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Optimal composite structures in the forewings of beetles

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Abstract

In order to develop optimal biomimetic composite structures, research was conducted on the structural characteristics of *Allomyrina dichotoma* beetle forewings, with these characteristics to be further expounded upon. From this research, the following results were obtained: (1) It is found that the males, in comparison to females have both lighter and thinner forewings with a lower tensile fracture force, with the biological reasons behind these differences to be discussed later in depth. (2) It was found that densely distributed chitin fibers are located around the void lamination in the endocuticle of the forewing. They were found to have a rectangular cross-section with maximum reinforcement of fiber volume fraction; likewise, there exist sparsely distributed ones on the exocuticle in the Epipleuron tip of the forewing. These are of a circular cross-section, with a protein matrix that provides strong reinforcement. (3) Macroscopically the chitin fibers appear to exist independently of each other. However, this research discovered that, microscopically, the fibers have a reticular structure and through this structure, provide two-dimensional reinforcement to the same lamination of fibers. In comparison to a cloth weaving, it has many advantages, such as being unbendable and lacking concentrated stress points by crossing between the fibers, because they are not weaving cross points with those fibers. Lastly, the schematic structural model of the reticular structures of the fibers was proposed.

Keywords: Biomimetics composite structure; Beetle forewing; Laminated structure; Two-dimensional reinforcement; *Allomyrina dichotoma*

1. Introduction

Light composite materials represent an important field of study [1,2], as they contribute not only to the aeronautical industry, but also greatly contribute to the medical field, construction engineering, and sports equipment. In order to obtain a suitable method for the structural design of composite materials, a new design technique is needed. One of the ways is to have the fibers at the most areas where they are most needed, along with the exact quantities required [3]. Many examples of composite materials exist in nature which are considered to possess the optimal structures for their environments through their natural evolution. For this reason, the structures of the beetle forewing and its mechanical behaviors were examined in order to simulate and develop biomimetic composite materials in current research [4–7].

Within the forewings of insects, researchers have found laminated structures in which the forewing proteins act as the soft matrix, while the chitin fibers act as the reinforcing fibers [8–10]. Both the laminated arrangement of the chitin fibers [8–11] and the mechanical characteristics of these equiangular laminating layers of the biomimetics composites [12–14] have been reported previously. In addition, the authors have devoted much of their efforts on the biomimetics of the beetle's forewing. This includes studies on its macro-structures [4,7], its non-equiangular laminating structures [5] and three-dimensionally reinforced structures [6]. The subjects used in this study were male *Allomyrina dichotoma* beetles. It is well known that the somato-types of beetles differ from one another due to their sex, with the larger male bearing a horn. In this present

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study, based upon the research of the characteristics of somato-type beetle, forewing, tensile fracture force of the forewing and its suitability subject to sex are conducted. Both optimal structures of the fiber's cross-section and the typical reticular cross-linking of two-dimensional reinforced structures within the beetle's forewing are to be discussed.

2. Experimental

2.1. Specimens and somato-type measurement

Two types of specimens were selected for both male and female beetles, as shown in Fig. 1. The physical size of the beetle was measured using a Kanon slide caliper and did not include the foot or, in the case of the male, the horn in the measurement. The experimental bio-samples included a total of 12 males and 12 females with measurements of each beetle's weight, its forewing dimensions and its physical size.

In order to investigate the microstructure of the laminated cross-section, the *A. dichotoma* forewing is cut off on the surface both normal and slanted to the X–Y plane. The specimens are then observed by a Nikon, ESEM-2700, and treated with a 10% KOH solution for 3 h at 100 °C [11]. Untreated specimens were also used [4].

2.2. Preparation of specimens

The different orientations of the tensile test specimens were prepared as shown in Fig. 2, with four central lines taken at 0° and/or 90° CCW from the Y axis as shown in Fig. 2a, 45° and 135° CCW from the Y axis relative to the beetle's right forewing as shown in Fig. 2b,c. The tensile test specimens measuring 4 mm wide were then sliced and prepared by a special parallel cutting blade [5]. A total of 22 test specimens for both the left and right forewings were prepared. Under the conditions of constant room temperature and humidity (20 ± 2 °C, 60% ± 5%RH), the tensile test was carried out on a Shimazu AUTOGRAPH DSC-10T with a special low load cell and jig at a tensile strain rate of 0.5 mm/min, where the distance between clamps was 5 mm. Also, a special clamp head attached using cloth tape to prevent failure was used.

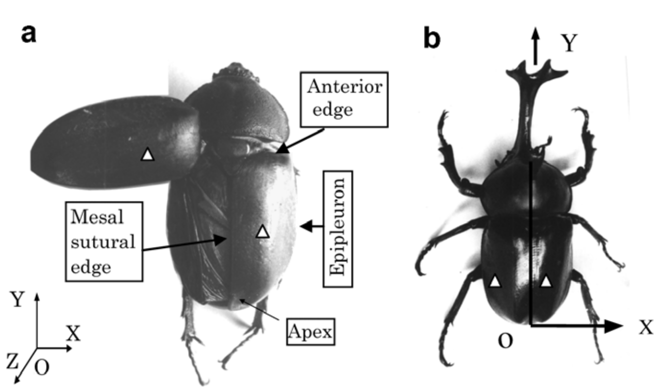

Fig. 1. Example: (a) Female, and (b) male beetle.

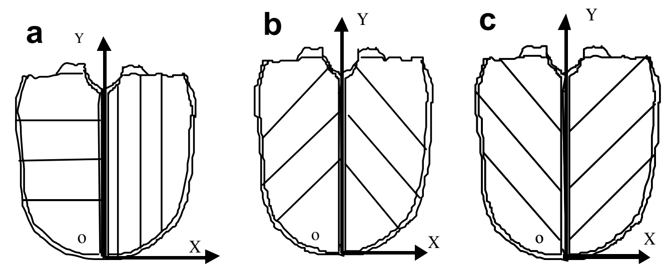

Fig. 2. Example position in (a) 0° or 90°, (b) 45°, (c) 135° of the forewing of beetle.

In addition, after the tensile test the thickness of both the upper and lower lamination were measured at four points using the ESEM-2700, and the tensile strength of the specimens were evaluated by taking into account the average thickness in each specimen.

3. Experimental results and discussions

3.1. Somato-types

Table 1 shows the measurement results of the somato-types of *A. dichotoma*, along with the weight and size of the forewings. This also includes the mean values and standard deviation values (STDEV).

In order to identify the differences of sex between male and female *A. dichotoma*, a T-test [15] was performed from these experimental results between sample A (male) and sample B (female). The results of the T-test are shown in Table 1. When probability is $P(t_0) \leqq \alpha$ (generally $\alpha = 0.05$ at normal significance level), there exists a significant difference and a * is labeled in that specific cell of the Table 1. It is clear that the male *A. dichotoma's* weight and physical size is larger than that of the female's. The male forewing is 28.7 mm in length and 14.8 mm in width, whereas the female's is 28.3 mm in length and 13.6 mm in width. The significant differences indicate that the male is larger than the female; however, the forewings of the male and female have a similar weight. In fact, females have a forewing weight of 0.160 g while males have a forewing weight of

Table 1
Measurements of the A. dichotoma forewing

Beetle	Weight(g)		Length(mm)		Width(mm)	
	Male	Female	Male	Female	Male	Female
AVERAGE	5.58	4.72	46.13	42.82	23.30	21.79
STDEV	0.83	0.97	2.96	2.75	1.14	1.10
P(t0)	0.03	*	0.01	*	0.00	*
Forewing	Male	Female	Male	Female	Male	Female
AVERAGE	0.151	0.160	28.70	28.30	14.80	13.60
STDEV	0.015	0.022	1.26	1.23	0.65	0.56
P(t0)	0.27		0.01	*	0.00	*