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Effects of sandwich microstructures on mechanical behaviors of dragonfly wing vein

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Abstract: Dragonfly wings, which consist mainly of the veins and membranes, are highly specialized flight organs adapted to cope with the individual flight behavior of each dragonfly. Therefore, it is important and necessary from a bionic view to investigate how the microstructures affect their mechanical behaviors of elements. In this study, it is focused on effects of microstructure on mechanical characteristics of dragonfly wing vein. These results indicate that the microstructure of vein is a complex sandwich structure, which consists of chitin shell and protein/muscle with some fibrils. This sandwich structure can be subjected to the rather greater bending loading and torsional deformation based on the von Mises stress and flexural deformation analysis of finite element analysis (FEA). It assists us to understand and design the new high strength-to-weight ratio of composite materials or structure.

Key Words: A. Wing vein; B. Microstructure; B. Mechanical properties; C. FEA; D.SEM;

1. Introduction

In flight, the wings of insects cyclically varying three-dimensional (3-D) shape is determined partly by the forces and partly by the detailed structures of wings themselves, which response aeroelastically to the inertial and aerodynamic forces. As with a complex structure of insect wing, their mechanical responses to loads or deformation are due partly to gross structure and partly to the properties of materials from which these components are constructed based on the studies in experiments and finite element analysis (FEA) [1-7]. However, these studies mainly focused on the investigations about the membrane structure and mechanical properties of insects. Although the membrane is a barrier for the passage of air through the wing, in some areas at least, it plays only a structure role in a stressed skin, forms the tight knit framework of veins. In order to withstand heavy mechanical stress with minimum material expenditure, the type of building materials used and their distribution are very important [8, 9]. The basic framework of vein system of insect wings is made of chitin, a long-chain, crystalline polymer the characteristics of which are similar to cellulose or technical materials [10]. These apparent differences suggest that there should be local variation in the mechanical properties, hence, in the structure of the membrane within the wing, with profound implications for their functioning in flight.

The general organization of insect cuticle is well known [11]. Two main layers are usually distinguished: the thickness of epicuticle is seldom more than 1.5 μm, and the thickness of procuticle can reach at several millimeters. So far as it known, the epicuticle contains no chitin. The procuticle, generally by far the thicker layer, consists of chitin and some micro fibrils, normally approximately 20 nm in diameter, in a matrix of proteins and acting as a fibrous composite [12,13]. Most insect cuticle fits this basic plan, but with many variations. The most obvious is the thickness of the cuticle as a whole and of the individual layers. Other variations included the proteins present, the degree and nature of the cross-linking [14], the ratio of protein to chitin and the alignment of the chitin with the micro fibrils. All these can be expected to influence the mechanical properties of the composite procuticle, often very locally, because the details of cuticle secretion may vary from epidermal cell to epidermal cell. Therefore, the investigations on the relationship between the microstructure and mechanical behaviors of insect wing vein are rarely reported in these references, although the vein microstructure as a framework system of wing has been reported in many references [2-7].

The main aim of this work focuses on investigating the microstructures of wing veins and analyzing effects of microstructures on mechanical behaviors of vein based on the tensile and 3-point bending tests as well as analysis of the torsional and bending moment individually by the finite element analysis (FEA).

2. The characterizations of microstructure and experimental methods

The typical dragonfly used in this work is defined as the pantala flawescens, which widely lives in China as shown in Fig.1. To obtain good experimental results, all samples were kept the relative humidity, which every test was finished within about 10 minutes because the tissues of wing are not atrophic and hold the mechanical properties of wing in vivo in this period. The dragonfly forewing’s sizes are as follow:

the length is about 44 mm in spanwise and the different width of fan zones average value are about 10 mm, 11 mm, 12 mm, respectively. The sizes of hindwing are as follow: the length is about 40 mm in spanwise and the width of fan zones arrange from 10mm to 16mm. The microstructures of wings, for example the microstructure of the forewing, mainly consist of the reticulate veins and thin membranes at various sites for the wing, where the spanwise veins are the similar to round or elliptical sections tubular element. The wing mainly consists of 6-8 spanwise veins to form a framework structure which stiffens itself to against aerodynamic bending and torsional moments, and the thin membrane also is a multilayer composite structure [5], and their sizes and configurations are different as shown in Fig. 2. When the wing was broken off under the tensile loading, the fracture cross-section of wing indicates that the veins and membranes are approximately brittle fracture and the tensile loading should be mainly subjected by these veins as shown in Figs. 3(a). It is interesting to find there are the different cross-sections of tubular veins, which are a part of typical round sections at the B and C zones and the other part of un-symmetric shape cross-sections at the A zone is as shown in Fig. 2 and Figs. 3(b)-3(c), respectively. These microstructures and roles of tubular veins were seldom reported although the microstructures and roles of wing membranes have reported in many references [5, 6, 11, 15, 16]. For the typical round section of veins, there are two typical microstructure characterizations, which are the approximate same wall thickness and may be the multi-layers of chitin and proteins with fibrils formed the sandwich structure, maybe present like the multi layers of chitin and protein meat with some fibrils such as at left diagram in Figs. 3(b). This is mainly because the sandwich microstructure could subject a rather greater torsional deformation in minimal mass based a mechanics view if the flexing stiffness of the vein keeps a constant. And the torsional deformation of veins mainly comes from a couple of the membranes at two sides of the vein as shown in Figs. 3, which tilt up and down to result the "umbrella" effect [16]. But in the un-symmetric shape section of other tubular veins, the wall thickness is not the same ($\delta_1 > \delta_2$), wherein δ_1 is the wall thickness of the tubular veins toward to the up camber of "umbrella" in the un-symmetric shape section, and δ_2 is the opposite wall thickness as shown in Figs. 3c.. These structural characterizations hint that the change of vein's microstructure agrees good with the requirement of the flight that the torsional deformation closed to the greater size of veins is less than that closed to the smaller size of veins in the margin of fan zones.

The "engineering curves" about the maximum flexural deformations of dragonfly wings, which include the membranes and veins, are plotted based the results in 3-point bending tests (the bending span is 20 mm). All flexural deformations were measured by a reading optician microscope (±0.01mm) and the error of transverse load is about 1mN, and the transverse load applied equably at the middle of wing's length in order to satisfy the assumption of plane bending stress state as shown in Fig. 4. In addition, the effective tensile tests are defined as that the forewing or hindwing of dragonfly was held by two clamps, one attached to a load cell, the other to a moveable cross head. The effective fracture section is defined to occur nearly at the middle part of dragonfly wings. The mechanical parameters and related sizes of dragonfly wings are listed in the table 1 based own results and cited from the literatures [3, 4, 8, 17, 18]. In order to simply estimate the mechanical properties of wings, the cross-sections of wings could be defined as the system of the tubular-elements and thin membranes as shown in Figs. 3(a). Therefore, the cross-section area can be determined accurately according to the fracture location of wings.

3. Results and discussions

3.1 Effects of vein microstructure on Young's modulus

The Young modulus of biomaterial is a key parameter in their applications. As the dragonfly wings can possess kinds of flight abilities to support the weight of themselves, the dragonfly wings are subjected to the torsional and flexural deformations. And the torsional and flexural rigidities of dragonfly wings are the important parameters to elevate the aerodynamic ability. The torsional moment M, which resists the external moment, has two components as follow[19]:

$$M = GJ\partial^2\theta / \partial^2 x - EI\partial^4\theta / \partial^4 x \quad (1)$$

where θ is the torsional angle, the first term is the moment described by Saint-Venant's theory of torsion, and the second term is the warping moment [3, 20]. J, I is the torsional and warping constants, respectively, and G, E are the rigidity and Young's modulus of wing system that they are, respectively, affected by the framework structure of wing. In this equation, these constants relate to the size and microstructure of veins, which is able to be defined as a total frame structure if the membranes are assumed only to provide the applied stress to veins. Therefore, it is important to evaluate the mixed moment because the size and microstructure of veins can be easily determined. It is clearly seen that there are still rather differences for these parameters as shown in table 1 due to the methods and styles of dragonfly. To avoid the different of mechanical properties of wing, the flexural Young's modulus of dragonfly wings structure should be obtained based on the 3-point bending tests. In this work, all mechanical properties of dragonfly come from the pantala flawescens, which widely lives in China except for illuminating. Therefore, the simple relationship between the flexural Young's modulus E and the maximum flexural deformation ($\delta_{\max}$), applied load (P) is as follow:

$$E = \frac{P\ell^3}{48 I_z \delta_{\max}}$$
$$I_z = n\frac{\pi}{64}(D^4 - d^4) + \frac{\bar{b}t^3}{12} \qquad (2)$$

where ℓ is bending span (20 mm), n is the vein's numbers, d (D) is a diameter of tubular element, $\bar{b}$ is an average width of wing fan. I_z is a product of inertia of wing. t is an equivalent thickness of membranes. Therefore, the flexural Young's modulus of dragonfly wing structure is easily determined once the structure sizes are obtained step by step based on the model as shown in Figs. 3(a).

Figs. 4(a) shows the simple relationship between the transverse load and the maximum flexural of wings under 3-point bending loading. These relations mean that they are approximately linear. The slopes of curves are different because the flexural rigidity of hindwing is the two times larger than that of forewing. Compared with the size and longitudinal vein numbers of wings as shown in Fig. 1 and Fig. 2, it can be found that one of the reasons is that the sizes of hindwing are slightly larger than that of forewing, such as the thickness of tubular element, veins distribution and veins pitches. These veins pitches indicate the dragonfly has a corrugated ability of thin membranes. In addition, the main spanwise veins lengths of hindwing are a quarter shorter than that of forewing. And the arrangement of these veins is concentrate on the vicinal centrobaric zone of the dragonfly body so that they hold the agile flight. Therefore, it is main reason that the vein's microstructure plays as the dominant role to resist to deformation of wing. On the other hand, the larger warping rigidity means the wing can be much thinner when it provides the maximum deformation. Such a thinner, lighter wing is more suitable for beating flight [21, 22], because in a species the flight economy is rather important, the minimization of wing mass may be extremely important, and the dragonfly may have evolved to use the thinnest, lightest membrane and vein whose properties are acceptable.

Figs. 4(b) shows the effects of wing vein numbers and fan width on the flexural Young's modulus. It means that the flexural Young's modulus of wings do not vary with the fan width of wings because the estimating method has been considered the properties of veins and membrane. At the same time, the effect of fine veins in edge of wing (C zone as shown in Fig. 2) on the flexural Young's modulus has been ignored. That is why the pliability near C zone of wing is rather better than other part of wing, such as A zone, so that it can satisfy the aerodynamic requests for insects. In addition, the fore and hindwing's veins arranging pitches varied with the membranes' corrugation extent so that the Young's modulus of wing structure has the maximum and the minimum values. Therefore, the wing's membrane corrugation, which increase I in Eq.(1), is important for preventing large torsional deformation caused by resonance, which the wing of insects can flap in high frequence of about 20-30 Hz and afford a large amplitude of about 30-50 degree in a stroke [21-23]. In this work, the effects of frequence and amplitude of flapping on the mechanical properties of wing were contained in torsional and warping deformation capability [4]. However, the changes are suitable for the request of dragonfly flight [17]. This characteristic is useful for assisting us to design a minimization mass of advanced composite materials, such as metal foams and micro parts of an apparatus and sensor [24].

3.2 Effects of vein microstructure on the strength

Figs. 4(c) shows the relationships between the tensile strength and vein's numbers, fan width parameters of dragonfly wings. These curves indicate that the strength of dragonfly wings decrease with increasing of the vein numbers and fan width of wing. And the effect of vein's numbers on the strength is more obvious due to the decreasing of the tubular element size. It means that the strength of dragonfly wing is mainly determined by the veins tubular microstructure and their longitudinal arrangement veins system. It can obtain a conclusion that the fracture type is a mixed fracture model, which consists of the macroscopic brittle in chitin zone and microscopic ductile fractures in muscle/protein zone from the fracture section as shown in Figs. 3(b) and 3(c). This is because the vein's fracture section presents the certain concavity in the meat of sandwich structure and it means the meat may consist of muscle/protein with less amount fibrils organized structures on the tubular elements. These fibrils in sandwich structures of vein can play important role in the enhancement fracture toughness and adapting to cope with the individual flight behavior for the dragonfly. The fracture morphology of tubular vein (as shown in Figs. 3(b)) shows that it may be the multilayer ring-shells microstructure consisting of the protein with fibrils and chitin, which stiffens the wing against aerodynamic bending moments and greater torsional deformations of dragonfly wings. The dragonfly wings appear as highly functional and largely optimized mechanical constructions of veins and membranes. A series of stabilizing constructional elements have been ‘designed’ to cope with loading during the flight. As regards the mechanical properties of composite microstructure systems, many excellent applications have been widely validated in the construction of the building and aeronautical materials [4, 24].

3.3 Effects of microstructure of vein on the stress distribution based on the FEA

Other investigators have already been made to focus on an insect wing membrane, e.g. references [25-28]. They are not only a construction but also a mechanism so that they must cope with a kind of load or loads combination. In addition, the insect wings impress one deeply with the marginal mount of building material used in their construction. Although the wings only occupy more than 1-2% of total body mass, they possess great stability and a high load-bearing capacity during flapping flight. In order to withstand the greater mechanical stress with minimum material expenditure, the structural type of building materials used and their distribution are also very important.

The main aim of this section is to determine the stress or stain distribution of vein sandwich microstructure of chitin, protein with some fibrils under bending or torsional loading by the finite element analysis (FEA). This analysis enables one to take into account the individual variations in structural parameters which are particularly helpful in dealing with the problems concerning the stability of a construction.

With the help of the FE computer system ANSYS, the models are built and analyzed. These models contain the tubular shell microstructure of three layers vein. All shape parameters of vein tubular shell structures are defined as follow based on the forewings: the total thickness of vein tubular shell structure is a constant value about 17 μm, then it is assigned to the two layers of chitin shells and one layer of protein/muscle to form a sandwich structure, the thickness of which are about 7 μm, 5 μm and 5 μm, respectively. The inside and outside radiuses of tubular shell are 33 μm and 50 μm, respectively based on the Figs.3b.

Models of calculation in FEA are bearded the torsional or bending moment (M_T or M_b). The torsional moment is defined as about 0.206 N·m as shown in Eq. (1) and θ is about 70 ° [7, 29]. As the assumption that the lifting load is about 12 times of the inset's weight [7, 29], the bending moment is defined as 5×10^{-4} MPa in per vein. The chitin and protein of vein are modeled as an isotropic material with a Young's modulus of about 40 GPa and 3 GPa [30], respectively. The Poisson's ratio is assumed to be 0.3 and 0.4, respectively. The spanwise length of the vein is defined as about 200 μm. Therefore, the vein as a sufficiently slender and an elastic beam of uniform section of tubular elements is loaded in simple average moments, the bending M_b in the beam or the torsion M_T at the free end of a beam. Another end of beam is completely constrained.

Fig. 5 shows the von Mises stress distribution under the bending loadings. The result indicates that the maximum stress mainly occurs at the constrained end and on the outside layer of sandwich structure to be good agreed with the similar results in references [31-35]. The chitin layers mainly withstood bending moment, especially the out chitin layer. The greatest stress is about 0.035 MPa. The meat of sandwich structure can be thought like a protein layer so that it is almost not subjected to the bending moment, which also has been validated by this FEA result. Therefore, this structure is beneficial for the construction of strength-to-weight ratio of composite material. Fig.6 shows the curve between vertical displacement and pressure at the free end of beam which is in good consistent with the Figs. 4a.

Fig. 7 shows the strain of YZ-direction at free end of vein under the torsional moment. The result indicates that the torsional deformation mainly occurs at the meat of protein in X-Y plane as shown in Fig.7 and the maximum and minimum strain are the relative rotational angle of about -61.28° and -125.12° between the outside and inside of chitin shell, respectively. This angle is smaller than that of the experimental measure by reference [29] between the outside and inside of chitin shell because the angle of about 70° obtained from the corrugation of wing membrane is a deflect angle of total wing.

All results indicate that the bending strength failure of vein mainly occurs at the chitin shell and the critical torsional deformation of vein occurs at the interface between the shell and meat. These results confirm that the sandwich structure can be satisfied for the specialized flight requirement.

4. Conclusions

The following conclusions have been obtained:

1. The multi chitin shell layers structure of vein are mainly subjected to the bending loading, and the protein with fibrils as the meat of sandwich structure is mainly subjected to the torsional deformation, which can be transformed an angle between the chitin shells and the maximum and minimum strain are about -61.28° and -125.12°, respectively. Therefore, the vein of chitin shell structure do not easily damaged in the action of torsional deformation during flight. This sandwich structure of vein is superior to one typical material vein.
2. The flexural Young's modulus of wing consisted of veins and membranes and tensile strength decreases with the vein numbers increasing. Therefore, it means that the tensile strength is contributed by the veins near the end of dragonfly. In addition, the vein's maximum pitch at the end of dragonfly is smaller than that at the margin of wings due to the membranes corrugation.
3. The fracture analysis by FEA and SEM images of fracture of wing veins indicate that the vein sandwich structure consists of the macroscopic brittle in chitin zone and microscopic ductile fractures in muscle/protein zone.

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Figure Captions

Fig.1 Figuration of the *Pantala flewescens*

Fig. 2 Dragonfly wing structure to consist of veins and membranes

Figs.3 Sandwich microstruture of veins.

Figs. 3a Cross-section of veins and membranes.

Figs. 3b Microstructure of tubular vein in B zone

Figs. 3c Microstructrue of tubular vein in A zone

Figs. 4 Curves of mechanical parameters vs. flexural deformation/ vein numbers/fan width.

Figs. 4a Relationships between the transverse load and flexural deformation of wing.

Figs. 4b Relationships between the flexural Young's modulus and the vein numbers, width.

Figs. 4c Relationships between the tensile strength and vein numbers, width of wing.

Figs. 5 the von Mises stress at the constrained end

Figs. 6 the curve between vertical displacement and pressure at free end of beam

Figs. 7 the strain of YZ-direction at free end of vein

Fig.1 Figuration of the *Pantala flewescens*

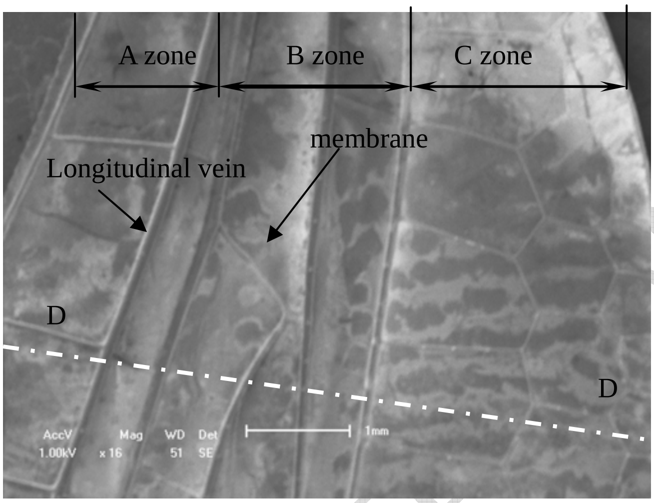
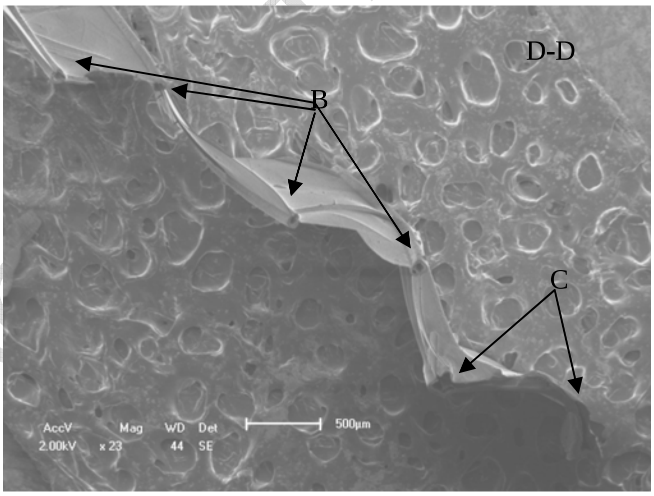
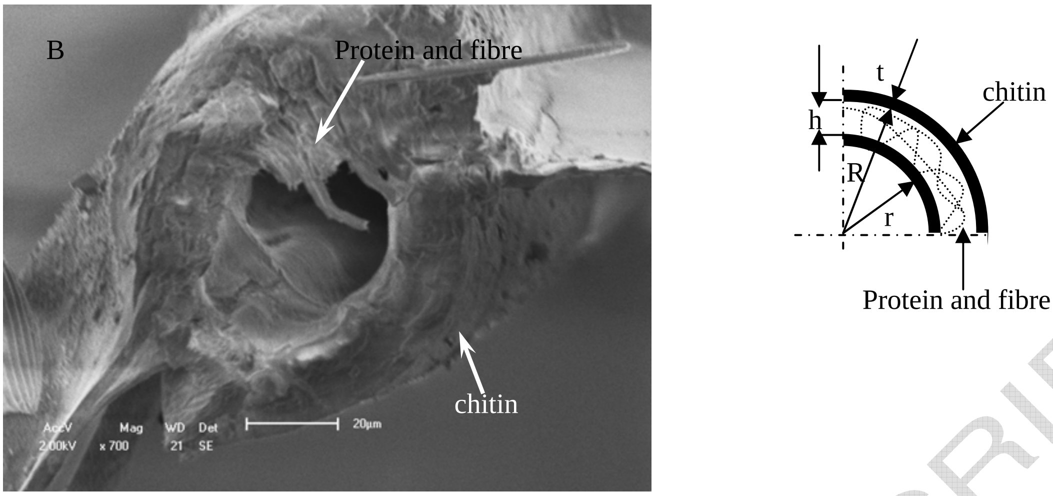


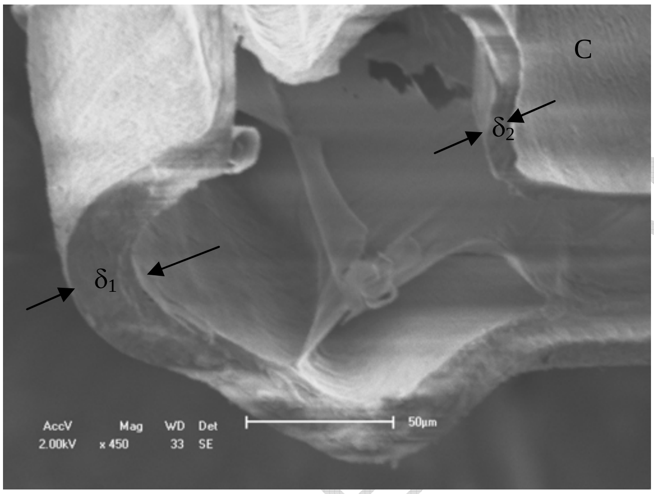
Fig. 2 Dragonfly wing consists of veins and membranes



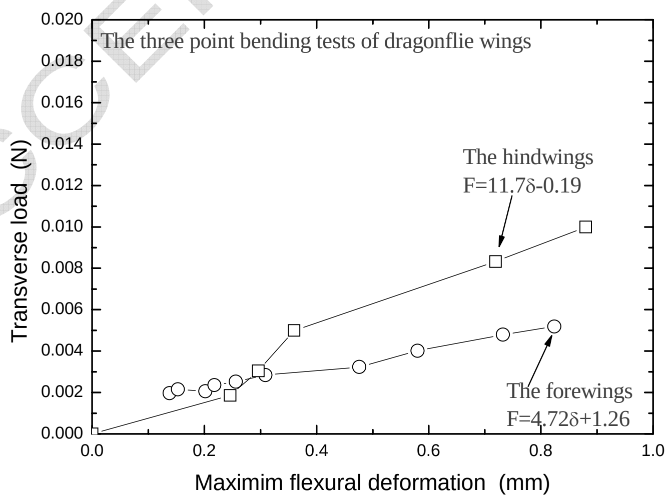
Figs. 3a The cross-veins model of wing used the estimating mechanical properties.



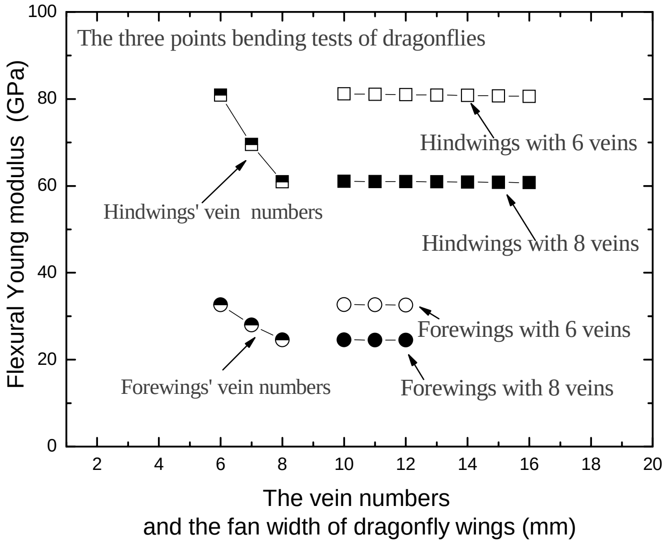
Figs. 3b Microstructure of tubular vein



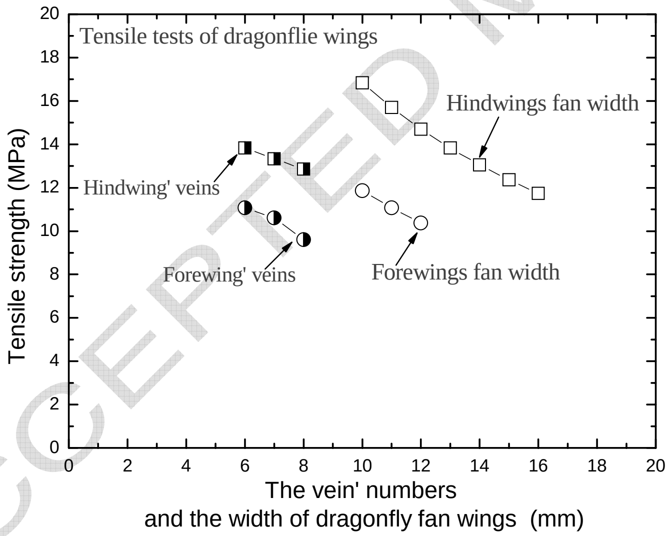
Figs. 3c Microstructrue of tubular vein



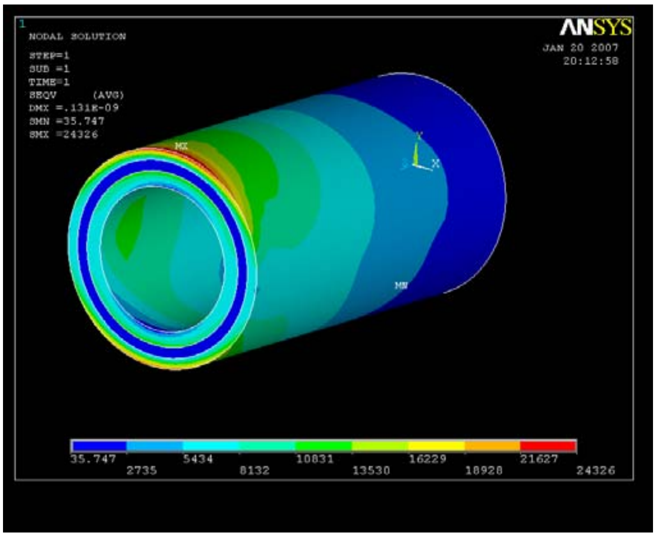
Figs. 4a Relationship between the transverse load and flexural deformation of wing.



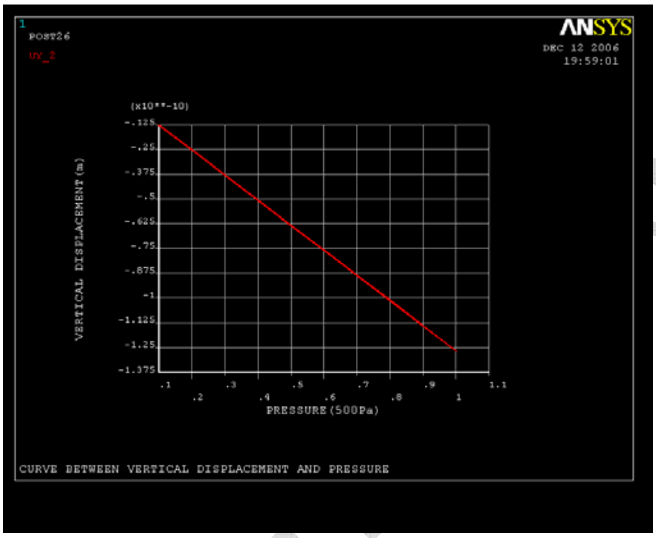
Figs.4b Relationship between the flexural Young's modulus and the vein numbers, fan's width.



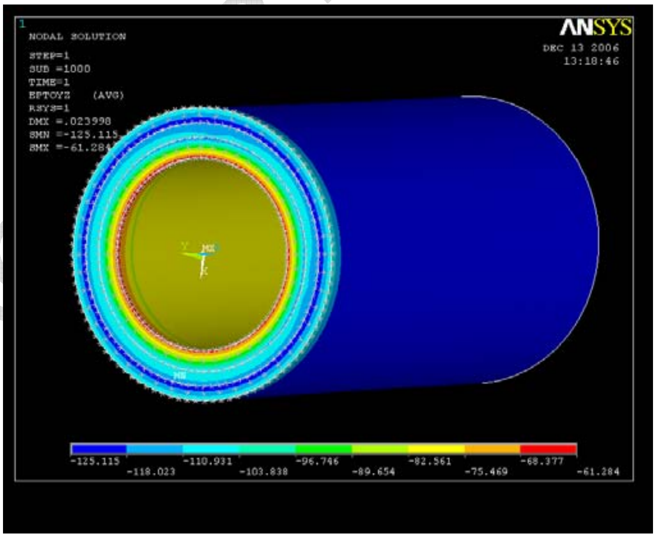
Figs. 4c Relationship between the tensile strength and vein numbers, fan's width of wing.



Figs. 5 the von Mises stress at the constrained end



Figs. 6 the curve between vertical displacement and pressure at free end.



Figs. 7 the strain of Y-Z direction at free end of vein

Table 1. Compared with the mechanical parameters of dragonfly wings by different estimating methods

Items	Considered the effect of sizes Based this work.	Without considered the effect of sizes based the literature [3, 4, 8, 17, 18].
L(mm)	44(F), 40(H)	99.8,101.8[18], 53[3],
b (mm)	10~12(F),10~16(H)	12[3],
i=L/b	4.4~3.67(F),4~2.5(H)	1.1~8.3[18], 4.4[3],
A(mm^2)	480(F), 520(H)	890,1100[18],
t (μm)	5~10(F), 5~10(H)	3.6~4.8[18], 1.2~4[4,8],10[3]
δ (μm)	20~25(F), 20~30(H)	25[4,8]
D (μm)	70-80(F), 70~90(H)	135[4,8]
n	6,7,8 (F and H)	~
g (mg)	350	790[18], 27~670[3]
E (GPa)	24~32(F), 60~80(H)	6.1[17],20[3,17]
σ_K (MPa)	10~11(F), 12~14(H)	~

Where L is a spanwise length of dragonfly wing, b is an average fan width of wings, A is an effective wing area, t is a membrane thickness, δ is a thickness of vein's tubular, D is a diameter, n is the vertical vein's numbers, g is a mass of dragonfly, E is a flexural Young's modulus and σ_K is an average fracture strength of wings. F and H show the forewings and hindwings, respectively.