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THE ARCHITECTURE OF THE DRAGONFLY WING: A STUDY OF THE STRUCTURAL AND FLUID DYNAMIC CAPABILITIES OF THE ANISOPTERA'S FOREWING

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ABSTRACT

This paper studies the smart behaviour observed in the dragonfly wing combining advanced digital modelling techniques with non-linear structural analysis. The morphology of the dragonfly wing is an optimal natural construction built by a complex patterning process, developed through evolution as a response to force flows and material organisation. The seemingly random variations of quadrangular and polygonal patterns follow multi-hierarchical organizational logics enabling it to alter between rigid and flexible configurations. By means of digital experiments, this paper reveals how the geometrical complexity of the wing responds to function and efficiency, displaying emergent behaviour and being responsible for its performance capacity in passive flight.

INTRODUCTION

This paper is based on a broader biomimetics research study, which aimed to derive the adaptable and performative logics of the dragonfly wing. The work presented in this paper focuses however on the digital experiments made to understand multiple-pattern geometries and the role of corrugations which render a unique structural behaviour and efficiency in passive flight performance, characteristic of dragonflies. The first part of this paper will focus on the literature study made of dragonfly wings as well as preparing the reader for the second part of the paper that will concentrate on the technical analysis of the wing, through digital modelling.

EMERGENT BEHAVIOUR

The wings of dragonflies are complex flexible aerofoils, whose deformations in flight are encoded in the distribution of rigid and compliant components within their structure. The wings have 'smart properties' adapted to deform automatically and appropriately in response to the forces they receive [1]. The multiple configurations of the wing geometry could be understood by several factors, which influence the deformation; namely plan form geometry, corrugations, flexural stiffness, joints, mechanics, cambered infill membrane and hydraulics. These factors, which will be explained further in the following subsections, complement one another and collectively provide the dragonfly wing with a 'complex emergent behaviour', which is not the mere sum of the parts.

PLAN FORM GEOMETRY

The wing of dragonfly shows a seemingly complicated system of veins, which could be simplified by understanding the arrangement of cells. The wing is connected by main and cross veins both transversely and longitudinally, with main veins running approximately parallel to one another while cross-veins make a meshwork of 'cells'.

A number of cells at close proximity and in between two main veins will be arranged in one row forming quadrilateral shapes (Figure 1.a). If instead of one row there are two rows of cells, intercalated between a pair of main veins, one row will fit into another at angles of 120° as a result of coequal tension, but both cells are at right angles when they meet the main vein as in the former case (Figure 1.b). For numerous rows of cells, all the angles between them tend to be co-equal angles of 120°, and hence the cells resolve into a hexagonal/polygonal meshwork (Figure 1.c). This differentiation gives various degrees of flexibility to the wing.

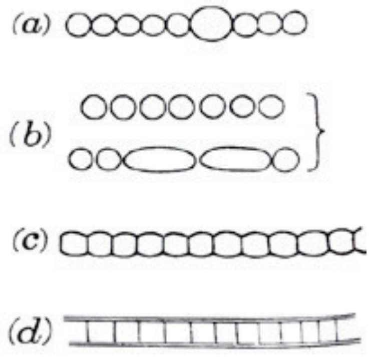

Fig. 1: Chains of cells in various lower Algae.

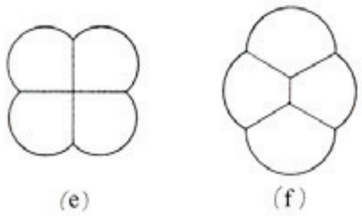

Fig. 2: Diagrams illustrating co-axial tension experiments with soap bubbles.

D'Arcy Thompson [2] explained the cell arrangement in dragonfly wings through soap bubble experiments. When four soap bubbles meet in a plane, they arrange in two symmetrical ways: (Figure 2.e) either with four partition-walls intersecting at right angles, or (Figure 2.f) with five partitions meeting three and three walls, at angles of 120°. The later arrangement turns out to be stable and the former of unstable equilibrium. If we try to bring four soap bubbles into the form (Figure 2.e) that arrangement endures only for an instant, the partitions glide upon one another to form (Figure 2.f), with its two triple, instead of a quadruple conjunction. This occurs due to the balancing out of surface tensions with internal and external air pressures [2].

The combination of quadrangular and polygonal patterns with more than four sides, allows for a greater degree of manipulation of the wing's structural configuration. The wing has a stiff leading edge made of quadrangular cells capable of withstanding large wind pressures; while a more flexible trailing edge is made of polygonal meshwork. The reduction in the veins size, as they approach the trailing edge, also compliments the flexibility of this part of the wing (Figure 3).

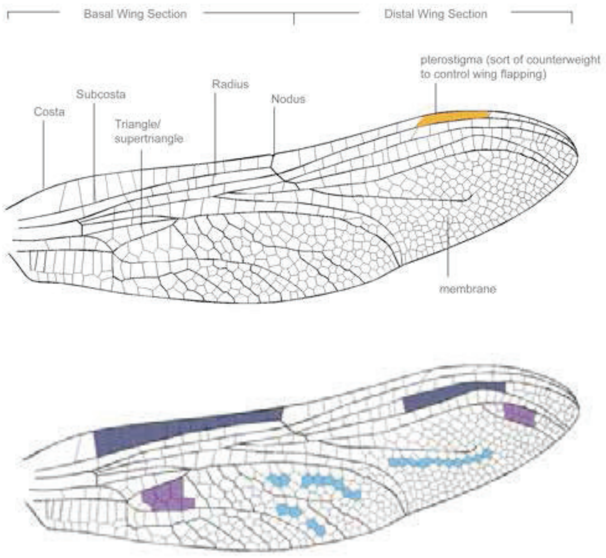

Fig. 3: Plan form geometry of the forewing of Anisoptera illustrating the different type of cells and their location.

CORRUGATIONS

The wings experience significant bending moments, particularly as they accelerate and decelerate. The leading edge of the wing has evolved into high relief, through corrugations between the main veins to resist moments. Next to the nodus the three most anterior veins form a lattice girder, with a 'V'shaped cross-section, linked by strong bracket-like cross veins acting as compression resistant struts. The veins forming the leading edge spar and around the 'Mediocubital bar' are configured for high relief. The depth of the corrugation diminishes towards the tip and the posterior margin. These corrugations form profile valleys in which rotating vortices develop reducing the wind resistance to a considerable degree. The cross-sectional configuration varies greatly along the longitudinal axis of the wing rendering different local aerodynamic properties (Figure 4).

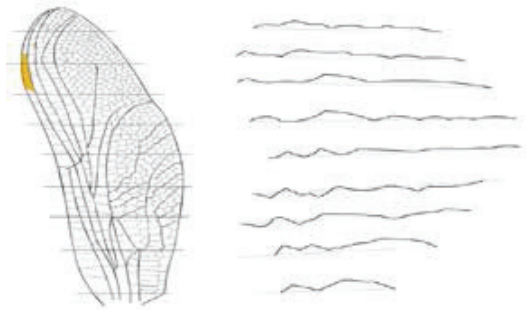

Fig. 4: Sections along longitudinal wing axis illustrating corrugations.[8]

JOINTS

Two main types of joints occur in the dragonfly wing: mobile and immobile. Some longitudinal veins are elastically joined with cross veins, whereas other longitudinal veins are firmly joined with cross veins. Scanning electron microscopy (Figure 5) reveals a range of flexible cross-vein and main-vein junctions in the wing, which allow for local deformations to occur. The occurrence of resilin (a rubberlike protein) in mobile joints enables the automatic twisting mechanism of the leading edge [1].

Immobile joints are firmly connected veins whereas mobile joints have one vein serving as a turning axis for a cross-vein. The cross-vein is usually interrupted next to the axis, and contains resilin in the area connected to the longitudinal vein. This allows the cross-vein end to rotate slightly around the axis of the longitudinal vein. There are horn-like structures (Figure 5.c, 6) on the upper and the lower sides which act as shear keys, which restraint the extent of the rotation (Figure 6).

Mobile joints are strategically distributed over the surface of the wing to control corrugations and hence, flexibility. Depending on its chemical composition, the fibrous composite material forming the wing allows it to have different stiffness across the wing. The elastic elements act as viscous dampers and are responsible for gradual twisting of the leading edge, permitting slow manoeuvrable flight and hovering [3].

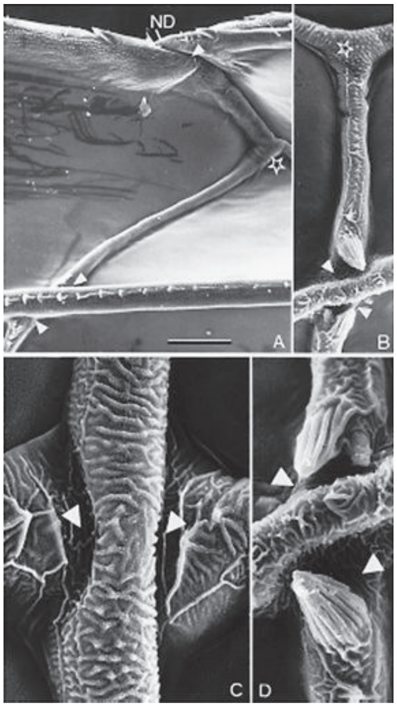

Fig. 5: A) Nodus region; B) tertiary veins; C) mid longitudinal vein and cross vein. D) Tertiary veins and cross vein. Arrowheads indicate mobile joints; stars indicate immobile joints.

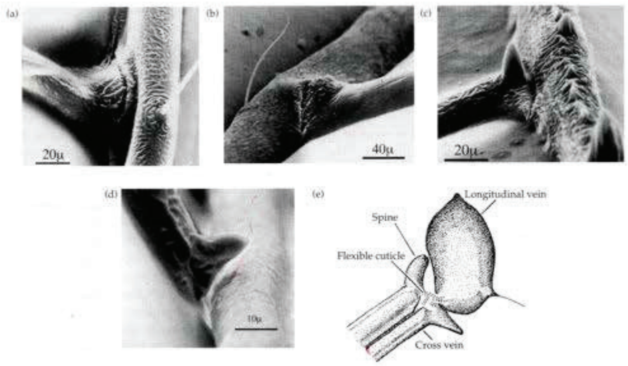

Fig. 6: Flexible cross vein junctions.

CAMBERED INFILL MEMBRANE

The rigidity of the wing structure is enhanced by the infill membrane, which contributes to the overall stiffness of the structure acting as a 'pre-stressed skin'. The membrane is only 3 microns (3E-06mm) in thickness while the average diameter of the vein is 0.5mm. The membrane being extremely thin, acts only as a tension component, transferring the wind loads to the periphery of the cell and hence the veins.

The membrane is cambered between the cells with its cambering pattern varying non-linearly across the wing between convexity and concavity. Aerodynamically forces make the membrane to change from convex to concave, imposing a torsional effort on the main veins, which make them rotate, and creating different global configurations.

STRUCTURAL ANALYSIS

Although all constructions are continuously moving, deforming and vibrating, they are all initially dimensioned from the outcome of a static analysis. This is because forces are usually applied to buildings in a very slow pace; even wind is prescribed by codes as static loading, which covering worst case scenarios, provides conservative results when sizing the members of the structure. Wind tunnel testing is however necessary for special structures such as long span bridges and skyscrapers for which prescribed static wind loading might not be representative of the worst conditions.

Dynamic analysis is therefore necessary for flexible structures subject to rapidly applied loads, with a variable intensity. The wing of the dragonfly flaps with a frequency of 33Hz, i.e. 33 times in one second. The loading on the wing is essentially the pressure of the air generated by its flapping. Dynamic analysis is therefore required to understand the mechanisms behind passive flight in a dragonfly, although static analysis was undertaken to help calibrating the model that would later be used for the dynamic analysis.

Structural analysis was completed with computer fluid dynamic (CFD) analysis, which aimed to explore the aerodynamical performance of the wing. The software packages used for structural and CFD analyses were GSA (Arup in-house structural software) and ANSYS respectively.

The CAD model was built up in Rhinoceros using photograph-scanning techniques including pictures taken at different angles. It was subsequently exported to both GSA and ANSYS for analysis.

STATIC ANALYSIS

Apart from being the starting point for the posterior dynamic analysis, the static model aimed to prove the effects of a variant flexural stiffness (EI) across the wing. The mechanism behind this property is the variant flow of hemo lymph inside the veins and its internal pressure. The inertia (I) is constantly being modified from that of a hollow section to an in filled tube section. The value of the Young's modulus (E) is also varied across the wing's structure as per [4]. This occurs particularly at the mobile joints, between main and cross veins, where when the internal blood pressure increases the joint becomes more rigid limiting its movement. The Young's modulus of the veins varies between 1GPa and 5GPa [5].

The static analyses will contrast the above hypothesis by comparing results using a homogenous Young's modulus, versus a variant value. The preparation of the model was completed using the following material and section properties:

1) Poisson's coefficient (ν), which was defined as 0.25 with the density being that of water based on previous research studies by [6].
2) Sectional properties were extracted from previous research and confirmed via measurement of nano-scale photographs.
3) Hierarchy between main and cross-veins was established based upon their diameters ranging from 0.50 to 0.35mm for main veins, and decreasing to 0.10mm for the smallest cross veins [1].

Following the definition of material and section properties, calibration of the model was carried out by comparing the deformation at the tip of the wing, to a calculated value from the frequency and velocity. The frequency of flapping for the wing is approximately 33Hz and the velocity measured at the wing's tip is 1m/s [7]. The wavelength is therefore 30mm and thus, the maximum displacement from the horizontal plane is 7.5mm. Two static models were tested: one with a constant Young's modulus and the other one with a variant value. The distribution of the variant value of E along the wing's span follows the approach outlined in [4]. The first model revealed a maximum displacement in z of 7.76mm; while from the second model, 7.9mm were measured. The proximity between the two models proved calibration assumptions being successful. However, deformation patterns were significantly different when compared among each other. From looking at the elevation of both models in motion, one can observe that a non-homogenous value of E causes a self-induced twisting in the wing (Figure 7).

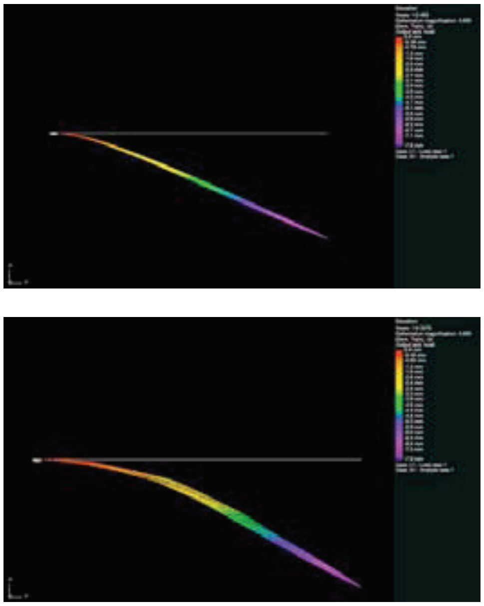

Fig. 7: above: constant E value; below: variant E value.

Twisting of the wing is crucial for its passive flight and it is induced by the elastic torsion of the wing and not by the musculature that attaches it to the body. By twisting of their wings, dragonflies have the ability to change the angle of stroke without modifying the orientation of their bodies. Thrust is generated both by the movement of the wing through the air and by the twisting of the wing at the ends of each stroke (Figure 8).

Apart from the contribution from a variant E value, the twisting of the wing is due to the three-dimensional corrugated reliefs located at the leading edge, which provide high rigidity to the span of the wing. This causes the flexural stiffness along the span to be 1-2 orders of magnitude greater than along the chord [1]. The camber of the leading edge inverts at the nodus and its torsional properties abruptly change (Figure 9.d). The rigid ante nodal component resists both bending and torsion but ends at the nodus sub-costa as a free vein; while the post-nodal spar has a shallow, inverted 'V' section, with slender cross veins. Hence there is an asymmetry in the torsional property of the ante-nodal and post-nodal components, which allows significant inertial twisting in the distal area of the wing.

The model using the variant value of E (Figure 7, above) was therefore proven to be more realistic and thus, taken forward to the dynamic analysis.

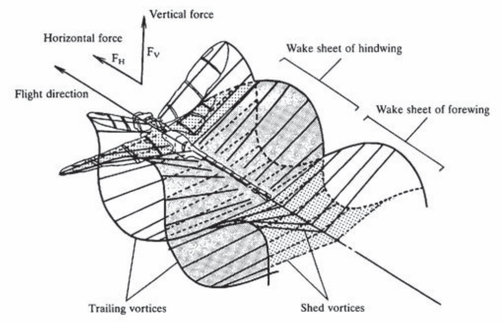

Fig. 8: Diagram illustrating the wake vortices and the sinusoidal movement of the wings.

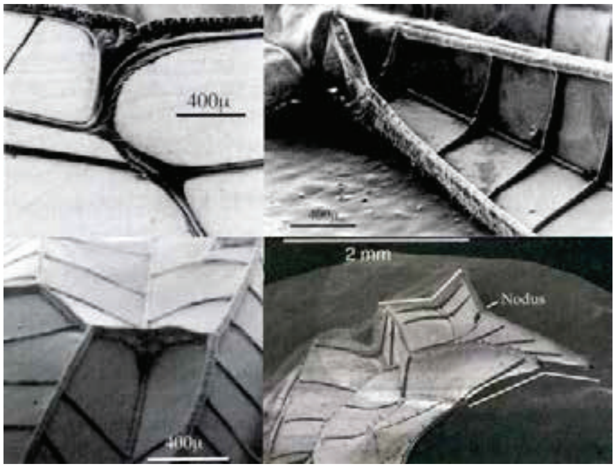

Fig. 9: a) antenodal cross-veins; b) nodus and high-relief subnodal bracket; c) mediocubital bar; d) nodus along leading edge.

DYNAMIC ANALYSIS

As introduced above, the wing of a dragonfly is clearly a dynamic structure for which vibration studies are necessary to obtain realistic deformation patterns and thus, understand its structural behaviour. In a static analysis there is a unique set of displacements results while in a modal analysis the displacements are mode shapes. The goal of a modal dynamic analysis is to characterize the dynamic response of a structure in discrete modes. Modal analysis helps in determining vibration characteristics, since it calculates the natural frequencies and mode shapes of a structure.

In a modal analysis there is a structure mass matrix in addition to structure stiffness matrix, assembled from the element mass matrices in a similar way to the stiffness matrix. The way mass of the structure is to be accounted for is decided during the set up of the model. In our case, we chose to the option for having the mass lumped at the nodes, which for a beam element means that half of the mass is assigned to each node. Other methods such as calculation of masses from the element shape function led to individual vibration of elements rather than the structure as a whole.

A total of ten vibration modes were calculated. The first mode is the one that requires less energy. Higher modes require greater energy levels since they occur at higher natural frequencies. Due to the high frequencies exhibited in modes beyond the first one, our eyes are usually incapable of recognizing the different modal shapes of the third, fourth, fifth vibration modes, which occur almost simultaneously. In our case slow motion pictures featuring the real flight of the dragonfly, allowed us to identify up to the third mode of vibration by comparison with that calculated in the analysis.

Figures 10, 11 and 12, show the third, fifth and ninth deformed vibration modal shapes with blue representing down-lift (maximum deformation towards negative z) and red representing up-lift (maximum deformation towards positive z). These three illustrated modes of vibration are all present in the dragonfly wing during flight. They illustrate the correlation described earlier between the geometrical patterns and the different degrees of flexibility. The rectangular pattern found at the uppermost zone of the wing, is designed to withstand load perpendicular to the leading edge taken by the wing during flight, while corrugations help with resisting loads perpendicular to the plane of the wing. A torsional wave at the trailing edge can be observed throughout the different modes; this occurs due to the tendency of the elements closer to the wing's tip, to twist ahead of those nearer to the base, creating a torsional wave. Located at the leading edge the nodus acts as the reinforcement and the shock absorber. The nodus copes with combined torsion and bending stress concentrations at the junction of the rigid concave ante-nodal and the torsionally compliant post-nodal spars. The concentration of stresses and bending moments must have imposed strong selection pressure in the development of the nodus, which combines a stress absorbing strip of soft cuticle with strong, three dimensional cross bars across the entire spar between the costal margin and the leading edge.

The deformed modal shapes demonstrate that the pentagonal-hexagonal pattern is designed to deform and thus, provide the thrust necessary to maintain the dragonfly in the air. The 120° angle present in these geometries, allows for the polygons to reorganise from being in a single plane to form a concave surface, utilising much less energy than that of the rectangular pattern (Figure 10).

In order to understand the significance of the high density of the penta/hexagonal pattern in relation to the less dense quadrangular pattern, a simple digital experiment was undertaken. It consisted on progressively removing hexagonal cells at the zone of highest density. Results were compared for different modes of vibration for both geometries. The altered pattern shows much limited flexibility and restrained modes of vibration. The cumulative reaction of the points in the grid allows for larger deformation, when the density is reduced. It is interesting to observe that the high deflection zone has shifted to the denser zone in the altered grid (Figure 12).

FLOW ANALYSIS

Aiming to understand how the wind flow interacts with the dragonfly wing, we undertook a series of CFD analysis comparing the real corrugated morphology of the wing with a planar model. The two models were tested under two different wind flows. For all the simulations the characteristics of the flow were identical (air ideal gas, laminar flow, temperature 20 °C, velocity 20m/s), but the direction of the flow was different. In the first case, the direction of the wind vector is parallel to the surface of the wing, while the second one it is perpendicular.

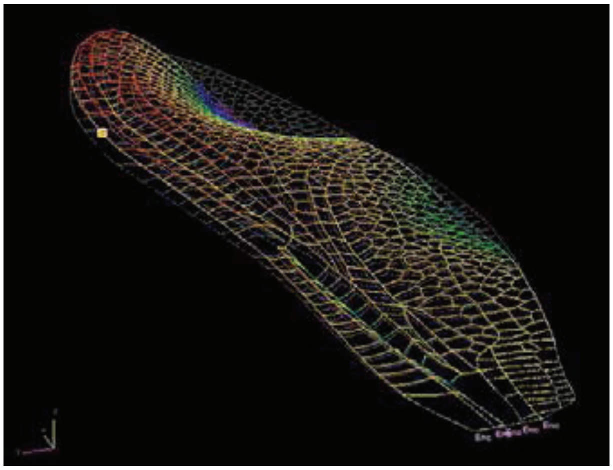

Fig. 10: Third vibration mode of the dragonfly wing.

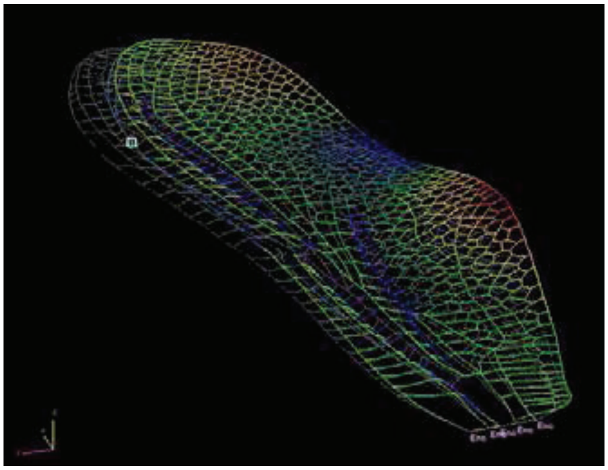

Fig. 10: Fifth vibration mode of the dragonfly wing.

In both models, the highest negative pressures (represented in blue in the pressure map) occur where the wing is corrugated (Figure 13). Although this could have been predictable for the corrugated model, it was unanticipated for the planar model. The only main difference was in the values of the pressure suffered by the wing, which was found to be lower for the corrugated model. These observations led us to the conclusion that a planar version could have been initially tried by nature and later evolved to optimise areas that experienced higher pressures, leading to a corrugated wing that could prove sufficiently rigid without compromising its overall flexibility (Figure 13).

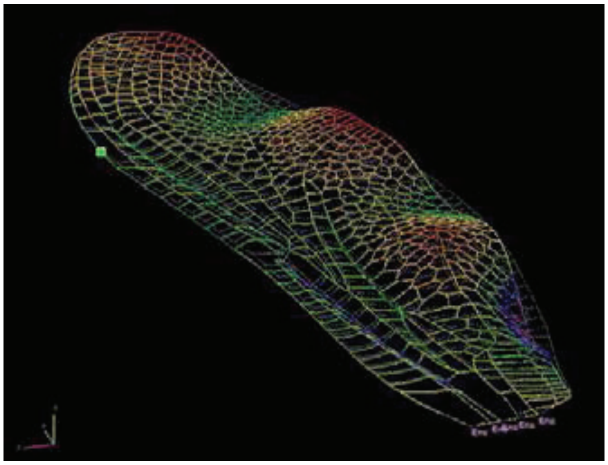

Fig. 11: Ninth vibration mode of the dragonfly wing.

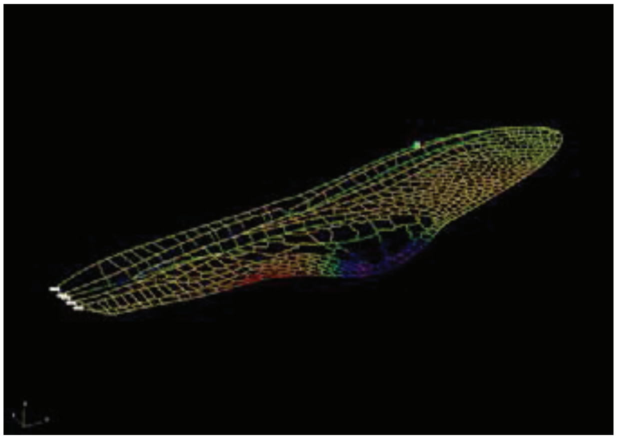

Fig. 12: Deformed shape resulting from the digital experiment performed to prove the impact of pentagonal-hexagonal patterns in the localized flexibility of the wing.

Calculated pressure maps also confirmed the contribution of corrugations to create vortices and thus, a more turbulent flow, which enhances the flight performance of the wing by generating lift.

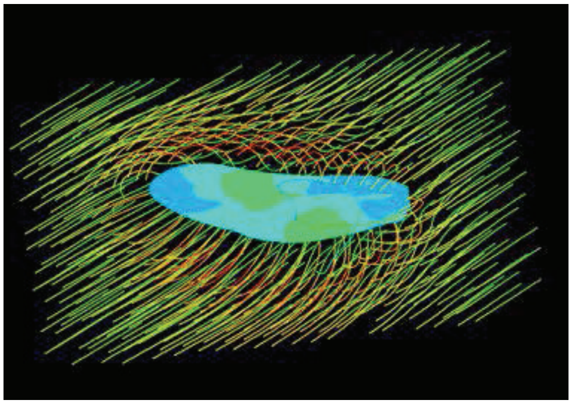

Fig. 13: Flow analysis results from ANSYS CFX featuring the planar model.

CONCLUSIONS AND FURTHER RESEARCH

This paper focused on several simulation studies of the forewing of Anisoptera. Structural analyses and CFD analyses were performed to understand the dynamics of the wing. Several factors discussed in the performative capacity section such as plan form geometry and hydraulics could be beneficial in architectural structures for dynamic applications. Factors such as corrugations could aid is reducing wind drag and resistance in high rise constructions. The physical mechanism of the wing and joints would be helpful in designing moving parts for dynamic structures.

During the course of research it was understood that further dynamic simulations of the dragonfly wings would be helpful to extract more interesting ideas for architectural applications. The areas of further research are elaborated as follows.

- Simulation of hind wing in combination with forewing. The work shown in this document concentrated on the aero dynamical behaviour of the forewing only. However, part of the research has revealed that, fore and hind wing work together to improve the dragonfly flight. Therefore, it is worthwhile noting that the analysis of both wings in combination could provide more accurate results.

- Simulation of the flow inside the veins. An interesting feature of the dragonfly wings that has been suggested in several papers but that has not been proved yet is the relation between the blood flow inside the veins and their stiffness. This analysis was discounted given the timeframe of the study but could constitute an interesting area for further research.

- Highly flexible joints. This document has covered the main mechanisms responsible for the exceptional flexibility of the dragonfly wing. A protein named reslin released at the main joints between the veins was found to be responsible for the wing's flexibility. However, there are still many uncertainties regarding the composition of reslin. The study of this substance could lead to the development of a material that self-repairs itself when damaged or to reduce fatigue problems in manmade structures.

- The anchorage points of the wing to the dragonfly's body have been considered to be fully encastrated for the purpose of this analysis. However, as further research it could be interesting to study the effect of these anchorage points on the twisting mechanism.

ACKNOWLEDGMENTS

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ILLUSTRATION CREDITS

Figure 1: Thompson, D. 1961, “On Growth And Form, An Abridged Edition. Cambridge University Press**, 98**, pp.99.

Figure 4: Till D, Wanke S., Et Al. 2006, “Modelling and Manufacturing of a Dragonfly Wing as Basis for Bionic Research”, International Design Conference, **15**, pp.18.

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Figure 8: Wang, Z.J., and Russell, D, “Effect of Forewing and Hindwing Interactions on Aerodynamic Forces and Power in Hovering Dragonfly Flight”, Theoretical and applied mechanics. Cornell University, New York, **3**, pp.4.