the test, though this effect was mitigated as the test continued and the specimen was compressed. It is worth noting that as each cell compressed, the sinusoidal beam within the cell did not perfectly change phase.

During the unloading portion of the test, the reaction force decreased dramatically, but never switched to a negative value, implying the cells never underwent tension and were metastable, rather than bistable. Each row returned to its original configuration all at once as the material was expected to, however each cell showed some buckling of the sinusoidal beam and permanent plastic deformation. Near the end of the test, the fourth row of cells fractured completely, twice per cell, separating the top and bottom halves of the specimen (See Figure 8). It is suspected that either the rocking motion during compression applied bending moments to the material which weakened the specimen, or the water jet machining process weakened the material itself, or some combination of the two effects were at play. It is worth noting that the force display maintained a reading of 5 kN after the specimen fractured, far larger than the weight of the specimen and setup, indicating some drift or damage to the load cell.

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Despite the material failure, the design still displayed the desired serrated loading behavior, as shown by the stress-strain plot in Figure 9. Upon unloading the reaction force also oscillated slightly, indicating slight snapback behavior. There is also a large gap between the loading and unloading stress-strain curves, resulting in 1.278 kJ of energy dissipation. This energy was dissipated through a combination of sound, heat loss, and material deformation.

The results of one of these tests are shown in Figure 11. Snapthrough and snapback behaviors are both clear, with each peak corresponding to one of the ribs deforming; however, the applied load did not return to zero at the end of the cycle as expected. This could be a result of friction with the internal guide or of plastic deformation of the sample. The energy dissipated by this specimen was 0.0752 joules. Of note is the fact that the first two ribs deformed asymmetrically; one side of the rib changed phase before its other side did, leading to the double peaks seen in the loading curve. This behavior can also be observed when the straw is tested manually in bending modes, and additional study is warranted to determine the rib mechanism’s full bending behavior.

3. Bending Straw Rib
For the investigation into the bending straw’s ribbed mechanism’s behavior, common plastic bending straws with 11 ribs were used as specimens (See Figure 10). The exact material could not be determined; however, this was deemed acceptable as this study is only concerned with general behaviors. One of the first behaviors found was that, once expanded, the ribs buckle very easily, and are difficult to collapse uniformly. To create an internal guide in the test specimens which prevents this buckling, the straws were cut in half, and the side without the ribs was folded in two, then inserted into the other half of the straw. These specimens were then tested in an MTS Insight 10 kN load frame equipped with a 10 kN load cell. The specimen underwent a single compression-tension cycle at a rate of 2 mm/min over a one-way displacement of 14 mm.

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4. Kresling Pattern Cylinder
Test specimens were constructed from manila folders, as copy paper specimens did not produce reactions large enough for the material’s behavior to be visible through the noise. A property of Kresling pattern cylinders is the fact that without adjacent layers to reinforce the hexagonal shape of the cell’s ends, the mechanisms themselves are not bistable and cannot function. Therefore, layers on the ends of a cylinder require an endcap to both maintain the cell’s shape and to allow for the attachment of axles, which are required to apply uniform axial loading while
allowing rotation. For all but the single cell test, each specimen consisted of six cells. Specimens were tested in an MTS Insight 10 kN load frame equipped with a 10 kN load cell (see Figure 12), and unless otherwise stated, underwent a single compression-tension cycle over a one-way displacement of 180 mm at a rate of 20 mm/min.

The first test was of a specimen with completely free rotation, the results of which are shown in Figure 13. This design also shows strong snapthrough behavior in the loading curve, though the reaction force each cell provides before transforming increases as more cells achieve their second stable configuration. While unloading, the material exhibits two behaviors; it initially acts like a spring, with a strong linear correlation between force and displacement, before demonstrating snapback behavior more than halfway through the unloading process. This design also displayed an energy absorption of 0.455 J.

The results of a second test in which the cylinder’s rotation was resisted through friction, but not fully constrained, are shown in Figure 14. When compared to the free rotation test, it is clear the material performs better under these circumstances, producing reaction forces of higher magnitudes which facilitate a stronger energy dissipation of 0.854 J. However, if rotation is fully constrained, the cells of the Kresling cylinder are unable to transform and the entire structure buckles and becomes unusable. This has been observed through further tests. Figure 15 shows the force-displacement behavior of a single isolated cell. This cell on its own exhibited .039 J of energy dissipation, far less than a simple sixth of the result of the first test. This indicates each cell of the Kresling cylinder interacts with the others in an as-of-yet undetermined manner. Another point of note is that, like the bending straw, each Kresling specimen did not return to zero load at the end of the cycle, indicating some plastic deformation of the material.

Figure 12: Kresling pattern cylinder and bending straw rib test setup.

Figure 13: Free rotation Kresling cylinder test results. Video: https://youtu.be/yifFFVekkBQ [19].

Figure 14: Resisted rotation Kresling cylinder test results

Figure 15: Isolated single cell behavior
friction with the axles, or a combination of both. The Kresling cylinder’s snaphthrough and snapback behavior is also apparent when manually tested under torsion, and future tests are warranted to determine this design’s full behaviors.

5. Conclusions
Phase-transforming cellular materials (PXCMs) are an emerging class of material which show great promise in their ability to absorb and diffuse mechanical energy in a reversible and reusable manner. While the development of new PXCM structure designs is valuable, so too is the assessment of the performance of existing materials. The recently developed sinusoidal beam mechanism shows strong energy-absorbing behavior even under imperfect loading. However, new base materials and manufacturing techniques should be explored to fully determine this PXCM design’s effectiveness in industrial applications.

The common bending straw’s ribbed mechanism also displays similar behavior under axial loads, though its tendency to buckle under compression without an internal or external guide somewhat limits its usefulness. Further experimentation with material, size, and thickness is warranted to see if this effect can be mitigated, and other tests should be done in the future to determine the mechanism’s performance in bending.

Finally, the Kresling pattern cylinder also demonstrates energy absorption behaviors in situations where its rotation can be accounted for, but its inability to perform in situations with its rotation constrained limits its potential applications. Nevertheless, future testing of this design’s torsional behavior, as well as of ways to construct this design from more robust materials, could prove beneficial.

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References


