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Compressive and flexural properties of biomimetic integrated honeycomb plates

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ABSTRACT

The characteristics of honeycomb plates composed of an upper and lower lamination are employed to create a novel single-sided bonded honeycomb plate (SBHP) design, and the compressive and flexural properties of these biomimetic integrated honeycomb plates are investigated. The results demonstrate that even during the fracturing of the honeycomb plates (honeycomb core), no abrupt compression paralysis occurs (which would cause the load to decrease rapidly); furthermore, our honeycomb plates exhibit superior compressive properties compared to biomimetic sandwich plates manufactured using Zhang's needle-injection method. The interfacial bonding surface and bonding quality have no significant effect on the flexural stiffness but do affect the failure modes and flexural failure strength of the honeycomb plates. The ultimate failure of the biomimetic integrated honeycomb without a bonding layer between the panel–core layers is determined by the material strength itself; therefore, the honeycomb possesses good mechanical properties. This experimental study confirms, for the first time, the effectiveness of the biomimetic integrated honeycomb structure manufacturing method.

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1. Introduction

Honeycomb structures are a common form of lightweight, high-strength composite [1–3]. Studies and applications related to honeycomb structures are numerous [4–8], ranging from nanomaterials [9,10] to large structures such as those used in Boeing 787 and Airbus 380 airplanes [11]. Many studies have been conducted on the development of honeycomb structures and on the mechanical properties of honeycomb structures, yielding positive results using both experimental and theoretical methods [12–19]. Commercially available honeycomb sandwich plates are currently manufactured by adhesively joining the plate and core components, which are produced separately using different processes [20,21]. However, in sandwich plates produced using the aforementioned process, the side plates and the core are easily separated, and this separation is a factor that limits both strength and side sealing. Furthermore, the use of adhesive is not only environmentally harmful but also expensive [22,23].

Learning from living creatures is a productive approach to the development of lightweight composite materials [24,25]. Motivated by the fact that the forewings of beetles are of high strength and minimal weight, characteristics that are required for defense and flight, respectively, we have been studying their architectures since 1997 [26]. We have also investigated the three-dimensional (3D) structures and mechanical properties of these forewings [27,28]. These investigations have led to the discovery of a new type of lightweight biomimetic composite that consists of a completely integrated honeycomb structure with fiber-reinforced trabeculae at the corners of the honeycomb cores. Presently, commercial honeycomb plates are manufactured by adhesively joining the plate and core components, which are fabricated separately using different processes [29]. The side plates and core of these sandwich plates are easily separated, limiting both the strength and side sealing of such structures. We developed a manufacturing method that integrates the fabrication and joining of the plate and core components, and this integrated manufacturing method overcomes the weaknesses of the traditional manufacturing method [30,31]. However, the mechanical properties of integrated honeycomb plates have primarily been discussed only from a theoretical perspective based on biomechanical laboratory findings and finite element analysis from the literature [30]. In this study, the characteristic features of honeycomb plates with upper and lower lamination (Fig. 1) are used to design single-sided bonded honeycomb plates (SBHPs, Fig. 1(b)). The lower lamination (Fig. 1(b), left) and core lamination (Fig. 1(b), right) are assembled into an integrated whole, whereas the upper lamination and core

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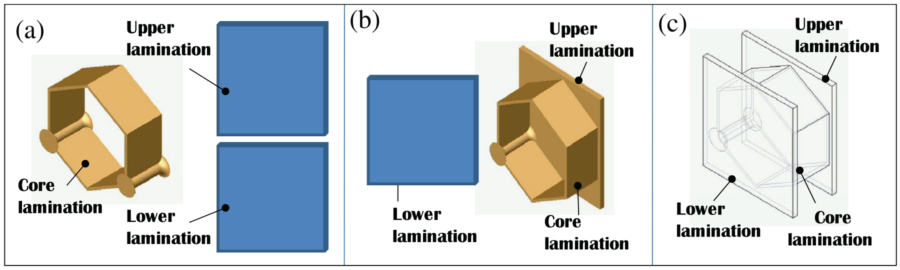

Fig. 1. Schematics of the manufacturing methods for honeycomb sandwich plates, which are manufactured by adhesively joining: (a) three parts or (b) two parts (SBHP), as well as using (c) integrated honeycomb technology.

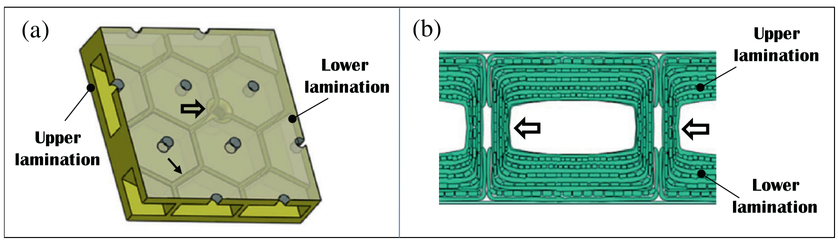

Fig. 2. Structural schematic of a trabecula–honeycomb: (a) integrated honeycomb plate and (b) schematic illustration of the reinforcing fibers in the cross section of a forewing. The thin and thick arrows indicate the honeycomb wall and the trabeculae, respectively.

lamination (Fig. 1(b), right) are formed using an integrated molding [30]. The mechanical properties of the integrated honeycomb plates (Fig. 1(c)) and those of commercial honeycomb plates (Fig. 1(a)) are compared and analyzed using SBHP tests. The compressive and flexural properties of the biomimetic integrated plates are discussed, and an effective method for determining the mechanical properties of biomimetic integrated honeycomb plates is provided.

2. Experimental details

2.1. Background

Approximately 10 years ago, we sought to create a 3D structural model of biomimetic integrated honeycomb plates with a honeycomb–trabecular structure based on the forewing structure of the beetle *Allomyrina dichotoma* (Fig. 2(a)) [32,33]. This research revealed that the fibers in the small trabeculae and in the upper and lower laminations formed a continuous structure (Fig. 2(b)) [27]. Due to the complicated biological structure of *A. dichotoma*, establishing a method to imitate this structure was a formidable task. Two distinct integrated molding methods, which are illustrated in Fig. 3, had been previously reported [32,34,35]; however, these methods only include the sandwich plates with the trabeculae, not the honeycomb structure.

After years of effort, we recently developed a set of biomimetic integrated molding tools that include both the trabeculae and honeycombs. Furthermore, we have successfully developed a prototype of the integrated honeycomb product. The matrix material is epoxy resin (ER), and the reinforcing material is basalt fiber (BF, black arrows in Fig. 4). The shapes of the honeycomb and trabeculae can be clearly observed in Fig. 4: short fibers are distributed throughout the entire specimen, and long fibers are distributed in the upper and lower laminations. However, there is still a significant difference between the biomimetic specimen and the beetle forewing structures, including the former's low BF ratio and uneven fiber distribution. In addition, the mechanical properties of the biomimetic specimen were initially only discussed from a theoretical perspective by comparison with structures reported in the literature [26–31,36]; that is, the properties were not confirmed experimentally. Therefore, this study focuses on experimentally determining the mechanical properties of biomimetic integrated honeycomb plates.

2.2. Experiment

To save time and improve efficiency, an experimental scheme that features both the assembled and integrated molding in one honeycomb plate was designed, combining the characteristics of the honeycomb sandwich structure with two plates. The lower plate and core are an integrated molding (referred to as the partially integrated honeycomb plate), whereas the upper plate and core are bonded together (forming the SBHP). The mechanical properties of the materials produced using the two different preparation methods could then be compared through mechanical property tests.

2.2.1. Preparation of SBHPs

Fig. 5 illustrates the molds used to prepare the SBHPs. Fig. 6 presents images of the SBHP samples with trabeculae. The samples in Fig. 6(c) were produced by adhesively joining the two parts shown in Fig. 4(a) and (b). The mold is primarily composed of two parts: the partially integrated mold (Fig. 4(a)) and the mold of the upper plate (Fig. 4(b)). A round thimble apparatus was designed to facilitate demolding (Fig. 4(a), red[1] coils). In accordance with the GB/T 1456-2005 standard [37], the height of one side of the adhesively integrated honeycomb plate (Fig. 6(a)) and that of the upper plate (Fig. 6(b)) were designed to be 8.7 and 2.3 mm, respectively; the total height was 11 mm (Fig. 6(c)). The thickness of the cellular wall was 2.0 mm, and the trabecular diameter was 6.9 mm. On average, each cell contained two thirds of a trabecula (Fig. 6(a)).

The experimental materials and preparation of the SBHPs are as follows:

(1) *Reinforced fiber*: basalt fiber.
(2) *Preparation of adhesive solution:* thoroughly mix the epoxy resin, curing agent, and diluent at a ratio of 10:3:1 [38,39].

[1] For interpretation of color in Figs. 4 and 8, the reader is referred to the web version of this article.

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