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COMPOSITE SANDWICH STRUCTURES WITH BI-STABLE MECHANICAL METAMATERIAL CORE

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ABSTRACT

Inspired by nature, scientists are developing artificial composites with complex structures called mechanical metamaterials. This research developed a shape-reconfigurable sandwich core constructed from bi-stable mechanical metamaterials capable of snapping between two stable states. The proposed meta-sandwich structure can alter its shape and mechanical properties post-manufacturing, such as transitioning its flexural stiffness from rigid to soft. Finite element analysis was used to analyze the dimensional changes of the structure. A three-point bending test was performed on additively manufactured sandwich meta-structures made of thermoplastic polyurethane via the filament deposit method to evaluate its flexural stiffness. Results showed that the flexural stiffness decreased by 79.6% after shape transformation compared to its undeformed state. This research highlights the potential of meta-sandwich structures in various applications requiring multi-functionality, such as smart wings, paving the way for innovative advancement in this field.

1 INTRODUCTION

Sandwich structures are nowadays extensively applied in aerospace, automobile, and building industrial sectors, mainly due to their excellent multifunctional properties, such as high specific flexural stiffness, thermal insulation, and high energy absorption capabilities [1]. Sandwich structures consist of two thin solid face sheets with high flexural stiffness, separated by a relatively thick light-weight core [1]. The mechanical performance of a sandwich structure depends on its constituent material, geometrical parameters, and core cell topology [1, 2].

Recently, a new class of lightweight architected sandwich structures, made of mechanical metamaterials as the core, was introduced and named meta-sandwich structures [3, 4]. Mechanical metamaterials are man-made matter that obtain their effective properties by architecture rather than composition [3]. Via a rational structural design, the properties of mechanical metamaterials can surpass those of the base material [4]. Meta-sandwich structures thus show many advantages, such as a high stiffness-to-weight ratio and high energy absorption capability [4, 5]. However, once fabricated, designable structural modifications of the core are generally difficult, making it rare to find meta-sandwich structures that can be reconfigured beyond their original design [5]. The current concepts highly limit design freedom and versatility [4, 5]. A meta-material core with shape transformations is thus desired to facilitate sandwich structures with post-manufacturing properties switching. This research developed a shape-reconfigurable sandwich core constructed by bi-stable mechanical metamaterials that can snap through between two stable stages. The proposed 3D-printed sandwich structures have bending stiffness switchable between rigid and compliant dominant structures.

2 BI-STABLE MECHANISM

The developed meta-sandwich structure was inspired by the snap through-mechanism, like a push-pop bubble that has two stable states (Fig. 1-a II). In the first stable stage (State A), the unit cell's beam exhibits zero strain energy (Fig. 1-a and b). When a vertical load, F, is applied to the beams' top end, they begin to bend, accumulating strain energy until a local maximum is reached (Fig. 1-a and b). Beyond this point, the beam elements recover to their original configuration and strain energy starts decreasing until obtaining the local minimum strain energy, which is the second stable state (State B). The pin-jointed beams' reaction force and strain energy variations are represented by dash lines in Fig. 1-b. The difference between the maximum and minimum strain energy is the energy barrier, which is the energy required to switch between the two stable stages (Fig. 1-b).

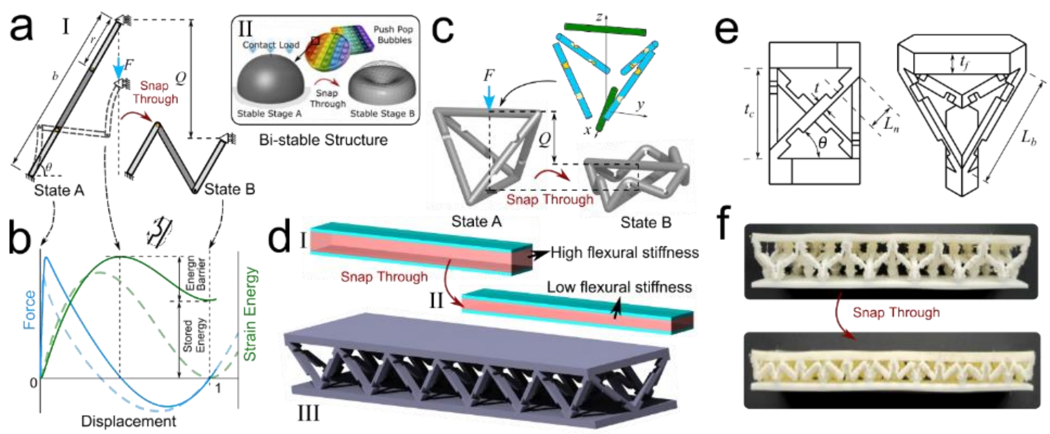

Figure 1: a) Pin-jointed bi-stable beams. b) Strain energy and reaction force change with respect to displacements. c) Tetrahedron Building Blocks. d) Meta-sandwich Structures. e) Unit Cell important parameters. f) Additively manufactured Meta-sandwich structures

To ease manufacturing, a compliant mechanism (notch) replaces hinges (Fig. 1-c) [7]. A tetrahedral building block is constructed via four bi-stable beam elements and thus can snap through between two stable stages (i.e., States A and B in Fig. 1-c). The mechanical metamaterials with tetrahedron building blocks can then replace the sandwich structure's core (Fig. 1-d). By changing the cross-section shapes, sandwich structures in State A provide higher flexural stiffness than those in State B. Section 3 will determine the dimensions' effect on the bi-stability (Fig. 1-e). Once those parameters are determined, the 3D-printed sandwich structure is manufactured (Fig. 1-f).

3 BI-STABLE PARAMETERS

This section aims to understand the influence of critical parameters on the bi-stability of the structure when designing meta-sandwich structures. The study involved simulating various parameters to optimize the best tunability performance, which implies the ability of the structure to adapt based on the loading conditions. Via FEA simulation, the key parameters influencing bi-stability were identified as 1) the skew angle of the bi-stable beams with respect to the face sheet, 2) the notch location, and 3) the thickness of the beam (Fig. 2).

To allow the sandwich structure to be used in multiple applications, the skew angle was tested between the angles of 35° to 55°. The angle change significantly impacts the energy barrier between the two stable stages: a low skew angle of 35° resulted in the structure with a low energy barrier for bi-stability (Fig. 2-a). As for the notch location, varying its position had a noticeable effect on the local minimum strain energy. Observing the limit of bi-stability, the configuration with the highest bi-stability is achieved at L_b=26% (Fig. 2-b). The beam's thickness also affects the unit cell's bi-stability, although not as drastic as the skew angle. Limits were identified as 1.61 mm and 2.99 mm before the energy barrier became too small to maintain the bi-stability of the structure (Fig. 2-c).

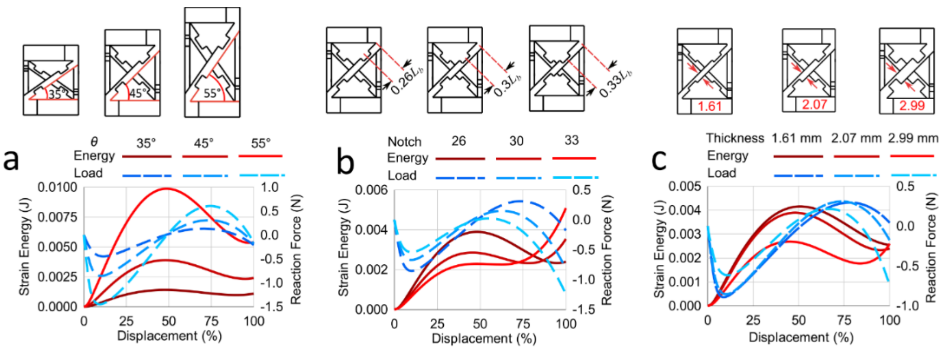

Figure 2: Bi-Stable Parameters a) Skew Angle's Strain Energy and Load b) Notch Location's Unit Strain Energy and Load c) Thickness of Cell's Strain Energy and Load

Bi-stability is fundamental for the structure's tuning capability, emphasizing the need to understand how geometry affects mechanical properties. Utilizing the homogenization method by simulating with ANSYS Parametric Design Language (APDL), the relative properties of the unit cell were evaluated and compared to those of base material, i.e., TPU (Fig. 3). Key parameters influencing bending resistance are the in-plane elastic modulus (*E*), shear modulus (*G*) and height change (*h*).

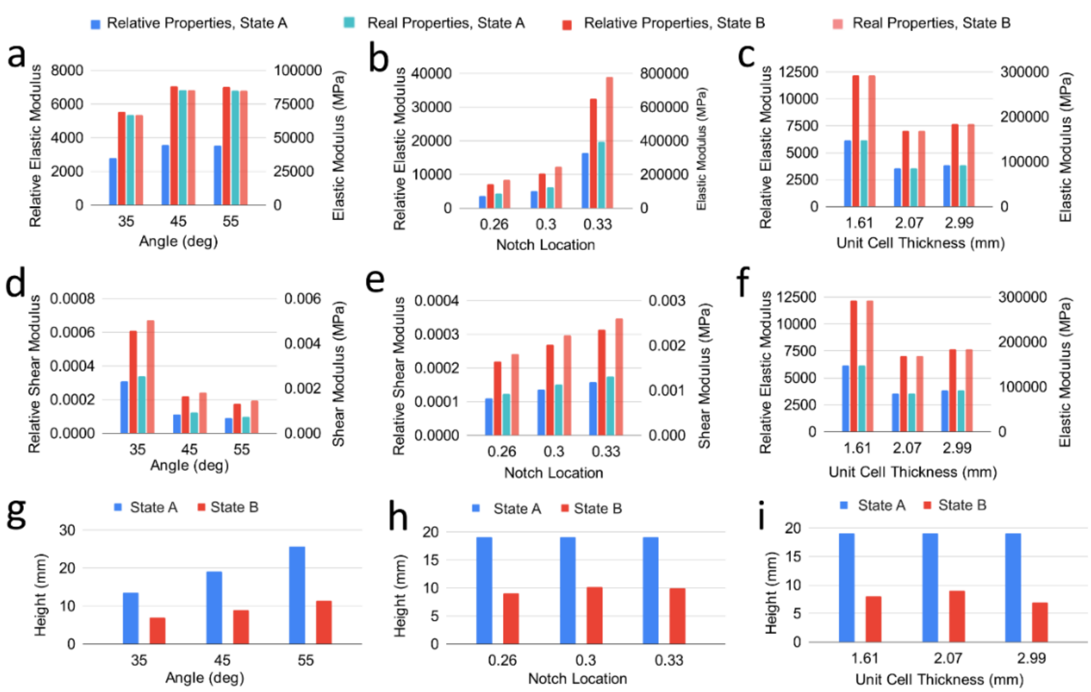

Figure 3: Relative and real properties of the unit cell change with respect to the geometrical parameters

It was observed that deformed (State B) properties are slightly higher than undeformed (State A) properties across all parameters. *E* increased proportionally with the skew angle with a minor difference beyond 45° (Fig. 3-a). The influence of the notch location on the *E* was observed to drastically increase at a notch of 33%, although the bi-stability is optimized at 26% (Fig. 3-b). Comparatively, increasing the bar thickness led to a decrease in *E*, highlighting the importance of maintaining a small thickness for optimal bending resistance (Fig. 3-c). Compared to the undeformed, the deformed unit cell exhibited slightly higher *E* due to its smaller average volume, resulting in more compacted energy. The height change was seen to have an overall effect on the properties (Fig. 3-g to i). This is because the change in height will decrease the volume of the unit cell, which allows for the sandwich structure to have less porosity and increase overall relative density. Also, the change in height influences the second moment of inertia, which directly impacts the flexural stiffness. This is beneficial to allow the sandwich structure to change from a high to low flexural stiffness.

4 METHODOLOGY

4.1 Manufacturing

After finding that the skew angle highly influenced both the bi-stability and the mechanical properties of the unit cell, the sandwich structures were manufactured with a 26% notch location and 2.07 mm bar thickness while the skew angle was changed. FDM 3D-printing method was applied due to the complexity of the shape and this manufacturing method allows superior quality of the sample at a cheap price [8].

The material selected for the sandwich structure is TPU. TPU is a highly flexible material, so to ensure the print quality is good, a support material, polyvinyl acetate (PVA), is needed [10]. To ensure it does not affect the properties of the printing, the sample was soaked in water for at least 24 hours. To get consistent test results, the length and width of the three-sandwich structures remained constant: width of 36 mm, length of 200 mm and face sheet thickness of 3mm (Fig 1-f). The main difference between the three samples comes from the skew angle changes in the height of the specimen. For the undeformed height, 35° is 16.58 mm, 45° is 22.11 mm and 55° is 28.76 mm. The deformed heights for 35° is 10.04 mm, 45° is 12.02 mm and 55° is 16.58mm.

4.2 Testing

The flexural stiffness of the structure was tested according to ASTM D5023 standards using three-point bending tests for both the undeformed and deformed sandwich beams. Testing was conducted on three specimens with different skew angles to determine the flexural strength of the two stable phases [12]. A test instrument (Transcell D65L-11) was used for the tests on beams of total length of 200 mm, which was consistent for all specimens. According to ASTM D5023 standards, at least 10% of the total length of the specimen must overhang on each side, resulting in 20 mm on each side [12].

The testing standards required a small increasing load up to a total displacement of 5% of the specimen length to ensure no fracture occurred [11]. This method ensured consistent displacement regardless of the height variations between the deformed and undeformed specimens [12]. The displacement was set based on their actual lengths, which slightly differed due to printing tolerances compared to the modelled version.

5 MATERIAL PROPERTIES

From the 3-point bending test, the flexural rigidity (D) of the octet truss sandwich structure was calculated from the sandwich structure theories [1]. Since the face sheet and the core are made of the same material, the thin face sheet weak core assumption couldn't be used [1]. To find the flexural rigidity EQ. 1 was used [1]. Combining the equation for sandwich structures for flexural rigidity with the deformation of a rectangular beam yields Eq. 1 for *E* of the sandwich structure [1].

$$E = \frac{P}{w}\left(\frac{12L^3}{96{t_f}^3 + 6t_c\left(t_f + t_c\right)^3 + {t_c}^3}\right) \tag{1}$$

Where *E*= modulus of elasticity; t_f= face sheet thickness; t_c= core thickness; *D*= Fluxtural Rigidity; *P*= load; *L* = sandwich length; and w = deformation.

E for each specimen was calculated via Eq. 1, using the slope of the line as P/w from the experimental three-point bending results (Fig 4-a to c). This resulted in the following values: 35°: undeformed 3.41 MPa, deformed 2.2 MPa; 45°: undeformed 200.8 kPa, deformed 40.94 kPa; 55°: undeformed 146.8 kPa, deformed: 20.73 kPa. The results show that the sandwich structure can decrease the flexural strength by 79.6%, which highlights the tuning capability when optimizing the core.

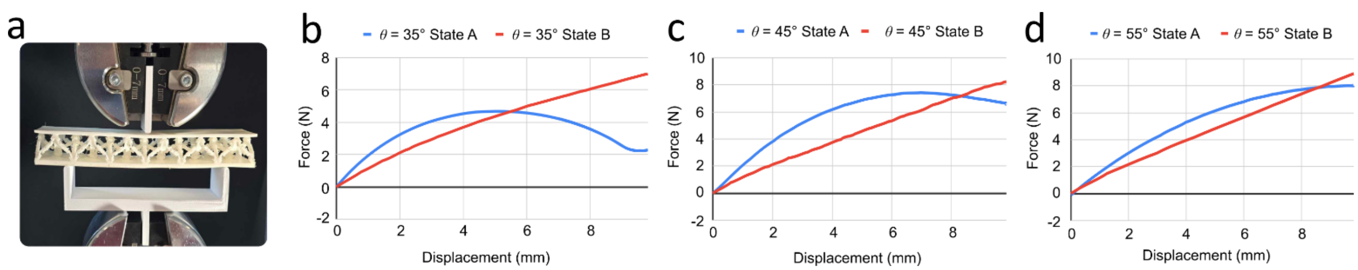

Figure 4: Bending Test Results of Bi-Stable Sandwich Structure Undeformed and Deformed a) Skew Angle 35°. b) Skew Angle 45°. c) Skew Angle 55°.

These results were consistent with the homogenization method, showing that the deformed E was maximum 8.7 times higher than its undeformed sandwich structure's E (Fig 4-c). However, there was a slight deviation from the expected trend since the homogenization method predicted an increase in E with increasing skew angle, but it was the opposite. This discrepancy may be attributed to the simulation being conducted using a single unit cell, neglecting the interaction between cells within a sandwich structure. These results are more consistent with the reality of the sandwich theories, which considers the fact that cells will interact with each other, and the deformation of one cell influences the neighbouring before fracture, as seen as the decrease of the force on the cell of the undeformed (Fig 4-a to c). Furthermore, the results also collaborated with the bi-stability simulation since 35deg was barely bi-stable and wanted to instantly return to its first stable stage after deforming. Despite this deviation, the experimental results confirmed that the undeformed structure exhibits characteristics of a stretching dominant structure with lower E, while the deformed structure demonstrates bending dominant behavior with higher E due to its reduced volume.

6 CONCLUDING REMARKS

The unique properties of meta-sandwich structures, including the ability of the metamaterial core to transition between stable stages, contribute significantly to their impact resistance and energy absorption capabilities. This was observed with the second moment of inertia of the undeformed cell allowing for increased energy absorption compared to its deformed cell. Furthermore, the lower flexural stiffness of the deformed unit cell indicated its ability to withstand larger deformations without fracturing. Combining these properties, the ability to tune the impact bending resistance post-manufacturing of the sandwich structure enables its versatile applications. This research highlights the potential of metamaterial core in achieving tunable sandwich structures through the designing of skew angles, tetrahedron bar thickness, and notch locations. While further work is required using different composite materials, the research has identified the key parameters for achieving bi-stability through various testing and simulations.

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