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In-situ mechanical test of dragonfly wing veins and their crack arrest behavior

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ABSTRACT

In natural biological systems, many insects in complex environments exhibit exemplary mechanical properties. Dragonfly wings are light and strong enough to withstand wind loading. Their rigid veins play supporting and strengthening roles to enhance resistance to fatigue. To explore the effect of veins on arresting cracking in the wing, the costa, subcosta, radius R1, and two areas of dragonfly hind wings were samples for in situ tensile tests. The fracture process of the samples was observed with a high-speed camera and a scanning electron microscope. The mechanical properties of the veins and the results of nanomechanical tests on the wings were analyzed. The costa was stiffer and more resistant to deformation than the subcosta and radius, but it was less tough. The results of this study may provide inspiration for the design of mechanical structures and materials.

1. Introduction

In engineering fields, material surface characteristics and the fatigue of structural components can lead to premature failure that can severely restrict service life and work efficiency. For example, when a brake hub is subject to fast braking, alternating thermal stress will cause thermal fatigue, leading to cracks on the surface and fatigue failure. However, in insects, wings in flight can withstand complex external airflow conditions and alternating loads, and they show excellent crack arrest abilities due to their overall morphology, structure, composition, and mechanical properties. These features may provide important insights in the area of antifatigue research in engineering.

Dragonflies are known to be some the most skilled fliers in the world. Their wings are often exposed to external pressures and mechanical effects, but they can still fly safely without the appearance of cracks caused by fatigue, wear, and tear (Li et al., 2014). Wings are highly specialized flying organs that are flexible and stretchable and show superior stability and load-bearing capacity during flying. Wings also exhibit anti-fatigue, self-cleaning, and noise-reduction characteristics. These properties are closely related to their configuration, morphology, structure, and composition (Wang et al., 2008; Ren and Li, 2013; Wootton and Kukalova, 2000). Dragonflies have excellent flying ability and can fly in a vertical direction while hunting (Lai and Shen, 2013). Their wings, which compose only 1% to 2% of total body weight, have good stability and good load-bearing capacity while flapping, gliding and hovering (Dong et al., 2010; Mccauley et al., 2015; Dompreh et al., 2013). Newman (1982) found that the diameter and cross-sectional shape of dragonfly veins could affect the flexibility of the entire wing structure. By observing the microstructure of dragonflies in cross section, Wang et al. (2008) found that the wings had a "sandwich" structure that could withstand considerable bending load and torsion deformation. A previous study that compared the surface and cross-sectional structure of dragonflies with Chinese bees and flies suggested that the smooth connection between the veins may increase the load-bearing capacity (Zhang, 2008).

Many studies have examined insect wing fracture. Researchers have found that locust wings typically behave like brittle materials up to the fracture point and are highly sensitive to stress concentration (Rajabi et al., 2015). It has been shown that corrugations play an important role in increasing the torsional rigidity of insect wings (Ren et al., 2012). Some studies have shown that the thick veins at the base and at the leading edge make these parts of the wings stronger than other areas (Combes and Daniel, 2003b, 2003c). Cross-veins can temporarily stop the propagation of cracks, increasing the wing's resistance to fracture (Dirks and Taylor, 2012; Rajabi et al., 2015). Furthermore, longitudinal veins significantly enhance wing stiffness in the wingspan direction, especially near the leading edge of the longitudinal vein (Combes and Daniel, 2003a).

Many studies have examined the structure, composition and performance of dragonfly wings, but few have discussed crack arrest by the nanomechanical behavior of dragonfly wing veins. In this study, dragonfly wings were taken as the research object in the context of anti-

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fatigue and crack-arrest requirements for mechanical parts in engineering fields. First, the costa, subcosta, and radius R1 of the hind wing were chosen as samples for in situ tensile testing. The fracture process was observed with a high-speed camera, and the fractured samples were observed with a scanning electron microscope (SEM). A nanomechanical test was then carried out to further investigate the role of the wing veins in crack arrest.

2. Experimental procedures

2.1. In situ tensile test

To study the veins' tensile properties and their effects on tensile fractures, in situ tensile testing was carried out using a miniature tensile tester. Before the tensile test, the position of the test fixture was adjusted. Excessive clamping force can distort the edge of the material being tested, leading to load reduction, so it is necessary to properly control the force that acts on the samples. The miniature tensile tester was loaded to confirm that the system was correctly reset.

Pantala flavescens dragonflies were collected from Changchun Jingyuetan National Forest Park in Jilin Province, China. Five dragonfly specimens were kept in relative temperature and humidity for up to 12 h. They were anesthetized and killed within an hour of testing as fresh samples. Their wings were cut off their bodies when they were still alive to retain their in vivo structures. Each test was conducted as quickly as possible so that dehydration of the wings would not affect the results (Samways and Osborn, 1998; Wang et al., 2008). Samples measuring 1.2 cm × 0.6 cm were taken from two areas of the hind wings, as shown in Fig. 1. The costa, the subcosta, and the radius R1 were selected as the main vein samples and were separated from the hind wings with a razor blade. The samples were wrapped in a thin layer of sponge and polytetrafluoroethylene film and placed into the gripper. The tensile tests were repeated five times, and the entire process of crack initiation, propagation, and fracture was recorded with a high-speed camera.

The structures of the fracutre surface were observed with a scanning electron microscope (SEM) (Zeiss EVO 18, Cambridge, England). The main parameters of SEM were test magnification range: 13–50000 times, minimum resolution: 3.0 nm, and instrument type: tungsten filament. First, samples were fixed on the sample column surface with conductive tape. Then, all the treated samples were coated with gold by ion sputter JFC-108. Finally, the structures of the fracutre surface were observed.

The structures of the fracture surface were observed with an SEM (Zeiss EVO 18, Cambridge, England) with a test magnification range of 13 × to 50,000 × , a minimum resolution of 3.0 nm, and a tungsten filament. The samples were fixed on the sample column surface with conductive tape and coated with gold with an ion sputter JFC-108.

2.2. Nano-mechanical test

To determine the nanohardness of the wing veins and membranes, nanomechanical testing was carried out with a maximum load of 30 mN, a minimum load of 100 nN, a loading resolution of 1 mN or less, a longitudinal displacement step of 13 nm, and a thermal drift of 0.05 nm/s or less.

Stereoscopic photographs of five test positions on the wings and three test positions on the membrane were chosen to examine the nanomechanical properties of the dragonfly wings. The five test positions of the veins were positions 0, 0.3L, 0.5L, 0.7L, and 1L of the costa, subcosta, and radius R1 (L = total length of the wing). The three test positions of the membrane were at the base, middle, and tip of the wings (indicated by red dots in Fig. 1). For the nanomechanical test, the wings were fixed to slides with instant glue. Nine indentation experiments were performed for each position of the diameter of the 0.006-mm round edge of the uniform, and the average results were calculated. In the process of testing, a force displacement curve was obtained in real time (Zhao, 2007). The nanohardness and elastic modulus were determined according to the force-displacement curve.

3. Results and discussion

3.1. Tensile properties and wing vein parameters

As the tensile force increased, the displacement increased almost linearly, as shown in Fig. 2. The slope at the end of the stretching curves was small, indicating excellent toughness of the vein interlayer. The maximum load was reached when the displacement was a certain length. The curves then dropped sharply when the veins were broken. The maximum load was the ultimate load, recorded as F_{max}. The average values of the ultimate loadings of the samples are shown in Table 1.

Stretching the wing veins cannot accurately simulate the wing forces during dragonfly flight. However, the wing veins could withstand the ultimate load, which may explain how the veins can arrest cracking.

The results show that the limit load of the costa was the highest, followed by the subcosta, and then the radius R1. Like the diameter variation of the veins, the tensile force decreased along the chord. In the same load region, the veins and the membranes were thicker near the wing base. The dragonfly wings close to the body was greater than at the other locations, consistent with the results from the tensile test. Unlike the results for the wing veins, the load-displacement curves of the wings were periodically "stepped" when the veins cracked resulting in a slight decline in wing carrying capacity.

Due to the complexity of the biomaterial structure of the wings, the changes in the diameter and the cross section were ignored after the veins were stretched. The shape of the cross sections of the samples was observed by SEM and the area, stress, and strain were calculated. The

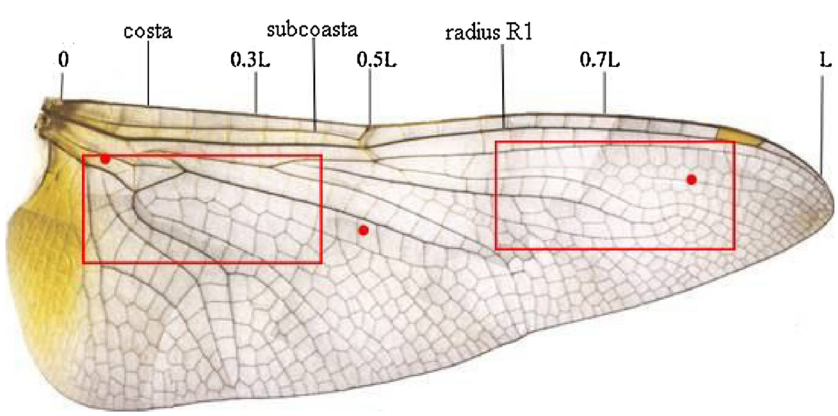

Fig. 1. Morphology, vein distribution, and test positions of dragonfly hind wings.

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