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The deformation mode and strengthening mechanism of compression in the beetle elytron plate

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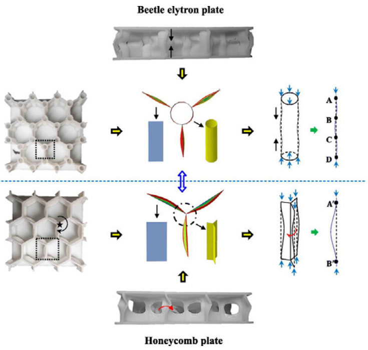
HIGHLIGHTS

- The compressive properties of a beetle elytron plate (BEP) are better than those of a honeycomb plate of the same cost.
- The core structure of a BEP undergoes convex deformation with three half-waves under compression.
- The strengthening mechanism of high energy absorption in BEPs is found and elucidated.
- The biological and engineering implications of the high energy absorption in BEPs are revealed.

GRAPHICAL ABSTRACT



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ABSTRACT

For the development of lightweight biomimetic functional-structural materials, the compressive deformation mode of beetle elytron plates (BEPs) and their strengthening mechanism of high energy absorption were investigated, with the following results: compared with honeycomb plates, the compressive strength and the energy absorption properties of BEPs are significantly increased. This is because in a BEP, the hollow trabeculae with high torsional stiffness cause the deformation behavior to be dominated by compression, generating a convex curve with three half-waves, which is consistent with the deformation of the honeycomb walls. This study reveals not only the compressive deformation mode and the mechanism of high energy absorption in BEPs but also the relationship between the biological prototype of a BEP and its function. The findings show that BEPs represent a significant improvement over honeycomb plates and show potential for widespread application as novel energy-absorbing sandwich structures.

1. Introduction

The collisions and impacts that occur in various disasters pose a tremendous threat to the safety of human lives and property. Therefore, various structures [1–3] that offer high energy absorption capabilities are continuously being sought for their properties of crashworthiness and impact resistance. For this purpose, the honeycomb plate (HP), as a kind of lightweight, high-strength structure [4–6], has found many applications in the fields of aerospace [7–9], transportation [10], and architecture [11–13]. Consequently, the mechanical properties of HPs and their applications have been extensively studied [14–16]. The biological prototype for an HP is a honeycomb. Commercially available honeycomb sandwich plates are currently manufactured by adhesively or

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mechanically joining their skin and core components, which are produced separately using different processes [17]. However, as an alternative inspiration from nature, various species of beetles have survived since the age of the dinosaurs. Thus, after their long process of evolution, beetle elytra possess a remarkable biological structure that exhibits several unique biological functions. For example, the structural color [18–21] in beetle elytra is a typical instance of the combination of a subtle fine structure and camouflage. Meanwhile, the inner three-dimensional structure of elytra, with its corresponding biological functions of not only facilitating flight but also protecting the main body of the insect, can be understood to be an advanced evolutionary biological structure that is both light in weight and high in strength and exhibits excellent mechanical performance [22]. Therefore, our group has performed bionic studies of beetle elytra from the end of the last century; the biological prototype for beetle elytron plates (BEPs) is an *Allomyrina dichotoma* (*A. dichotoma*) beetle elytron, which is a typical sandwich structure consisting of both upper and lower skins as well as a trabecular-honeycomb structure [22,23]. Chitin fibers are arranged on the outside of each trabecula, whereas protein materials are found in the center [22]. It has been proven that the outermost fibers of the trabecula are arranged in either a spiral or linear manner along the trabecular axis to connect with the fibers of the upper and lower skins [24]. These connections continuously and organically spread thousands of trabeculae [23,25], forming a natural sealing-edge structure [23].

Later, our group has developed a reasonably complete preparation technique for FIHPs and has revealed that this kind of new sandwich plate possesses excellent mechanical properties [26]. In recent research, from the mechanical perspective, we discovered the shared mechanism of trabecular-honeycomb structure [27]. Thus, we predicted that FIHPs, with hollow trabeculae, should possess better properties of compression, deformation and energy absorption than HPs. Furthermore, we renamed our FIHPs as beetle elytron plates (BEPs) to express our respect to the beetle. However, this prediction was not experimentally verified, nor was the deformation mode or strength mechanism of BEPs investigated. Therefore, this paper reports the first utilization of 3D printing technology to manufacture BEPs and the investigation of the compressive deformation mode of this structure and its strengthening mechanism of energy absorption by means of compressive experiments and the finite element method (FEM). Based on this investigation, the authors discuss the relationship between the biological prototype and its function as well as a major innovation for application in novel energy absorption sandwich structures.

2. Experimental and modeling methods

2.1. Model design and experimental methods

As mentioned in the introduction, in this study, a BEP model with hollow trabeculae was designed and compared with an HP (Fig. 1). The fundamental difference between the BEP and the HP lies in their core structures. Therefore, no edges were included in the designed models, the dimensions and structures of which are shown in Fig. 1, and they were designed to have the same volumes in their core structures. When the honeycomb dimension R was the same, the wall thickness T must be different due to the different core structures. The dimensions of the plates were designed in accordance with the requirements for standard compressive test specimens [28]. As for the material, experimental samples were previously produced using chopped-basalt-fiber-reinforced polymer (BFRP). However, when BEPs with hollow trabeculae are fabricated using this material, problems of inhomogeneous fiber distribution and difficulties in template production arise during manufacture. Moreover, the sandwich plates that are currently used in various fields can be made of aluminum alloys, composite materials, plastics, papers and various other materials. The differences in the mechanical properties and deformation modes of HP and BEP structures fabricated from resin could be effectively compared because resin is uniform, stable, and suitable for use in 3D printing with small errors. Therefore, resin was chosen for this experiment, and the test samples were created via 3D printing.

The compressive test device used was a T5105 electronic testing machine manufactured by MTS, shown in Fig. 2(a). The test models were subjected to displacement loading at a rate of 1 mm/min, with a sample size of 5 for each type of plate and cylindrical specimen. For each sandwich plate, when the stress in the core structure declined to about 20% of the highest stress observed in the plate, the compressive experiment was terminated. The dimensions of the cylindrical specimens and the material properties of the resin (DSM Somos 14120) are illustrated in Fig. 2(b). An IPRO™ machine (based on StereoLithography Apparatus (SLA), requiring an environmental temperature of 23° ± 2° for 3D printing) was used to print these experimental samples. Considering that the deformation of a sandwich plate mainly occurs in the core structure rather than the upper and lower skins, the energy absorption per unit volume of the core structure (Eq. (1), hereafter referred to as the energy absorption; and volume of the core structure V_c was used because the material density of BEPs and HPs are same) is used as the index to evaluate its energy absorption capacity in this paper.

$$E_c = \frac{\int_0^D F d\delta}{V_c} \tag{1}$$

Here: E_c—energy absorption per unit volume of the core structure; $F = \sigma A$—vertical load on the core structure, σ: stress in the core structure, A: cross-sectional area of the core structure; $\delta = \varepsilon h$—vertical deformation of the core structure, ε: vertical strain in the core structure, h: height of the core structure; $D = \varepsilon_{max} h$—maximum deformation of the core structure, ε_{max}: maximum strain in the core structure; V_c—volume of the core structure.

2.2. FEM

Finite element models (FEM, the simulation software is ABAQUS, the simulations have been nonlinear) corresponding to the experimental

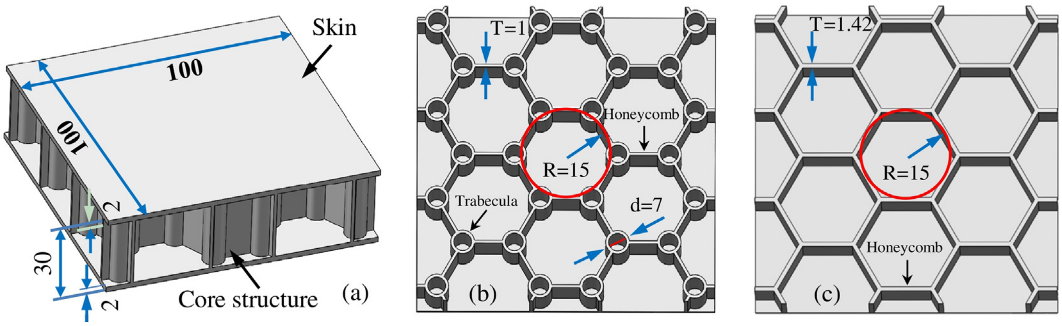

Fig. 1. The dimensions and structures of the sandwich plates. (a) Overall dimensions. (b) The core structure of the BEP. (c) The core structure of the HP. In these images, R is the radius of the honeycomb unit, which is the distance from the center of the honeycomb unit to the center line of honeycomb wall; the distances are expressed in units of mm.