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Role of Soft Matter in the Sandwich Vein of Dragonfly Wing in Its Configuration and Aerodynamic Behaviors

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Abstract

The microstructure of the main longitudinal veins of the dragonfly wing and the aerodynamic behaviors of the wing were investigated in this paper. The microstructure of longitudinal vein presents two circumferential chitin layers and a protein-fiber soft layer. The dragonfly wing is corrugated due to the spatial arrangement of longitudinal veins. It was found that the corrugation angle could significantly influence the lift/drag ratio across a range of attack angles by the wind tunnel experiments. The results of the finite element analysis indicate that the protein soft layer of vein facilitates the change of the corrugation angle by allowing substantial relative twisting deformation between two neighboring veins, which is not possible in veins without a soft sandwich layer.

Keywords: dragonfly wing, longitudinal vein, sandwich structure, soft matter, corrugation behavior

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1 Introduction

Although the sandwich microstructure of dragonfly wing vein[1] has been reported and accepted[2–13], the biomechanical behavior and the influence on aerodynamic performance is rarely documented. For example, the role of the sandwich microstructure in the biomechanical behavior of dragonfly wings is not clear[2,4,6]. Many efforts to understand the effect of microstructures on the aerodynamic behaviors of insect flight have been attempted. Ennos[14] argued that the corrugated wing is stiffened by V-section leading edge spars in bending, but compliant in torsion. A camber is developed in the wing when it twists resulting from the free motion of rear spars[14–16]. However, whether the twisting behavior of the wing induces different structural responses during the fluttering process is lack of discussion. Sane *et al*.[17,18] investigated the aerodynamic of insect flight based on a two-dimensional (2-D) computational fluid dynamic model indicating that flight forces are further enhanced by rotational circulation and wake capture during the wing rotation. Based on a static 2-D unsteady simulation, Kim *et al*.[19] found that the wing corrugation plays an important role in the gliding performance of the dragonfly. It was confirmed that more airflow vortexes are caused by the rotation and corrugation of the wing to keep a balance of the insect body[14,17,20–23]. However, most of the previous models about the insect wing microstructure including the vein and membrane described the cross-section merely by pipe and shell elements[14,17,24]. Recently, it was found that the longitudinal veins of the dragonfly wing possess a composite sandwich structure composing of cuticle and resilin with organic junction[11], and the membrane with a multi-layer structure[1,6,11,16,24,25]. The microstructural differences of the dragonfly wing induce different biomechanical and aerodynamic behaviors. Because the main longitudinal veins are close to the leading edge of the dragonfly wing, they are subjected to the bending and torsion loadings during the flapping process. Therefore, the longitudinal veins and membranes should function accordingly and efficiently during flight.

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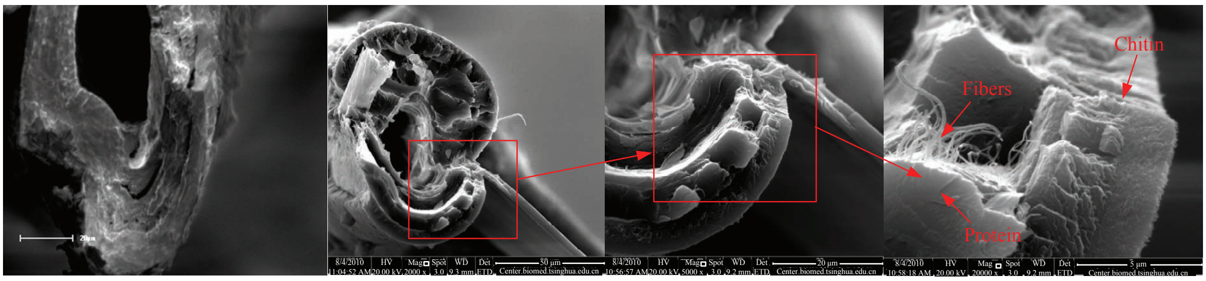
Torsion deformation of the leading edge veins can directly cause translation and rotation of the adjacent longitudinal veins and membranes[1,14,17,25]. The corrugation angle of the wing can be altered, which influences its aerodynamic efficiency[17]. In this paper, the corrugation mechanism and the relative motion of the main longitudinal veins will first be demonstrated by Finite Element (FE) analysis, which focuses on the effect of the soft matter in the sandwiched layer of longitudinal veins[1]. Then the wind-tunnel experiments based on a wing model with different corrugation angles are performed to investigate the effect of the corrugation on its aerodynamic performances, and the results are compared with the previous ones[26–32].

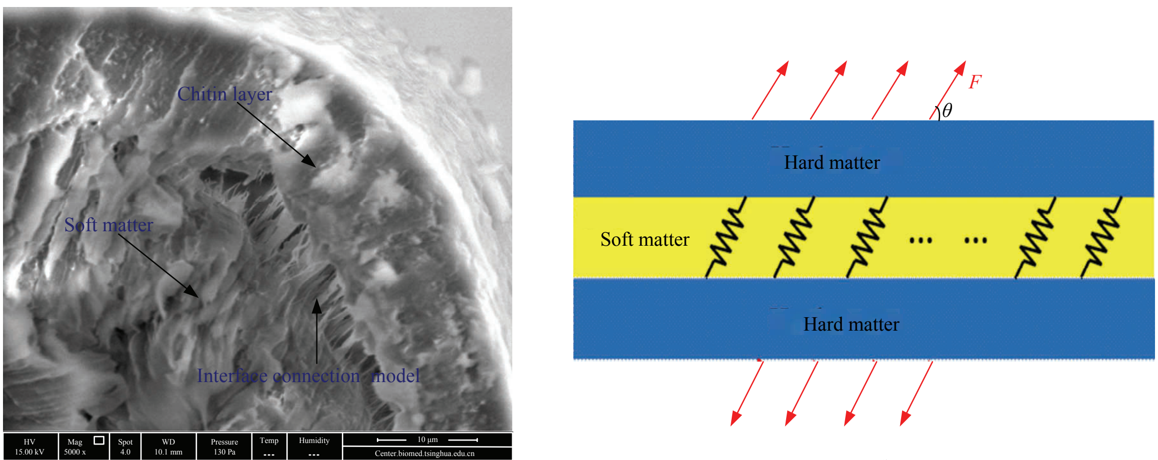
2 Microstructural feature of dragonfly wing vein

Longitudinal veins of the dragonfly wing (*Pantala flavascens*, in China) were observed by Scanning Electron Microscopy (SEM). All samples were fresh with intact morphology of the longitudinal veins and all experiments were performed within 10 minutes to avoid the atrophic tissues in the SEM chamber. The cross-sections of longitudinal veins were treated by chemical and physical methods, as shown in Fig. 1. Fig. 1a displays the cross-section of the longitudinal veins through the chemical corrosion treatment with the alkali solution (about 40% concentration of alkali), where the sandwich structure can be observed in the cross section of the longitudinal vein. Figs. 1b–1d present the microstructural details of the longitudinal vein after physical treatment by first freezing the samples with liquid nitrogen and then breaking them manually. The results indicate that the sandwich microstructure of the longitudinal vein exhibits two chitin layers and a protein-fiber composite middle layer with fibers circumferentially embedded. There is clear evidence that the sandwich microstructure requires a more detailed representation rather than shell, pipe[14,19,26] and plate structures reported previously[14,17,26,28]. The interfaces between the chitin and protein layers are delineated in Fig. 2a and a sketch of the interfacial connection is



(a) (b) (c) (d)

Fig. 1 Microstructures of the longitudinal veins. (a) After corrosion treatment with the alkali solution; (b–d) after freezing treatment with different scale bars (copyright permission).



(a) (b)

Fig. 2 Interface connection model of the sandwich vein. (a) SEM image of the cross-sectional vein; (b) model of the interface connection[33].