ADDITIVELY MANUFACTURED THERMALLY BISTABLE STRUCTURES

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ABSTRACT

This study aims to mimic the shape memory effect in polymers by proposing an innovative structural design. There is only a limited number of materials exhibiting the shape memory effect that enables programming the response of structures via temperature changes. In addition, the response to thermal load is considerably slow in those materials, and programming is required to guide the deformation of materials. In order to overcome these limitations, we resort to structural bistability to design a thermally bistable unit cell, which exhibits abrupt shape memory behavior without requiring any pre-programming. The bistable structures have a binary response to loading conditions, i.e., they can have two stable configurations, and they have been recently used in designing deployable structures. In the current study, we explore the effect of the wall stiffness of the structure on the bistability of a mechanically bistable element and its nonlinear response. Then, we utilize the thermal softening behavior of two different polymers to design a bistable bimaterial structure that restores its original shape when the environment reaches a specific temperature, referred here as triggering temperature. The proposed concept offers new opportunities to utilize bistable structures as self-sensing actuators, as they can be designed to deform in response to certain changes in temperature.

1 INTRODUCTION

As the name suggests, bistable materials and structures have two stable configurations; meaning that they can remain in a non-initial stable equilibrium after deformation. When a body undergo a permanent deformation, it is often irreversible since it may be associated with material failure or plasticity. However, bistable structures can demonstrate reversible permanent deformation. The long-known bistability concept has been recently revived due to its potential applications in soft robots [1], deployable structures [2, 3], actuators [4, 5], and reusable energy absorbers [6]. In addition, advances in additive manufacturing (AM), e.g., fused filament fabrication (FFF) and direct writing (DW), provide the means to fabricate multistable one-dimensional and two-dimensional structures with tailored buckling for restorable shock absorbers [7, 8]. The variety of topologies proposed for bistable architectures paves the path for designing structures with targeted stable configurations.

Bistable structures can have two stable initial and deformed configurations, which is called binary response. This binary response enables the utilization of bistable structures in the design of smart devices [12, 13], where we require a key or structure which can transform between two different states by applying a load. However, specific applications may require a robot or an actuator that reacts to a non-mechanical environmental stimulus. As a result, a few investigations tried to design and fabricate bistable structures whose deformation can be controlled and programmed by magnetic [14-16], electric [4], thermal conditions [17, 18], and liquid diffusion [19]. Magnetic actuation of bistable structures allows fast transformations between complex 3D printed ferromagnetic materials [14]. The possibility of reprogramming bistable actuators through applying a magnetic field was also demonstrated through tessellated mechanical metamaterials with stable memories [15]. Reconfiguring a structure to its second stable configuration by applying an electrical field was enabled by a trilayered polymeric material containing dielectric elastomers [4]. A few studies proposed the possibility of thermal actuation of a bistable structure, i.e., configurational changes by increasing temperature [17, 18, 20]. However, these bistable structures often require attaching a shape memory polymer to the bistable structure, which has a limiting effect on the direction of loading and slows down the response. In another word, the direction of loading depends on the orientation of SMP muscle and cannot be placed in arbitrary directions.

In this study, we use the concept of transition between monostability and bistability to introduce a thermally bistable unit cell. We present a strategy to reconfigure a bistable state without requiring any inherent shape memory properties, nor any thermal programming. Our design does not need any external mechanical element as a lever or muscle to trigger the geometry restoration and it will restore by to its initial shape by increasing the ambient temperature. Furthermore, we can customize the design for any polymeric material as it only relies on the thermal softening of polymers, which is ubiquitous among most polymers [21]. The programmability is achieved by varying geometrical features (i.e. struts‘ thickness and the width ratio of stiff vs soft material), which can be readily handled via AM. The shape memory effect in special alloys and polymers occurs when a temperature-induced phase transformation reverses deformation [22].

Figure 1a presents a typical cycle of load-deformation-temperature in the proposed structure. The load-displacement-temperature curve of our developed bistable multi-material structure resembles that of SMA. When we apply a compressive load of a certain value and then remove the load, the structure retains its deformed stable configuration. Then, the structure restores its original shape as soon as its temperature surpasses a critical value. In Figure 1a, the area under the curve with negative value force is defined as "Bistability Energy (U_{bs})". The strategy we propose in this study helps to reproduce the shape memory effect (SME) without relying on the intrinsic memory effect in material and only by harnessing the bistability of a structure and thermal softening of polymeric materials. A schematic of the unit cell of this bistable structure is shown in Figure 1b, in which the bi-material walls on each end of the struts have varying stiffness depending on the material composition, geometry, and temperature.

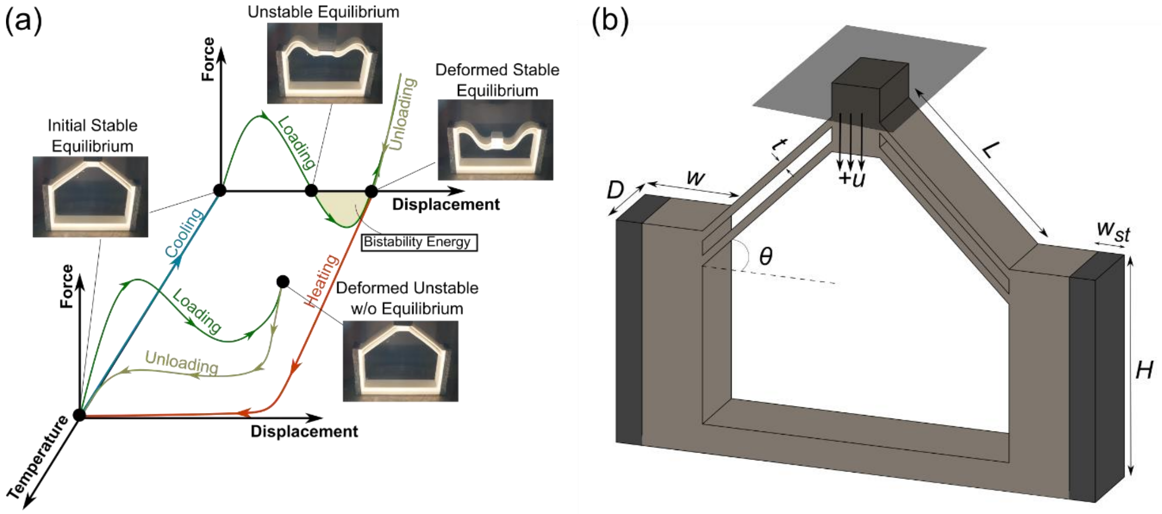

Figure 1. a) Force – Displacement – Temperature curve of a thermally bistable structure, b) schematic view of the design.

2 RESULTS AND DISCUSSION

We apply finite element (FE) simulation and experimentation to investigate different design parameters and their effects on the response of thermally bistable structures. FE simulations are conducted using the transient structural module of commercial ANSYS software version 2021R1. Unit cells are analyzed based on the nonlinear two-dimensional (2D) plane strain theory and each cell is discretized with approximately 50,000 elements. Three-node linear triangular element geometry with Nodal Based Strain (NBS) formulation is selected as the element type for modeling the structure. A rigid body is attached to the top of the lattice structures to apply the deformation-driven loading on each cell, while the bottom part of the body is completely fixed. Element and body self-contact effects are taken into account by defining frictional contact between different parts of each unit cell. The friction coefficients between body and rigid parts and body self-contact are set at 0.1.

In Figure 2a, we present the FE results for the effect of changing different design parameters on the force-displacement curves of the mechanically bistable unit cell made from only one material. We find that increasing the number of struts (n), strut angle (θ), or strut thickness (t) leads to higher absolute values of maximum force, when the strut length, $L = 50\mathrm{mm}$, $w = 10\mathrm{mm}$, and $D = 20\mathrm{mm}$ are held constant. We present a new approach to customize the force-displacement curves by adding a ribbon of stiffer material on each side of the wall and without changing the total size of the 1D unit cell. Figure 2b presents the force-displacement curves for unit cells with different relative widths of a stiff material (w_{st}/w). We observe that this ribbon of stiff material can have a critical effect on the force-displacement curve and the bistability energy: a higher value of the relative width of the stiff material (w_{st}/w) increases the absolute value of the maximum and minimum reaction forces, and consequently, the bistability energy increases.

We propose a strategy to accumulate the effect of different parameters affecting the wall stiffness by introducing a non-dimensional equivalent wall stiffness parameter (K_{eq}) to study the effect of wall stiffness on the bistability of a unit cell. Assuming the side walls of the unit cell as a cantilever beam with the length of H and a point load at the end, its bending stiffness, *k*, can be written as:

$$k = \frac{3I_{eq}}{H^3} \tag{1}$$

where I_{eq} is the equivalent moment of inertia around the *y*-axis and obtained according to the composite beam theory. Then, we divide the flexural stiffness by the length of the strut, L, to make it non-dimensional; hence, the non-dimensional wall stiffness parameter is be obtained by:

$$K_{eq} = \frac{3I_{eq}}{H^3 L}. \tag{2}$$

Figure 2c shows that the equivalent stiffness parameter, K_{eq}, increases uniformly by increasing the relative width of a stiffer material in the wall of unit cells. Plotting the non-dimensional bistability energy versus the equivalent wall stiffness parameter for unit cells with $n = 2$, $\theta = 40°$, and $H/D = 3$ shows there is a threshold value for the equivalent wall stiffness parameter depending on the strut thickness (Figure 2d). In another words, a structure is not bistable unless its equivalent wall stiffness is higher than a threshold value which is mainly determined by the strut thickness and angle. Figure 2d also shows that the bistability energy increases rapidly for a limited range when the equivalent wall stiffness goes beyond the threshold value and after that, the bistability is almost independent of the wall stiffness.

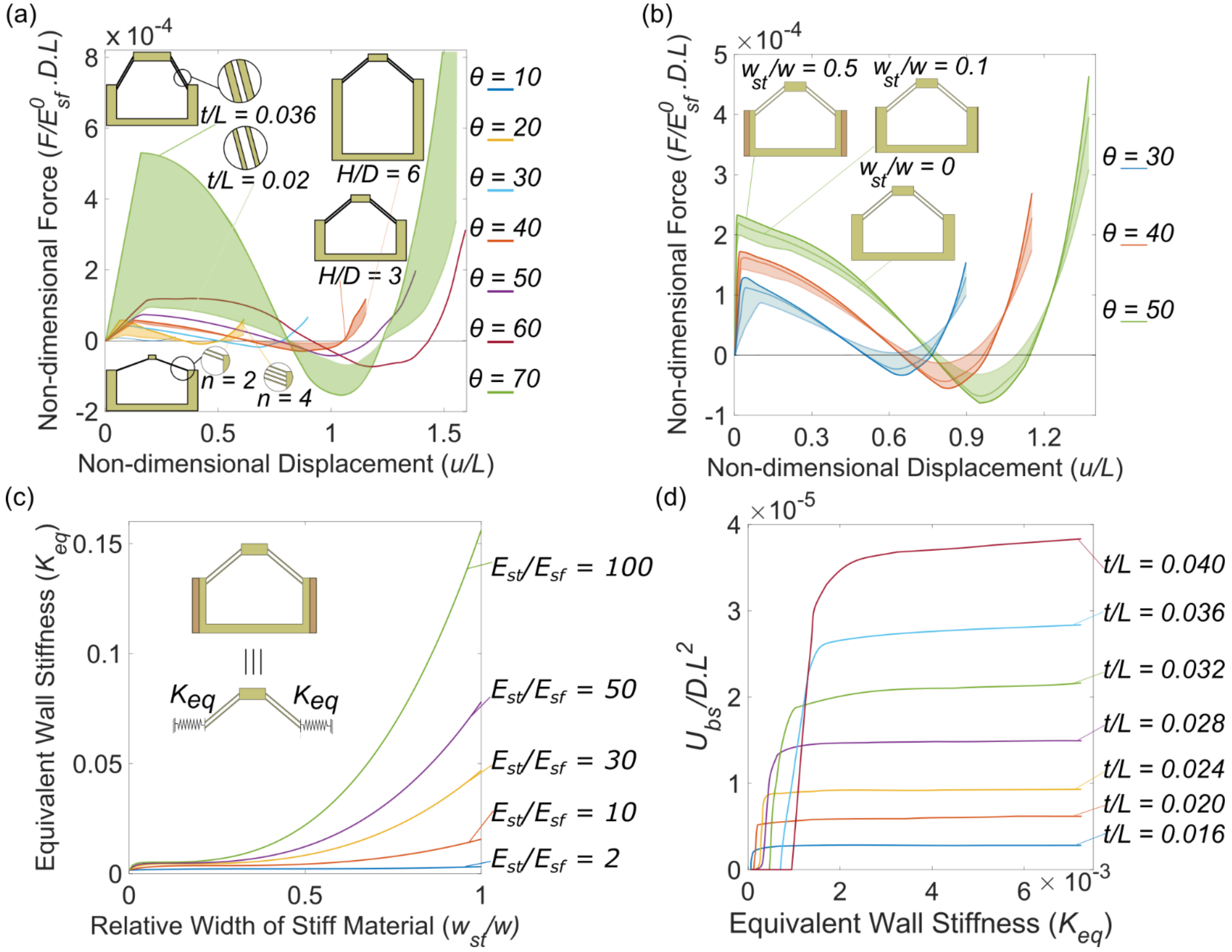

Figure 2. (a) The effect of different geometric design parameters on the snap-through behavior of the single-materials bistable structure. (b) Force-displacement curves of snap-through behavior of the bi-material unit cell with a different strut thickness of a stiff material attached to the soft walls. (c) Variation of equivalent wall stiffness (K_{eq}) for different constituent materials. (d) Non-dimensional bistability energy versus equivalent wall stiffness parameter for unit cells with different strut thickness.

The correlation between the wall stiffness and bistability of the structure enables controlling the response of a snapping unit cell without changing the overall dimensions of the structure. Here, we take advantage of this possibility to program the thermal response of the structure and the temperature at which the restoration is triggered (*Triggering Temperature*); consequently, two materials with distinctive stiffness versus temperature properties are used for the fabrication of the wall. Dynamic Mechanical Analysis (DMA) of elastic moduli of these two polymers are conducted and the outcome is entered in the materials models used in the simulation.

Figures 3a and 3b depicts force-displacement temperature for unit cells with various strut thicknesses with different angles, which are mechanically and thermally bistable structures. Unlike shape memory alloys and polymers, a thermally bistable structure restores its initial configuration swiftly at a specific temperature, i.e., the triggering temperature. Figure 3c shows that the triggering temperature has an inverse relationship with strut thickness, meaning that a mechanically bistable structure with higher strut thickness has a lower triggering temperature. The colormap in Figure 3c presents the triggering temperatures for different unit cell designs with a $40°$ strut angle. We observe that the highest triggering temperature belongs to the structures with the minimum strut thickness, while a structure with thicker struts may be mechanically or thermally monostable depending on their wall stiffnesses (K_{eq}). Figure 3c also shows that although the structures with thicker struts lead to higher bistability energy and more stable deformed configuration (Figure 2a), their triggering temperature is often lower than unit cells with thinner struts. Figures 3d present the force-displacement curves for four different designs obtained by finite element simulations and experimental tests. Comparing FE and experimental data shows that the numerical simulation generally overestimates the absolute value of the force compared to the experimental data, while they both predict the same trend for the effect of different design parameters.

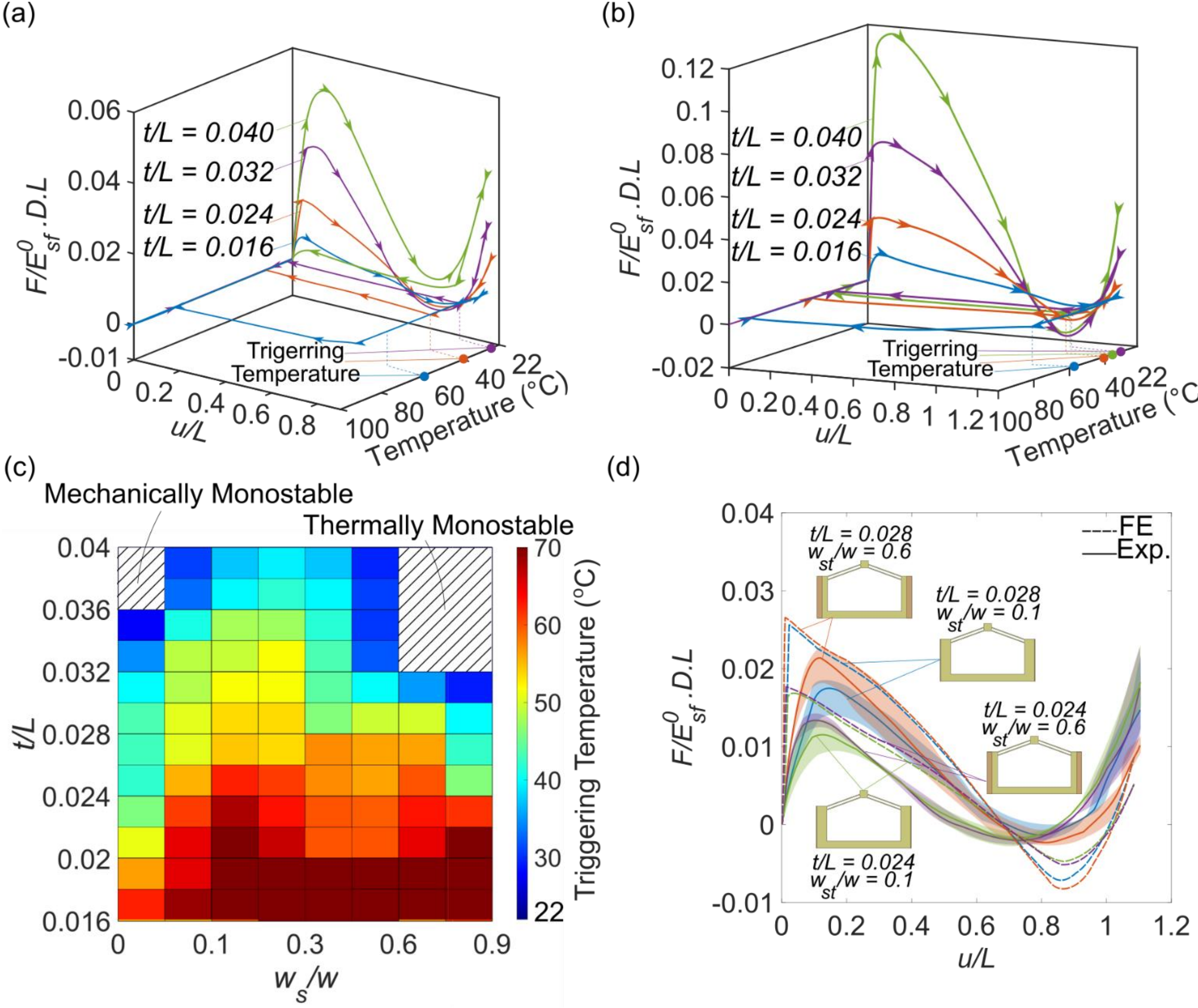

Figure 3. Force – displacement – temperature response for unit cells with different thickness and strut angles of for strut angles (a) $\theta = 30$℃ and (b) $\theta = 50$℃. (c) Triggering temperature for unit cells with different strut thicknesses and stiff material on the wall for strut angle $\theta = 40°$. (d) Comparison of force-displacement curves obtained from FE and experiments for strut angle $\theta = 30°C$

3. Conclusions

The main advantage of the proposed design is enabling the utilization of a wider range of materials for memory effect. without inherent shape memory properties and without the required SME programming. Our study indicates that the bistability behavior of a snapping unit cell significantly depends on its boundary conditions, i.e., surrounding walls; stiffening the wall can transform a monostable structure to a bistable one, and vice versa. Therefore, we design a bistable unit cell with bi-material walls in order to control wall stiffness by changing the combination of the constituent materials of the walls. The thermal softening nature of polymeric walls' materials enables us to control the bistability behavior of the structure by changing temperature. The resulting structure is thermally bistable; a structure that can have distinctive configuration by changing temperature. The triggering temperature of the structure can be controlled and programmed by changing the dimensions and the ratio of constituent materials.

Inducing a relatively large deformation to a body by changing temperature has so far been observed only in SMPs and SMAs but the proposed design paradigm offers to generate the same response for any polymers whose elastic moduli change with temperature. Furthermore, SMPs and SMAs response to temperature is gradual while the proposed thermally bistable structure can transform to different stable states in a sudden snap-like behavior. This behavior paves the path for the utilization of thermal bistability for self-sensing actuators in soft robots and drug delivery, since they often demand a quick responds, which is enabled by a thermally bistable structure.

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