AmirKabir University of Technology
(Tehran Polytechnic)

AmirKabir Jounrnal of Science & Research
Mechanical Engineering
(ASJR-ME)
Vol. 48, No. 2, Summer 2016, pp. 61-64

Experimental and Numerical Investigations of Crack Propagation in Dragonfly Wing Veins

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(Received 10 March, 2015, Accepted 8 February, 2016)

ABSTRACT

The vinous wings of insects are complex biological structures with remarkable mechanical behavior. The wings mainly consist of veins and membranes. The membranes of the wing are not mechanically tough. But, the whole wing structure reveals a significant resistance to crack propagation. In this paper, a combination of scanning electron microscopy technique, experimental tensile tests and numerical simulation is employed to investigate the effect of the veins on the "toughening mechanism" of the wings. The numerical simulation of crack propagation in the vein is based on the extended finite element method. Linear elastic material properties and linear traction-separation law are used to simulate the constitutive behavior of the vein materials. The microscopic images show that the veins have a tubular microstructure that consists of layers made of chitin and protein. The results from numerical simulations demonstrate that each vein layer effectively cope with the stresses due to external loading. But, the presence of protein plays an important role in arresting the crack growth. Comparison of the results reveals a very good agreement between numerical simulations and experimental data.

KEYWORDS:

Dragonfly Wing, Scanning Electron Microscopy, Extended Finite Element Method, Tensile Test, Crack Propagation.

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1- Introduction

Insect wings are light-weight biological composites with high resistance to external dynamic forces during flight. Among all insects, probably dragonfly wings can serve as the best examples [1-4]. The wings enable the insect to achieve a high maneuverability and robust flight. Obviously, both microscopic and macroscopic characteristics play an important role in improving the flight capabilities of the wings.

Due to the environmental mechanical stresses, the nucleation and propagation of cracks in biological structures are almost unavoidable. Many of these natural structures such as plants, bone, skin, possess self-healing abilities [5-7]. However, dragonfly wings are not able to heal themselves [8]. Therefore, the only way to maintain the flight performance in such cases is to avoid the propagation of an induced crack.

The previous empirical investigations performed by the authors and other researchers indicated that the presence of ambient veins can prevent tearing of the wings [9]. But how are these veins able to arrest the crack propagation in an insect wing?

In absence of an experimental or a numerical investigation, we tried to answer this question by using a combination of microscopic techniques, experimental studies and numerical modeling. The results of this study may be used in the design and fabrication of the wings of flapping robots with high fracture toughness.

2- Methodology

2-1- Scanning Electron Microscopy

A Philips XL 30 scanning electron microscope (SEM) was used to investigate the microstructure of wing veins from the dragonfly Orthetrum sabina (Odonata libellulidae). After drying the wings and cutting them into suitable sizes, the wing samples were coated by a very thin layer of gold-palladium alloy.

2-2- Tensile Test

Tensile testing was performed to study the fracture behavior of wing veins subjected to normal stresses. The same method as that previously used by the authors and other researchers [2, 10] was employed in this study. The wing samples were located into a tensile testing machine (Instron 5566). A tensile force in the axial direction with a relatively low loading speed (0.05 mm/min) was applied to the samples. Before testing, a small crack with a length of about 0.1 mm was induced on the outer surface of the vein samples. We tried to finish the experiment on each sample in less than 10 minutes, because desiccation may changes their mechanical properties.

2-3- Modeling

The data from microscopic images were utilized to model the vein microstructure by using the finite element (FE) software package Abaqus. The simplified vein model has been composed of 3 layers with the thickness of 7.69 μm, 7.11 μm and 6.35 μm from the outer layer to the middle layer and the inner one, respectively. Similar to the experiments, an initial crack was induced on the vein model by using the model of a plate which is in contact with the main model. The solid elements C3D8 were used to describe the geometry of the vein structure. As it is likely that there is a strong contact between the layers in the vein, a rigid contact was assumed between them in the developed model. After assigning the suitable material properties to the chitin and protein inside the vein structure, the loading and boundary condition were used to simulate the experimental tensile test conducted in section 2-2 of this study.

The extended finite element method (XFEM) was used to simulate the propagation of the initial crack through the vein model. We used the principal stress criterion as the failure criterion. A linear traction-separation law was employed to describe the separation of the elements after the start of the crack growth.

3- Results and Discussion

The results from SEM indicate that the vein in the wings of the dragonfly O. Sabina consist of up to 3 layers. These layers, from the outer one to the inner one, have average thicknesses of 7.69 μm, 7.11 μm and 6.35 μm, respectively. Interestingly, the fracture surface of the veins is very similar to that of brittle materials.

Figure 1 represents the results from the numerical simulation of crack propagation of the vein model, in 6 steps. In order to better represent the crack the crack propagation, we show a cut-view of a quarter of the main model. The first step in this figure shows the beginning of the crack propagation in the outer layer of the vein. In the second step, a small crack is induced into the inner layer. In this step, the initial crack propagates in the outer layer without transferring to

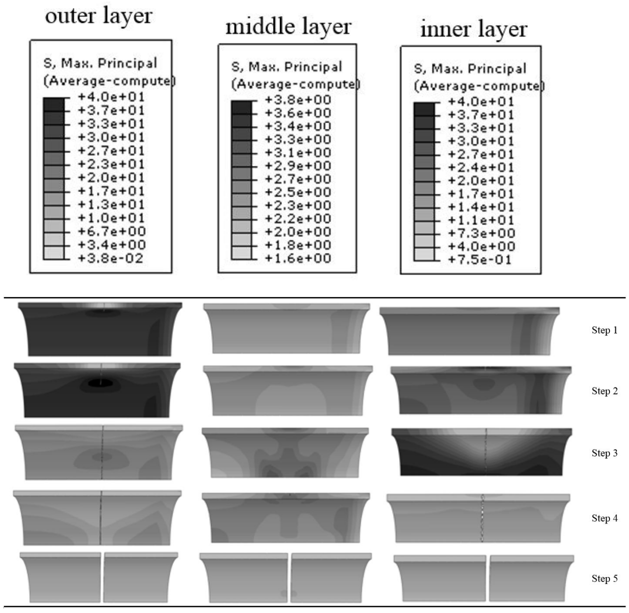

Figure 1. The crack propagation and stress distribution in the vein model in 5 steps (stress is given in MPa)

the middle one. The reason is the higher toughness of the middle layer which contains more resilin, the rubber like protein, compared to the other two layers. In the third step, the cracks presented in the outer and inner layers propagate, but still there is no crack nucleation in the middle layer of the vein. The fourth step displays the nucleation of a crack in the middle layer. Interestingly, the crack in this layer initiates when the other two layers are completely broken. The fifth step indicates the final failure of the vein structure.

This study shows a good accuracy between the stress-strain curves obtained from the experimental and numerical methods. By plotting their graphs, one can see that, both graphs have 3 peaks. The first, second and third peaks in this graph indicate the failure in the outer, inner and middle layers, respectively. The measured errors in the prediction of the failure stress in the first, second and third peaks are -1.8%, 7.2% and -7.0%, respectively. The decrease in the slope of the stress-strain curve after each peak indicates the decrease in the stiffness of the vein after each stage of the crack growth. In other words, the occurrence of failure in each layer causes a decrease in the resistance of the vein to deformation.

4- Conclusion

The results of this paper suggest that wing veins in the dragonfly O. Sabina contain a layered microstructure which is made up of up to 3 layers. Based on the data obtained from experimental and numerical methods the presence of the protein inside the vein microstructure has an important influence on increasing the fracture toughness of whole vein structure. The results further indicate that a relatively simple layered microstructure with reasonable material properties can successfully simulate the mechanical behavior of the vein.

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