



Thermally driven reusable dual-phase honeycombs with enhanced mechanical properties

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ABSTRACT

This work develops dual-phase honeycombs combining a hyperelastic soft material phase (thermoplastic polyurethane, TPU) and an elastoplastic hard material phase (polylactic acid, PLA) to balance mechanical performance and reusability. Encasing the hard phase within the soft phase leverages PLA's shape memory and TPU's shape recovery to enhance energy dissipation, shape recovery, and structural robustness. Fabricated via fused deposition modeling, the design was tested under quasi-static compression across various tessellations (periodic square, hexagonal, triangular, and aperiodic hat). At 60 °C thermal recovery, the structure restored 98.8% of its original height on average. Higher hard phase content improved mechanical performance but reduced reusability. Hexagonal tiling showed superior energy absorption and cyclic stability, while square and triangular designs optimized stiffness and strength. Heat treatment at 160 °C (PLA's melting point) further enhanced plateau stress and recovery. This dual-phase design offers a reusable solution for applications like sports helmets, knee pads, and packaging, achieving a synergistic balance of mechanical robustness and reusability through tailored phase composition and geometry.

1. Introduction

Honeycomb materials are characterized by their distinctive cellular architecture, typically consisting of a periodic array of unit cells, which confers an exceptional strength-to-weight ratio [1,2] and outstanding energy absorption performance [3,4]. This remarkable energy absorption capacity stems from the progressive, predictable collapse of their cellular walls through elastic buckling, plastic deformation, or fracture, making them ideal candidates for protective applications [5,6]. Moreover, the versatility of honeycomb materials enables the design of customized structures to realize various functional demands. For example, honeycomb materials can realize adjustable thermal expansion and bandgap characteristics [7], tunable stiffness and Poisson's ratio [8], and flexible mechanical response [9]. More unique mechanical properties [10], such as negative stiffness [11,12], negative thermal expansion [13,14], and negative Poisson's ratio [15,16], can be further achieved by specially designing the unit cell configuration. Consequently, these lightweight, multifunctional structures are widely employed as core materials in sandwich composites across diverse industries, including aerospace [17,18], automotive [19,20], and

packaging [21,22], where efficient load-bearing and energy dissipation are critical.

However, conventional honeycombs used in impact protection applications, typically composed of metals such as aluminum alloys or steel, are generally single-use and economically inefficient. In contrast, honeycombs capable of reusable energy absorption not only offer environmental benefits but also support the development of sustainable, cost-effective solutions. There are several strategies to design structures with reusable energy absorption, including multi-stability, friction, shape memory effect (SME), and shape recovery effect (SRE). Reusable energy absorbers based on multi-stable or friction strategies rely heavily on structural design to achieve multiple equilibrium states or efficient friction behavior. Multi-stable metamaterials, a pioneering class of architected materials, are typically composed of bi-stable beams [23,24] or bi-stable shells [25,26], enabling transitions between two or more stable equilibrium states. This property allows them to reversibly switch between distinct geometric configurations through external stimuli without requiring continuous energy input, while maintaining structural integrity in the process [27]. Such materials demonstrate tunable mechanical properties [28], including programmable stiffness [29,30],

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adaptive shape morphing [31], and efficient energy trapping [32], making them ideal for advanced applications such as repeatable impact protection [33]. However, after compression, multi-stable metamaterials transition from their original stable state to another, necessitating external energy for recovery to the initial configuration before subsequent impacts. Friction-based energy absorbers dissipate energy by converting impact kinetic energy into heat. These systems often rely on independent frictional components, which can be categorized into three types: (1) granular materials such as particles [34,35] and cylinders [34,36], constrained by elastic components; (2) deliberately designed frictional interfaces, such as convex interfacial structures [37,38] and paired walls with a minor gap [39], which allow scalable array configurations akin to traditional cellular materials [40,41]; and (3) intertwined structures combining prestressed stiff cores and porous soft elastomers [42], which absorb energy under both compression and tension. A critical limitation of friction-based systems is the need for manual or mechanical recovery due to hysteresis-induced residual deformation.

Reusable energy absorbers based on SME and SRE, by contrast, depend primarily on the inherent properties of selected materials. Shape memory materials are widely used in 4D printing [43,44] and can also be fabricated into reusable energy-absorbing structures. Commonly used shape memory materials can be divided into shape memory polymers (SMP) and shape memory alloys (SMA), such as shape memory resin [45], liquid crystalline polymer [46], PLA [47,48], and nickel-titanium (NiTi) alloy [49,50]. These materials can recover their original shapes when stimulated, typically through heating to temperatures exceeding their glass transition points. With advances in additive manufacturing, SMP and SMA have been processed into complex configurations, such as honeycombs [50,51] and lattices [52,53] through fused deposition modeling (FDM), selective laser sintering (SLS), and selective laser melting (SLM). Such temperature-responsive shape memory metamaterials represent a key pathway toward intelligent materials and structural systems [54]. However, energy absorbers based on SMAs often exhibit limited recoverable strain due to localized deformation bands, leading to irreversible plastic deformation and fractures under large deformations [53,55]. In contrast, SRE-based energy absorbers can autonomously recover their original shapes upon unloading, a phenomenon commonly observed in polymers such as rubber [56] and TPU [57], which exhibit reversible hyperelastic and viscoelastic deformations [58,59]. While hyperelastic deformations can recover rapidly within minutes, viscoelastic deformations require longer recovery times, limiting the complete recovery of SRE-based systems under repeated loading [60]. Additionally, integrating liquid metal lattices has been shown to enhance both the strength and energy absorption capacity of SRE-based energy absorbers [61,62]. Recent advances in metallic temperature-responsive metamaterials have also demonstrated that bimetallic strips can produce large, reversible shape changes under thermal cycling [63,64]. These bimetallic-based metamaterials exhibit excellent recoverability without relying on phase transition mechanisms, offering complementary design strategies for reusable energy-absorbing systems.

Despite significant progress in the development of reusable metamaterials, achieving a synergistic balance of high stiffness, strength, and energy absorption capacity, while enabling broader application scenarios, remains a significant challenge. Existing strategies, such as those based on multi-stability, friction, and SRE, suffer from inherently limited energy absorption mechanisms, while SME-based systems typically exhibit diminished shape recovery after multiple cycles. Furthermore, traditional multi-material designs for reusable energy absorbers [51,65] have not yet achieved the coupling of SRE and SME to simultaneously enhance reusability and energy absorption performance across diverse working conditions. To address these challenges, this work proposes a novel dual-phase design strategy that combines the advantages of SRE and SME to simultaneously improve mechanical properties and reusability, demonstrating potential applications in energy absorbers [66],

sensors [67], adaptive systems [68]. In this design, the dual-phase structure comprises two distinct materials: the hard phase (PLA), which exhibits SME and elastoplastic behavior, and the soft phase (TPU), which demonstrates SRE and hyperelastic behavior. Notably, the soft phase's melting temperature is deliberately set higher than that of the hard phase to ensure effective coating at the melting temperature of hard phase. The higher melting temperature of the soft phase relative to the hard phase is critical for maintaining structural integrity at elevated temperatures. Specifically, when the temperature exceeds the melting point of the internal hard phase, the external soft phase serves as a supporting scaffold to prevent the structure from collapsing due to melting. As a widely adopted fabrication method in mechanical design [69,70], FDM was employed to manufacture the dual-phase honeycombs due to its cost effectiveness, sufficient printing accuracy, high design flexibility, and easy post processing. However, existing limitations such as interlayer gaps and poor interfacial bonding between dissimilar materials may compromise the mechanical performance of printed components [71], which are also evaluated in this work using scanning electron microscope (SEM). The dual-phase honeycombs exhibit two distinct post-compression recovery modes depending on working conditions. Spontaneous recovery at room temperature through SRE is suitable for short-term multiple impacts, while thermally driven recovery above the glass transition point of PLA, enabled by the coupling of SRE and SME, is appropriate for long-term repeated energy absorption.

In Section 2, the design principles of the dual-phase honeycomb are systematically introduced, emphasizing the integration of SRE and SME mechanisms. Section 3 details the fabrication process using FDM and the quasi-static mechanical testing methodology. Key evaluation metrics are also introduced, including elastic modulus and compression strength for assessing load-bearing capacity, as well as plateau stress and specific energy absorption for quantifying energy absorption performance. The reusability of dual-phase honeycombs is evaluated by the shape recovery ratio and mechanical performance retention ratio, critical parameters that quantify the extent of structural restoration after deformation. Section 4 presents a comparative analysis between the dual-phase honeycomb and its corresponding single-phase counterparts, demonstrating the advantages of the dual-phase design in terms of mechanical properties and reusability. This section further investigates the performance of the dual-phase honeycomb under variations in the soft phase percentage and hard phase percentage, analyzing the trade-off between the proportions of hard and soft phases to balance mechanical properties and reusability. To explore the influence of structural configuration, four monotile configurations are considered: three conventional periodic tiles (triangular, square, and hexagonal shapes) representing regular structures and one special aperiodic tile (hat shape) for an irregular structure. Additionally, the impact of heating temperature during the thermally driven recovery process is investigated, with three temperatures above the glass transition point of the hard phase in which one equals the melting temperature of the hard phase. However, this work primarily focuses on the quasi-static energy absorption characteristics of the dual-phase honeycombs, as this serves as a foundational basis for evaluating energy absorption performance. Therefore, it is meaningful to further investigate the dynamic behavior of dual-phase honeycombs in future studies, as this would provide a more comprehensive understanding of their performance across different loading scenarios, particularly in real-world applications where dynamic impacts are prevalent. Furthermore, the integration of advanced optimization methodologies, particularly machine learning-based algorithms, presents a promising avenue for inverse design approaches in future studies [72], enabling the systematic exploration of optimal material distribution and structural parameters.

2. Design of dual-phase honeycombs

The detailed design concept of dual-phase honeycombs is elaborated

in this section. As shown in Fig. 1a, traditional single-phase honeycombs fabricated from elastoplastic materials typically exhibit complete functional failure after impact events due to irreversible plastic deformation. In contrast, as illustrated in Fig. 1b, single-phase honeycombs constructed from hyperelastic materials demonstrate excellent reusability through energy absorption via reversible elastic deformation. However, the inherent lower elastic modulus of hyperelastic materials compared to elastoplastic materials results in reduced structural stiffness and strength in hyperelastic honeycombs. To address this trade-off between mechanical performance and reusability, a dual-phase honeycomb design strategy is proposed for engineering applications. As depicted in Fig. 1c, the outer yellow layer represents the soft phase (hyperelastic phase), while the inner red layer corresponds to the hard phase (elastoplastic phase), which exhibits a comparable elastic modulus to conventional single-phase hard honeycombs. Importantly, the hard phase is entirely encapsulated within the soft phase, resulting in a constrained deformation mode that enhances both energy dissipation and shape

recoverability. Especially, if the melting point of soft phase is larger than that of hard phase, the reshaping of the hard phase can be achieved by heating the temperature to the melting point.

In this work, PLA and TPU are selected as the hard phase and soft phase, respectively, both of which are widely used commercial materials in FDM and are environmentally friendly. Based on their distinct material properties, PLA demonstrates SME under thermal stimuli due to the cross-linking interactions between crystalline and non-crystalline regions. When ambient temperature exceeds the glass transition temperature (T_g), the non-crystalline matrix releases residual stresses, enabling partial shape recovery. In contrast, TPU exhibits SRE through its microphase-separated structure comprising soft segments (responsible for rapid hyperelastic recovery) and hard segments (associated with slow viscoelastic recovery). The SRE process can be accelerated by increasing the ambient temperature, as higher temperatures facilitate faster molecular chain mobility. By integrating the shape memory capability of PLA (hard phase) with the rapid shape recovery of TPU

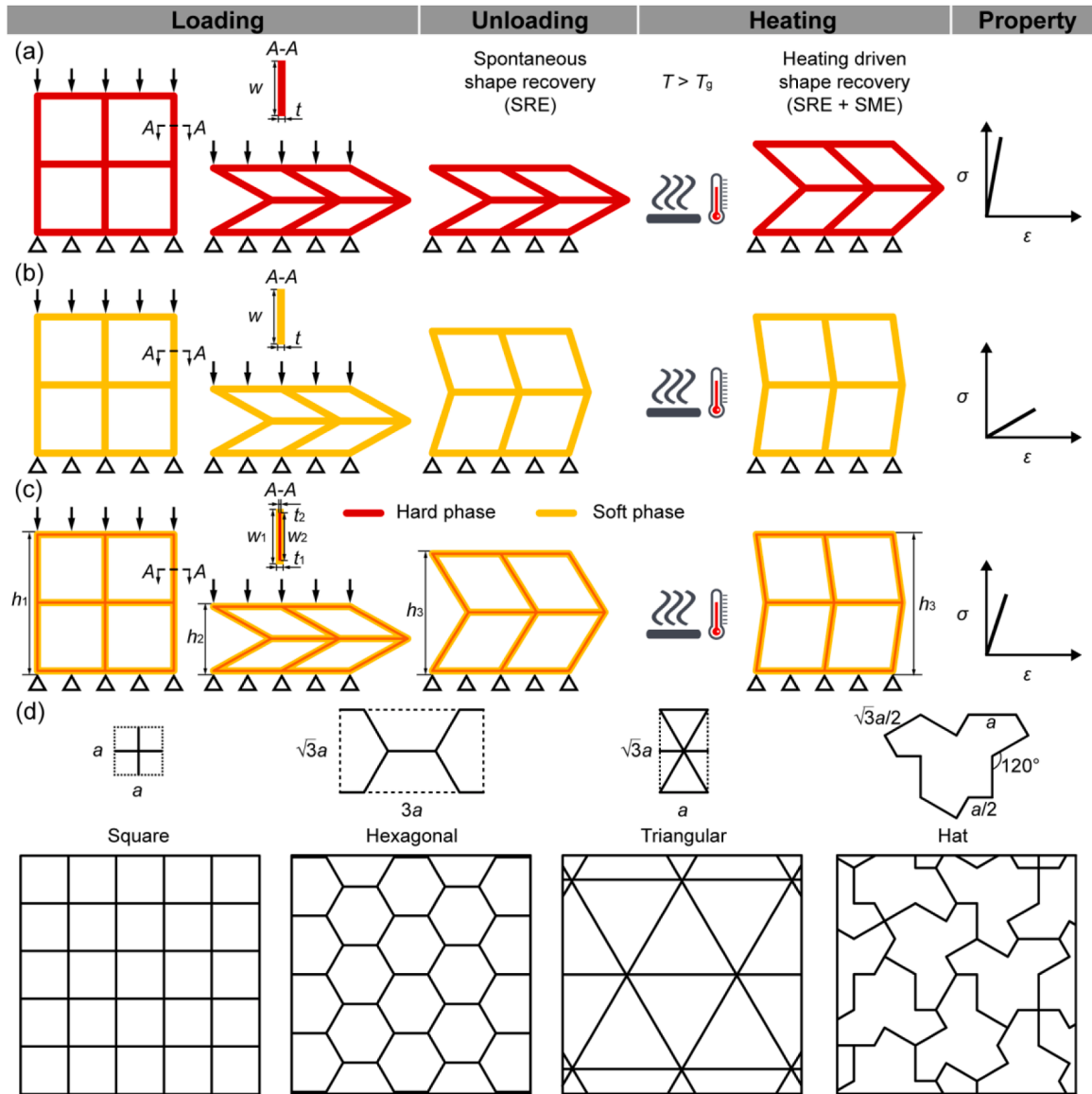


Fig. 1. Design strategies for dual-phase honeycomb with reusability. (a) Single-hard-phase honeycomb with elastoplastic material: high stiffness with limited self-recovery, partial recovery achievable via shape memory effect (SME) under thermal actuation; (b) Single-soft-phase honeycomb with hyperelastic material: low stiffness but rapid self-recovery due to shape recovery effect (SRE), enhanced recovery speed under thermal actuation; (c) Dual-phase honeycomb combining elastoplastic and hyperelastic phases: balanced performance with high stiffness and moderate self-recovery, integrating advantages of (a) and (b); (d) Honeycombs with periodic and aperiodic tile configurations. T_g is the glass transition point of hard phase.

(soft phase), the dual-phase honeycomb architecture achieves a synergistic balance between mechanical performance and multi-scenario reusability. Furthermore, TPU demonstrates superior interlayer adhesion and filament-to-filament bonding properties, as well as excellent abrasion resistance, which contributes to maintaining structural integrity.

As depicted in Fig. 1d, the proposed design strategy was validated across various tessellation configurations within a square design domain, including square, hexagonal, triangular, and hat tiles. Notably, the hat tile represents an aperiodic monotile pattern [73], distinguishing it from the conventional periodic tilings. To establish a consistent reference framework, the dimensions and relative density of the square tile were adopted as baseline parameters for defining other structural configurations. However, this approach resulted in incomplete cells along the design boundary due to geometric clipping. To address this limitation, a closed boundary strategy was strategically implemented to ensure complete deformation of boundary cells. This modification not only enables a more equitable comparison of mechanical performance across different configurations but also optimizes the structural functionality by maintaining geometric continuity throughout the design domain. For structural analysis purposes, the basic units of the square, hexagonal, and triangular tessellations are defined as black dot line blocks shown in Fig. 1d, which simplify mass estimation for the honeycomb structures. The total length of the tessellation pattern can be mathematically described by the following equation

$$L = n_x n_y L_m + 2n_x L_e^x + 2n_y L_e^y + 4L_c \quad (1)$$

where n_x and n_y , L , L_m , L_e^x , L_e^y , and L_c are the number of completed tiles along the x and y directions, the total length of the tiling, the total length of the unit at the middle region, the total length of the unit at the edge along x direction, the total length of the unit at the edge along y direction, and the total length of the unit at the corner region, respectively. It should be noted that the naming rule of honeycombs in this work is as follows: The first letter indicates whether the structure is dual-phase (D) or single-phase (S). The letters from the second to the fourth represent the configuration of the structure (Tri for triangular tile, Squ for square tile, Hex for hexagonal tile, and Hat for hat tile), and the digit in the fifth position is the serial number of the structure. For example, DSQu0 refers to the zeroth dual-phase honeycomb composed of square tiles. Details of each parameter for each configuration can be found in Section S1. Design domain dimensions are specified as $50 \times 50 \times 10 \text{ mm}^3$, while the length l and height h are both 50 mm, and the width w_1 is 10 mm. In the dual-phase configuration, the PLA phase width w_2 is precisely maintained at 9.2 mm. To ensure equal total lengths across different tessellations, the edge length parameters a for square, hexagonal, triangular, and hat tiles are set to 10.0 mm, 7.1 mm, 22.9 mm, and 8.6 mm, respectively. The thicknesses t_1 of DSQu0, DSQu1, DSQu2, DSQu3, DSQu4, and DSQu5 are 1.00 mm, 1.26 mm, 2.10 mm, 2.94 mm, 2.52 mm, and 2.94 mm, respectively. The thickness t_2 of DSQu0, DSQu1, DSQu2, and DSQu3 are both 0.42 mm, while those of DSQu4 and DSQu5 are 0.84 mm and 1.26 mm, respectively. Moreover, the t_1 and t_2 parameters for DHex4, DTri4, and DHat4 are directly aligned with those of DSQu4, maintaining dimensional consistency across tile types.

3. Materials and methods

This section provides a detailed description of the constituent materials and the fabrication process of dual-phase honeycombs, followed by an introduction to the key performance metrics employed to evaluate their mechanical behavior and reusability. The experimental methods, including quasi-static compression testing and thermally driven recovery, are also outlined. Finally, the section investigates the underlying mechanisms of mechanical degradation by examining the microstructural evolution of dual-phase honeycombs through scanning electron microscopy.

3.1. Materials and sample fabrication

As illustrated in Fig. 2a, the dual-phase honeycombs were manufactured using a dual-material 3D printer (Bambu H2D, Bambu Lab Ltd, China) via FDM. The hard-phase and soft-phase filaments were selected as PLA-Lite and TPU-95A-HF, both with a 1.75 mm diameter, supplied by Bambu Lab Ltd, China. Key material properties of these filaments are summarized in Table 1. The standard for the exchange of product model data (STEP) files were prepared using the computer aided design (CAD) software, sliced with Bambu Studio (Bambu Lab Ltd, China), and subsequently converted to 3D manufacturing format (3MF) files for 3D printing fabrication. The printing parameters were optimized to achieve a balance between print quality and production efficiency: nozzle diameter of 0.4 mm, print line width of 0.42 mm, layer height of 0.2 mm, heated bed temperature of 55 °C, 100% infill density, 0% seam gap, extrusion temperatures of 220 °C for PLA-Lite and 230 °C for TPU-95A-HF, and print speeds of 60 mm/s for PLA-Lite and 40 mm/s for TPU-95A-HF. The overall honeycomb width of 10 mm corresponds to 50 printed layers along the z-direction. A specialized infill pattern was implemented: the 1st, 2nd, 49th, and 50th layers contained rectilinear infill oriented at 45°, while the remaining layers featured linear infill aligned with the wall direction, as shown in Fig. 2b. This pattern was specifically designed to enhance the sealing integrity of the TPU phase for the PLA phase. To ensure high-quality dual-material printing, a prime tower feature was employed during fabrication, and seam positions were randomly distributed across all layers to mitigate potential manufacturing defects. As depicted in Fig. 2c, the final printed samples, DSQu4, DHex4, DTri4, and DHat4, demonstrate sufficient macroscopic dimensional accuracy despite the known layer-to-layer and filament-to-filament interface defects inherent in FDM fabrication [74,75].

3.2. Metrics of mechanical properties

To quantitatively assess the mechanical performance of dual-phase honeycombs, several key metrics are introduced, including Young's modulus, compression strength, plateau stress, specific energy absorption, specific energy dissipation, and specific energy storage. As illustrated in Fig. 3a, Young's modulus is calculated from the slope of the linear elastic portion of the stress-strain curve, while compression strength is conventionally defined as the initial peak stress in the stress-strain response. However, for dual-phase honeycombs exhibiting a stress-strain curve without a distinct peak, compression strength is determined using the offset method. This involves constructing a line parallel to the linear elastic region, offset by 0.02 permanent strain. The compression strength is then defined as the stress at the intersection point between this offset line and the experimental stress-strain curve. The plateau stress σ_p is calculated as the mean stress value over the strain range of 0.1 to 0.4, expressed mathematically as

$$\sigma_p = \frac{\int_{\varepsilon_{0.1}}^{\varepsilon_{0.4}} \sigma d\varepsilon}{\varepsilon_{0.4} - \varepsilon_{0.1}}, \quad (2)$$

where $\varepsilon_{0.1}$ and $\varepsilon_{0.4}$ correspond to strain levels of 0.1 and 0.4, respectively.

As depicted in Fig. 3b, the total energy absorption of dual-phase honeycombs is composed of dissipated energy and stored energy, with the latter being released during unloading. Dissipated energy predominantly arises from interfacial friction between honeycomb walls, molecular chain reorientation in the soft phase, and crack propagation and plastic deformation in the hard phase. Moreover, stored energy corresponds to the reversible kinetic energy required for the structure to recover from deformation. To fairly compare energy absorption performance across different structures, energy absorption metrics are normalized by structural mass. Consequently, specific energy absorption (SEA) is defined as

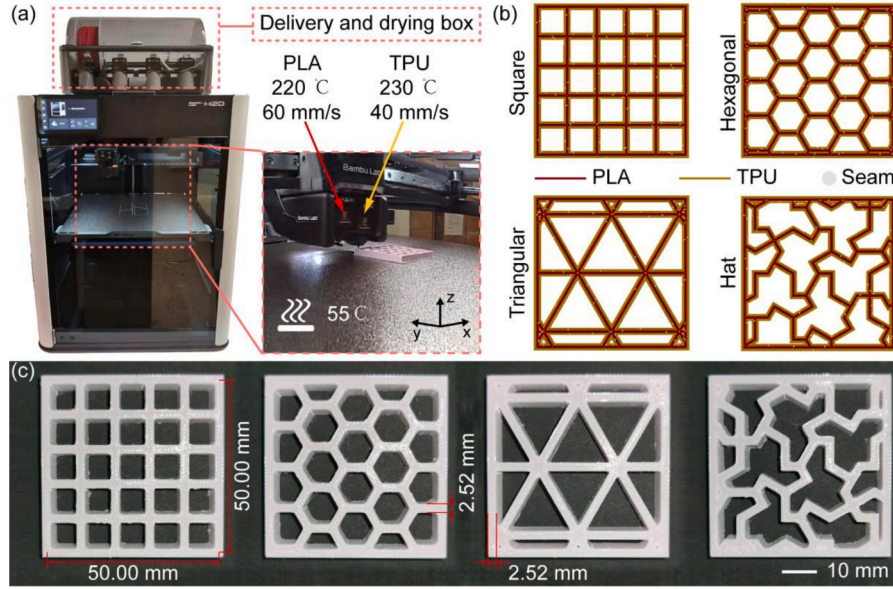


Fig. 2. Fabrication of dual-phase honeycombs: (a) Bambu H2D 3D printer; (b) Printing path and material distribution; (c) Dual-phase honeycombs with different tiling configurations but identical relative density.

Table 1

Basic material parameters for PLA-Lite and TPU-95A-HF consumables.

Name	Density (g/cm ³)	Young's modulus (MPa)	Tensile strength (MPa)	Glass transition temperature (°C)	Melting temperature (°C)
PLA-Lite	1.40	2170	32.0	53	160
TPU-95A-HF	1.22	9.8	27.3	N/A	183

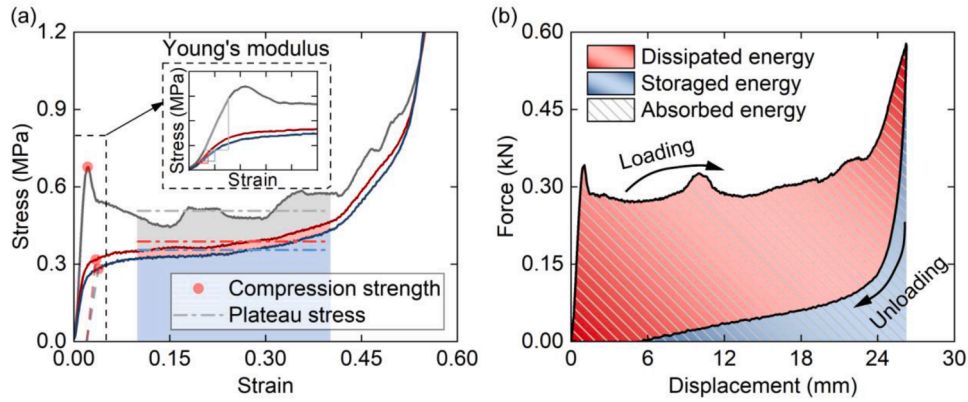


Fig. 3. Evaluation metrics for the mechanical properties of dual-phase honeycombs: (a) Young's modulus, compression strength, and plateau stress; (b) Energy absorption performance.

$$SEA = \frac{1}{m} \int_0^{\delta} F_{loading}(\delta) d\delta, \quad (3)$$

where δ denotes compression displacement, m represents the mass of the structure, and $F_{loading}$ is the force during loading. Similarly, specific energy dissipation (SED) and specific energy storage (SES) are calculated using

$$SED = \frac{1}{m} \left(\int_0^{\delta} F_{loading}(\delta) d\delta - \int_{\delta_r}^{\delta} F_{unloading}(\delta) d\delta \right), SES = \frac{1}{m} \int_{\delta_r}^{\delta} F_{unloading}(\delta) d\delta, \quad (4)$$

where δ_r represents residual displacement after unloading, and $F_{unloading}$

signifies the force during unloading. In this study, two displacement selection criteria are adopted for defining SEA, SED, and SES. The first criterion employs the densification displacement δ_D , corresponding to the displacement at which energy absorption efficiency η reaches its maximum value. Energy absorption efficiency is defined as

$$\eta(\delta) = \frac{\int_0^{\delta} F(\delta) d\delta}{F_{max} \cdot h}, \quad (5)$$

where F_{max} denotes the maximum force within the displacement range of 0 to δ . The second criterion utilizes a fixed strain of 0.5, with the corresponding displacement denoted as $\delta_{0.5}$. Consistently, SEA, SED, and SES values derived from these displacement definitions are labeled with subscripts D and 0.5 for clarity. The shape recovery ratio can be used to evaluate the shape recovery capacity of dual-phase honeycombs [51],

and is defined as

$$R_s = \frac{h_3 - h_2}{h_1 - h_2} \times 100\%, \quad (6)$$

where h_1 , h_2 , and h_3 represent the original height, compressed height, and recovered height of samples, as shown in Fig. 1c. The mechanical recovery capacity of dual-phase honeycombs can be assessed using the retention ratio, which is expressed as

$$R_p = \frac{P_i}{P_0} \times 100\%, \quad (7)$$

where P_i denotes the mechanical property of the dual-phase honeycomb in the i th compression.

3.3. Mechanical test and heat treatment

To compare Young's modulus, compression strength, energy absorption performance, and shape recovery capacity of dual-phase honeycombs with varying design parameters and heat treatment protocols, a combination of quasi-static compression tests and controlled thermal treatments was employed. As shown in Fig. 4a, an MTS material testing machine was utilized to perform quasi-static uniaxial compression tests. The samples underwent both monotonic and cyclic compression, with the applied compression force and displacement recorded by the testing machine. Loading and unloading rates were set to 4 mm/min and 12 mm/min in displacement control mode, respectively, to ensure quasi-static conditions. All samples were stored in a desiccator with a humidity of 20% prior to testing, and experiments were conducted at room temperature and humidity. It should be noted that all experiments were conducted with three independent samples per configuration and experimental condition. All data are presented as mean values, while error bars in the figures represent standard deviation. As illustrated in Fig. 4b-c, two distinct testing methods were implemented to investigate

mechanical performance: (1) uniaxial compression tests combined with heating-driven shape recovery, and (2) uniaxial cyclic compression tests combined with spontaneous shape recovery. The uniaxial compression test (T1) was the primary experiment to evaluate the heating-driven shape recovery capacity and mechanical property restoration of dual-phase honeycombs with varying design parameters, configurations, and thermal treatment conditions. Following full densification, the honeycombs were heated in an air-circulating thermostatic oven for 3 hours to restore their shape and mechanical properties. This specific heating duration was determined based on ensuring complete melting of the PLA phase under 160 °C. For the 60 °C and 110 °C treatments, identical heating durations were maintained to ensure consistent experimental conditions across all temperature regimes. The uniaxial cyclic compression tests were further divided into two sub-procedures: (1) fixed-displacement cyclic compression (T2), and (2) progressive-displacement cyclic compression (T3). In T2, samples underwent three loading/unloading cycles, with both loading and unloading displacements set at 50% of the original height. This protocol, executed without relaxation time for shape recovery, was designed to investigate the minimum level of honeycombs for reuse. In T3, samples were subjected to five graded loading/unloading cycles to simulate complex work conditions. The loading displacements increased incrementally from 5 mm to 25 mm in 5 mm steps, with the compression plate returning to its original position after each loading cycle. In this work, orders of compressions 1–5 are abbreviated as C1–C5. It should be emphasized that this study considers extreme deformation levels, which induce substantial damage to the constituent materials of dual-phase honeycombs. Consequently, the experimental results obtained in this work represent the lower threshold of the reusability potential for this class of metamaterials.

As illustrated in Fig. 4d, the mechanical behavior of DSqu4 under different testing protocols exhibited distinct characteristics. Comparing results from DSqu4-T1, DSqu4-T2, and DSqu4-T3 in C1 revealed consistent stiffness, compression strength, and plateau force across the

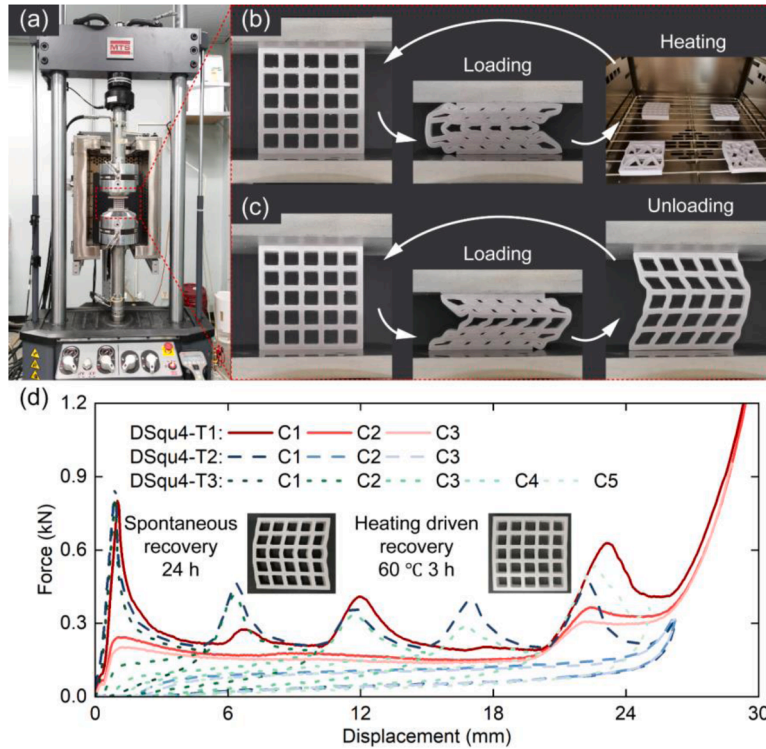


Fig. 4. Quasi-static experiment for dual-phase honeycomb: (a) Test machine; (b) Uniaxial cyclic compression with heating driven shape recovery; (c) Uniaxial cyclic compression with spontaneous shape recovery; (d) Force-displacement curves of dual-phase honeycomb under different test methods, where T1-T3 denote distinct experimental methods and C1-C5 correspond to compression cycles 1 through 5 in a test.

three tests, demonstrating excellent printing reproducibility. However, in DSqu4-T2, the stiffness, compression strength, and plateau force in C2 and C3 showed significant reductions compared to those in C1, indicating that the initial compression in C1 caused irreversible damage to the PLA phase. The force-displacement curves of DSqu4-T2 in C2 and C3 basically overlapped, as further damage to the PLA phase did not progress appreciably. Notably, the unloading force-displacement curves for DSqu4-T2 showed limited dependency on cycle numbers. Progressive functional degradation was observed in DSqu4-T3, as evidenced by the decreasing stiffness, compression strength, and plateau force across cycles. When the compression displacement exceeded the maximum historic loading displacement, the force recovered to the baseline level observed in DSqu4-T1-C1. Following each compression, DSqu4-T1 was heated to 60 °C for 3 hours, resulting in a significant shape recovery compared to spontaneous recovery. 60 °C exceeded the glass transition temperature of PLA, facilitating the release of stress-induced strain in the PLA phase and activating the shape memory effect. Simultaneously, higher temperatures reduced the stiffness of the TPU phase, enhancing viscoelastic recovery. Comparing the results of DSqu4-T1 in C2 and C3 with those of DSqu4-T2, the heating treatment restored stiffness and plateau force, though the compression strength remained substantially reduced compared to the original values. The observed reduction in compression strength indicates that the initial buckling-induced damage was not fully eliminated, as subsequent deformation followed the trajectory of the initial compression. This inherent mechanism of mechanical degradation is further elucidated by analyzing the microstructural morphology of dual-phase honeycombs through scanning electron microscopy (SEM). As illustrated in Fig. 5a-c, the printing quality of the samples is sufficiently high, with no discernible damage

observed on the PLA phase, TPU phase, and their interfacial regions. However, as depicted in Fig. 5d-f, significant damage manifests after compression, including the formation of microholes and cracks, along with minor interfacial delamination between PLA filaments. The average crack length is 8.8 μm , and the interfacial separation width is measured to be 20.0 μm . The density of microholes increases from 1.2 mm^{-2} before compression to 8.7 mm^{-2} after compression. Upon heating at 60 °C, as shown in Fig. 5g-i, no apparent changes were observed in the undeformed regions. The microcracks became less visible due to the high-level shape recovery, although the interfacial separation remained irreversible. In conclusion, the dual-phase design, combined with thermal treatment, demonstrates an excellent balance between mechanical performance and reusability.

4. Results and discussions

This section systematically investigates the mechanical performance and reusability of dual-phase honeycombs. It begins with a comparison to single-phase honeycombs to highlight the benefits of combining hard and soft phases, followed by an analysis of the influence of phase thickness on mechanical properties and recovery. Different tiling configurations (periodic: triangular, square, hexagonal; aperiodic: hat) are evaluated for their impact on mechanical behavior and reusability. Finally, the effect of heating temperature on shape recovery and mechanical restoration is examined.

4.1. Comparison with single-phase honeycombs

To analyze the mechanism behind mechanical property

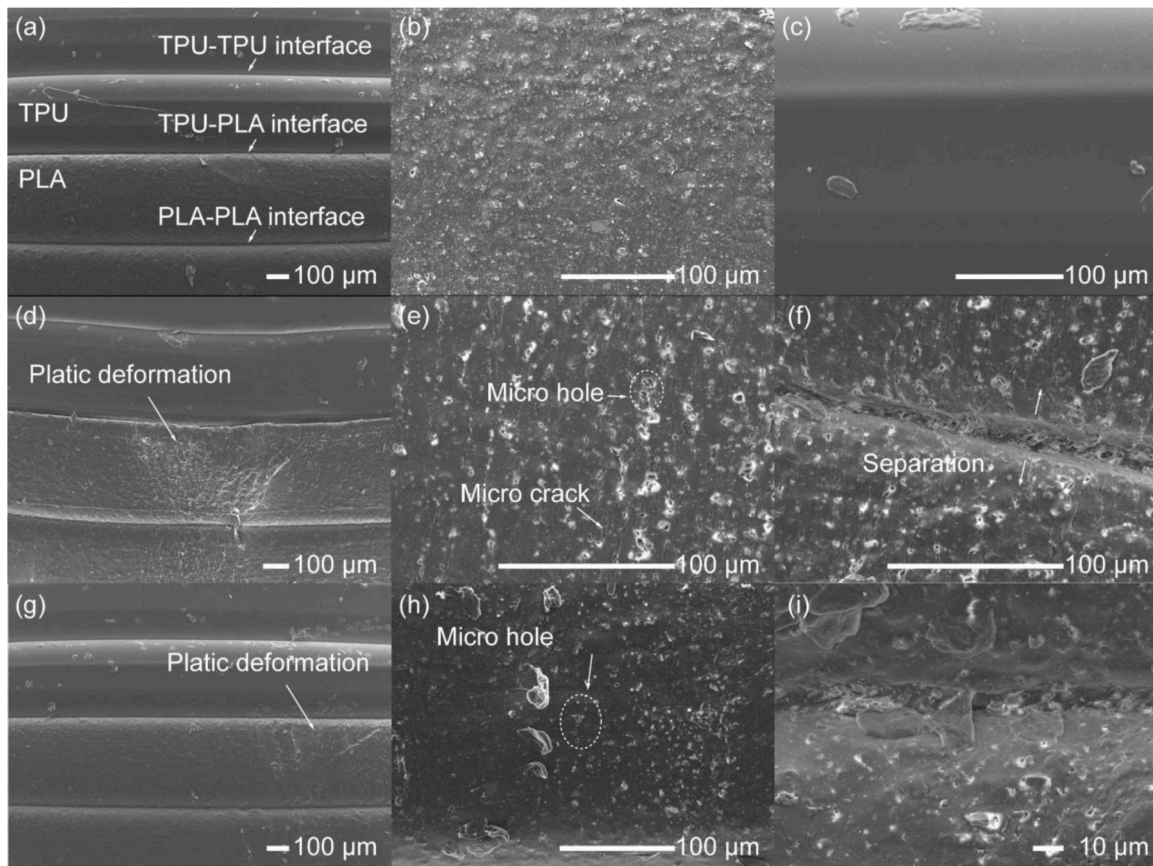


Fig. 5. SEM micrographs of dual-phase honeycombs: (a) Interfaces between PLA and TPU phases; (b)-(c) Surface morphology of the PLA and TPU phases, respectively; (d) Plastic deformation region surface morphology; (e) Plastic deformation region surface morphology in the PLA phase; (f) Interface separation between PLA/PLA regions induced by deformation; (g) Plastic deformation region surface morphology processed at 60 °C; (h) Plastic deformation region surface morphology in the PLA phase processed at 60 °C; (i) Interface separation between PLA/PLA regions processed at 60 °C.

enhancement, the hard and soft phases of DSqu4 were individually fabricated, named DSqu4-H and DSqu4-S, respectively. Additionally, a single soft phase honeycomb with the same dimensions as DSqu4 was fabricated for comparative analysis, designated SSqu4-S. As shown in Fig. 6a, DSqu4 exhibits significantly higher stiffness (125.85 MPa) compared to DSqu4-S (0.45 MPa), while being comparable to the stiffness of DSqu4-H (145.50 MPa). This indicates that the hard phase plays a dominant role in enhancing the stiffness of dual-phase honeycombs, achieving an 859% increase compared to single-phase honeycombs composed of TPU (13.12 MPa). Similarly, the compression strength of DSqu4 (1.52 MPa) is improved by the inclusion of the hard phase, surpassing that of SSqu4-S (0.77 MPa). As illustrated in Fig. 6b, during the compression process, the PLA filaments in DSqu4-H undergo separation due to the low cohesive strength of the material, a phenomenon also observed in previous work [16], leading to crack propagation and localized structural damage. In contrast, no such separation is observed in DSqu4-S, highlighting the soft phase's ability to act as a constraint and improve the mechanical performance of the dual-phase structure through the interaction between the soft and hard phases. Despite the inherently low fracture strain of PLA relative to TPU, the TPU phase acts as a constraint that suppresses localized straining at the nodal junctions, where PLA filaments are prone to cracking. Consequently, no visible PLA filament fracture is observed in DSqu4 under the same compression conditions. A simplified analytical model (see Appendix) explains that the hard phase increases the moment of inertia and fully plastic bending moment of walls in dual-phase honeycombs, owing to its higher Young's modulus and yield stress. This enhancement directly contributes to the observed improvements in stiffness, strength, and plateau force, thereby highlighting the critical role of the hard phase in optimizing the mechanical behavior of the dual-phase honeycombs. Fig. 6c-d further demonstrates the shape recovery behavior of the samples under different thermal conditions. While DSqu4-S exhibits considerable recovery at both room temperature and 60 °C, indicating its inherent spontaneous shape recovery capacity, DSqu4-H shows minimal recovery at room temperature but achieves substantial recovery at 60 °C. This difference

is attributed to the activation of the shape memory effect in the PLA phase, which is triggered by heating above the glass transition temperature. The results confirm that the dual-phase design effectively balances mechanical performance with shape recovery capability, leveraging the unique properties of both phases.

4.2. Thickness of the soft phase

As discussed in Section 4.1, the soft phase in dual-phase honeycombs enhances shape recovery, while the hard phase requires external thermal activation to recover its configuration. This highlights the necessity of investigating how variations in soft phase thickness influence both recovery performance and mechanical properties of dual-phase honeycombs. In this section, the soft phase percentage is systematically varied while the hard phase thickness is fixed at 0.42 mm to explore the effect of the soft phase, and the detailed design parameters are introduced in Section 2. As depicted in Fig. 7a, the stress response of dual-phase honeycombs increases with an increase in soft phase percentage, while the densification displacement decreases under the same loading conditions. Corresponding SEA at the densification displacement are illustrated in Fig. 7b, and these results reveal a performance degradation in C2 and C3 compared to C1. Notably, the SEA_D retention ratio remains above 70% for C2 and above 63% for C3 across all configurations. Experimental results further demonstrate a non-linear energy absorption degradation pattern in reusable dual-phase honeycombs, where the degradation rate diminishes progressively through successive compressions. For example, DSqu3-T1 remains 100% SEA_D in C1, exhibits a 29.1% reduction in C2, and only a 5.0% further decline in C3, demonstrating a decelerating deterioration rate. Similar degradation trends are observed in both Young's modulus and compression strength, as evidenced by the data presented in Fig. 7c-d. The Young's modulus retention behavior reveals an inverse relationship between soft phase content and mechanical stiffness degradation. In C2, the retention ratios increase from 24.6% to 73.3% as the soft phase percentage rises from 58% to 85.71%. Similarly, in C3, the retention ratios show an increase from

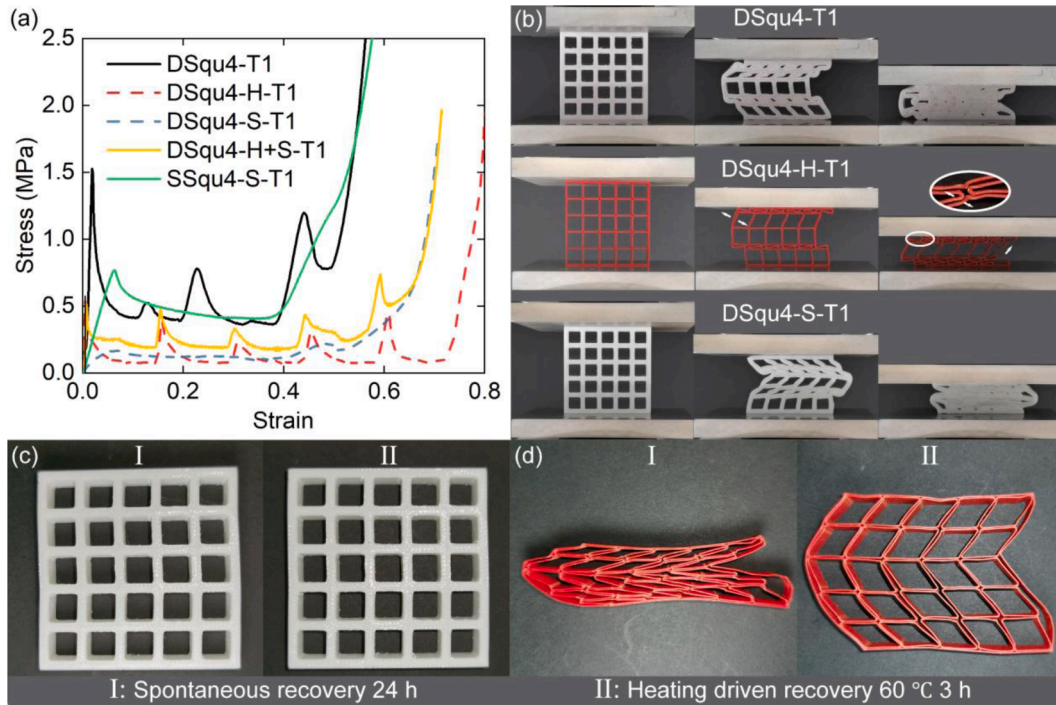


Fig. 6. Mechanical properties and recovery characteristics of dual-phase and single-phase honeycombs: (a) Stress-strain curves, where DSqu4-H and DSqu4-S denote the individual hard phase and soft phase in dual-phase DSqu4, respectively. DSqu4-H+S represents the combined results of DSqu4-H and DSqu4-S, while SSqu4-S indicates single-soft-phase honeycombs with identical dimensions to DSqu4; (b) Deformation process under quasi-static compression; (c)-(d) Recovery behaviors of DSqu4-S and DSqu4-H under different thermal conditions, respectively.

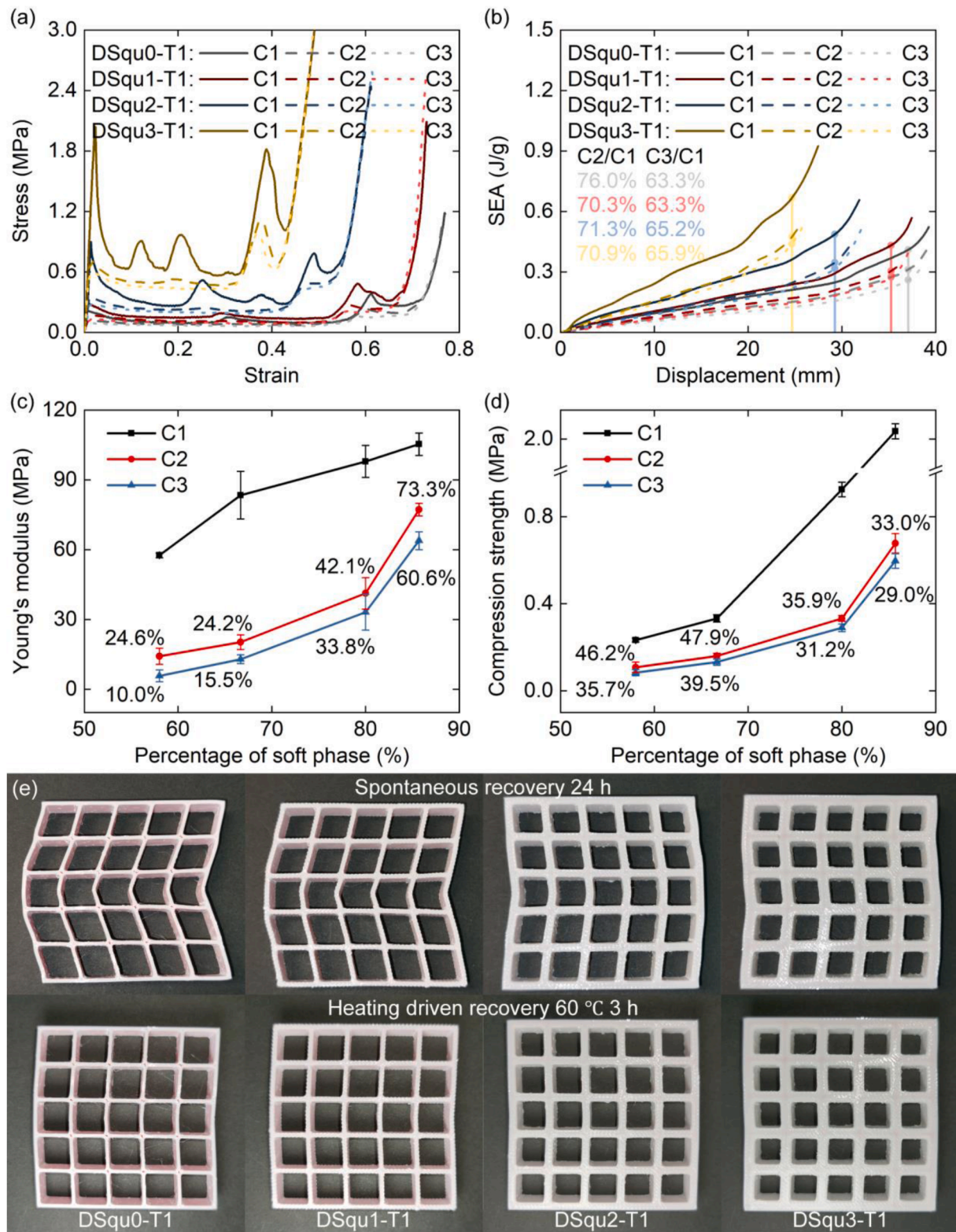


Fig. 7. Compression performance and recoverability of dual-phase honeycombs with varying soft phase thickness: (a) Stress-strain curves; (b) SEA-displacement curves; (c) Relationship between Young's modulus and percentage of soft phase; (d) Relationship between compression strength and percentage of soft phase; (e) Shape recovery states under different thermal conditions. The percentage numbers in each subplot represent the mechanical property retention ratios calculated by Eq. (7).

10.0% to 60.6% under the same soft phase composition variation. This suggests that higher soft phase percentage effectively mitigates stiffness degradation during repeated loading. Conversely, the compression strength retention ratios show an inverse trend, decreasing with increasing soft phase percentage. This is exemplified by DSqu3, which exhibits the lowest retention values of 33.0% in C2 and 29.0% in C3 among all configurations, directly correlating with its high soft phase percentage.

All dual-phase honeycombs with varying soft phase percentages in C1 and C2 exhibit a progressive folding mode, characterized by the formation of multiple localized stress peaks on their stress-strain curves (see Fig. S1a–d). Notably, the final peak stress typically ranks second to the initial peak stress due to the relatively low wall height of the last structural layer, which can be explained by the buckling theory (see Appendix). In C1, no initial buckling is observed on the honeycomb walls. As a result, both the Young's modulus and compression strength attain their maximum values in C1. However, the hard phase of dual-phase honeycombs undergoes irreversible plastic deformation during compression, making it challenging to fully recover to the original configuration. As demonstrated in Fig. 7e, dual-phase honeycombs struggle to achieve complete shape recovery at room temperature after 24 hours. Interestingly, samples with a higher soft phase percentage demonstrate superior recovery performance, as evidenced by minimal residual deformation. To facilitate shape recovery, a heating-driven approach is employed, and all tested samples achieve excellent shape recovery under 60 °C for 3 hours, with a shape recovery ratio exceeding 99.0% for samples with varying soft phase thicknesses (DSqu0–DSqu3,

see Table S1). Despite this, some residual deformation persists in the samples, which introduces initial buckling during subsequent compressions. Consequently, the deformation mechanism in C2 mirrors that of the first cycle, reducing stiffness and compression strength. The energy absorption capacity of dual-phase honeycombs is primarily governed by the plateau stress resulting from wall bending rather than the initial shape. This intrinsic characteristic ensures a relatively higher retention ratio of energy absorption compared to the retention ratios of Young's modulus and compression strength. This observation highlights the distinct restoring ability of energy absorption capacity, even in the presence of residual deformation and structural degradation.

4.3. Thickness of the hard phase

The hard phase plays a critical role in enhancing the mechanical properties of dual-phase honeycombs due to its high Young's modulus and strength. To quantitatively analyze the influence of the hard phase, this section evaluates three dual-phase honeycombs with varying hard phase thicknesses, 0.42 mm, 0.84 mm, and 1.26 mm, while maintaining a fixed soft phase thickness of 0.84 + 0.84 mm. As depicted in Fig. 8a, the stress response of the honeycombs increases with increasing hard phase thickness. Additionally, honeycombs with a higher percentage of hard phase exhibit more pronounced stress fluctuations during compression. Fig. 8b–d further illustrate significant differences in mechanical performance across configurations. Specifically, DSqu5 demonstrates markedly higher values of Young's modulus, compression strength, and SEA_D compared to DSqu2 and DSqu4. However,

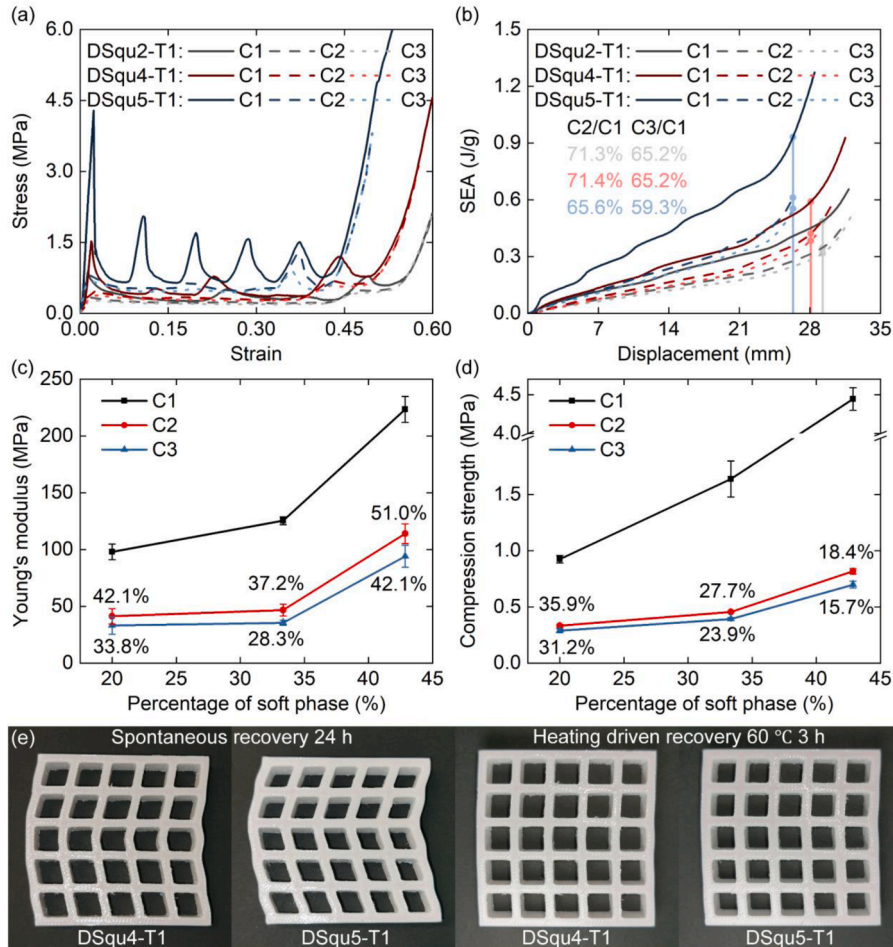


Fig. 8. Compression results and recoverability of dual-phase honeycomb with varying hard phase thickness: (a) Stress-strain curves; (b) SEA-displacement curves; (c) Relationship between Young's modulus and percentage of hard phase; (d) Relationship between compression strength and percentage of hard phase; (e) Shape recovery states under different thermal conditions. The percentage numbers in each subplot represent the mechanical property retention ratios calculated by Eq. (7).

configurations with excessively high hard phase percentages exhibit reduced retention ratios in subsequent compressions. For example, the SEA_D retention ratios of DSqu5 are 65.6% in C2 and 59.33% in C3, while its compression strength retention ratio falls below 20%. Interestingly, DSqu5 exhibits superior retention of Young's modulus compared to DSqu2 and DSqu4, with a retention ratio that follows a distinct trend compared to SEA_D and compression strength.

When comparing the experimental results of DSqu3 and DSqu5 (see Fig. S2), it becomes evident that a higher hard phase percentage significantly enhances mechanical performance in dual-phase honeycombs with the same wall thickness. Specifically, performance of DSqu5 in C1 exceeds that of DSqu3 by factors of 2.12, 2.16, and 1.40 for Young's modulus, compression strength, and SEA_D , respectively. While the relative performance advantage of DSqu5 over DSqu3 diminishes during subsequent compressions compared to C1, DSqu5 maintains superior performance across all metrics. In C2, DSqu5 demonstrates 1.48, 1.20, and 1.29 times the values of DSqu3 for Young's modulus, compression strength, and SEA_D , respectively. This performance level is further maintained in C3 with factors of 1.47, 1.17, and 1.26. The reduced performance gap between DSqu5 and DSqu3 in later compressions is attributed to the higher hard phase volume fraction in DSqu5, which accumulates more irreversible damage during cyclic loading. These findings emphasize the necessity of achieving a balanced hard-soft phase composition to optimize both reusability and mechanical performance.

The deformation behavior of dual-phase honeycombs with higher hard phase content during compression loading follows a progressive pattern analogous to that described in Section 4.2. The deformation mechanisms observed in subsequent compressions remain consistent with those in C1 (see Fig. S1e-f). However, the hard phase lacks inherent capability for spontaneous shape recovery at room temperature, relying instead on the recovery force generated by the soft phase during its self-recovery for partial restoration. This dependency results in residual deformation in DSqu2, DSqu4, and DSqu5 after 24 hours at room temperature, as evidenced by Fig. 7e and Fig. 8e. Notably, structures with elevated hard phase content, such as DSqu5, exhibit significantly greater residual deformation. This phenomenon is directly related to the increasing recovery force required to restore the hard phase as its volume fraction rises. The self-recovery force provided by the soft phase becomes insufficient to fully reinstate the hard phase to its original configuration, progressively reducing the overall recovery rate in systems with higher hard phase proportions. However, these honeycombs demonstrate remarkable shape recovery capabilities when subjected to heating at 60 °C for 3 hours, underscoring the recoverability of the dual-phase architecture. The incorporation of shape memory characteristics in the hard phase is pivotal to enhancing the global shape recovery performance of dual-phase honeycombs, emphasizing its critical role as a fundamental design element in achieving reusability and mechanical enhancement.

4.4. Configuration of dual-phase honeycombs

In the preceding section, only dual-phase honeycombs with square unit cells were considered, which may not be an optimal configuration for practical applications. To provide a comprehensive evaluation of the dual-phase design, three additional configurations with the same relative density, hexagonal, triangular, and hat, are considered here. These configurations include both periodic and aperiodic tiling patterns, primarily to increase the diversity of the sample set and to demonstrate that the dual-phase design concept is applicable across different architectural arrangements. Moreover, it is interesting to explore whether aperiodic structures might offer specific advantages for reusable energy absorption applications, given that previous studies have shown that aperiodic or disordered architectures can exhibit superior fracture resistance and damage tolerance compared to periodic ones. Notably, unlike the isotropic mechanical behavior observed in square dual-phase

honeycombs, the hexagonal, triangular, and hat configurations demonstrate pronounced anisotropy. Consequently, their mechanical characteristics are evaluated independently along two primary directions. As illustrated in Fig. 9a, the stress fluctuations of DHex4-Y, DTri4-Y, DHat4-Y, and DHat4-X are significantly lower compared to those of DSqu4, DHex4-X, and DTri4-X. Notably, the suffixes X and Y denote the compression direction along the x-axis and y-axis, respectively. This reduction is attributed to the decreased presence of structural elements aligned with the applied compressive loading direction. Except for DSqu4, all other configurations exhibit minimal stress oscillations during subsequent compressions, a behavior that is highly advantageous for energy absorption. Among these, the hexagonal configuration, specifically DHex4-Y, demonstrates the most stable stress response throughout the entire compression process. Fig. 9b reveals that DHex4-Y consistently achieves the highest SEA across most compression displacement ranges in C1, C2, and C3, thereby confirming its superior energy absorption capacity. In contrast, the energy absorption performance of DTri4-Y and DHat4-X remains suboptimal throughout the tests. Interestingly, DHat4-Y exhibits a continuously increasing rate of energy absorption with displacement, a trend directly attributable to the monotonically rising compressive stress observed during strain larger than 0.1.

As depicted in Fig. 9c, Young's modulus of DTri4-X in C1, 128.14 MPa, is higher than that of DSqu4 and DTri4-Y. The Young's moduli of DHex4 and DHat4 are markedly lower than those of the square and triangular configurations. Fig. 9d further shows that DSqu4 achieves the highest compression strength of 1.64 MPa in C1, while DTri4, DHex4, and DHat4 follow in descending order. However, all sample configurations exhibit substantial reductions in both Young's modulus and compression strength during subsequent compressions due to the residual deformation, underscoring the strong dependence of these mechanical performances on geometric shape. In subsequent compressions, the performance sequences of compression strength shift, while those of Young's modulus remain unchanged. For compression strength, DHex4-X ascends to the first echelon, while DHex4-Y and DHat4 occupy the second and third echelon, respectively. Notably, the disparities in compression strength among the samples significantly diminish. As illustrated in Fig. 9e, the plateau stress of DHex4-X in C1 reaches 0.55 MPa, the highest among all samples, whereas DTri4-Y exhibits the lowest value of 0.31 MPa. Notably, the retention ratio of plateau stress under cyclic loading remains significantly higher compared to those of Young's modulus and compression strength. In C2, DHat4-X achieves the highest retention ratio of plateau stress, 73%, while in C3, this value decreases slightly to 69%, still maintained by DHat4-X. Conversely, DTri4-X demonstrates the lowest retention ratio of plateau stress in C2, 62%, and further declines to 58% in C3, highlighting its relatively poorer cyclic stability compared to other configurations. These results emphasize the distinct behavior of plateau stress retention under repeated loading, which is less sensitive to mechanical degradation than other performance metrics. The most significant degradation in mechanical properties occurs between C1 and C2, whereas the performance degradation from C2 to subsequent cycles is considerably smaller. For reusable applications requiring stable performance over multiple cycles, the pre-compressed and thermally recovered state (C2) represents a more practical design baseline than the original state (C1). Therefore, the mechanical properties of the samples in C2 are selected as the baseline, while the maximum values of each metric across all configurations are used as denominators to achieve normalization. As shown in Fig. 10, the square configuration demonstrates superior performance in terms of Young's modulus and compressive strength, while the hexagonal configuration exhibits exceptional potential in enhancing energy absorption capacity. Notably, all structural configurations consistently demonstrate remarkable shape recovery capabilities, underscoring the superiority of dual-phase design.

By observing the compression process illustrated in Fig. 11a-f, the underlying mechanisms governing the energy absorption characteristics

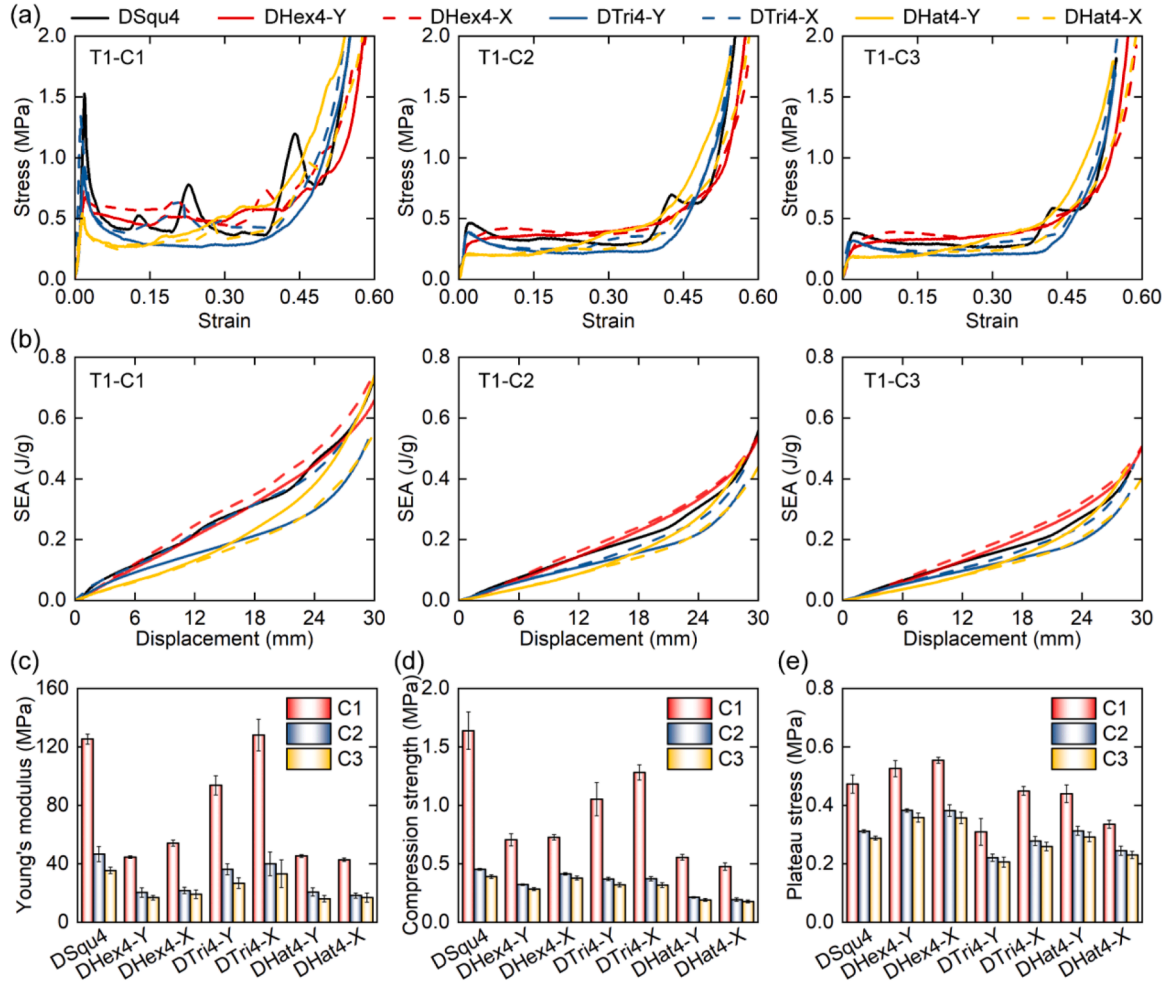


Fig. 9. Results of dual-phase honeycombs with different configurations under test 1: (a) Stress-strain curves; (b) SEA-displacement curves; (c) Young's modulus; (d) Compression strength; (e) Plateau stress.

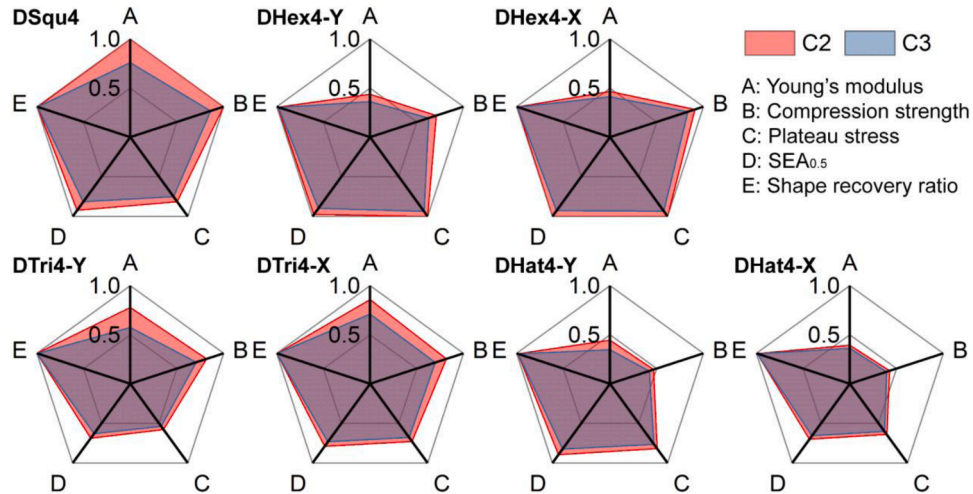


Fig. 10. Normalized mechanical properties of dual-phase honeycombs under various configurations. The best mechanical properties of the samples in C2 are taken as the baseline, reflecting the properties following pre-compression and thermal-driven recovery.

can be systematically analyzed. The horizontal panels in DSQu4 exhibit limited deformation, a trend also observed in DTri4-Y, which decreases their energy absorption capacity. However, SEA of DSQu4 exceeds that of DTri4-Y. This discrepancy arises from the additional presence of

numerous vertical panels in DSQu4, which are short in length and thus generate a significant buckling force upon compression. In contrast, DTri4-Y features longer inclined panels, which require less force to undergo bending, resulting in a lower SEA. This mechanism is

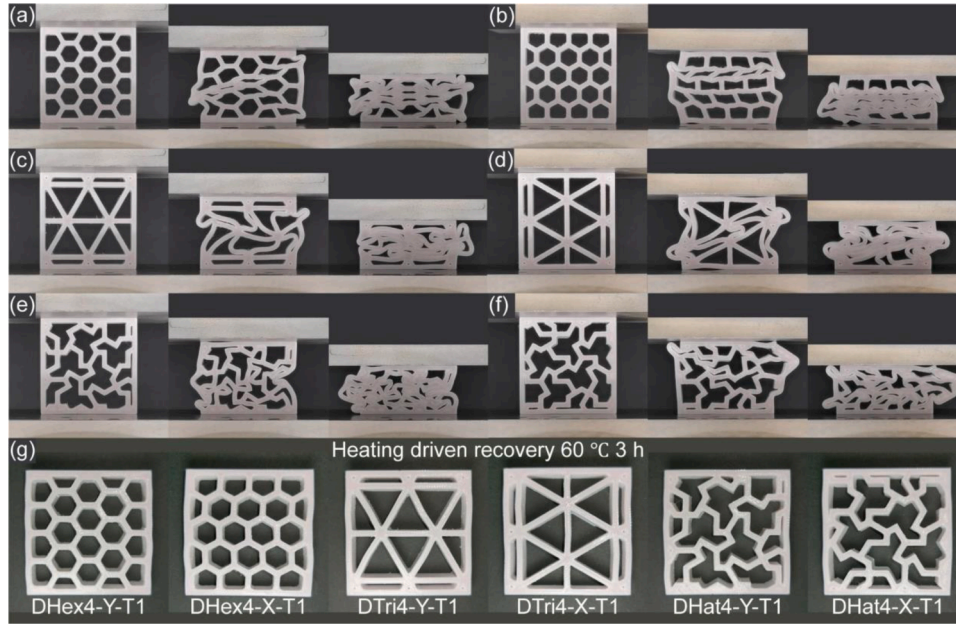


Fig. 11. Deformation processes and shape recovery states of dual-phase honeycomb with the different configurations and compression directions: (a)-(f) Deformation processes of DHex4-Y, DHex4-X, DTri4-Y, DTri4-X, DHat4-Y, and DHat4-X, respectively; (g) Final recovery shapes of dual-phase honeycombs under 60 °C for 3 hours.

corroborated by the SEA of DHex4-X and DTri4-X, both of which contain a high number of vertical panels, further validating the critical role of such panels in energy dissipation. The influence of vertical panel continuity on mechanical performance is also evident. Continuous vertical panels significantly enhance both the Young's modulus and compression strength, whereas discrete vertical panels contribute minimally to these properties. This is consistent with the experimental results, as DSqu4 and DTri4-X, which contain continuous vertical panels, exhibit high Young's modulus and compression strength, while DHex4-X, characterized by discontinuous panels, shows inferior mechanical performance. Additionally, tile stability plays a pivotal role in determining mechanical robustness. For example, the low Young's modulus and compression strength observed in DHex4 and DHat4 can be attributed to their weak tile configurations. The plateau stress is primarily governed by the number of bending joints and the cumulative bending angle across all panels. As shown in Fig. 13a-f, these bending joints typically form at the midpoints and ends of panels, serving as critical energy

dissipation sites. Notably, DTri4-Y exhibits the lowest plateau stress due to its limited number of bending joints and small cumulative bending angles, which restrict the overall energy absorption capacity. As depicted in Fig. 11g, all samples demonstrate a high recovery ratio after compression; however, residual deformations remain evident. Furthermore, the inner hard phase sustains material damage that is not fully recoverable at 60 °C. These two factors, residual deformation and material damage, synergistically contribute to the progressive degradation of mechanical performance in dual-phase honeycombs under repeated cyclic loading.

To further investigate the cyclic performance of dual-phase honeycombs, the fabricated samples underwent ten compressions, with their corresponding retention ratios documented in Fig. 12. As illustrated in Fig. 12a, DHex4-Y, DHat4-Y, and DHat4-X demonstrate superior Young's modulus retention capacity, achieving retention ratios of 25.77%, 23.35%, and 23.38%, respectively. In contrast, DSqu4 and DTri4-X exhibit lower retention, with respective Young's modulus ratios

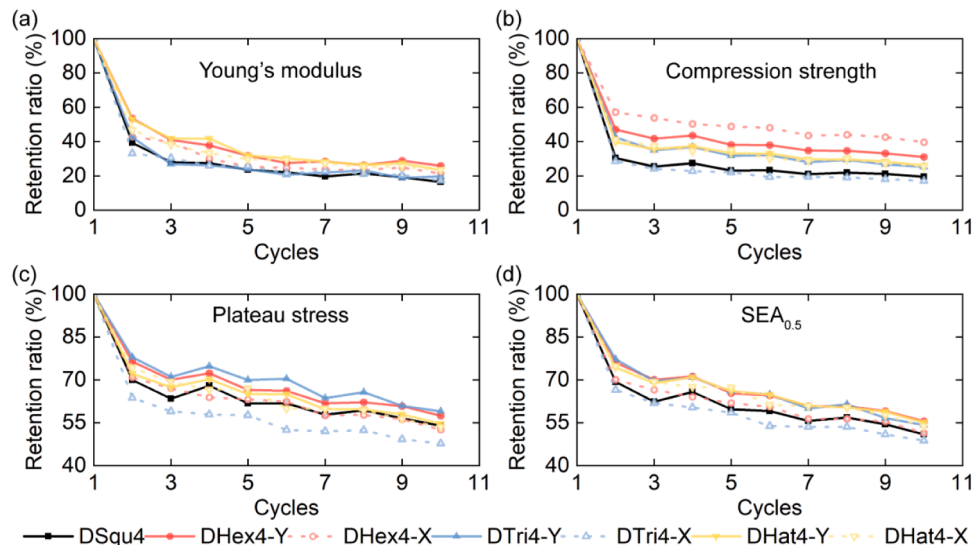


Fig. 12. Retention ratios of dual-phase honeycombs with different configurations: (a) Young's modulus; (b) Compression strength; (c) Plateau stress; (d) $SEA_{0.5}$.

of 16.47% and 17.15%. Regarding compression strength in Fig. 12b, DHex4-X exhibits the most favorable retention performance, with a retention ratio of 39.61%. Notably, the lowest compression strength retention is observed for DSqu4 and DTri4-X, which achieve 19.45% and 17.12%, respectively. For plateau stress in Fig. 12c, the triangular configurations show divergent behavior. Specifically, DTri4-Y achieves the highest plateau stress retention ratio (59.06%), while DTri4-X records the lowest (47.76%). DHex4-Y maintains a robust performance, with a plateau stress retention ratio of 57.46%. In terms of $SEA_{0.5}$ retention ratio in Fig. 12d, DHex4-Y and DHat4-Y demonstrate superior performance, achieving 55.58% and 55.17%, respectively. Interestingly, DTri4-X remains the sample with the lowest $SEA_{0.5}$ retention ratio (48.81%). The total $SEA_{0.5}$ values for DSqu4, DHex4-Y, DHex4-X, DTri4-Y, DTri4-X, DHat4-Y, and DHat4-X in ten cycles are 3.26 J/g, 3.49 J/g, 3.61 J/g, 2.45 J/g, 2.96 J/g, 3.23 J/g, and 2.52 J/g, respectively. Notably, the hexagonal configuration is the most advantageous for cyclic energy absorption when excluding Young's modulus and compression strength as performance metrics. In conclusion, DHex4-Y consistently ranks among the top two samples across all retention metrics, whereas DTri4-X is consistently ranked among the bottom two, underscoring the significant influence of structural geometry on the cyclic performance of dual-phase honeycombs. These findings emphasize the importance of tailoring geometric configurations to optimize specific mechanical properties depending on the application requirements.

Furthermore, investigating the energy absorption performance of dual-phase honeycombs under continuous cyclic compression is essential for evaluating their applicability in scenarios involving multiple impacts within short time intervals. As depicted in Fig. 13a, the stress responses of dual-phase honeycombs in C2 and C3 demonstrate significantly reduced values compared to those observed in Fig. 11a. This phenomenon arises from two key mechanisms: (1) the viscoelastic strain in the soft phase remains trapped due to the limited recovery time, and (2) residual strains persist in the hard phase without thermal activation, collectively impeding complete shape recovery. Consequently, the

mechanical properties of these honeycombs in the cycling state are markedly inferior to those achieved through high-temperature processing. As illustrated in Fig. 13b, the $SES_{0.5}$ of all samples exhibits minimal decay throughout the cycling process. In contrast, the $SED_{0.5}$ of all samples rapidly diminishes to match the $SES_{0.5}$ levels observed in C2. Notably, DHex4-X maintains superior energy absorption performance across all testing cycles, with $SED_{0.5}$ of 0.46 J/g in C1, 0.14 J/g in C2, and 0.12 J/g in C3. Conversely, DHat4-X displays the poorest performance, recording $SED_{0.5}$ of 0.27 J/g in C1, 0.09 J/g in C2, and 0.08 J/g in C3. Interestingly, the SES of dual-phase honeycombs with varying configurations remains statistically similar, and their unloading stress-strain curves show remarkable consistency, suggesting that structural configuration has a relatively minor influence on the overall energy storage efficiency. These findings establish a critical baseline for future investigations aimed at optimizing the durability and recovery capacity of dual-phase honeycombs under short-time cyclic loading conditions.

4.5. Heat treatment temperature

As a key parameter in the recovery of shape and mechanical properties in dual-phase honeycombs, understanding how the heat treatment temperature affects their reusability is important. In this section, three heating temperatures, 60 °C (H1), 110 °C (H2), and 160 °C (H3), were employed to recover compressed dual-phase honeycombs. These temperatures all exceed the glass transition temperature of the hard phase, PLA, with 160 °C being exactly the melting temperature of PLA. Notably, this is lower than the melting temperature of the soft phase, TPU. Consequently, the outer soft phase remains in its solid state under these heating conditions, ensuring the overall shape stability of the honeycomb structures. To examine the influence of the heating temperature on the mechanical performance, the study considered four configurations: DSqu4, DHex4-Y, DTri4-Y, and DHat4-Y. The compression stress of all configurations subjected to heating at 60 °C and 110 °C exhibits highly similar stress-strain curves across subsequent compressions, C2 and C3 (see Fig. S3a-d). However, samples heated at 160 °C display

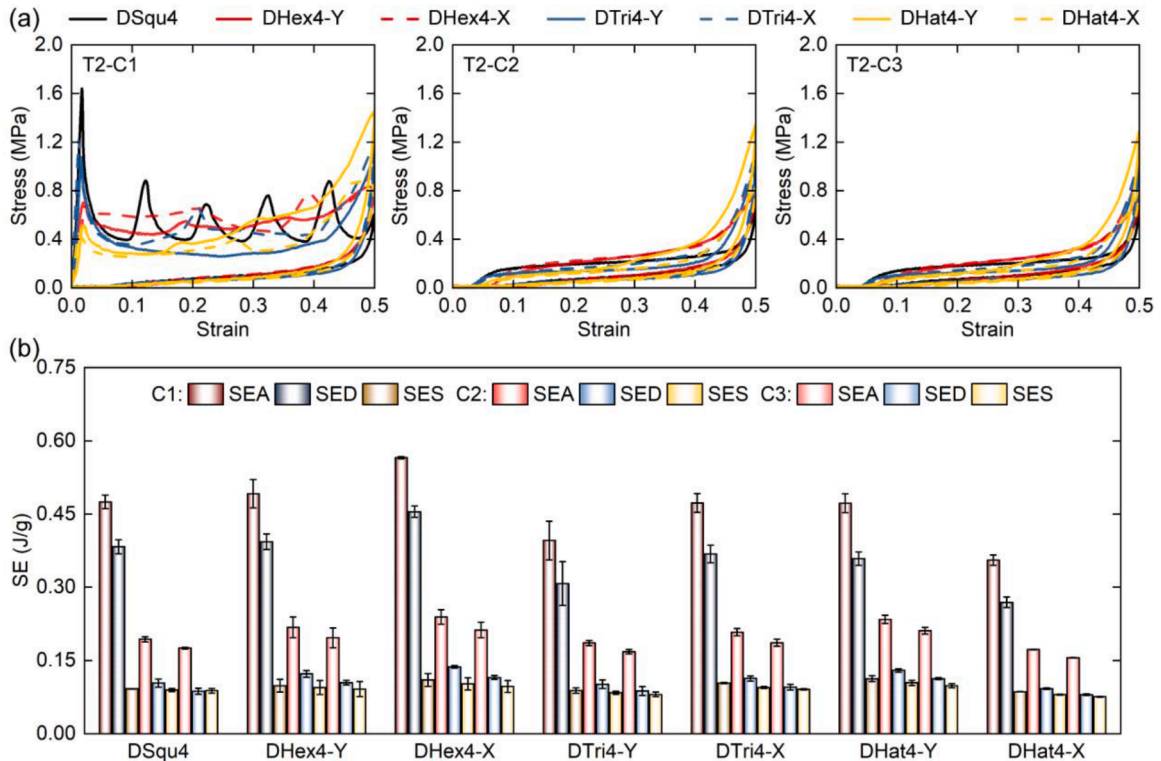


Fig. 13. Results of dual-phase honeycombs with different configurations under T2: (a) Stress-strain curves; (b) The energy absorption performance.

significantly higher compression stress in subsequent compressions compared to their first compression, with this effect being particularly pronounced in DSqu4 and DHex4-Y. This trend is further reflected in their energy absorption performance (see Fig. S3e–h). The SEA of DSqu4-H3 and DHex4-Y-H3 increases significantly in both C2 and C3 compared to C1. In contrast, for DTri4-Y-H3 and DHat4-Y-H3, the SEA increases are only significant at strains greater than 0.3. Furthermore, when the heating temperature is raised from 60 °C to 110 °C, the SEA values of all configurations remain largely consistent, suggesting that the influence of increasing temperature within this range on enhancing energy absorption recoverability is minimal.

As shown in Fig. 14a, the influence of heating temperature on Young's modulus exhibits divergent trends compared to its effect on SEA. For DSqu4, DTri4-Y, and DHat4-Y, the Young's modulus in both C2 and C3 is significantly reduced under all heating temperatures compared to C1. In contrast, DHex4-Y shows an anomalous trend under H3, with its Young's modulus in C2 and C3 reaching 107% and 113% of that in C1, respectively. Furthermore, Young's modulus retention ratios across the configurations under different heating temperatures reveal distinct behaviors. In C2, the retention ratios of all samples under H2 are consistently higher than those observed under H1. However, the retention ratios under H2 and H1 become similar in C3. Notably, under

H3, the Young's modulus retention ratios remain stable across subsequent compressions. In contrast, under H1 and H2, these ratios decrease in subsequent compressions. As illustrated in Fig. 14b, the influence of heating temperature on compression strength aligns closely with that on Young's modulus, albeit with subtle differences. For DHat4-Y under H3, the compression strength in C2 and C3 increases compared to C1, although this increase is less pronounced than in DHex4-Y under H3, where the compression strength in C2 and C3 reaches 147% and 146% of that in C1, respectively. The plateau stress, a critical indicator of energy absorption performance, further reveals differentiated responses to heating conditions, as depicted in Fig. 14c. While the plateau stress of DSqu4, DHex4-Y, DTri4-Y, and DHat4-Y decreases under H1 and H2 in C2 and C3 compared to C1, it increases under H3. Specifically, under H3, DHex4-Y exhibits the highest plateau stress and retention ratio in both C2 and C3, achieving values of 0.89 MPa (181% retention) and 0.71 MPa (144% retention), respectively. Interestingly, the plateau stress retention ratios of DSqu4, DHex4-Y, and DHat4-Y under H1 are slightly lower than those under H2, whereas the retention ratio of DTri4-Y under H1 is marginally higher than that under H2. Across all configurations under H3, the plateau stress retention ratios in C3 are lower than those in C2, with the most substantial decline observed for DHex4-Y, a 37% reduction. It should be noted that exposing the soft phase (TPU) under H3 may

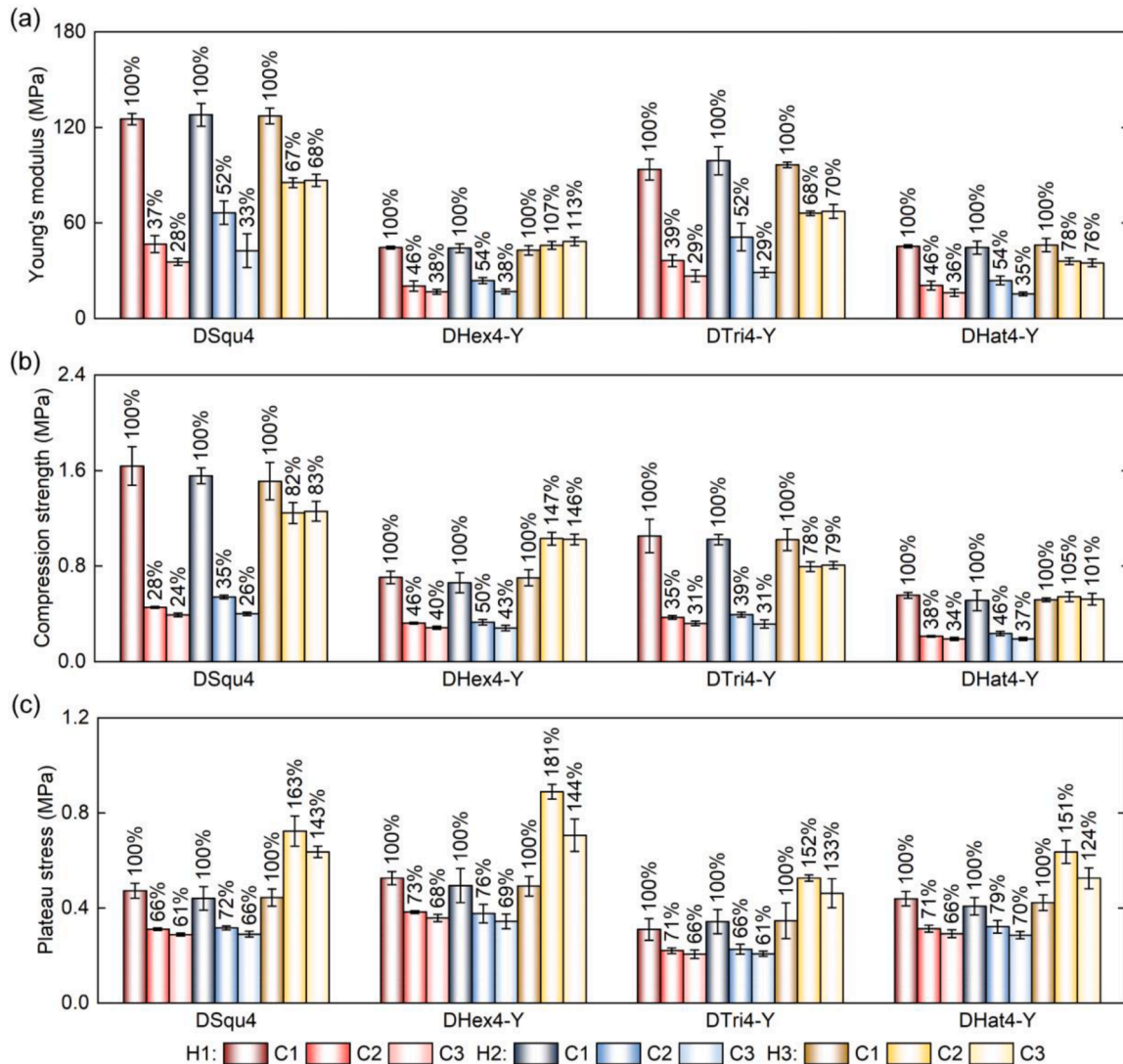


Fig. 14. Mechanical properties of dual-phase honeycombs processed by different heating treatment temperatures: (a) Young's modulus; (b) Compression strength; (c) Plateau stress. The percentages represent the mechanical property retention ratio.

cause moderate softening, as confirmed by additional tests on pure TPU samples (Fig. S5). Nevertheless, the overall mechanical enhancement observed in dual-phase honeycombs after H3 treatment indicates that the positive effect from PLA remelting and interfacial fusion dominates over the softening of TPU. In summary, heating dual-phase honeycombs to the melting temperature of the hard phase, 160 °C, not only facilitates the recovery of mechanical properties but also enhances the plateau stress, highlighting the potential of this approach to improve performance under cyclic loading conditions.

The deformation processes of DSqu4, DHex4-Y, DTri4-Y, and DHat4-Y in C2 recovered by H2 and H3 are similar to those recovered by H1 (see Fig. S4). However, while the samples driven by H2 in C2 continue to deform along the same path established in C1, some samples, specifically DSqu4 and DTri4-Y, recover via H3 in C2 and exhibit distinct deformation paths compared to those observed in C1. This observation suggests that heating at 160 °C can effectively alleviate the unrecoverable strain resulting from compression and significantly alter the state of the hard phase. As further demonstrated in Fig. 15a–b, the samples recovered at 160 °C achieve a higher recovery ratio compared to those recovered at 110 °C, with values nearly identical to those of the original shape. It should be noted that the red coloration observed in the soft phase is caused by pigments from the hard phase that diffuse into the surrounding soft phase under elevated temperatures. As illustrated in Fig. 15c, the extent of pigment diffusion increases with rising temperature. Importantly, the state of the hard phase remains largely unaffected at temperatures below 160 °C, as evidenced by the persistence of distinct filaments formed during the printing process. However, when

the temperature reaches 160 °C, these filaments merge to form a continuous, unified structure. As shown in Fig. 15d, this phenomenon is further confirmed by the microstructural morphology of dual-phase honeycombs processed at 160 °C. The PLA-PLA interface is no longer present, while the TPU-TPU interface remains unchanged. Additionally, in certain regions of the TPU-PLA interface, the seam becomes less pronounced, indicating a reduction in interfacial discontinuities. This structural transformation is the primary reason for the observed improvement in mechanical properties and reusability, which effectively avoids the separation of PLA filaments and eliminates the accumulated damages in PLA phase.

5. Conclusions

The dual-phase honeycomb design, integrating a hard phase with high structural stiffness and a soft phase with superior shape recovery capabilities, successfully addresses the critical trade-off between mechanical performance and reusability in traditional single-phase honeycombs. The following conclusions can be drawn:

By leveraging the shape memory effect of PLA and the shape recovery effect of TPU, the dual-phase honeycombs achieve a synergistic balance, enabling enhanced structural stiffness, significant energy absorption, and repeatable deformation recovery under cyclic loading. Quantitatively, under H1 treatment, all dual-phase honeycomb samples achieved an average shape recovery ratio of 98.8% of their original height after three compression cycles. These characteristics make the dual-phase honeycombs particularly suitable for diverse energy

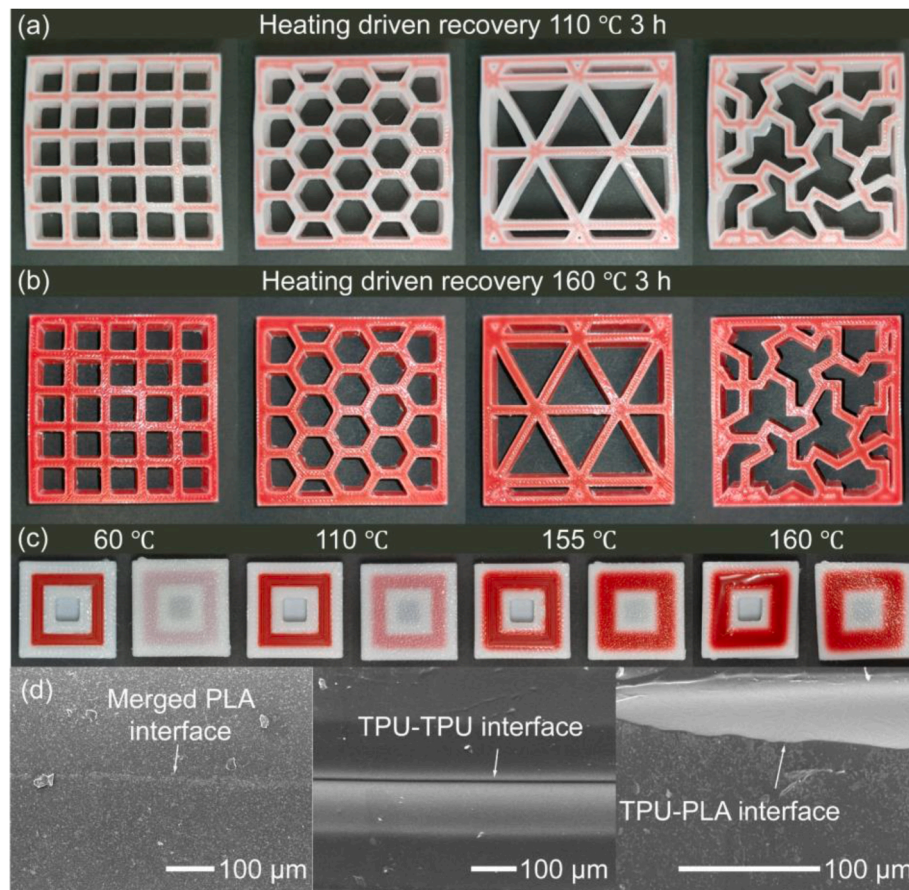


Fig. 15. Final recovery shapes of dual-phase honeycombs under different temperatures and the corresponding state of the hard phase: (a) 110 °C; (b) 160 °C, which leads to the reconstruction of the hard phase; (c) Top and bottom views showing the state of the hard phase under various heating temperatures, while the red color on TPU phase is due to the pigment diffusion. The dimensions of the specimens are 20 × 20 × 2.4 mm³, with the soft phase and hard phase having thicknesses of 2.5 + 2.5 mm and 2.5 mm, respectively. The heights of the soft and hard phases are 2.4 mm and 2.0 mm, respectively; (d) Surface morphology of dual-phase honeycombs processed at 160 °C, demonstrating the reconstruction of deformation induced damages and hard phase filaments.

absorption scenarios, with short-term multiple impacts relying on spontaneous recovery and long-term repeated energy absorption relying on thermal-driven recovery.

Quantitative experimental results demonstrate the effectiveness of the dual-phase design. Compared to single-phase TPU honeycombs, the dual-phase structure achieves an 859% increase in stiffness and a 1.52 MPa compression strength, surpassing the 0.77 MPa of single-phase soft-phase structures. The soft phase percentage significantly enhances shape recovery but compromises mechanical performance, with higher soft phase content reducing compression strength retention. In contrast, higher hard phase content improves mechanical performance but reduces reusability due to irreversible damage accumulation. In practical applications, the phase percentage of dual-phase honeycombs should be carefully optimized to balance the mechanical properties and reusability.

Systematic configuration analysis further reveal that the hexagonal configuration (DHex4-Y) emerges as the optimal design for energy absorption, exhibiting a large total SEA_{0.5} of 3.49 J/g over ten compressions and maintaining 57.46% plateau stress retention after ten cycles. This configuration outperforms other geometries in energy absorption and reusability due to its oblique panel arrangement, which contrasts with the higher stiffness and strength observed in configurations with panels aligned along the loading direction (e.g., triangular and square). These insights provide a framework for tailoring honeycomb geometries to specific application requirements.

Crucially, heat treatment at 160 °C (PLA's melting point) significantly enhances mechanical recovery, with DHex4-Y achieving 107% retention of Young's modulus, 147% compression strength, and 181%

retention of plateau stress in the second cycle compared to the first. Moreover, the higher thermally driven recovery temperature can effectively mitigate the limitations caused by higher hard-phase percentage, due to the ability to eliminate residual damage.

CRediT authorship contribution statement

Sicong Zhou: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Liuchao Jin:** Writing – review & editing, Visualization, Validation, Software. **Guoquan Xie:** Visualization, Software, Methodology. **Kang Zhang:** Software, Methodology, Formal analysis. **Qiang Gao:** Writing – review & editing, Methodology, Investigation. **Wei-Hsin Liao:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.ijmecsci.2026.111900](https://doi.org/10.1016/j.ijmecsci.2026.111900).

Appendix. Simplified analytical models for explaining the mechanical mechanism

Simplified analytical models, neglecting shear effects, are established to elucidate the mechanical behavior of dual-phase honeycombs. The compression strength of these structures is strongly influenced by the buckling resistance of the composite panels. As illustrated in Fig. A1a, the critical buckling force F_{cr} of the panels of length l can be determined using elastic buckling theory for a column with elastically restrained ends. Unlike idealized clamped supports, cell walls in honeycomb structures are not perfectly fixed at the nodes due to the rotational flexibility of adjacent walls. Following the analysis of Gibson et al. [76] for two-dimensional cellular materials, the rotational restraint provided by the neighboring walls can be modeled as a torsional spring of stiffness K . The critical buckling force is then given by

$$F_{cr} = k \frac{\pi^2 EI}{l^2}, \quad (A1)$$

where E is the effective elastic modulus of the composite panel, I is the moment of inertia, and k is an end-constraint factor ($1 \leq k \leq 4$) that depends on the rotational spring stiffness. For example, the Gibson model yields $k \approx 2.0$ for the regular hexagonal geometry, which is intermediate between the pinned-pinned ($k = 1$) and fixed-fixed ($k = 4$) idealizations. To calculate the bending stiffness of the composite panels, the equivalent cross-section method is employed (Fig. A1c). The elastic modulus ratio α between the two phases is defined as

$$\alpha = \frac{E_2}{E_1}, \quad (A2)$$

where E_1 and E_2 denote the elastic moduli of TPU and PLA phases, respectively, resulting in $\alpha > 1$. The equivalent width b'_2 of PLA phase's cross-section is calculated by

$$b'_2 = \alpha b_2, \quad (A3)$$

where b_1 and b_2 represent the original width of the cross-section for TPU and PLA phases, respectively. Consequently, the equivalent moments of inertia for cross-sections A and B are determined as

$$\begin{cases} I_{\text{equiv,A}} = 2[b_1 t_1 (t_1^2/3 + t_2^2 + t_1 t_2) + \alpha b_2 t_2^3/3]; \\ I_{\text{equiv,B}} = b_1 t_1^3/12 + \alpha b_2 t_2^3/12 - b_1 t_1 t_2/2; \end{cases} \quad (A4)$$

where t_1 and t_2 denotes the thicknesses of the TPU and PLA phases, respectively. Using these parameters, the critical buckling forces for the two panel types are expressed as

$$F_{cr,A} = k \frac{\pi^2}{l^2} E_1 I_{equiv,A}, F_{cr,B} = 2k \frac{\pi^2}{l^2} E_1 I_{equiv,B}. \quad (A5)$$

It is evident that $F_{cr,A} > F_{cr,B}$, demonstrating that filament separation reduces the compression strength of dual-phase honeycombs.

As shown in Fig. A1b, the plastic hinge model can be applied to analyze the compression force [77], expressed as

$$F = \frac{2M_p}{l \cos \theta}, \quad (A6)$$

where M_p is the fully plastic bending moment, l is the length of panel, and θ denotes the inclined angle. For cross-sections A and B, the fully plastic bending moments are given by

$$M_{p,A} = \sigma_{y,1} b_1 t_1 (t_1 + 2t_2) + \sigma_{y,2} b_2 t_2^2; \quad (A7)$$

$$M_{p,B} = \begin{cases} \frac{1}{2} \sigma_{y,2} b_2 t_2^2 + \sigma_{y,1} b_1 t_1 (t_1 + t_2) - \frac{(\sigma_{y,1} b_1 t_1)^2}{2\sigma_{y,2} b_2}, & \text{if } \sigma_{y,1} b_1 t_1 \leq \sigma_{y,2} b_2 t_2; \\ \frac{1}{2} \sigma_{y,1} b_1 t_1^2 + \sigma_{y,2} b_2 t_2 (t_1 + t_2) - \frac{(\sigma_{y,2} b_2 t_2)^2}{2\sigma_{y,1} b_1}, & \text{if } \sigma_{y,1} b_1 t_1 \geq \sigma_{y,2} b_2 t_2; \end{cases} \quad (A8)$$

where $\sigma_{y,1}$ and $\sigma_{y,2}$ represents the yield stresses of the TPU and PLA phases, respectively. Therefore, the compression forces F_A and F_B are expressed as

$$F_A = \frac{2M_{p,A}}{l \cos \theta}, F_B = \frac{2M_{p,B}}{l \cos \theta}. \quad (A9)$$

It is clear that $F_A > F_B$ due to $F_A/F_B > 1$, indicating that filament separation reduces the energy absorption capacity of dual-phase honeycombs. However, owing to the hyperelastic nature of the TPU phase, a true yield stress does not exist. Instead, considering TPU as a linear elastic material, $\sigma_{y,1}$ can be expressed as

$$\sigma_{y,1}(\theta) = \frac{2E_1((t_1 + t_2)^3 - t_2^3)}{3L_p((t_1 + t_2)^2 - t_2^2)}(\theta_0 - \theta), \quad (A10)$$

where L_p is the length of plastic hinge, and θ_0 denotes the initial inclined angle. The compression displacement is calculated by

$$\delta = l(1 - \sin \theta). \quad (A11)$$

Combining Eqs. (A5), (A9), and (A11), the stress-strain response of the dual-phase honeycomb is obtained as

$$\begin{cases} \sigma = N_x F_{cr,A} / A, & \text{if } \varepsilon = 0; N_x F_A / A, & \text{if } \varepsilon \neq 0; \\ \varepsilon = N_y \delta / h; \end{cases} \quad (A12)$$

where A is the cross-sectional area perpendicular to the compression direction, and N_x and N_y are numbers of panels along the x and y directions, respectively. This simplified analytical model is applicable to dual-phase honeycombs with square configuration due to their regular and complete unit cells. Therefore, experimental data from DSqu0–3 are utilized to validate the model accuracy. The end-constraint factor k is influenced by boundary conditions and was calibrated as 1.6, 2.0, 4.0, and 4.0 for DSqu0–3. Additionally, $L_p = t_1$, $N_x = 6$, and $N_y = 5$, respectively. As shown in Fig. A2, the analytical model accurately predicts the compressive strength and plateau stress of DSqu0–2 with minimal error. However, discrepancies increase for DSqu3 due to its larger wall thickness, where shear effects become non-negligible. Quantitative comparisons reveal relative errors in compressive strength of 2.74%, 0.88%, 0.31%, and 27.48%, and even larger deviations in mean stress, measuring 19.72%, 25.05%, 27.56%, and 44.00%, respectively.

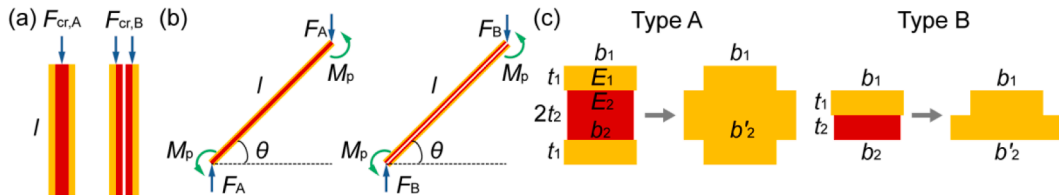


Fig. A1. Simplified analytical model: (a) Buckling force; (b) Compression force; (c) Equivalent cross-section for two different filament states. Yellow and red represent the TPU and PLA phases, respectively.

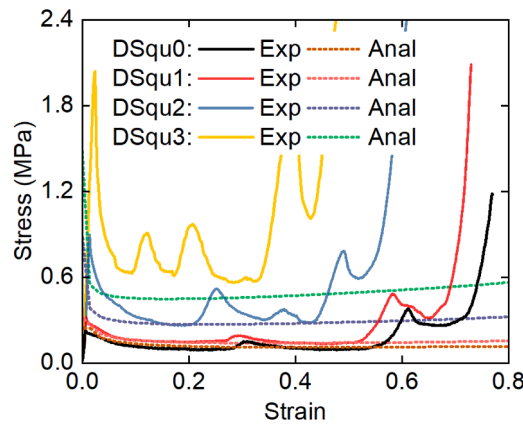


Fig. A2. Comparison between experimental results and analytical predictions for DSqu0–3.

Data availability

Data will be made available on request.

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