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Circumcolumnar microstructure of Tumblebug cuticle and biomimetic application

B. Chen [a,*], X. Peng [a], C. Cai [b], J. Fan [a], X. Wu [a]

[a] *Department of Engineering Mechanics, Chongqing University, Chongqing 400044, PR China*
[b] *Department of Applied Physics, Chongqing University, Chongqing 400044, PR China*

Abstract

The elegant microstructures of insect cuticle obtained through long-time evolution endow the cuticle with excellent mechanical properties. Scanning electron microscope (SEM) observation shows that the cuticle of Tumblebug (an insect) has a basic characteristic of laminated structure consisting of highly oriented chitin fibers and sclerotized protein matrixes. Compared with manmade advanced composites, it contains more detailed heterogeneous microstructures. The observation also shows that there are many tiny holes in the cuticle and fibers distribute continuously round the holes forming a kind of circumcolumnar layup. With the observed results, a kind of special composite laminate specimen with the circumcolumnar layup is designed and fabricated. Its rupture strength is tested and compared with that of the conventional one with the holes drilled. The comparison shows that the rupture strength of the former is obviously higher than that of the latter. The larger the hole, the larger increase in the rupture strength can be achieved. The experimental result is verified with the representative models of the circumcolumnar and drilling-hole layups.

Keywords: Tumblebug cuticle; Circumcolumnar microstructure; Fiber distribution; Biomimetic design; Strength

1. Introduction

Insect cuticle is a kind of natural biocomposite material made of chitin fibers and matrix of crosslinked proteins and other components. The chitin fibers are embedded in protein matrix, forming a fiber-reinforced laminate [1], astonishingly like synthetic advanced composites [2]. Although each component of insect cuticle, carbohydrate or protein, in general, possesses poor mechanical properties, the insect is able to combine them with unique microstructures to produce a high-performance composite [3]. The research on the microstructures and the corresponding mechanical properties of insect cuticle may provide beneficial information for improving the mechanical properties of current advanced composites and developing new high-performance composites [4].

Several models have been proposed to describe the fiber-ply orientation in insect cuticles. A model of helicoidal ply was firstly proposed by Bouligand [5] and has been repeatedly confirmed. In addition, the dual-helicoidal model presented by Schiavone and Gunderson [3] has also received extensive attention. On the other hand, the holes in insect cuticles, which are mainly used as transporting channels, were also investigated. Schiavone and Gunderson [3] found that holes in Bessbug beetle's cuticle aid to transport wax from the epidermal cells through the thickness of the cuticle to the epicuticle surface for waterproof purpose, and believed that cracks travel around the these holes instead of passing across them. Skordos et al. [6] researched the strain and displacement fields associated with circular or elliptical openings in laminated plates in order to investigate their potential for integrated strain sensors. Inspired by these researches the mechanical properties of the composites containing preformed holes were made with carbon/epoxy unidirectional tape [7]. Yang et al. [8] proposed an iterative method for the design of preformed-hole structure of a single ply, then the mechanical property of the laminates consisting of such structure was analyzed. The computation showed that the obtained laminates possess higher load carrying capability compared with conventional ones [9]. The surface microstructure and mechanical properties of insect cuticles also got special attentions. Tong et al. [10] investigated the geometrical features and the wetting behavior of the pronotum cuticle surface of dung beetle Copris ochus Motschulsky. It was concluded that the beetle has embossed textured surfaces on its pronotum, clypeus and elytra surfaces, which improves the wetting behavior of the cuticle surfaces. Sun et al. [11] examined the nano-indentation properties of the femur cuticle of the dung beetle's forelegs with a

* Corresponding author.
E-mail address: bchen@cqu.edu.cn (B. Chen).

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nano-indenter, the examined result shows a kind of viscoelastic and creep phenomenon of the cuticle. Vincent and Wegst [12] reviewed the formation and microstructure of arthropod cuticle, then analyzed the remarkable mechanical performance of the cuticle and compared it with that of other materials using the charts of material properties and material indices. They found that the stiffness of insect cuticle can range from tens of GPa to 1 kPa. It can also be hardened by addition of Zn or Mn [13]. In addition, since insect cuticle has to perform all the functions of skin and skeleton, it also is preternaturally multifunctional [14]. It not only supports the insect, it gives it its shape, means of locomotion, waterproofing and a range of mechanical tricks [13].

In this paper, the microstructures of Tumblebug cuticle were observed with a scanning electron microscope (SEM), It was found that the cuticle is a fiber-reinforced composite similar to man-made advanced composite, and possess heterogeneous structural characteristics. The observation also shows there are many tiny holes in the cuticle. The fiber plies near the holes round the holes continuously, forming a kind of circumcolumnar fiber layup. Based on the observed result, a set of composite laminate with the circumcolumnar layup was biomimetically fabricated. The rupture strength of the biomimetical composite laminate containing circumcolumnar layup was tested and compared with that of the composite laminate with drilled-hole layup. The results show that the strength of the composite laminates containing circumcolumnar layup is markedly larger than that of the composite laminates containing drilled hole layup. At last, the experimental result was analyzed with the representative models of the circumcolumnar and drilled-hole layups, respectively.

2. Observed microstructure of the cuticle of Tumblebug

The insect used in this study is the Tumblebug, which is easily caught during summer in the south of China. Two sections of the insect were observed with scanning electron microscope. One is the pronotum (a protective cover for the prothoractic, or upper body section), and the other is elytra (a pair of hard outer "wings" which protect the inner wings and the body of the insect). The SEM samples were prepared by the following steps: separating the cuticle from the insect, cleaning its surfaces with 95% alcohol, and then cutting it into the size of samples. The microstructural characteristics on the surface of the cuticle and the sections with different orientations were mainly researched. In order to observe the microstructures more clearly, the cuticle was carefully peeled from the surface of the cuticle. The samples were then placed on a small metal plate with a gummy fabric, and had a coat of gold powder about 10 nm in thickness sprayed on the surfaces with a sputter coater. These specimens were then observed using an Amray KYKY-1000B SEM under the voltage of about 20 kV and magnifications ranging between 20 and 12,000.

Fig. 1 shows the microstructures of the cuticle on the surface of the cuticle. It can be seen that the insect cuticle is a fiber-reinforced biocomposite composed of chitin fibers and various protein matrixes. The chitin fiber plies are embedded in the protein matrixes, almost parallel with the surface of the cuticle. The fibers in a layer have identical orientation and are well arranged, but the fibers in different layers have different orientations. The combined microstructure of the chitin-fiber layers and the protein matrixes is very similar to manmade advanced fiber-reinforced composites often used in aircrafts and space shuttles. The fiber-reinforced laminated structures, in both the cuticle and manmade advanced composite, are jointly adopted by smart insects and light-duty man-made aircrafts. Fig. 2 shows the ruptured surface of the cuticle. It can be seen that the size, shape and distribution of the chitin fibers vary at different location of the section. The size of the fibers near the surface is smaller, circular than that of the fibers near the center. The orientation of fibers near the surface changes more distinctly than that near the center. Such heterogeneous microstructure, including different sizes, shapes and distributions of fibers at different locations, is adopted to meet the structural and functional demands with least material. In contrast with the heterogeneous structural characteristic, manmade composites often possess relatively simpler structures, where the size and shape of the fibers and the structure of the fiber layup are often fixed. It is believed that, after the centuries' evolution, the cuticle is of finer, more

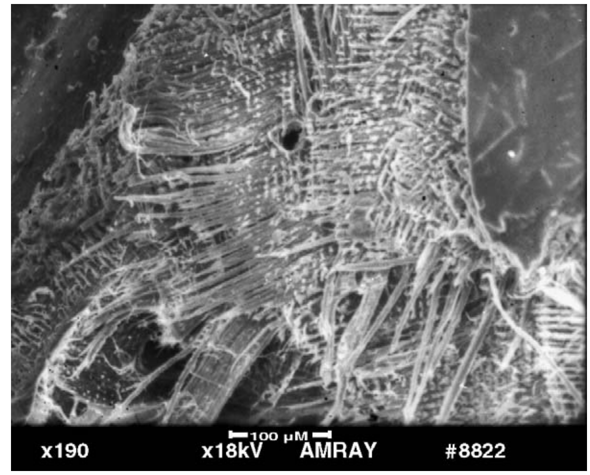

Fig. 1. The chitin-fiber plies arranged parallel to the surface of the cuticle.

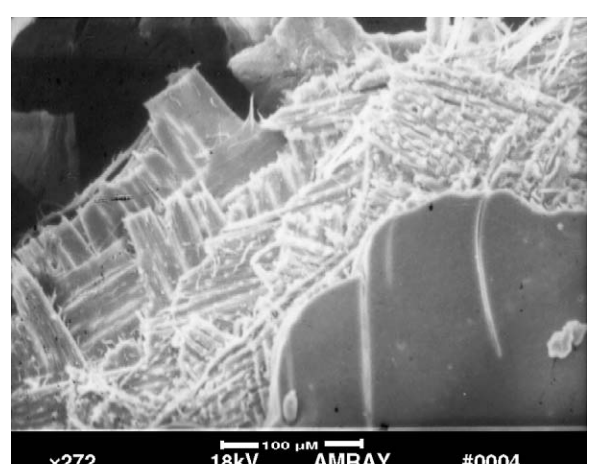

Fig. 2. The heterogeneous fiber plies in the cuticle.

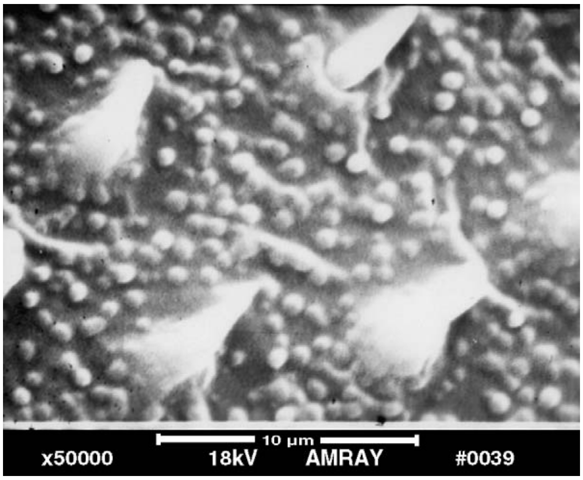

Fig. 3. The setas (sense organ) on the surface of the cuticle.

rational and more complicated microstructures than manmade composites. Besides the above observed microstructure, many setas and holes (or pore canals) in the cuticle were also observed (Figs. 3 and 4), which serve as the sensors and transport channels for the transportation of the external excretion, nourishment, and reconstruction matter of insects, respectively [3]. The fiber-reinforced microstructures near these setas and holes can be observed with larger magnification. Fig. 4 shows a particular form of fiber plies near a hole. The fibers near the hole enwrap the hole and form a kind of circumcolumnar fiber layup. This microstructure can improve the strength at the brim of the hole and reasonably match the high level of stress at the vicinity of the hole. It takes much more advantaged over the conventional man-made composites, where most holes are often used to join and fasten the parts as well as to install intelligent elements such as wires and pipelines, are usually fabricated by mechanical methods, such as drilling or punching. During drilling or punching process, the fibers located in the holes were cut off and no longer continuous, the fiber number decrease and a concentration of stress would appear at the brim of the holes where the strength of the material does not increase. The decrease of fibers and the large stress concentration at the hole brim would make it become the site of initiating failure and degrading the strength of whole composite structure.

3. Experiment of the rupture stress of the circumcolumnar layup

In order to explore the advantage of the circumcolumnar layup observed in the cuticle and the possibility of applying the layup over manmade composites, the biomimetic composite laminates with circumcolumnar layup were fabricated. Then their rupture strengths were tested and compared with that of the composite laminates with drilled holes. The materials used are glass-fiber fabric and epoxy resin. Firstly, a special mould (see Fig. 5) was made, which includes an upper and a bottom board. The bottom board contains many circular pillars with different diameters ($d = 6$, 8, 10, 12 mm), and the upper board includes many holes that can be inserted by those pillars on bottom board. Then ten layers glass-fiber fabric were dipped with epoxy resins and laid on the bottom board sequentially. In this course, it is necessary to let the plies be penetrated by the circular pillars reliably. A typical form of the fabric inserted by those pillars can be seen in Fig. 5. When this process was finished, the upper board was put on the top of the fabrics, letting the protruding portion of the pillars inset into the holes on the upper board. The whole mould was then placed in a hot-press and cured at 230 °C and 120 MPa for 14 h when the composite laminate was solidified. Finally, the composite laminate was cut into the specimens, each containing a hole (Fig. 6). Because these holes are accomplished by molding during the processing of the composite laminate, the fibers at the neighborhood of the holes remain continuous around the holes. Another set of specimens used for comparison was also fabricated with ordinary plane mould at the same time, and a set of holes with different diameters was drilled at the center of the specimens. Then the rupture tensile strengths of the two kinds of the specimens were tested on an Instron 1342 Material Testing System. The rupture strength can be calculated with

$$\sigma = \frac{P}{(a - d)b} \quad (1)$$

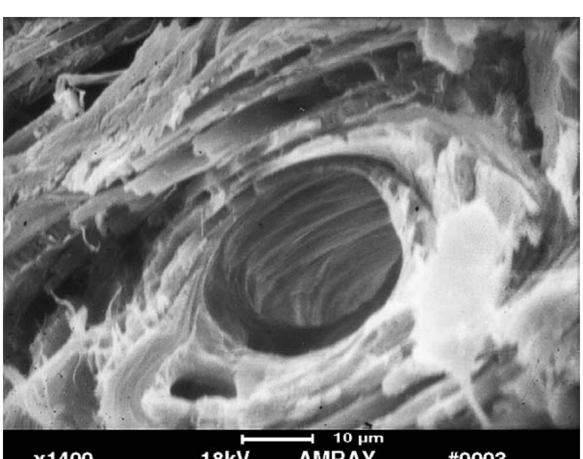

Fig. 4. The hole in the cuticle and the fibers surrounding the hole.

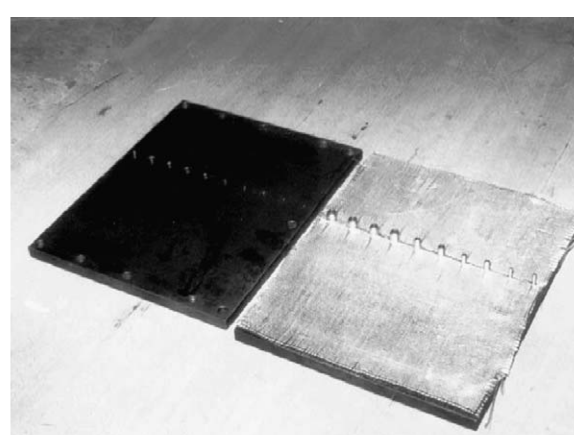

Fig. 5. The mould boards and the fiber fabric inserted circular pillars.

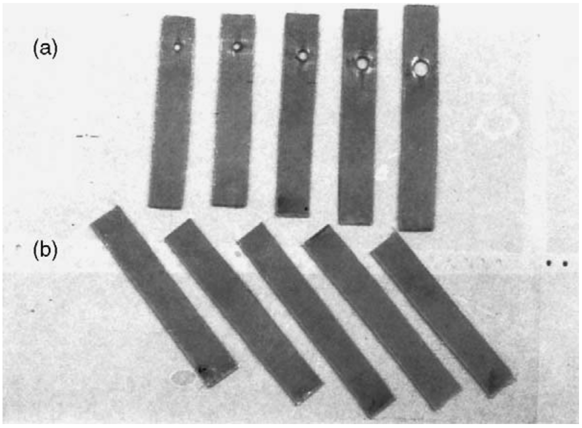

Fig. 6. (a) Obtained specimen with circumcolumnar layup and (b) Obtain specimen used for drilling hole.

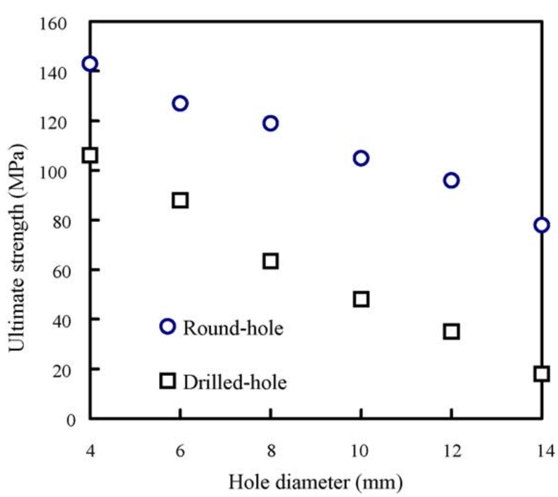

Fig. 7. The rupture strengths of the specimens with the circumcolumnar and the drilling-hole-fiber layups.

where P is the maximum load, a and b are the width and thickness of the specimen, respectively. d is the diameter of the hole. The test results of the two kinds of specimens are shown in Fig. 7, where it can be seen that the rupture strength of the composite laminates with circumcolumnar layup is distinctly larger than that of the composite laminates with drilled holes. Another fact found is that the larger the diameter of the hole is, the greater the difference between the rupture strengths of the composite laminates with circumcolumnar layup and that of the drilled-hole layup.

4. Theoretical analysis to the rupture stress of circumcolumnar layup

In this section, the rupture strength of the circumcolumnar layup was analyzed with a representative model and compared with that of the conventional laminate with the holes drilled. The model consists of ordered unidirectional plies of fibers and a rectangular matrix. A pair of loads was applied to the two ends of the model in the direction of the fibers (Fig. 8). Most load are carried by the fibers, and the matrix mainly plays the role to

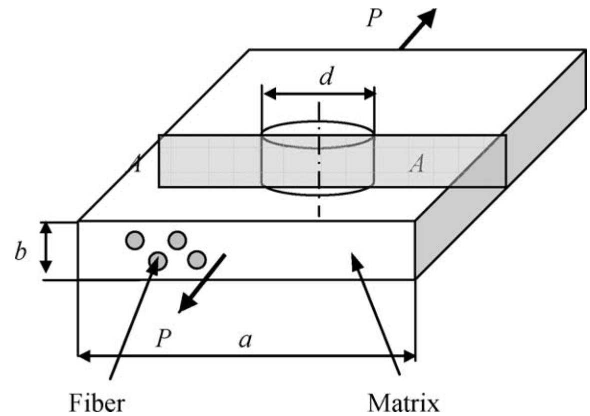

Fig. 8. The composite model with circumcolumnar layup.

transfer the load between the fibers. The width and the thickness of the model are a and b, respectively, the diameter of the hole located at the center of the model is d, and the fibers near the hole pass round the hole. For easy simplicity, half section of the model (Fig. 9) was used for analysis because of symmetry. The fiber volume fraction f can be expressed as

$$f = \frac{A_f}{A} \quad (2)$$

where A_f and A are the area of the fibers over the cross section and the overall area of the section. Because the fibers at the section were retained in circumcolumnar layup, the rupture load acted on the unit can be expressed as:

$$(P_{\max})_r = Af\sigma_b = abf\sigma_b \quad (3)$$

where σ_b is the rupture strength of the fiber. For comparison, the model with drilled-hole layup (Fig. 10) was also analyzed, in which the geometry and the volume fraction of fiber are identical with that of the composites with circumcolumnar layup. Because the fibers traversing the hole are severed during drilling process, the rupture load applied to the model can be expressed as:

$$(P_{\max})_d = (a - d)bf\sigma_b \quad (4)$$

compared with the rupture load of the drilled-hole layup, the increase of the rupture load of the unit of circumcolumnar layup

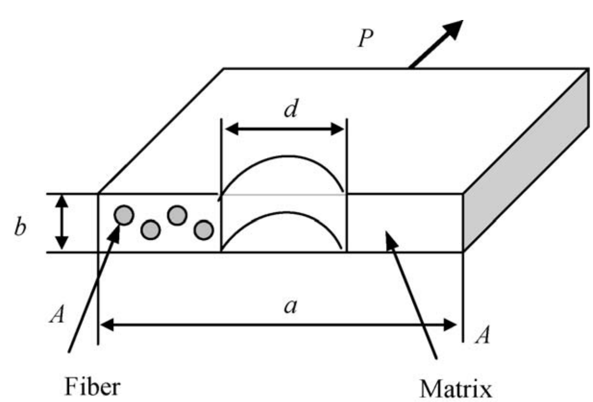

Fig. 9. The composite unit including a rounded-fiber hole.

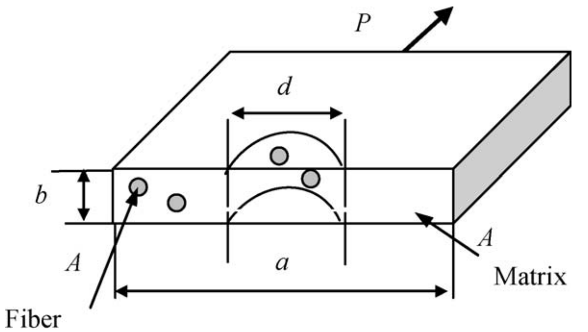

Fig. 10. The composite unit including a severed-fiber hole.

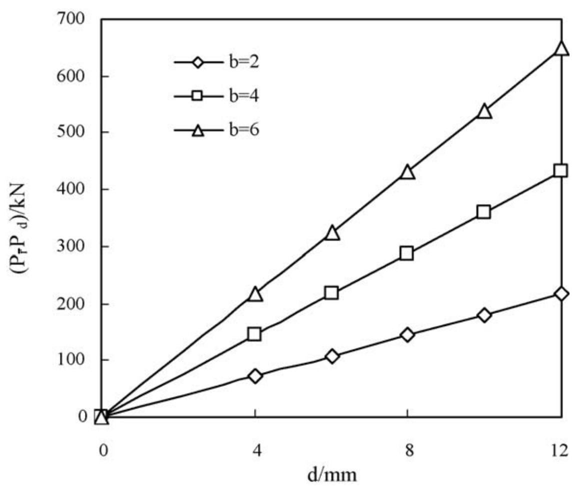

Fig. 11. The relationship between the differences of the rupture strengths and the hole diameters.

can be calculated with

$$\Delta P_{\max} = (P_{\max})_r - (P_{\max})_d = dbf\sigma_b \tag{5}$$

Fig. 11 shows the relationship between the difference of the rupture loads and hole diameter. From Fig. 11 it can be seen that the rupture load of the circumcolumnar layup is larger than that of the drilled-hole layup, and the larger the diameter of the hole, the larger the increase of the rupture load of the circumcolumnar layup compared with that of the drilled-hole layup.

5. Conclusions

SEM observation shows that the Tumblebug cuticle has the basic structural characteristics of fiber-reinforced composite. It consists of the plies of chitin fibers and the sclerotized-protein matrixes. The chitin fiber plies are parallel with the surface of the cuticle. The cuticle is of a heterogeneous microstructure, different from man-made composites. Observation also shows that in the cuticle there are many holes used to transport various matters or receipting external information. More careful observation shows that the fibers near the holes pass continuously round the holes, forming a kind of circumcolumnar layup. The circumcolumnar layup near the hole matches the high level of stress in this region, and improves the strength of the natural biocomposite. A set of biomimetic composite laminates with circumcolumnar layup was fabricated, and the rupture strength of the biomimetic composite laminates was tested and compared with that of the composite laminate with the holes drilled. The result showed that the rupture strength of the biomimetic composite laminates with circumcolumnar layup is distinctly larger than that of the composite laminates with drilled-holes. The testing result also shows that the larger the hole diameters are, the more the maximal load of the circumcolumnar layup will increase compared with that of the drilled-hole layup. This conclusion was also obtained with a theoretical analysis.

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