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The influence of processing holes on the flexural properties of biomimetic integrated honeycomb plates

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ABSTRACT

In this study, the flexural properties of fully integrated honeycomb plates (FIHPs) were analyzed using experimental methods and finite element analyses. The effects of the perforated surface on the flexural properties of FIHPs were investigated by analyzing the flexural failure patterns and load-deformation curves of the FIHPs. The direction of the perforated surface has a significant influence on the flexural strength, and the structure exhibits different destruction patterns depending on the orientation. The experimental results indicate that although destruction occurs in the lower skin regardless of whether the perforated surface is up or down, the strength of the material of FIHPs can be optimized if the perforated surface faces upward because the chopped basalt fiber-reinforced epoxy resin composite material is strong in compression and weak in tension. A sub-model of a thin honeycomb plate containing holes was developed to discuss these issues in detail. The analysis results suggest that the stress concentration around the hole is distinct and that cracks initially appear in this high-stress area. This paper provides some conclusions to support the better use of biological structures, and it offers some important theoretical support for the application of FIHPs in natural disaster emergency projects.

1. Introduction

The honeycomb plate is a common lightweight, high-strength composite material structure [1–5]. This structure has been widely used in aviation [6], and architecture applications and has played an important role in earthquake, flood and other natural disaster emergency projects, such as emergency bridge construction and improvised buildings for disaster victims and the military. Accordingly, the mechanical properties of the honeycomb structure and its applications have recently been the focus of numerous studies [7–14]. Many studies have been conducted on the development and mechanical properties of honeycomb structures, with promising results using experimental and theoretical methods. Commercially available honeycomb sandwich plates are currently manufactured by adhesively joining the skin and core components, which are produced separately using different processes [15,16]. However, in sandwich plates produced using the aforementioned process, the side skins and the core are easily separated, and this separation is a factor that limits both the strength and side sealing of the plates.

To overcome the weakness of multi-body forming honeycomb plates, the authors applied biomimetics [17] research methods [18] and found that the microstructure of beetle forewings is that of a fully integrated honeycomb plate (FIHP) with edge-sealing features [19,20]. Consequently, the authors developed an approach for producing FIHPs [21–23]. In a previous study [22], the characteristic features of honeycomb plates with upper and lower skins were skillfully used: after preparing a single-sided bonded honeycomb plate (SBHP) and long and short fiber-reinforced composite trabeculae, qualitative studies of the flexural and compression properties of SBHP were performed. The structural integrity of FIHP has been preliminarily confirmed. Because the biological structure is very complex, this structure cannot be precisely simulated at present [20]. There are two issues associated with our biomimetic samples: short fibers rather than long fibers are used in biological prototypes [18], and there are processing holes in the FIHPs [20]. The simulated effect on the compressive and shear mechanical properties when using short fibers rather than long fibers was investigated in a previous study [18]. The present article investigates the influence of the processing hole on the mechanical flexural properties of FIHP for the first time and provides a beneficial discussion on how to avoid adverse effects due to processing holes and on how to better utilize biological structures. This paper establishes the theoretical and application foundations of a new high-strength fiber-reinforced resin honeycomb plate for natural disaster emergency projects using the principles of biomimetics, particularly for emergency bridge construction and temporary housing for victims and the military after disasters.

2. Materials and methods

2.1. Background

As described in the introduction, the FIHPs were inspired by an excellent biological structure. The structure of beetle forewings (Fig. 1)

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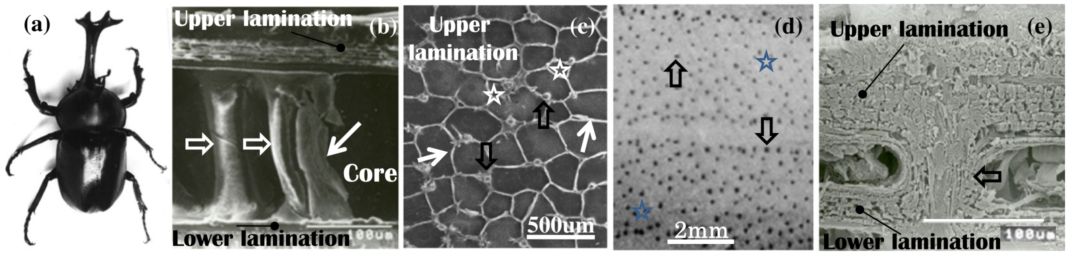

Fig. 1. A beetle and forewing microstructures. (a) *Allomyrina dichotoma*, (b) cross section, (c) air-sacs wall meshwork with trabeculae, (d) the distribution of trabeculae with 10% KOH treatment under penetrating light, (e) longitudinal section of a trabecula of *Prosopocoilus inclinatus*. The thin and thick arrows indicate the honeycomb wall and the trabeculae, respectively. [20].

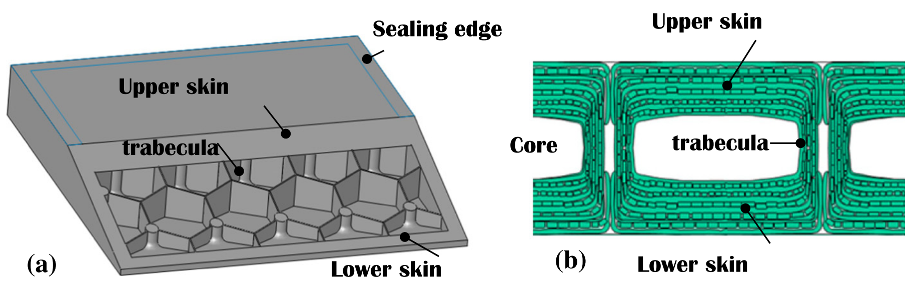

Fig. 2. The biomimetic three-dimensional model (a), and a schematic view of reinforcing fibers of beetle forewing (b) [19,20].

and its model (Fig. 2) was thought to be difficult to manufacture as an integrated body (Fig. 2a) [20,21]. It is this difficulty that motivated us to develop the honeycomb technology. As shown in Fig. 2(a), there are voids inside the honeycomb plate. Furthermore, the fibers are continuous and are located in the trabecula–honeycomb plate organically (Fig. 2b) [20,21]. The difficulties of manufacturing such structures by molding are obvious.

After years of efforts, we recently developed a set of biomimetic integrated molding tools that include both the trabeculae and honeycombs (Fig. 3a–d) [20]. Furthermore, we have successfully developed a prototype of the integrated honeycomb product (Fig. 3e) [20]. In the integrated honeycomb plate, there is a small processing hole in each core (Fig. 3d, e). However, processing holes have an adverse effect on the strength of the FIHPs and should be minimized or eliminated. To reduce the impact of processing holes on the strength of the FIHPs, methods, such as decreasing the diameter of the holes or reducing their number by using integrated male molds, are believed to be effective [20,23]. Therefore it is firstly to make clear for the impact of processing holes on the strength of FIHPs.

2.2. Experiment

2.2.1. Experimental materials and sample preparation

Short-cut basalt fiber (length: 3 mm, diameter: 13 μm) produced by ZHEJIANG GBF BASALT FIBER Co., Ltd. (Jinhua, China) was used as the reinforcement material. Bisphenol A-E51 epoxy resin produced by Xing-Chen Chemical New Materials Co., Ltd., Wuxi Resin Factory (Wuxi, China) was used as the matrix material [24,25]. Curing Agent 593 produced by Wuxi Shuo-Hua Environmental Protection and New Materials Co., Ltd. (Wuxi, China) was used as the curing agent. Reactive diluent 501 produced by Wuxi Pin-Hua Chemical Co., Ltd. (Wuxi, China) was used as the diluent. The matrix material consisted of the epoxy resin, curing agent and diluent in a ratio of 10:3:1 [21]. Paraffin wax was used to manufacture the male mold. Arawana brand bean oil was used as the releasing agent for the male mold because it does not dissolve in paraffin wax and has a low melting point. Trial internal and external releasing agent solutions for the female mold were prepared specifically for these experiments by Wuxi manufacturers. The integrated molding of the FIHP is shown in Fig. 1(a), and integrated honeycomb sandwich plates with different thicknesses were prepared in this experiment because the upper skin is thicker than the lower skin in the forewing of the beetle *Allomyrina dichotoma*. The specimens were rectangular, with a length of 110 mm, width of 50 mm and height of 13 mm. The inscribed circle radius of the FIHP was 7 mm, the thickness of the honeycomb cell wall was 1.75 mm, the diameter of the trabeculae was 6 mm, the upper skin thickness was 4 mm, and the lower skin thickness was 2.3 mm. The final fiber composite material samples decreased in volume by 2%.

2.2.2. Three-point flexural test methods

According to the test method recommended by GB/T 1449-2005 [26], three-point flexural tests were performed on pure resin and fiber composite FIHPs. The specimens were all rectangular, with physical dimensions of 110 × 50 × 13 mm. The finished pure resin and fiber

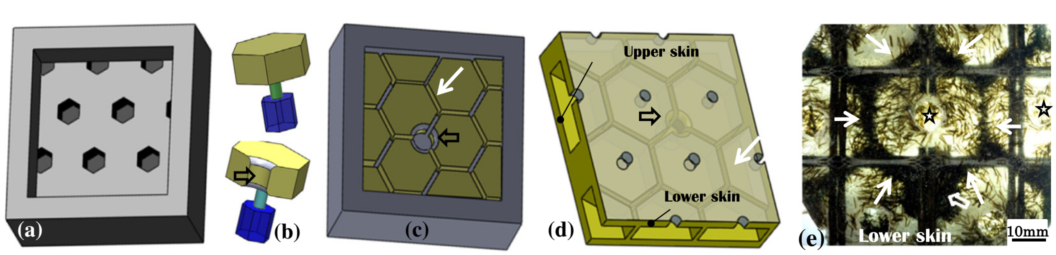

Fig. 3. Molding tools developed for the integrated manufacturing of trabecula–honeycomb plates: (a) a female tool, (b) basic male tools, (c) assembly of the tools, (d) a schematic of the expected product, and (e) the bottom view of an example. ⟹: a trabecula or the space used to form a trabecula, →: a honeycomb wall or the space used to form a honeycomb wall, ☆: a processing hole. [20].