OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 8, No. 7-8, July – August 2014, p. 794 - 799

Microstructure of the wings of dragonfly *Pantala flavescens* fabricius and finite element analysis of its mechanical property

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The dragonfly *Pantala flavescens* Fabricius has excellent flying capacity and its' wings are typical 2-dimensional composite materials in micro-scale or nano-scale. The microstructure of wings of *Pantala flavescens* Fabricius was examined by stereomicroscopy, laser confocal scanning microscopy (LCSM) and transmission electron microscopy (TEM). It was found that there are some microtrichias on the veins and the wings' membrane of the dragonfly is smooth. There is a wax layer existing and some scratches distributing on the surface of the wings' membrane of the dragonfly. The wing surface has an irregular corrugation and become flat near the wing tip. The longitudinal veins are situated on the highest points and the lowest points of the wings' corrugation and connected by the cross veins and membranes to form a dimensional truss structure. The veins of *Pantala flavescens* Fabricius wings are hollow and their cross sections are suborbicular. The wing membranes are combined with double layers of integument. The finite element models of dragonfly wing were established. The stress and strain under the uniform load were analyzed. It was shown that the grid structures of the dragonfly wing with excellent structural rigidity have excellent integrity. The understanding of dragonfly wings' structure would provide some reference for improving some properties of 2-dimentional composite materials through the biomimetic designs.

(Received November 5, 2013; accepted July 10, 2014)

Keywords: *Pantala flavescens* Fabricius, Membranous wing, Surface topography, Microstructure, Finite element analysis

1. Introduction

There are more than 1.5 million species of animals in the world, of which one million are insects. Insects are important biological resource for developing biomimetic techniques. Natural biomaterials have many optimized structures and functions adapted to their living surroundings well through their evolution over millions of years [1].

Some special structures, forms and functions of natural biomaterials have attracted many designers of engineering structures and scientists of materials [2]. The biomimetic research learning from natural biomaterials has displayed a great importance and significance and has acquired a series of research findings since 1980 in the world [3, 4]. The research of biomimetic materials can be divided into two aspects: one is the research on natural biomaterials facing technical problems and the relationships between their structures and their properties or functions are understood and the structural models of natural biomaterials are established; the other is the design and manufacturing of the biomimetic materials learning from the structures of natural biomaterials [5]. The research on the relativity of structures and performances or functions is the basis of the development of biomimetic materials.

All species of insects with wings are flexible and mobile aircrafts and their skills and modes in flight are mainly originated from the smart structures of their wings. The wings of insects have the optimized structures, functions and materials through the evolution over millions of years. Dragonfly can hover, flap its wings for flight and accelerate [6]. The mass of the wings of a dragonfly is only 1-2％ of its whole body mass, but the wings can stabilize their body and have a high load-bearing ability during flight [7]. The understanding of dragonfly wings' structure characteristics would provide some reference for improving properties of 2-dimensional composite materials through the biomimetic designs.

2. Materials and methods

2.1 Collection of dragonfly specimens

The living dragonflies, *Pantala flavescens* Fabricius

(Odonata, Anisoptera, Aeschnidae, Anax), were collected in Changchun, China. Fig. 1 shows the stereoscopy photograph of a dragonfly *Pantala flavescens* Fabricius. The tests were performed within 24 hours after collecting the dragonflies so that the dragonflies were still alive and the *in-vivo* structures of the wings can be kept.

Fig. 1. Stereoscopy photograph of a dragonfly Pantala flavescens Fabricius.

2.2 Specimens preparation

Several living dragonflies were anaesthetised and their wings were cut off their bodies. So, the dragonfly wing specimens were prepared for analysis of their microstructures.

The membranous wings were adhered on blocks with double-side adhesive paper without any special treatments for the stereomicroscopy (OLYMPUS SZX12) and the laser confocal scanning microscopy (OLS3000) of surface topography of the membranous wings.

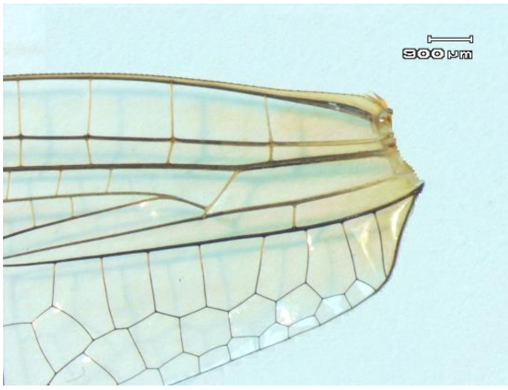
As for the preparation of the wing specimens for the analysis of the cross sections, each wing specimen was cut into three parts at the position of 0.3L, 0.5L and 0.7L (L is the wing length) respectively with a sharp blade. The specimen parts for stereoscopy of the cross sections were clamped with two thin glass sheets. The length (L) of the wing was measured with a vernier caliper through the cross section of the wing.

The specimens for transmission electron microscopy were fixed in the water solution with glutaral of 2.5%*wt* for 8 hours and then were washed with phosphoric acid. The fixation was performed again in the water solution containing osmic acid of 1%*wt* for 2 hours and then washed by phosphoric acid for several times. The dehydration treatment was required for the specimens for the transmission electron microscopy. The procedure of the dehydration treatment is as follows. The specimens had been in water solution with alcohol of 30％*wt*, 50％*wt*, 70％*wt* and 90％*wt* for 10 minutes for each concentration in turn and, then, dehydration treatment was performed by pure alcohol for three times, 10 minutes for each time. After dehydration by water solution of alcohol, the dehydration treatment was done by propylene oxide. The dehydrated specimens were embedded in epoxy resin (Epon812) and, then, the epoxy resin blocks had been polymerized at a temperature of 80℃ for 24 hours. The epoxy resin blocks with wing specimens were shaped to pyramid. The top parts of the epoxy resin blocks were shaped to a square with an area about 0.5×0.5 mm^2. The ultrathin sections of 40 nm to 60 nm thickness were prepared by an ultramicrotome after the longitudinal orientation of the wing and, so as to, the ultrathin sections can be used for transmission electron microscopy (JEM-1200EX).

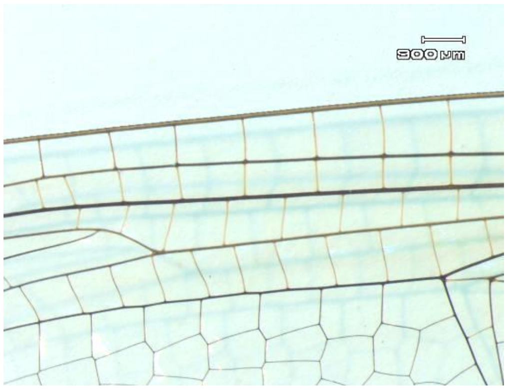
3. Results and discussion

3.1 Characteristics of surface topography of the wings

The surface topographies of the wings of the dragonfly *Pantala flavescens* Fabricius were examined by stereoscopy, as shown in Fig. 2. It was found by stereoscopy that, at low magnification, the membranous cuticle of the wings of the dragonfly is smooth.



(a)



(b)

Fig. 2. Stereoscopy photographs of the surface topography of the dragonfly wings. (a) The forewing; (b) The hindwing.

It was found by LCSM that there are some microtrichias on the veins of the wing, as shown in Fig. 3. In addition, there exist scratches on the wing membrane of the dragonfly wings as shown in Fig. 4.

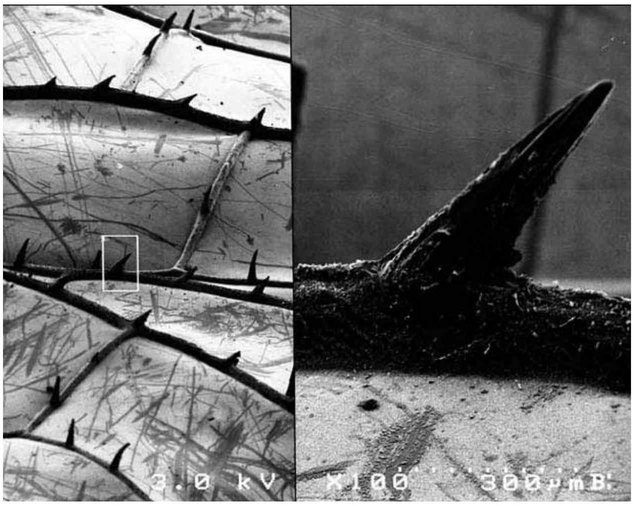
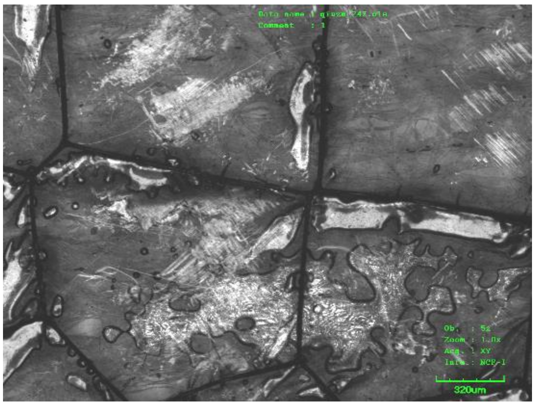


Fig. 3. LCSM photographs showing the microtrichias on the veins of the dragonfly wing.



(a)

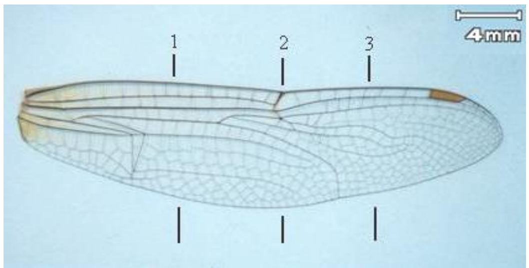
(b)

Fig. 4. LCSM photographs showing the scratches existing on the wing membrane of the wings. (a) The forewing; (b) The hindwing.

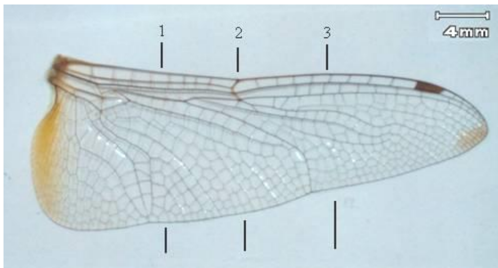
There is a wax-like crystal layer on the surface of the wing membrane. It was demonstrated that this wax-like crystal layer may be formed from wing epidermal cells [8]. In adult Odonata, epidermal cells do not secrete the wax-like crystal and the number of pores is reduced considerably, which means that the wax layer is secreted one time in the life-time of dragonfly and is not renewed thereafter. Some scratches formed at random on the surface of the wing membrane are due to the contact and friction between the wings' surfaces and their living surroundings (bush, weed). Therefore, the scratch pattern on the wings' surfaces of a dragonfly reflects its individual history of the dragonfly, as a rule, the number of scratches is more in older individuals' wing surfaces compared with younger ones' wing surfaces.

3.2 Corrugation properties of the wings

The stereoscopy photographs of the positions of three typical cross sections of the dragonfly *Pantala flavescens* Fabricius wings are shown in Fig. 5.



(a)



(b)

Fig. 5. Stereoscopy photographs showing the positions of three typical cross-sections of the dragonfly wings used for tests. (a) The forewing; (b) The hindwing.

The three typical cross-sections are at position of 0.3L, 0.5L and 0.7L of the wing, where L is the total length of the wing. The three typical cross-sections were selected on the basis of the rising and falling trend of Costa. Costa and Subcosta are integrated at the position of nodus and the nodus is on the minimum and middle point of Costa. Costa tends to a falling trend in front of the nodus and to a rising trend behind the nodus. The three typical cross sections are situated on the falling section, the middle point and the rising section, respectively.

The stereoscopy photographs of the cross sections at position of 0.3L, 0.5L and 0.7L of the wings are shown in Fig. 6. It was demonstrated that the dragonfly wings are not smooth or simple cambered surfaces. The cross-sectional profile of the wing has an irregular corrugation and the wing changes flat near the wing tip. The longitudinal veins are situated on the highest points and the lowest points of the wing corrugation and connected by the cross veins and membranes to form a dimensional truss structure. The wing corrugation can enhance the flexibility and, so as to, the wing has certain load-bearing ability during flapping flight [9, 10].

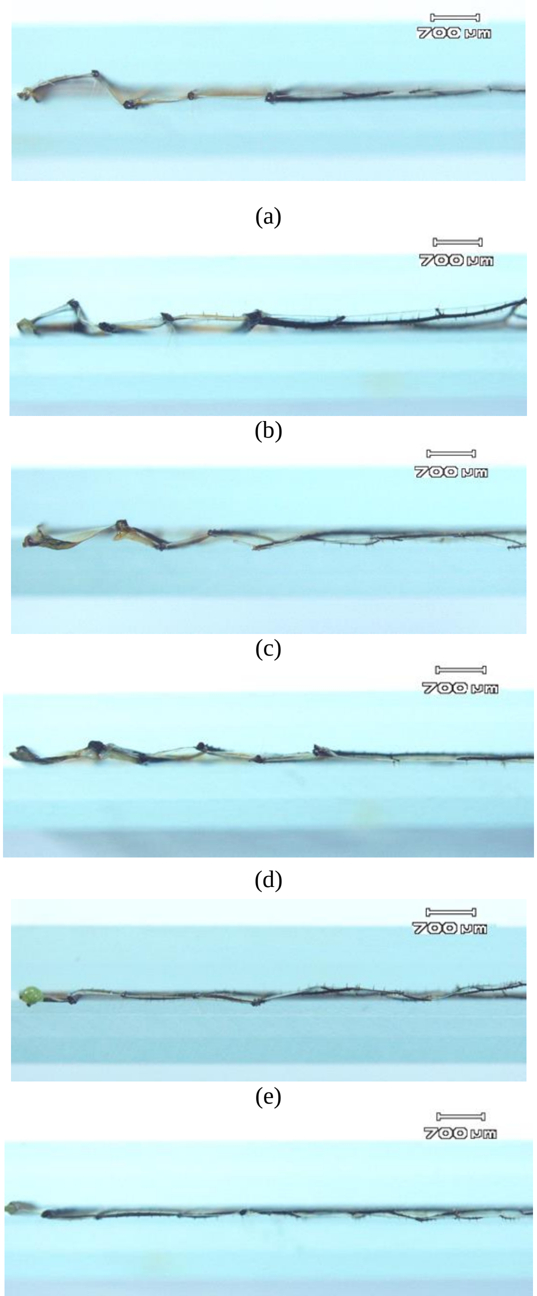
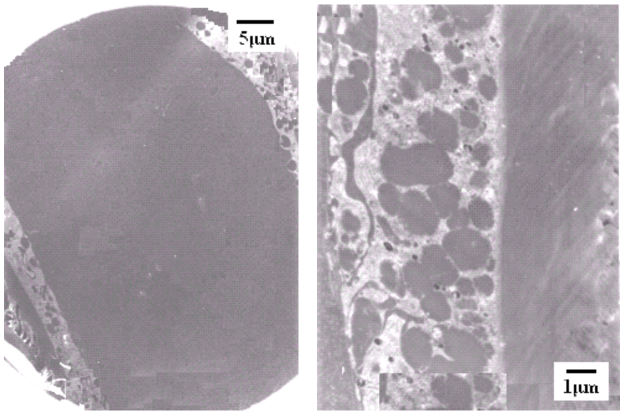


Fig. 6. Stereoscopy photographs showing the cross-sections of the dragonfly Pantala flavescens Fabricius wings at the cross-sections in the positions (a, b) 0.3L; (c, d) 0.5L; (e, f) 0.7L of (a, c, e) forewing; (b, d, f) hindwing.

3.3 Micromorphologies of the cross-sections of the wings

Fig. 7 shows the morphologies of the cross-section of a single vein and the magnified nerves in the vein. It was found from Fig. 7(a) that the vein has a hollow structure and its cross-section displays suborbicular. The area surrounded by the white strips in the vein cavity is tracheae and the parts on the white strips similar to gas bubbles are nerves. That is, there are tracheae, nerves and body fluid in the vein cavity. The veins were formed by thickening tracheae and the veins with ring structure in cross section have better flexibility [11].



(a) (b)

Fig. 7. TEM photographs showing the cross-sections of a wing vein of the dragonfly Pantala flavescens Fabricius. (a) The tracheae and nerves in the vein cavity; (b) The nerves (left zone).

The morphology of the cross-section of the wing membrane is shown in Fig. 8.

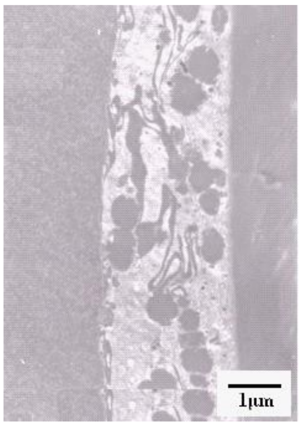


Fig. 8. TEM photograph showing the cross section of the wing membrane of the dragonfly Pantala flavescens Fabricius wing.

It was found from Fig. 8 that the wing membrane is formed by double layers of integument and there are nerves distributing in the wing membrane although it is very thin.

3.4 Finite element analysis of the mechanical properties of dragonfly wing

Dragonfly can hover, flap its wings for flight and accelerate and its membranous wings have a high load-bearing capacity for static and dynamic load during flight. The influence of geometrical nonlinearity was taken into account but material nonlinearity, and the finite element models were assumed in the elastic range. The finite element models of dragonfly wing were simulated only with structural statics in the present work and the deformation, the stress and the strain under the uniform load (the main load during flight) were analyzed.

The vertical uniform load was applied on the finite element model of dragonfly forewing. The applied uniform load is the ratio of the dragonfly gravity to area of its membranous wings, namely the lifting load to make the dragonfly hover in air. The mass of the dragonfly can be obtained with a FA series electronic analytical balance (FA2004) and the area of its membranous wings by a stereomicroscopy and its image analysis system (OLYCIA^{TM} M3), and then the lifting load and vertical uniform load can be described as follows.

$$F = G = mg = 1.783\times10^{-4}\times9.807 = 1.7486\times10^{-3}N = 1.7486\times10^{-6}KN \tag{1}$$

$$q = \frac{F}{2A_1 + 2A_2} = \frac{1.7486\times10^{-6}}{2\times34.8 + 2\times50.9} = 1.0202\times10^{-8}KN/mm^2 \tag{2}$$

Where, F is the lifting load to make the dragonfly hover in air, G the gravity of dragonfly, m the mass, g the acceleration of gravity, A_1 the area of a forewing, A_2 the area of a hindwing and q is the vertical uniform load, respectively.

The vertical uniform load calculated above was applied on the finite element models of dragonfly forewing. The displacement constraint was applied at the base of the models, and then the deformation, the stress and the strain of the models were analyzed, as shown in Fig. 9, Fig. 10 and Fig. 11 respectively.

The dragonfly wing is a dimensional truss structure with excellent structural rigidity and deforms only a little on forewing under the uniform load. It was found that the grid structures of the dragonfly wing deforming together at the boundaries of veins and membranes have excellent integrity. The deformation increases gradually from the base to the tip of the model and the maximum deformation is 1.908 mm. The result shows that, the larger the deformation is, the easier the damages to the wing is.

The heavy stress is mainly concentrated on the base of the model, smaller at the middle parts and the least at the wing tip and the rear edges under the vertical uniform load. The result shows that the maximum stress was 0.259×10^{-3}GPa and, the higher the stress is, the easier the damages to the wing is.

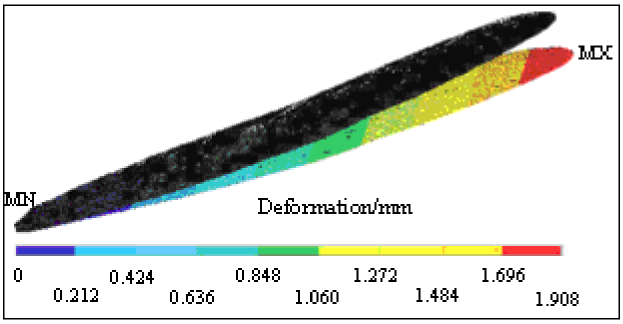


Fig. 9. The deformation of the finite element model of a dragonfly forewing under the uniform load.

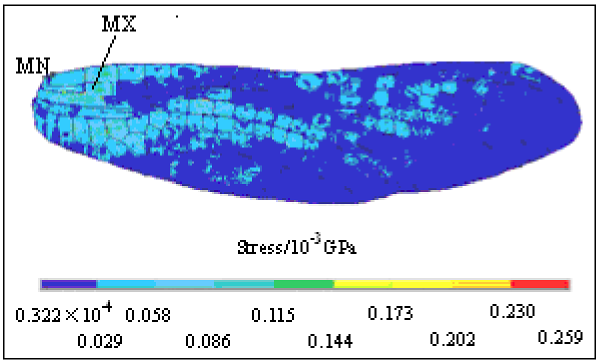


Fig. 10. The stress of the finite element model of a dragonfly forewing under the uniform load.

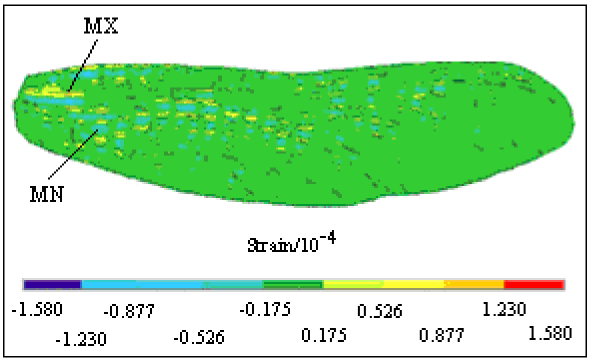


Fig. 11. The strain of the finite element model of a dragonfly forewing under the uniform load.

Starting from the base of the model, the great strain distributes radiately along the longitudinal veins. The maximum strain of 0.158×10^{-3} appears on the base of the model and reduces gradually to the wing tip and the rear edges.

4. Conclusions

The surface topography, the corrugation feature and the micromorphologies of the cross-section of *Pantala flavescens* Fabricius wings were examined and analyzed by stereomicroscopy, laser confocal scanning microscopy and transmission electron microscopy. It was found that, at low magnification, there are some microtrichias on the veins and the membranous cuticle of the wings of the dragonfly is smooth. There is a wax layer and some scratches on the surface of the wing membrane of the dragonfly wing. The typical structure of *Pantala flavescens* Fabricius wing is wing corrugation. The veins of *Pantala flavescens* Fabricius wing are hollow, whose cross-sections are suborbicular. The wing membrane is formed by double layers of integument although it is very thin. The finite element models of dragonfly wing were established. The stress and strain under the uniform load were analyzed. It was shown that the grid structure of the dragonfly wing with excellent structural rigidity deforming only a little have excellent integrity.

Acknowledgments

This work was supported by the 8th key subject of Henan province, by National Natural Science Foundation of China (grant no. 30600131, 50675087), by National Science Fund for Distinguished Young Scholars of China (grant no. 50025516), by Doctor Foundation of Henan Polytechnic University (grant no. B2008-74) and by Natural Science Research Item of Henan Education Department (grant no. 2011B410002).

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