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Biomimetic flow control

The structure and mechanical properties of dragonfly wings and their role on flyability

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ABSTRACT

Dragonfly wings possess great stability and high load-bearing capacity during flapping flight, glide, and hover. Scientists have been intrigued by them and have carried out research for biomimetic applications. Relative to the large number of works on its flight aerodynamics, few researchers have focused on the insect wing structure and its mechanical properties. The wings of dragonflies are mainly composed of veins and membranes, a typical nanocomposite material. The veins and membranes have a complex design within the wing that give rise to whole-wing characteristics which result in dragonflies being supremely versatile, maneuverable fliers. The wing structure, especially corrugation, on dragonflies is believed to enhance aerodynamic performance. The mechanical properties of dragonfly wings need to be understood in order to perform simulated models. This paper focuses on the effects of structure, mechanical properties, and morphology of dragonfly wings on their flyability, followed by the implications in fabrication and modeling.

1. Introduction

There is an interest in the development of Micro Air Vehicles (MAVs) which have the potential to revolutionize information gathering in environmental monitoring, homeland security, and other time-sensitive areas (Tamai [1]; Floreano et al. [2]; Ganguli et al. [3]). Because of their excellent flying characteristics, flying insects give researchers inspiration for biomimetic designs of MAVs. The understanding of the functions provided by objects and processes found in nature can guide researchers to imitate and produce nanomaterials, nanodevices, and processes (Bhushan [4]). Wootton et al. [5] summarized recent work on the structural modeling of insect wings and showed how such research has progressed from simple conceptual models of wing structure to analytical methods and numerical approaches. The insect wing is a complex mechanical structure. Some researchers have modeled it using the finite element method (FEM) (Kesel et al. [6]; Wootton et al. [5]). A limitation of these works is that detailed information about the structure and mechanical properties of the veins and membranes along the complete wing is required for the development of a finite element model.

Natural biomaterials are not only structural materials but also functional materials. Research into the relationship between the structure and performance of natural biomaterials is the basis for the development of biomimetic structures and materials (Vincent et al. [7]; Alberts et al. [8]; Meyers et al. [9]; Bhushan [4]). The structure and mechanical properties of the membranes, together with the venations of insect wings, are associated with the flight of the insects themselves (Wootton [10]; Wootton et al. [11]; Combes and Daniel [12,13]; Ganguli et al. [3]). Dragonfly wings possess great stability and high load-bearing capacity during flapping flight, glide, and hover, despite the fact that their mass is less than 2% of a

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Fig. 1. Photograph of a dragonfly and its wings.

dragonfly's total body mass (Fig. 1). Relative to the large number of papers on its flight aerodynamics (Azuma et al. [14]; Ho et al. [15]; Wang [16]; Tamai [1]; Shyy et al. [17,18]; Floreano et al. [2]), few researchers have focused on the insect wing structure and its mechanical properties.

Dragonfly wings are composed of a thin cuticular membrane that is supported by a system of veins. The veins are hollow branching tubes that form the supporting framework, which often have cross-connections that form closed "cells" within the membrane (extreme examples include *Odonata* and *Neuroptera*) (Needham [19]). The membrane is formed by two layers of closely apposed integument. Together, the veins and membrane form a complex design within the wing that gives rise to whole-wing characteristics. The microstructure of dragonfly wings is complex (Deubel et al. [20]). For example, wing corrugation has been found to be of great importance to the stability of the ultralight wings to handle the spanwise bending forces and mechanical wear that the wing experiences during flapping (Hu and Tamai [21]; Okamoto et al. [22]; Sunada et al. [23]; Machida, et al. [24]; Machida and Oikawa [25]; Wootton and Newman [26]). Aspects such as protuberances (the dark spade-shaped elements on the vein) (Bechert et al. [27]; Jongerius and Lentink [28]), flexible cross-vein junctions (Newman [29]), nodus (Wootton [10]; Yadav [30]; Wootton and Newman [26]), stigma (Norberg [31]), variation of vein size in the leading edge (Machida et al. [24]), and vein sandwich structure (Wang et al. [32]) are important features.

Before improvements in nanoindentation techniques, mechanical property measurements of dragonfly wings were primarily carried out through tensile tests. At present, nanoindentation has become a useful tool for characterizing the mechanical properties of thin elastic and viscoelastic materials. Different wing zones bear different loads, and their mechanical properties might be different because of adaptation. However, previous models established by FEM set the mechanical properties of veins and membranes as a constant value.

This paper focuses on the structure and mechanical properties of dragonfly wings on their flyability, followed by the implications in fabrication.

2. Structure

There are a number of key structures in the wing (Fig. 2) which contribute to the manner in which it bends in flight and therefore help to facilitate the wing's aerodynamic properties (Jongerius and Lentink [28]). Details are discussed in the following subsections.

2.1. Veins

The vein structure of the dragonfly has an optimum shape which is adapted to the forces acting at the location of the vein. The leading edge consists primarily of rectangular frames whereas the trailing surface is largely formed of hexagons and other polygons with more than four sides, which guarantee wing stability against loading (Darvizeh, et al. [33]). The vein and membrane thickness increases from tip to root, and the nodus and stigma are especially thick, which allows the wing to effectively bear both inertial and aerodynamic loads (Machida et al. [24]; Jongerius and Lentink [28]). Fig. 3 shows cross sections of the costa at various points. From root to nodus, the thickness of the costa decreases in the spanwise direction, while from nodus to stigma, the thickness increases in the chordwise direction. That thickness variety is adapted to the forces acting at the location of the vein (Sudo et al. [34]). The cross sections of the costa are not circular, which is believed to be responsible for the generated bending moment (Machida et al. [24]). It should be mentioned that the costa is discontinuous at the nodus. This discontinuity gives deformability to the wing (Sudo et al. [34]). Wang et al. [32] reported that the microstructure of the vein is a complex sandwich structure which consists of a chitin shell and protein/muscle with

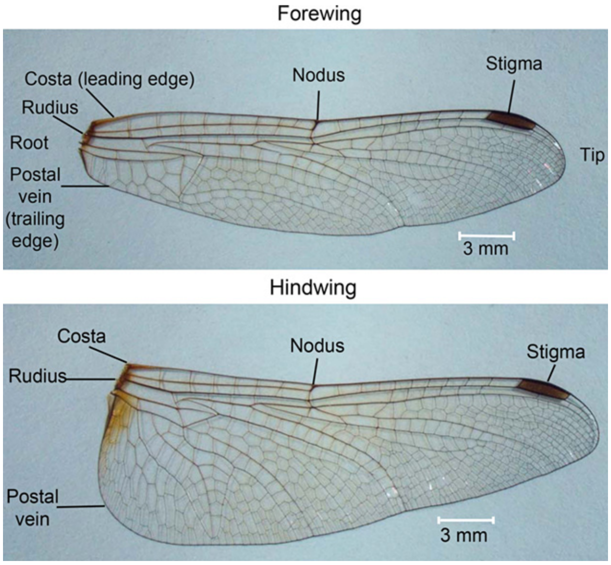

Fig. 2. Photographs of a dragonfly wing, which consists mainly of the tubular veins and membranes (the region surrounded by veins). The stigma is hollow and has a very special configuration. The nodus can rotate relatively to other stiff structures in wing (adapted from Sun et al. [51]).

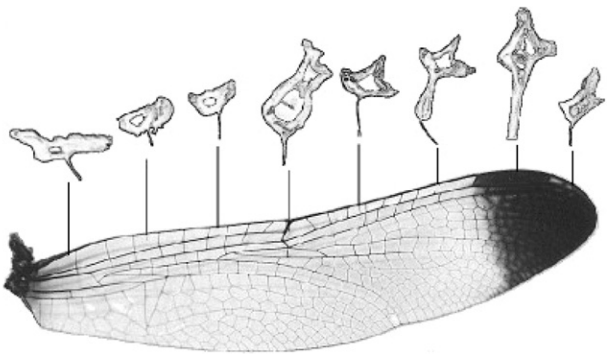

Fig. 3. Cross-section configuration of the costa. It shows that the cross sections of the costa at various points are different and are adapted to the forces acting at the location of the vein. The structures of those cross sections are not circular. It is supposed that the complicated configurations are closely related to the generated bending moment (Sudo et al. [34]).

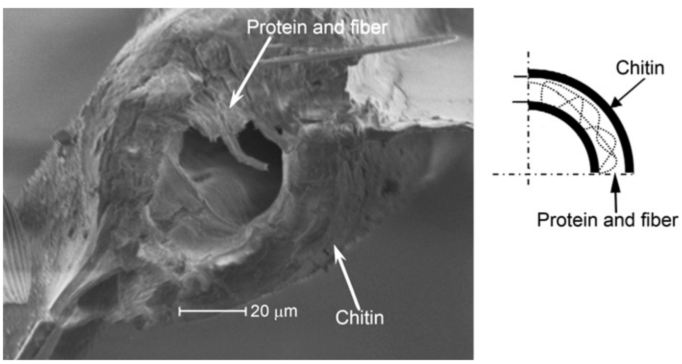

Fig. 4. Microstructure of tubular vein. These results indicate that the microstructure of the vein is a complex sandwich structure, which consists of a chitin shell and protein/muscle with some fibrils (Wang et al. [32]).

some fibrils (Fig. 4). It assists in the understanding and design of new high strength-to-weight ratio composite materials or structures.

Kesel [35] reported that there is a truly intriguing three-dimensional structure on the wing trailing edges, protuberances (the dark spade-shaped elements in Fig. 5), which was confirmed by experiments, that reduce the drag. Bechert et al. [27]

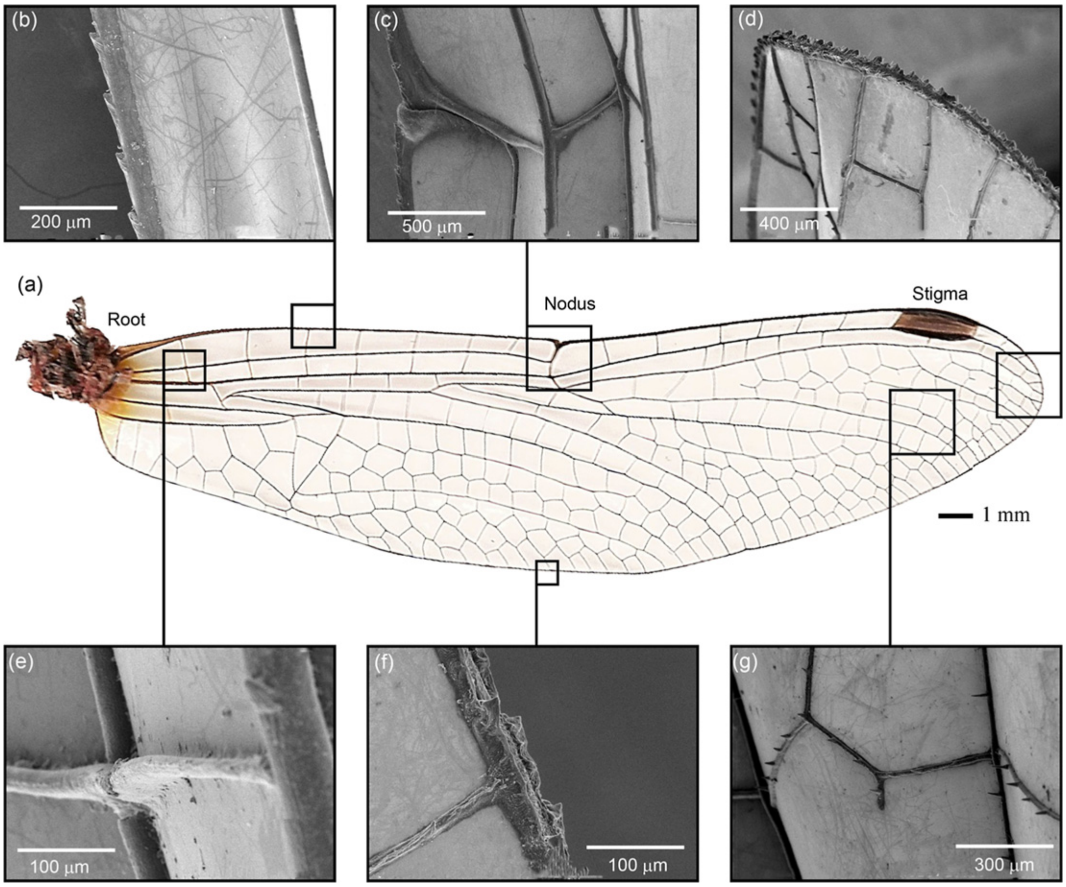

Fig. 5. SEM micrographs of (a) a dragonfly *Sympetrum vulgatum* forewing. Leading (top) and trailing (bottom) edge protuberances are believed to produce an increase in lift. (b) Protuberances on leading edge. (c) The nodus of the wing. (d) The wing tip. (e) Vein crossing near the wing root. (f) Trailing edge with protuberances. (g) Wing membrane surface near the wing tip (adapted from Jongerius and Lentink [28]).

interpreted the protuberances as vortex generators that destroy the two-dimensionality of the Gurney flap wake and in turn eliminate the absolute instability with its ensuing Kármán vortex street (a term in fluid dynamics for a repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid over bluff bodies). Jongerius and Lentink [28] indicated protuberances not only exist in the trailing edge but also in the leading edge.

Newman [29] reported a flexible cross-vein in the deformable part of the wing (Fig. 6). The attachment is a flexible band of membrane which allows the cross-vein end to rotate slightly around the axis of the longitudinal vein. The horn-like structures on the upper and lower sides appear to act as stops by pressing against the sides of the longitudinal veins and limiting the extent of this rotation.

2.2. Membrane

A wax layer was found in wing membranes. The 1–2 μm roughness is smaller compared to the roughness responsible for air microturbulence in animals with comparable low Reynolds numbers ($<$10,000), so it seems that wax roughness cannot contribute to “the shark-skin effect” (the phenomenon that if a body in a stream is provided with small ridges aligned in the local flow direction, a remarkable drag reduction can be reached under turbulent flow conditions) (Gorb et al. [36]). Scanning acoustic microscopy (SAM) measurements could be interpreted as an additional indication of the mechanical characteristics of the wax covering, modified by the scratches (Fig. 7). The increased stiffness affects the mechanical stability of the membranes and thus the stability of the whole wing system, as found by means of FEM (Kesel et al. [6]; Gorb et al. [36]; Kreuz et al. [37]). Song et al. [38] reported the wing membrane as three multi-layer structures including a dorsal surface, middle layer, and ventral surface, respectively.

While available air is trapped in spaces in the microstructure of the surfaces of the dorsal and ventral layers, the grooves on the columns efficiently increase the hydrophobicity of the dragonfly wings (Sudo et al. [39]; Nosonovsky and Bhushan [40]). The microstructure of the membrane surface has excellent superhydrophobicity with a water contact angle of about 174° (Fig. 8). The wax covering decreases the wettability of wings, which can be essential for insects closely connected

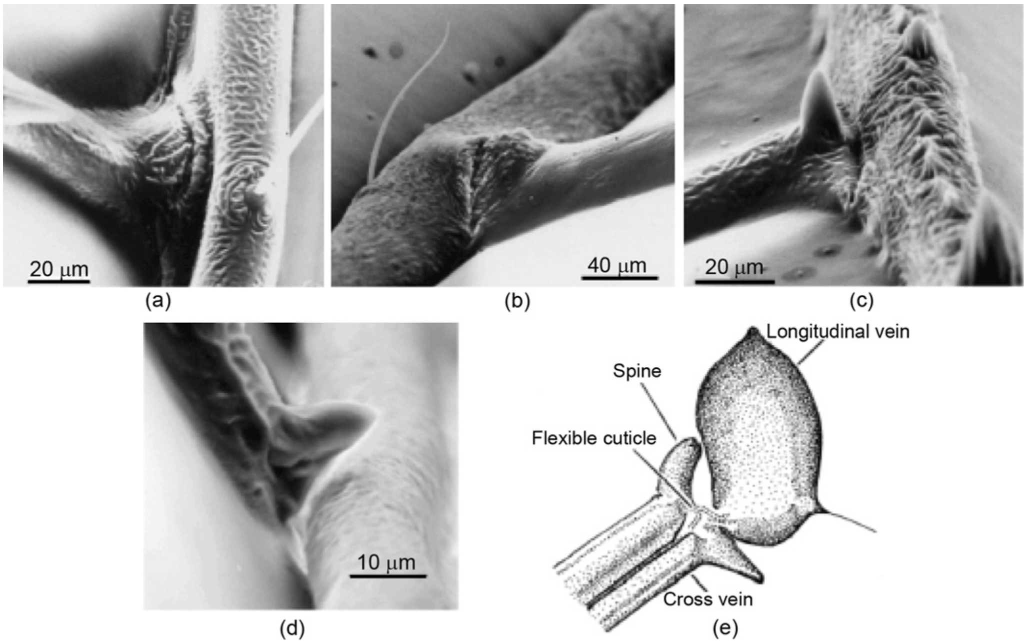

Fig. 6. Flexible cross-vein in the deformable part of the wings. (a), (b) *Aeshna cyanea* forewing; (a) ventral view and (b) dorsal view. (c) *A. cyanea* hindwing, cross-vein on ventral view. (d) *Calopteryx splendens*, cross-vein with dorsal view. (e) *C. splendens*, diagrammatic cross-section of a typical flexible junction. (Newman [29]).

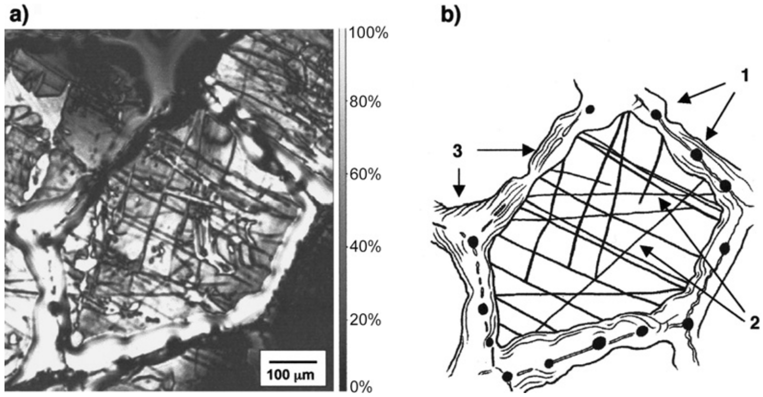

Fig. 7. The superficial wax layer in dragonfly wing membrane. (a) SAM micrograph of the wing cuticle of the posterior part of a natural dragonfly forewing. The wing membrane shows distinctly arranged contrast lines. (b) Schematic of the SAM image, 1) spine on the membrane framing veins, 2) interference lines along the vein, 3) contrast lines within the membrane (Kreuz et al. [37]).

in their life-history with waterbodies (Gorb et al. [36]). Also, the wax-like wing covering can prevent wing contamination (Wagner et al. [41]).

2.3. Stigma

The stigma (also called pterostigma) is developed upon the costa of the wing at the point of greatest impact against the air (Needham [19]). It would seem to serve the double purpose of firmly uniting the veins of the front margin and of increasing the efficiency of the wing stroke by adding weight at this striking point, shifting the center of mass towards the axis and regulating the pitching of the wing (Norberg [31]). Its shape and extent vary considerably and are often characteristic of groups, but the stigma seems to not contain within itself characteristics for the critical determination of the course of specialization as are furnished by the surrounding parts.

2.4. Nodus

The nodus is the stout cross vein near the middle of the costal border of the wing, joining the costa, the subcostal, and the radius. It is traversed by a more or less evident suture, making a flexible and elastic joint which, without loss of strength

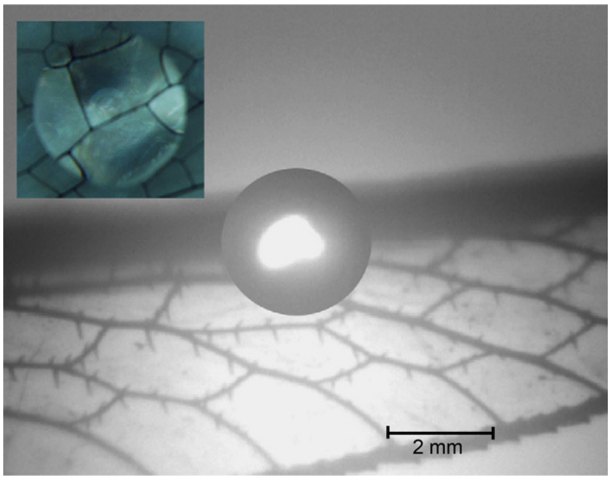

Fig. 8. Photographs showing an almost ball-shaped water droplet on the surface of the wing membrane of a dragonfly. Inset, the top view of a water droplet on the wing membrane shows a small contact region between water droplet and the surface (Song et al. [38]).

in the parts which need rigidity, would seem to allow more effective flexion of the distal parts of the wing (Wootton and Newman [26]).

The role of the nodus is to both provide reinforcement and shock absorber capability, coping with combined torsion and bending stress concentrations at the junction of the rigid concave antenodal and the torsionally compliant postnodal spars (Wootton and Newman [26]). The position of the nodus along the span varies between taxa and almost certainly determines the amount of passive twist that the wings undergo in flight (Wootton [10]).

2.5. Corrugation

Dragonfly wings are highly corrugated, which increases the stiffness and strength of the wing significantly and results in a lightweight structure with good aerodynamic performance (Fig. 9). The corrugation structure of the wings has been relatively extensively studied (Wootton [10]; Okamoto et al. [22]; Sunada et al. [23]; Machida et al. [24]; Machida and Oikawa [25]; Hu and Tamai [21]; Wootton and Newman [26]).

The configuration varies along the spanwise and chordwise directions and enhances the flight performance in several ways, such as absorbing stress against spanwise bending, allowing torsion to occur, and the development of the camber (Newman and Wootton [42]; Wootton [10]; Sudo et al. [43]; Machida et al. [24]; Wootton and Newman [26]). In addition, it was shown that the configuration of the costal vein is related to the nodus (Machida et al. [24]). Corrugation provides that the cross-veins are themselves flexible, either throughout or at their junctions with the longitudinal veins (Wootton and Newman [26]). Also the corrugation increases flexural rigidity which helps prevent fatigue fracture (Shyy et al. [44, 17]; Azuma [45]). Rigidity varies throughout the wing, and the factors which cause this variation are the depth of the corrugation and the rigidity of the longitudinal cross veins (Vargas et al. [46]). The thin nature of the insect wing skin structure makes it unsuitable for supporting compressive loads, which may result in skin wrinkling and/or buckling, i.e., large local deformations that will interact with the flow (Shyy et al. [18]).

3. Mechanical properties

Different wing zones bear different loads, and their mechanical properties might be different because of adaptation. However, previous models using FEM have used the mechanical properties of veins and membranes as a constant value. Relatively speaking, the mechanical properties of a real dragonfly wing vary with the position.

Quantitative analyses of parts of various insect wings have yielded a variety of modulus and hardness values, shown in Table 1. The moduli are often around the value of 1–6 GPa, but some tests on wing components have yielded values in the range of 60–80 GPa (Kesel et al. [6]; Kreuz et al. [47,48]; Kempf [49]; Song et al. [38]; Tong et al. [50]; Wang et al. [32]; Sun et al. [51]). This wide variety of values is the result of inconsistent testing methods, samples from different species of insect or different parts of the wing on the same one. It has been proposed by some that the wing's flexural stiffness varies along the wing span, and this model has been shown to have results which closely match an actual wings' behavior (Jongerius and Lentink [28]).

Because the vein is cannular in structure and the membrane is two sheets with intermediate tubules, the overall structure is a very thin complex sandwich structure on the micro- or nanoscale (Wang et al. [32]). Before improvements in nanoindentation techniques, dragonfly wing research was primarily carried out through tensile tests. At present, nanoindentation has become a useful tool for characterizing the mechanical properties of thin elastic and viscoelastic materials (Bhushan and Li [52], Bhushan [53,54]).

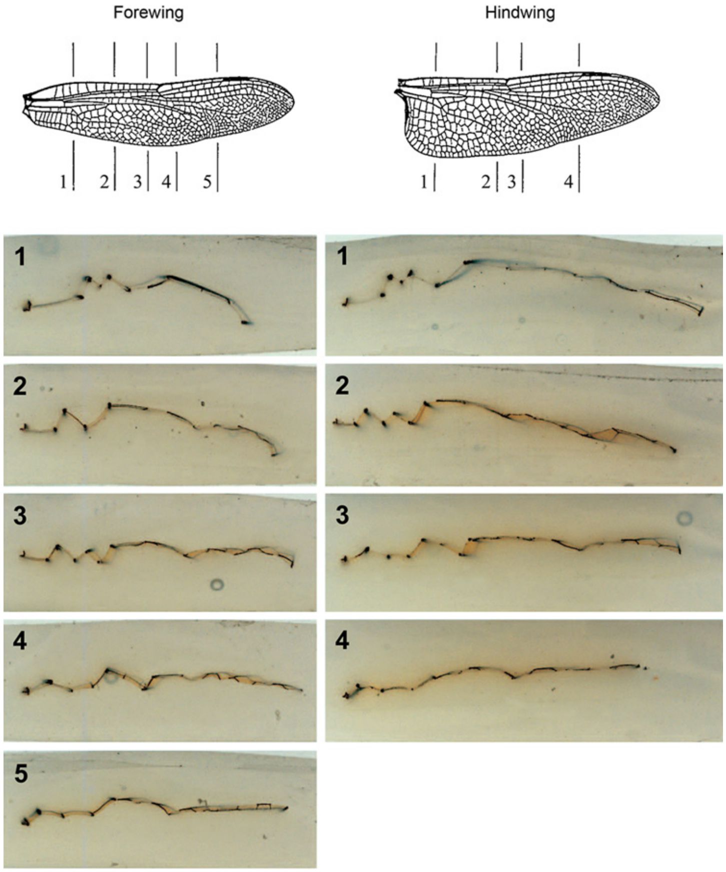

Fig. 9. The symmetrical corrugations at regular intervals along the chord length. Photographs of cross sections of the fore- and hindwing of a dragonfly taken through the positions shown in the diagrams at the top of the figure (Okamoto et al. [22]).

Table 1
Mechanical properties of dragonfly.

	Modulus (GPa)	Hardness (GPa)	Ref.
Dragonfly wing vein and membrane (U)	6.1		Kesel et al. [6]
Forewing vein (N)	2.9		Kempf [49]
Forewing vein (T)	24–32		Wang et al. [32]
Forewing vein, living (N)	0.7–3.8	0.02–0.15	Sun et al. [51]
Hindwing vein (T)	60–80		Wang et al. [49]
Hindwing vein, living (N)	0.02–3.5	0.002–0.35	Sun et al. [51]
Forewing membrane (N)	1.5		Kempf [49]
Forewing membrane, living (N)	2.85	0.14	Song et al. [38]
	1.41		Kreuz et al. [48]
Forewing membrane, dry (N)	1.5	0.2	Kreuz et al. [47]
Forewing membrane, dead (N)	2.74	0.10	Song et al. [38]
	1.37		Kreuz et al. [48]
Forewing membrane, remove wax (N)	1.1		Kreuz et al. [48]
Stigma of hindwing (N)	1.5–3	0.05–0.35	Tong et al. [50]
Nodus of forewing (N)	0.54	0.05	Sun et al. [51]
Nodus of hindwing (N)	0.58	0.03	Sun et al. [51]

T: Tensile testing; N: Nanoindentation testing; U: unknown.

Kempf [49] investigated different positions of a dragonfly cuticle using a nanoindenter, and the calculated moduli values are 4.7 ± 0.6 GPa, 2.9 ± 0.8 GPa, 1.5 ± 0.5 GPa for the dry body cuticle (abdominal tergite), dry wing veins, and wing membrane, respectively, as shown in Fig. 10. It demonstrates that the moduli of wing veins are larger than that of the membrane. It is supposed that the vein is the main load-bearing part.

Fig. 11 shows the difference between the nanomechanical properties of a dragonfly forewing and hindwing measured by nanoindentation. In general, the costa vein mainly bears pressure, and its mechanical properties should be the strongest. However, in the nanoindentation test, it was found that the radius vein is the stiffest vein, not the leading-edge costa vein,

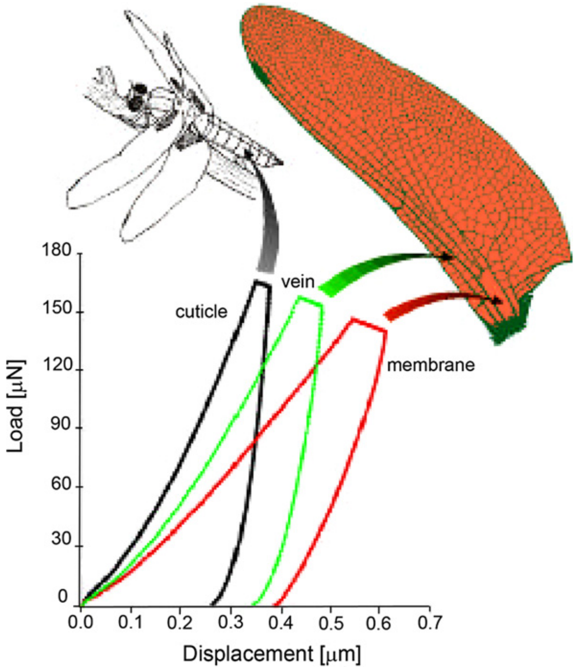

Fig. 10. Resulting force-displacement curves of different positions of dragonfly cuticle. The resulting force-displacement curves were used to calculate elastic moduli of 4.7 ± 0.6 GPa, 2.9 ± 0.8 GPa, 1.5 ± 0.5 GPa for the dry body cuticle (abdominal tergite), dry wing veins and wing membrane, respectively (adapted from Kempf [49]).

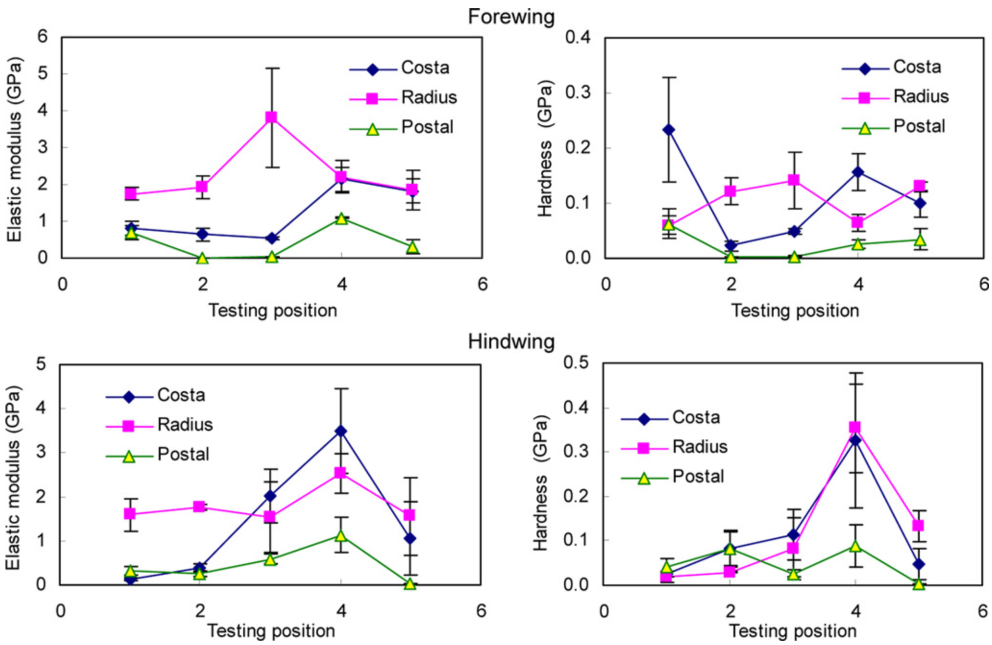

Fig. 11. Elastic modulus and hardness as a function of test position of costa, radius, and postal vein of dragonfly wings in the forewing and hindwing regions (Sun et al. [51]).

and the elastic modulus and hardness of the forewing are greater than that of the hindwing (Sun et al. [51]). Kesel et al. [6] pointed out that the radius veins of the hindwing play an essential role in the stability as a whole, and they greatly reduce the danger of buckling and structure failure. This will lend some guidance to the design of small artificial flapping wings, especially regarding the selection of materials for various wing components.

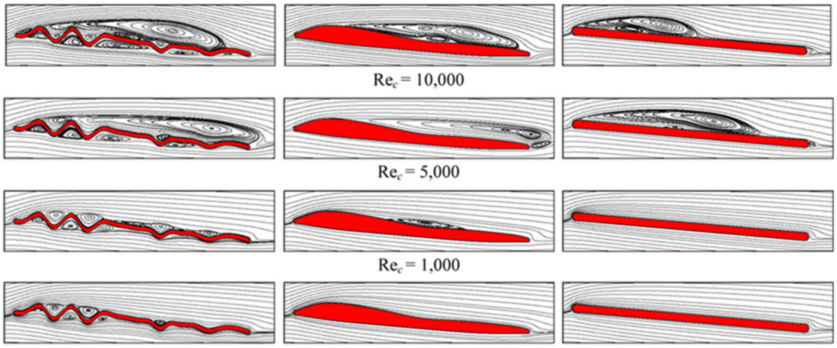

Fig. 12. Time-averaged streamlines of the pleated airfoil (left), profiled airfoil (middle) and flat plate (right) at $\alpha = 5°$ with $Re_c = 10{,}000$, 5000, 1000 and 500 (Vargas et al. [46]).

4. Aerodynamic properties

Insects have stimulated a great deal of interest among physicists and engineers because, at first glance, their flight seems improbable using standard aerodynamic theory (Sane [55]). As early as 1973, the clap-and-fling mechanism was first proposed by Weis-Fogh [56] to explain the high lift generation in the chalcid wasp *Encarsia formosa* (called the Weis-Fogh mechanism). A detailed theoretical analysis of the clap-and-fling mechanism can be found in Lighthill [57], and it was qualitatively verified by the empirical data of Maxworthy [58] and Spedding and Maxworthy [59]. The recent interest in developing insect inspired MAVs has fostered a number of strong collaborations between analytical and computational fluid dynamicists, micro-robotics engineers, and insect flight biologists (Spedding and Lissaman [60]; Wang [61]). It has helped in gaining an understanding of the fundamental fluid dynamic mechanisms underlying insect flight (Sane [55]).

As indicated from their ability to glide, dragonfly wings generate substantial lift in a steady flow process more so than any other insect wing. Wing kinematics were correlated with both instantaneous lift generation and vortex-dominated flow fields (Somps and Luttges [62]; Wakeling and Ellington [63]). This performance is attributable to many surface structural considerations, such as sharp leading edges which promote separation and hairs that extend outside the boundary layer which act as turbulators (Swanson [64]).

The effect of the corrugated wing configuration bears both structural and aerodynamic benefits to the dragonflies (Newman et al. [65]; Azuma et al. [14]; Somps and Luttges [62]; Wakeling and Ellington [63]; Kesel et al. [6]; Shyy et al. [44, 18]; Kesel [35]; Thomas et al. [66]; Vargas et al. [46]; Swanson [64]; Murphy and Hu [67]). Newman et al. [65] suggested that the improved aerodynamic performance would be associated with the earlier reattachment of the flow separation on the corrugated wings. As the angle of attack increases, airflow would separate from the leading edge to form a separation bubble, and the separated flow would reattach sooner due to the corrugation compared with smooth airfoils. It has been reported that a corrugated dragonfly wing could have comparable or even better aerodynamic performances (i.e., higher lift and bigger lift-to-drag ratio) compared with conventional smooth-surfaced airfoils in the low Reynolds number regime where dragonflies usually fly (Murphy and Hu [67]). The vortices filling the profile valleys of the corrugation 'smooth down' the profile geometry which helps to improve aerodynamic performance (Kesel [35]; Shyy et al. [17]).

Comprehensive wind tunnel experiments on pleated airfoils compared to technical airfoils have been conducted. At a chord Reynolds number (Re_c) ranging from 11,000 to 15,000, Okamoto et al. [22] found that the corrugated wing model outperformed the flat plate at all angles of attack. The lift produced by a dragonfly wing was found to be higher than that produced by streamlined airfoils. Wakeling and Ellington [63] stated that the enhanced lift produced by corrugated dragonfly wings is not attributed to the Reynolds number, the aspect ratio, or the wing area, but rather a surface feature, mainly the corrugations found in dragonfly wings. At a Re_c of 10,000, Kesel [35] investigated the performance of the airfoil by simply filling the valleys of the wing profile with solid materials. The results showed less favorable aerodynamic performances of the filled airfoils. Author suggested that negative pressure would be produced at the valleys of the corrugated dragonfly wing models, which would contribute to the increased lift.

Vargas et al. [46] conducted numerical studies to investigate the flow behaviors around corrugated dragonfly wings. Their simulation results confirmed that corrugated dragonfly wings would perform (in terms of the lift-to-drag ratio) as well as, and sometimes slightly better than, smooth technical airfoils. The existence of small vortex structures in the valleys of the corrugated dragonfly airfoils were clearly revealed from the simulation results. Fig. 12 shows the time mean streamlines for all the airfoils at the various Reynolds numbers studied here. The plots show that at an angle of attack of 5°, large regions of separation exist over all the airfoils for *Re* greater than 5000. Below this Reynolds number, the flow over the airfoils is mostly attached and does not show large regions of separation. Furthermore, when the $Re_c = 5000$ and 10,000 cases are compared, the separation is much more extensive at the lower Reynolds numbers. Thus, a further increase in the Reynolds number beyond this value tends to reduce the extent of separation. At the $Re_c = 58{,}000$–125,000, Murphy and Hu [67] clearly revealed that the corrugated airfoil has better performance over the smooth-surfaced airfoil and the flat

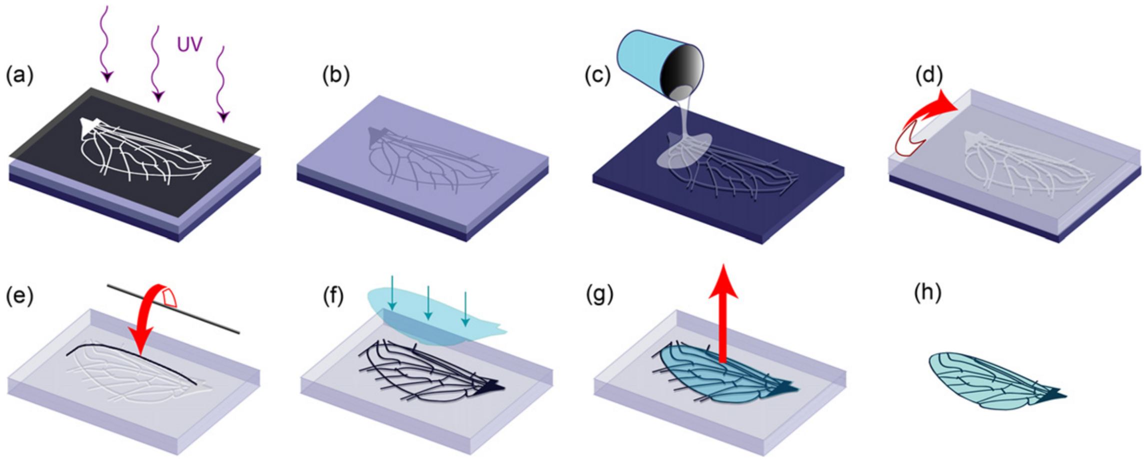

Fig. 13. Wing fabrication process, using photolithography to create a positive relief. (a) A transparency mask of the wing is overlaid onto a Si wafer spin-coated with photoresist, and exposed to UV light. (b) The unexposed photoresist is removed with a solvent, and the wafer is silanized. (c) PDMS is poured over the relief and cured. (d) The PDMS mold is removed from the wafer and silanized. (e) Laser micromachined carbon fiber prepreg veins are inlaid into the mold channels. (f) A membrane is laid on top, and the assembly is cured via a vacuum-bagging process. (g) The wing is released from the mold, and (h) the superfluous venation removed (Shang et al. [68]).

plate in providing higher lift and preventing large-scale flow separation and airfoil stall at low Reynolds numbers. While aerodynamic performance of the smooth-surfaced airfoil and the flat plate would vary considerably with the changing of the chord Reynolds numbers, the aerodynamic performance of the corrugated airfoil was found to be almost insensitive to the Reynolds numbers.

5. Fabrication and modeling of wing-inspired structures

The dragonfly has all the favorable characteristics a MAV needs in order to carry out the missions assigned to it, such as the small size and the ability to hover and accelerate quickly, both from a dead stop as well as from a hovering attitude. However, the delicate wings have numerous structural cells that would make the wing relatively heavy for MAV flight and are difficult to replicate. If reproduced mechanically, the biomimetic wings are always simplified.

Wing fabrication methods for flapping MAVs exist but are scarce (Shang et al. [68]). Existing methods are capable of achieving varying levels of structural complexity and mechanical stiffness, but often are geometrically limited or sacrifice mechanical anisotropy – a trait of biological wings – via vein material choice (Tanaka et al. [69]). An attempt was made to build a dragonfly's wing using pultruded carbon rod and fiber as a grid and electrospun fabric as the membrane. A dragonfly wing was enlarged four times and its features frozen, blood vessels and membrane along with the phenomenological models. The specific flexural stiffness to the nanofiber fabric wing was 260% of a commercial Nylon-6 film wing (Shivakumar and Lingaiah [70]). Some studies show that at low Reynolds numbers ($<10{,}000$), a corrugated wing section of the type found in dragonflies can generate more lift than a profiled wing with the same cross-section (Kesel [35]; Shyy et al. [17]; Vargas et al. [46]; Levy and Seifert [71]).

Shang et al. [68] introduced a novel fabrication process capable of achieving both high structural complexity and realistic mechanical stiffness, inspired by the following morphological consideration (Fig. 13). Photolithography was used to create the master as shown in Figs. 13(a) and 13(b), then poly(dimethylsiloxane) was cast onto a master having the relief structure of the desired vein design, where the height of the relief structure is the desired vein height as shown in Fig. 13(c). After curing, the elastomer is peeled off and silanized, Fig. 13(d), producing a wing mold. The unidirectional carbon fiber prepreg are inlaid into the mold's channels (Fig. 13(e)) and a membrane of 1.5 μm ultra polyester polymer thin film is aligned on top (Fig. 13(f)). The assembly is then cured by vacuum bagging to ensure uniform pressure distribution during the cure cycle. Finally, the cured wing is released from the substrate (Fig. 13(g)), and the superfluous venation is removed (Fig. 13(h)). After that processing, a biomimetic wing was fabricated. This work can enable rapid prototyping of wings. The corrugation structure of dragonfly wings needs to be studied and realized in the fabrication of the wing. Tanaka and Wood [72] used laser micromachined molds to fabricate corrugated artificial insect wings, which the morphological features of insect wings can be replicated at-scale with high precision, enabling parametric experiments of the functional morphology of insect wings. To ensure the reproducibility of the wing geometry for further adoptions, Deubel et al. [20] used a parametric 3D-CAD-system to build a digital model of the wing. The modeling makes it possible to create a variety of wing types for the reproduction of a real wing.

For fabrication, the analysis model of dragonfly wings should be established in advance. Wootton et al. [5] reviewed the approaches to modeling which have developed progressively in a logical sequence from conceptual models through simple physical models and simple analytical models to full-scale numerical modeling by FEM. Since the insect wing is a complex mechanical structure, some researchers have modeled it using FEM, and the structure models were always simplified relative

Table 2
The FEM analysis results of the combination of different cells.

	1-cell	2-cells	4-cells	16-cells
Max displacement, μm	7.78	4.20	5.38	5.05
Max stress, MPa	3.31×10^{-3}	1.08×10^{-3}	1.64×10^{-3}	1.16×10^{-3}
Max strain	0.72×10^{-6}	0.24×10^{-6}	0.36×10^{-6}	0.26×10^{-6}

to the original ones (Kesel et al. [6]; Sudo et al. [34,43]; Combes and Daniel [12,13]; Deubel et al. [20]; Tsuyuki et al. [73]; Darvizeh et al. [33]; Jongerius and Lentink [28]). Kesel et al. [6] was the first to use FEM to establish models of a dragonfly wing – Aeshnidae: *Aeshna cyanea*. They analyzed the mechanical load-bearing capacity of a light-weight plane. The model network was created from the real wing and only major veins were considered.

The topology optimization method solves the basic engineering problem of distributing a limited amount of material in a design space. The topology optimization method using the FEM is used in this paper, which incorporates all veins present in the wing. It is used to acquire the simplified wings model that meets the feasible fabrication requirements of a strong aerodynamic film. The solid95 program (special shell model topology optimization in ANSYS) was used with the following fly wing data: thickness of the vein and membrane $= 1.06 \times 10^{-2}$ mm and 1.2×10^{-3} mm, respectively, loading $= 4.5 \times 10^{-6}$ N/mm^2 (static loading with animal's own weight with reference to wing area) and elastic modulus for chitin (isotropic) and Poisson's ratio = 6.1 GPa and 0.25, respectively, as reported by Kesel et al. [6]. For analysis, the left side of the model was fixed, and a tensile distributed load was applied on the right side. For easier fabrication and higher stiffness, the optimization area from 20% to 40% was investigated, and it was found that for the optimization area of 25%, the structure is continuous and the simplest and was therefore chosen. The number of optimization steps selected was ten. The original network of the hindwing shown in Fig. 14(a) is compared with the optimization result (shown in Fig. 14(b)); the simpler frame can endure the same loading as the complex one. In order to produce a stronger film, several cells were assembled together. Figs. 14(c) to 14(e) show an example of an assembly of two, four, and sixteen cells. Table 2 shows the FEM analysis results of the combination of different cells. When the assembly changes to a 4-cell combination, there exists a long slanting blank region in the middle as shown in Fig. 14(d) which results in the large stress region. The same thing also occurs in a 16-cells assembly as shown in Fig. 14(e). The maximum stress and strain occurs for the 1-cell assembly as shown in Table 2, and the possible reason is the bilaterally asymmetrical structure distribution that leads to poor tensile properties. The minimum stress and strain occurs in the 2-cells model.

Fig. 15 shows tensile stress maps of the 1-cell, 2-cells, 4-cells and 16-cells model. In 1-cell model, the vein structures have uneven distribution and mostly exist on the top side which leads to the deformation of the bottom part and warping near the top in the end of film. This is possibly responsible for the maximum value of displacement, strain and stress as shown in Table 2. In the 2-cells model, the larger stresses (dark color region) occur in the region toward the ends as compared with the middle region because the ends have sharp features. In the 4-cells and 16-cells models, the blank regions present in the middle as shown in Figs. 14(d) and 14(e) lead to higher stress (dark color region) and overall poor tensile properties compared to the 2-cells region. For the maximum displacement, the 2-cells model exhibits the least deformation as shown in Table 2, because in the 4- and 16-cell model there are regular higher stress and strain regions which will easily lead to higher extension and in the 1-cell, little structure in the bottom region leads to high extension.

The FEM analysis of dragonfly wings has the following advantages: It is easy to describe the force and deformation profiles of dragonfly wings; It gives accurately analysis in their flight aerodynamic. Its disadvantages are: The wing is modeled as an isotropic and nonlinear material whereas it is a complex biological material with anisotropy performance; It ignores the microstructure effect on the dragonfly wing; and It ignores the veins flow of tissue fluid mechanics of dragonfly flight performance.

6. Summary and outlook

The vein and membrane thickness increase from tip to root which allows the wing to effectively bear both inertial and aerodynamic loads. The sandwich structure of the vein is needed in a high strength-to-weight ratio composite structure. The protuberances that exist in the leading and trailing edge of the wing are believed to produce an increase in lift. The nodus is a point of both strength and flexibility resulting in a powerful flight stroke without losing much energy on the return stroke. The changing thickness of the cross section of the costa is adapted to the forces acting at the location of the vein. The wax covering of the membrane has excellent superhydrophobicity and which, modified by the scratches, affects the mechanical stability of the membranes and thus the stability of the whole wing system. A corrugated wing increases the stiffness and strength of the wing significantly and results in a lightweight structure with good aerodynamic performance. Different wing zones bear different loads, and their mechanical properties might be different because of adaptation. The radius vein is the stiffest vein which plays an essential role in the stability as a whole and greatly reduces the danger of buckling and structure failure, and the value of the elastic modulus and hardness of the forewing are greater than that of the hindwing. The stigma is the counterweight to dampen wing vibrations.

The corrugated wing configuration is known to have an effect on dragonfly flight performance. For example, sharp leading edges promote separation, hairs extending outside the boundary layer act as turbulators, and the cross-section of corrugation

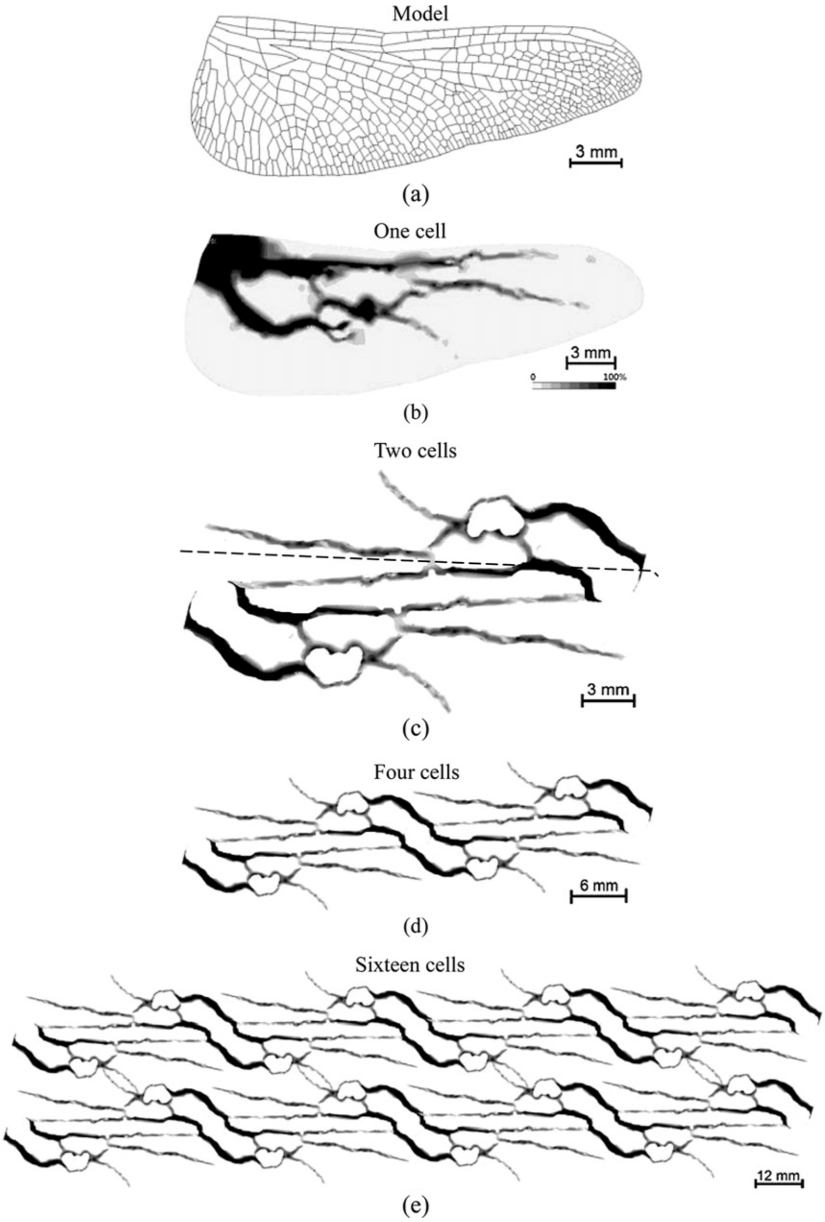

Fig. 14. (a) Original CAD figure of a dragonfly hindwing, and (b) the result of removing 75% of the original area by using the topology optimization method. The simpler frame can endure the same loading as the whole one: (c) to (e) images show the 2-, 4-, and 16-cells combination types.

has better aerodynamic performances compared with conventional streamlined airfoils in the low Reynolds number regime where dragonflies usually fly.

In order to understand how dragonfly wings could achieve such exact flight, it is necessary to fabricate replicas to carry out further research. Because dragonfly wings are complex, there are still many obstacles for accurate reproduction, such as the flexible junction of the nodus, the development of camber, corrugation of the leading edge, nonuniform mechanical properties of vein and membrane, and so on. Therefore, the structure and mechanical properties need to attract sufficient attention. The topology optimization method was used to extract vein structure and design biomimetic film.

Once the structure and material characteristics of dragonfly wings have been accurately quantified, design of biomimetic structures can begin and subsequently the actual testing to determine their accuracy. Light-weight and more precisely biomimetic designed wings could produce higher performance, such as less energy consumption, maybe due to suboptimal wing deformation and angle of attack that result from the simple sail-like wings of many flapping MAVs. Great maneuverability of dragonfly wings will also be helpful to develop light aircraft. The topology optimized structure can be used to develop strong aerodynamic films with feasible fabrication requirements.

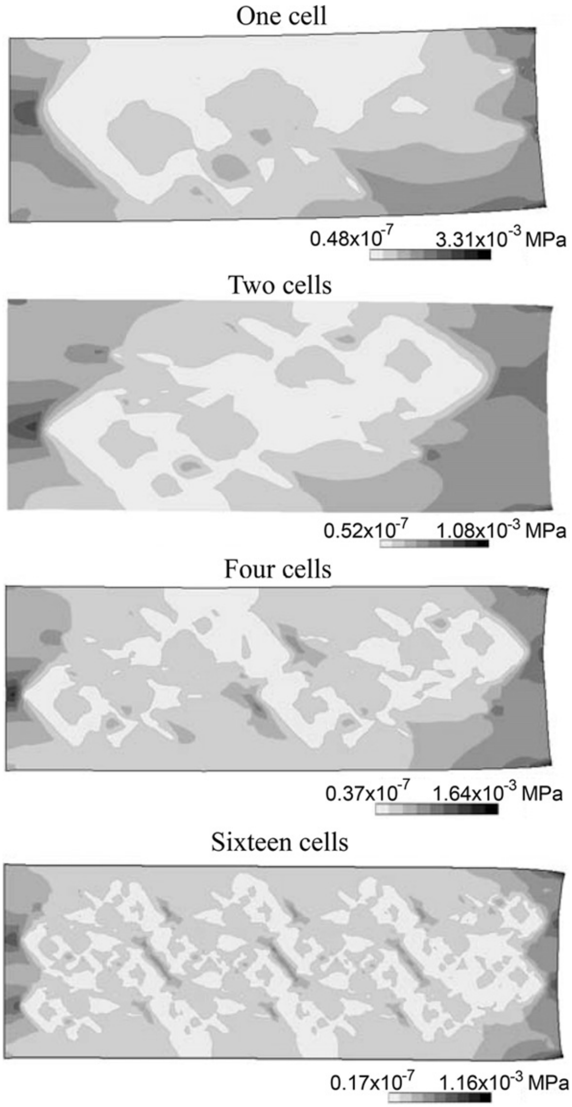

Fig. 15. The tensile stress maps of the 1-cell, 2-cells, 4-cells and 16-cells combination model using FEM analysis.

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