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Simulated effect on the compressive and shear mechanical properties of bionic integrated honeycomb plates

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ABSTRACT

Honeycomb plates can be applied in many fields, including furniture manufacturing, mechanical engineering, civil engineering, transportation and aerospace. In the present study, we discuss the simulated effect on the mechanical properties of bionic integrated honeycomb plates by investigating the compressive and shear failure modes and the mechanical properties of trabeculae reinforced by long or short fibers. The results indicate that the simulated effect represents approximately 80% and 70% of the compressive and shear strengths, respectively. Compared with existing bionic samples, the mass-specific strength was significantly improved. Therefore, this integrated honeycomb technology remains the most effective method for the trial manufacturing of bionic integrated honeycomb plates. The simulated effect of the compressive rigidity is approximately 85%. The short-fiber trabeculae have an advantage over the long-fiber trabeculae in terms of shear rigidity, which provides new evidence for the application of integrated bionic honeycomb plates.

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1. Introduction

Honeycomb structures are a common form of lightweight, high-strength composites [1,2]. There are numerous studies and applications related to honeycomb structures in the literature [3,4], ranging from studies of nanomaterials [5,6] to studies of large structures such as those used in Boeing 787 and Airbus 380 airplanes [7]. Many studies have been conducted on the development of honeycomb structures and on their mechanical properties using experimental or theoretical methods [8–15]. Commercially available honeycomb sandwich plates are currently manufactured by adhesively joining the plate and core components, which are produced separately using different processes [16,17]. However, in sandwich plates produced using the aforementioned process, the side plates (called skin) and the core are easily separated; this separation is a factor that limits both the strength and side sealing of the plates. Furthermore, the use of adhesive is not only environmentally harmful but also expensive [18,19].

Learning from living creatures is a productive approach for overcoming these weaknesses of the traditional manufacturing method [20]. Motivated by the fact that the forewings of beetles exhibit the high strength and minimal weight required for defense and flight [21], we previously investigated the three-dimensional structures and mechanical properties of these forewings [22,23]. These investigations led to our discovery of a new type of lightweight bionic composite that consists of an integrated honeycomb structure and fiber-reinforced trabeculae at the corners of the honeycomb cores, and we developed an integrated manufacturing method (Fig. 1a) [24,25]. The first trial production of integrated honeycomb plates encountered problems: the molding time was too long, the basalt fiber (BF) ratio was still low, and the distribution of BFs was uneven (Fig. 1b, c) [24]. Therefore, the material composition of the integrated honeycomb and its preparation process have been improved [26] through compressive and shear tests of the trabeculae. The similarities and differences in the compressive and flexural properties between bionic honeycomb plates and multi-formed honeycomb plates have also been investigated [27]. However, the reinforcement materials used in the skins, honeycomb core and trabeculae are short fibers, whereas natural honeycomb plates are composed of long fibers, which also connect with the skins and trabeculae as an organic living body. Although the most effective and reliable method for investigating these differences (simulated effect) is to perform experiments on the integrated honeycomb plates, to simplify these complicated issues, we selected trabeculae reinforced by long or short fibers as the experimental subjects. First, the trabecular composite materials were prepared, and then their shear and compressive properties were tested. Consequently, by testing the compressive and shear properties of the trabeculae, we were able to determine the effectiveness of substituting short fibers for long fibers in living prototypes. The present study preliminarily discusses the simulated effect of bionic integrated honeycomb plates on the compressive and shear properties of the plates, thereby establishing the foundation for developing integrated honeycomb plates.

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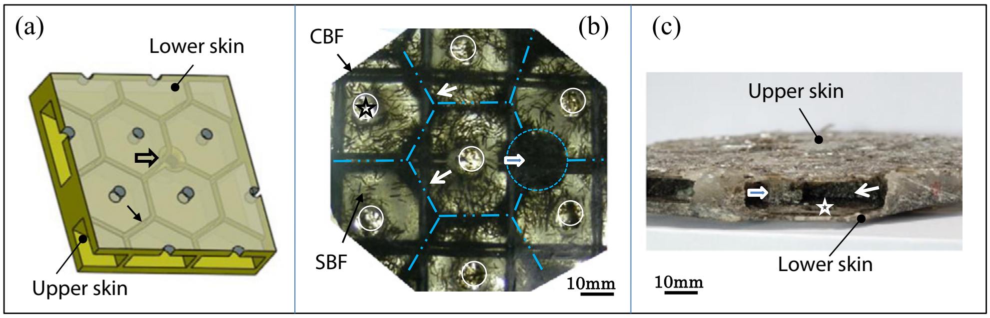

Fig. 1. Integrated trabecula-honeycomb plates. (a) Schematic of the 3D structure and (b, c) example of a composite produced by integrated molding: (b) top view (lower surface) and (c) side view. The thin and thick arrows indicate the honeycomb wall and the trabeculae, respectively. CBF: continuous basalt fiber; SBF: short basalt fiber; the star symbol indicates a positioning hole.

2. Experimental

2.1. Materials and Methods

2.1.1. Experimental materials and preparation of trabeculae

Short-cut basalt fiber (Zhejiang Store Gold Basalt Fiber Co., Ltd., Jinhua, China) was used as the reinforcement material. The fiber diameter was 13 μm, and its melting temperature was 1340 ± 30 °C. The number of nozzles in the drawing machine was 400, and the linear velocity of the drawing machine was 1640 m/min. The matrix material was bisphenol A-E51 epoxy resin [28,29] (Xing-Chen Chemical New Materials Co., Ltd., Wuxi Resin Factory). The curing agent was Curing Agent 593 (Wuxi Shuo-Hua Environmental Protection and New Materials Co., Ltd.), and the activated thinner was Activated Thinner 501 (Wuxi Pin-Hua Chemical Co., Ltd.). Based on our previous study [26], the matrix material was composed of epoxy, curing agent and diluent in a 10:3:1 ratio. The volume fraction of fiber was 30%, and the lengths of the short-cut basalt fibers were 6 mm and 120 mm. The diameter of the trabecula samples was 12 mm, and the length of the original trabeculae was 110 mm. Therefore, when the short fibers with a length of 120 mm were axially arranged, the distribution of fibers in the trabeculae was equal to that of the long fibers. Therefore, the trabeculae reinforced with fiber lengths of 120 mm and 6 mm were labeled as LF-trabeculae and SF-trabeculae, respectively. The mold for preparing the trabeculae and the technological process is the same as those used in our previous work [26].

2.1.2. Compressive and shear tests of the trabeculae

2.1.2.1. Compressive tests. Three specimens with lengths of 18 mm were prepared by cutting the original trabeculae. Then, the two ends of each specimen were polished. Following the compressive test criterion GB/T 1448-2005 [30], the specimens were loaded with a displacement loading pattern at a rate of 5 mm/min using an Instron 3367 test machine. Specimens with obvious defects were discarded. Additionally, five valid specimens per group were used for the shear and compressive tests.

The macroscopic compressive strength can be calculated as

$$\sigma_c = \frac{p}{A} \tag{1}$$

where σ_c is the macroscopic compressive strength (MPa), p is the yield load or failure load (N), and A is the cross-sectional area of the specimen (mm ^{2}).

2.1.2.2. Shear tests. The length of each specimen was 110 mm. Following the shear test criterion ACI440.3R-04 [31], the specimen was loaded with a displacement loading pattern at a rate of 2 mm/min using a SHT4605-W electronic universal material testing machine. The failure load was recorded when the specimen broke as a result of shear stress. The macroscopic shear strength can be calculated as

$$\tau_\mu = \frac{p_s}{2A} \tag{2}$$

where τ_μ is the macroscopic shear strength (MPa), p_s is the maximum failure load (N), and A is the cross-sectional area of the specimen (mm ^{2}).

2.1.3. Microstructure observation

After the compressive and shear tests, the post-failure microstructures of the trabeculae were observed using a camera and an Ultra Plus field-emission scanning electron microscope (FE-SEM; Carl Zeiss NTS GmbH, Oberkochen, Germany).

3. Results and discussion

In this section, by analyzing the results of the compressive and shear testing of the trabeculae, we discuss the simulated effect of integrated honeycomb technology and its features.

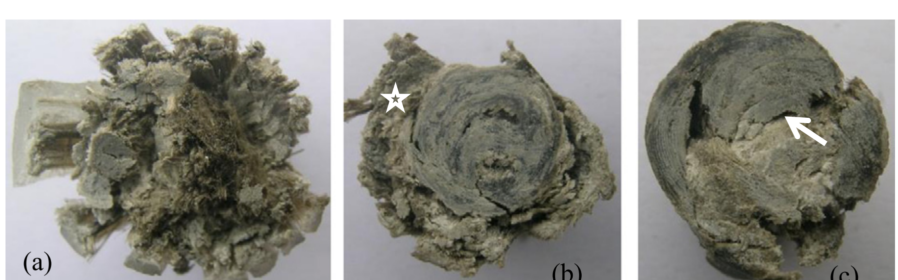

Fig. 2. The failure modes at the end surfaces of trabeculae in compressive tests. (a) LF-trabeculae: petal and (b, c) SF-trabeculae: b) cracking and c) splitting.

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