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Characteristics of the tensile mechanical properties of fresh and dry forewings of beetles

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ABSTRACT

Based on a tensile experiment and observations by scanning electron microscopy (SEM), this study demonstrated the characteristics of the tensile mechanical properties of the fresh and dry forewings of two types of beetles. The results revealed obvious differences in the tensile fracture morphologies and characteristics of the tensile mechanical properties of fresh and dry forewings of *Cybister tripunctatus* Olivier and *Allomyrina dichotoma*. For fresh forewings of these two types of beetles, a viscous, flow-like, polymer matrix plastic deformation was observed on the fracture surfaces, with soft morphologies and many fibers being pulled out, whereas on the dry forewings, the tensile fracture surfaces were straightforward, and there were no features resembling those found on the fresh forewings. The fresh forewings exhibited a greater fracture strain than the dry forewings, which was caused by the relative slippage of hydroxyl inter-chain bonds due to the presence of water in the fibers and proteins in the fresh forewings. Our study is the first to demonstrate the phenomenon of sudden stress drops caused by the fracturing of the lower skin because the lower skin fractured before the forewings of *A. dichotoma* reached their ultimate tensile strength. We also investigated the reasons underlying this phenomenon. This research provides a much better understanding of the mechanical properties of beetle forewings and facilitates the correct selection of study objects for biomimetic materials and development of the corresponding applications.

1. Introduction

Beetles have experienced a long evolutionary period that has resulted in species variation [1]. The forewings play dual roles in protecting the body and contributing to flight. The characteristics of beetle forewings include a high degree of optimization, a variety of designs, a light weight, and high strength [2–4]. Thus, the beetle is an ideal model for biomimetic objects composed of lightweight functional materials. Comstock reported the structure of the beetle forewing as early as the late 19th century [5]. In the 20th century, Zelazny and Hepburn et al. explored and described the mechanical properties of the naturally composite laminated structure in beetle forewings composed of chitin fibers and proteins [6–10]. Throughout this century, the three-dimensional structures and mechanical properties of beetle forewings have been studied further [11–14]. CT Xiang et al. [15–18] at Chongqing University performed numerous studies on the microstructures and tensile mechanical properties of elytra. In 2007, ZX Yang [19] at Nanjing University of Aeronautics and Astronautics (NUAA) measured the hardness and elastic modulus of the cuticle in beetles. In 2009, JY Sun [20,21] at Jilin University reported that the reduced modulus and hardness of the surface cuticle were characterized by anisotropy. These studies have contributed to laying the foundation for biomimetic research [22–26]. In 2010, ZX Yang reported that no clear difference in maximum strain between fresh and dry elytra could be found [27]; In response, in a recent review paper, JX Chen et al. raised doubts about those findings [28]. By reviewing the relevant literature, we learned that the average maximum global strain of the fresh pincher and crusher claw at tensile fracture was obviously higher than that of the dry version in the lobster and *Homarus americanus* [29,30], which has the same major components, including the chitin fibers and proteins [31,32], as beetle forewings. Therefore, in the present study, tensile experiments on fresh and dry forewings of *Cybister tripunctatus* Olivier (called *Cybister*) and *Allomyrina dichotoma* beetles were performed, and their fracture morphologies were accordingly observed. The reason for the differences in mechanical properties between fresh and dry forewings is discussed. These findings provide a better understanding of the mechanical properties of biomimetic objects and facilitate the correct selection of study objects for biomimetic materials. Specifically, our results provide

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valuable information for the development of a sandwiched plate structure with a step-wise fracture to absorb the energy of earthquakes [33, 34] and for the manufacture of multifunctional fibers [35].

2. Experimental materials and methods

2.1. Experimental materials

For the convenient comparison and sufficient elucidation of this subject, not only *Cybister* but also *A. dichotoma,* for which the mechanical properties of the fresh forewings had been previously measured, were selected again for this study. *Cybister* (Fig. 1a) and *A. dichotoma* (Fig. 1b,c) were purchased in Zaozhuang City in Shandong Province and Nanchang City in Jiangxi Province, respectively. The sampling locations (along the longitudinal direction of the forewings) and specimen numbers are indicated in Fig. 1(d). Their detailed dimensions are listed in Table 1. Table 1 clearly shows that male *A. dichotoma* had the largest dimensions and greatest weight, whereas *Cybister* was the smallest, which is also shown in Fig. 1(a–c). For the forewings, however, the weight of female *A. dichotoma* was slightly greater than that of male *A. dichotoma*; in addition, although *Cybister* was the smallest in terms of its dimension and weight, the weight of its forewings did not decreased proportionally. Therefore, the forewings of *Cybister* should exhibit a relatively thick structure. Based on the dimensions of the forewings of *Cybister* and *A. dichotoma,* a sample was obtained from one forewing of *Cybister*, and two samples were taken from *A. dichotoma.*

For the two beetles described above, the specimen in Fig. 1(e) was prepared with a simple slicing method involving cutting a crosswise section of the trabeculae with a sampling tool [3,36] made in-house. Both sides of the test section of the strip specimen in this test were sliced and thus had no zigzag damage, which could effectively reduce the stress concentration. The standard dimensions of test sections of strip specimens of the forewings of *Cybister* and *A. dichotoma* (that is, W × L) were 2 mm × 4 mm and 3 mm × 6 mm, respectively. For the tensile test of fresh forewings, all of the strip specimens were cut down and prepared together, and they were then tensioned together again after 1 h. The whole process was finished in 3 h. For the tensile test of dry forewings, the forewings were taken from living beetles, and then strip specimens were prepared before all specimens were placed in a vacuum-drying oven (Type: PR1600LA, Bossmen Inc., Taiwan; the temperature and relative humidity were 25 °C and 12%, respectively) for 2 weeks; finally, the dry specimens were tensioned. For the comparison of fresh and dry specimens, one sample was obtained from the left forewing as the fresh specimen, and one sample was obtained from the right forewing as the dry specimen (Fig. 1d). For *Cybister*, a single sample was obtained from the left or right forewing and numbered L-1 or R-1, respectively. For *A. dichotoma*, two samples were obtained from the left or right forewing and numbered L-1 and L-2 or R-1 and R-2, respectively. Moreover, the sampling numbers of both the fresh and dry samples were symmetrical.

2.2. The tensile test and observation of microstructures of fractures

The tensile tests were performed using an electronic universal testing machine-AG-X Plus (Shimadzu Corp., Nakagyo-ku, Kyoto 604-8511, Japan; precision: 1/1000; max load capacity: 10 kN). One end of the specimen was mounted in a lower wedge-shaped clamp fixed on the tabletop, while the other was fixed in an upper wedge-shaped clamp fixed on the movable crosshead. When the tensile test started, the crosshead was lifted until the specimen broke and the crosshead synchronously stopped. The loading procedure was controlled by displacement, and the loading rate was approximately 1 mm/min. The maximum capacity of the load cell was 10 kN, and its resolution was 0.03 N. To protect the specimen from being damaged by the clamps, the clamped ends of the specimen were enclosed in rubberized fabric (as shown in Fig. 1e). The tensile tests of fresh and dry forewings were performed for three groups of beetles: *Cybister*, female *A. dichotoma* and male *A. dichotoma*. Thus, six groups of tensile tests were performed, and the number of valid specimens in each group was 10. As described below, the tensile stresses of the specimens could be approximated by dividing the ultimate load by the sum of areas of the upper and lower skins, and the tensile strains could be obtained according to the elongation of test sections divided by the original length of the test sections.

SEM was performed using an Ultra Plus (Carl Zeiss AG, Oberkochen, Germany; resolution: 1 nm at 15 kV).

3. Results and discussion

3.1. Observation of the microstructures

Fig. 2 presents two fracture morphologies under the two conditions, fresh and dry, of *Cybister* forewings after the tensile tests. First, regarding the fracture of fresh forewings, Fig. 2(a) shows that the complete solid-core trabeculae (broad arrow) could be seen at the fracture, which indicates that the trabeculae situated in the interior of the core were not damaged, and fractures occurred at the cross-section only with the upper and lower skins and without trabeculae, that is, the cross-section where the cavity was located (the region between the two dashed lines). The partial fibers were pulled out from the upper and lower skins (triangle). However, there were also fracture morphologies with the trabeculae directly torn in half; there is a cavity on the left of the core in the fresh forewing shown in Fig. 2(b), and a trabecula is

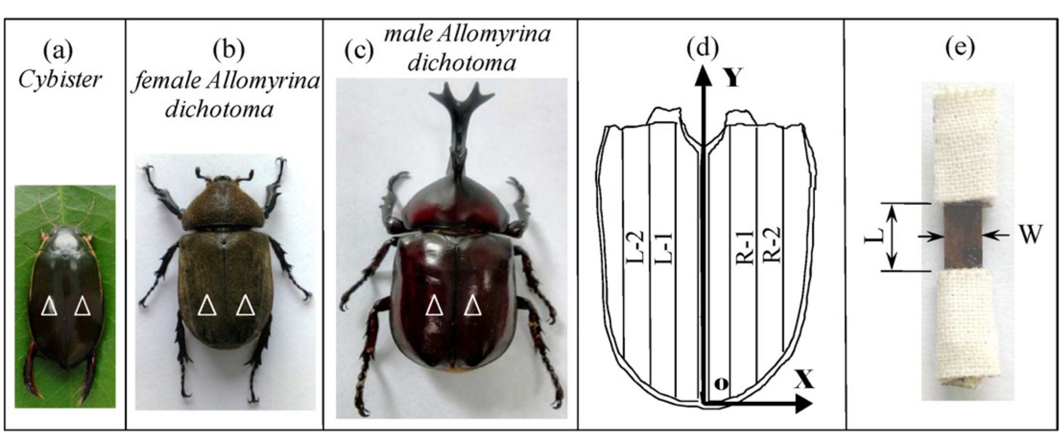

Fig. 1. Adult beetles *Cybister* (a) and *Allomyrina dichotoma* (b, c); Cartesian coordinates, specimen numbers and sampling locations (d); and a forewing specimen (e). The triangles indicate the beetle forewings.