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Biomechanical aspects of the insect wing: an analysis using the finite element method

Antonia B. Kesel*, Ute Philippi, Werner Nachtigall

Department of Zoology, University of Saarland, 66041 Saarbrücken, Germany

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Abstract

Insect wings appear as highly functional and largely optimized mechanical constructions. A series of stabilizing constructional elements have been 'designed' to cope with loading during flight. One such element is the expenditure of material in constructing the wing, i.e. the vein system of the wing and its arrangement. It functions like a zig-zag folding framework which stiffens the wing against aerodynamic bending moments. To quantify the quality of material distribution, models of a dragonfly wing and of a fly wing were calculated using the finite element method (FEM). © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Insect wing; Biomechanics; Statics; Finite element method; Dragonfly; Insects; Material distribution

1. Introduction

Insect wings are highly specialized flight organs adapted to cope with the individual flight behaviour of each insect. Numerous studies have already been made, e.g. Refs. [1–9], etc. All wings have two things in common. They are both a construction and a mechanism, so that they must cope with a variety of loads and load combinations. For example, during up and down stroke, the mechanism 'wing' accelerates the surrounding fluid in such a way that the resulting aerodynamic forces enable the insect to fly and, simultaneously, the construction 'wing' has to cope these attacking forces.

In addition, insect wings impress one with the marginal amount of building material used in their construction. Although the wings do not incorporate more than 1–2% of total body mass, they possess great stability and a high load-bearing capacity during flapping flight. In

* Corresponding author. Tel. +49-681-302-2711; Fax. +49-681-302-4610; E-mail: a.kesel@rz.uni-sb.de.

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order to withstand heavy mechanical stress with minimum material expenditure, the type of building materials used and their distribution are very important [10]. The basic framework of veins is made of chitin, a long-chain, crystalline polymer the characteristics of which are similar to cellulose or technical materials such as Teflon [11]. Since chitin is an energetically expensive material, its distribution and dimensions may therefore be defined as the optimizing parameters in insect wing design.

The main aim of this study is to determine whether the amount of material used and its distribution is sufficient to cope with the structural demands made on the ultralight aerofoil. To quantify the quality of material distribution, models of dragonfly and hoverfly wings were calculated using the finite element method (FEM). This method enables one to take into account the individual variations in structural parameters which is particularly helpful when dealing with problems concerning the stability of a construction.

2. Method

Preliminary studies have shown that the insect wing is such a complex construction, that a multi-level model is necessary to determine the role of individual constructional elements. The dragonfly, Southern Aeshna (*Aeshna cyanea*), plays a key role in our first series of tests. Although the vein system of dragonflies is very complex, their ability to glide allows a relatively simple load case. Ignoring the real angle of attack during gliding, the model wing is loaded perpendicular from below with the animal's own weight. No angles of attack or wing rotation, has to be considered.

With the help of the FE computer system ANSYS 5.0A wing models were built and analysed. These models contained pipe elements (elastic straight 3D-pipe16 with 2 nodes) as 'veins' and shell elements (plastic shell43 with 4 nodes) as 'membranes' (each with three translatorial and three rotational degrees of freedom per node).

2.1. Boundary conditions

The wing joint was assumed to be a simple clamp (membrane thickness, 0.135 mm), i.e. its force transmitting functions in the living insect were ignored. The model wing was loaded perpendicularly from below with the animal's own weight relative to wing area ($4.061E-06$ N/mm^2, see Fig. 3). The load is modelled as a homogeneous wing loading.

2.2. Material characteristics

The chitin of veins and membranes was modeled as an isotropic material with a Young's modulus of 6.1 GN/m^2 [11]. The Poisson's ratio was assumed to be 0.25.

2.3. Modelling

To begin with, a simplified model of the forewing (model I, Fig. 1B) was made. During ontogenesis, variations in the size of posterior wing sections and thus the density of veins

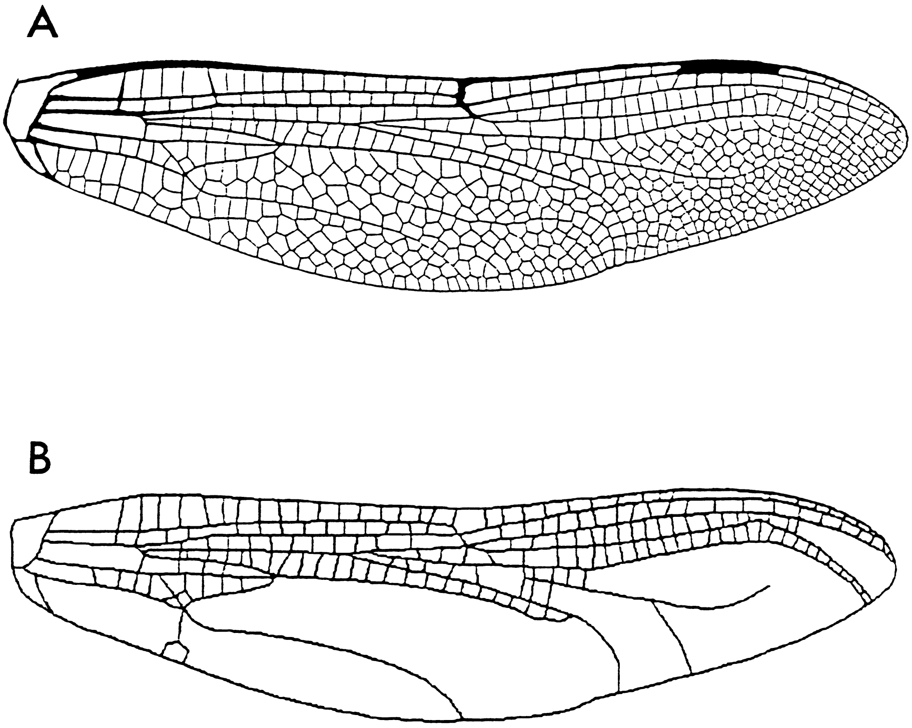

Fig. 1. (A) Network of veins in a dragonfly's forewing (transmitted-light photograph of a real wing). (B) Model network created from (A). Only major veins are reproduced in this preliminary phase analysis of model I. The veins are modelled by pipe-elements of uniform diameter, the sections of wing membrane are modelled with shell elements (thickness: 2E − 03 mm). Posterior wing sections modelled as 'smeared' material (membrane, vein) using shell elements (thickness: 4E − 03 mm). The model is two-dimensional, its topology is not taken into account.

between individuals occur. This 'accidental' distribution of veins and membranes was accounted for by modelling a similarly sized wing area of uniform thickness ('smeared' thickness values).

2.3.1. Characteristics of model I

(a) Two-dimensional model.
(b) All veins with the same cross-section (ring-shaped; outer diameter, 0.135 mm; wall thickness, 2.5E − 02 mm).
(c) Modelling the veins of certain wing areas only.
(d) Posterior wing section with 'smeared' membrane thickness (4E − 03 mm).
(e) Wing joint as a clamp (membrane thickness, 0.135 mm).
(f) Static load perpendicular from below (4.061E − 06 N/mm^2).
(g) Nonlinear analysis.

The next step was to integrate the actual topology of the wing into model II. Surface contours were determined by optical surface probing (TechNet, Rottweil, Germany). Three-dimensional contours were then ascertained by means of spline-interpolation of topological measurements. This second model now depicted a folding structure with stiffening supports (wing veins) along its folding edges and a profile preserved by the framelike vein surrounding the wing. Because of the unchanged vein cross-sections, this model consists of the same amount of material as model I.

2.3.2. Characteristics of model II

(a) Integration of topology data.
(b) to (g) Same as model I.

In model III, the vein diameters and wall thicknesses determined in the original specimen were also integrated. This model includes 78 groups of veins differing in diameter and wall thickness.

2.3.3. Characteristics of model III

(a) Same as model II.
(b) Realistic modelling of vein diameter values.
(c) to (g) Same as model II.

In model IV the entire vein network was modelled (Fig. 2). In order to slightly simplify the production of this model, the membranes of the posterior area were modelled either as triangles or squares. The vein diameters and thicknesses, however, were reproduced exactly, thus increasing the number of vein groups to 122.

2.3.4. Characteristics of model IV

(a) and (b) Same as model III.
(c) Modelling the veins in all wing areas.

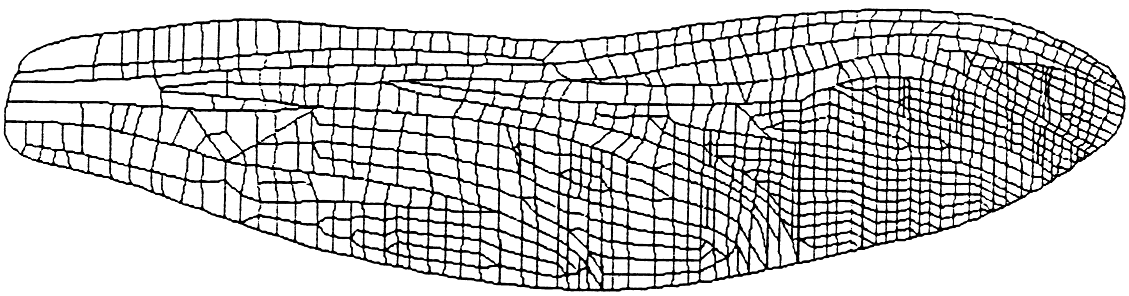

Fig. 2. FE grid of the fully structured model. Due to an increase in total vein length by adding extra pipe-elements the approximation volume values correspond to those of the original wing. Model data: number of elements, 4,409; number of nodes, 1,757; number of degrees of freedom, 10,488; veins, pipe elements (n = 2,639); membrane, shell elements (n = 1,770; thickness, 2E − 03 mm; joint area thickness, 0.135 mm); load, 4.061E − 06 N/mm^2 (animals own weight refers to wing area); Young's modulus of isotropic chitin, 6.1 GN/m^2 and Poisson's ratio, 0.25.

(d) Posterior wing section with real membrane (2E − 03 mm) and vein thickness.
(e) to (g) Same as model III.

2.4. Stress-stiffening influence

The out-of-plane stiffness of a structure can be significantly affected by the state of in-plane stress in that structure. This coupling between in-plane stress and transverse stiffness (stress-stiffening), is most pronounced in thin, high-stress structures, such as cables (here wing vein) or membranes (here wing membrane). This means that a membrane under tension stiffens in the transverse direction. This effect can also be taken into account with the finite element method.

Since such effects are found mainly in the membrane areas of a wing, a fly wing with comparatively large membranes was chosen as model (*Episyrphus balteatus*, Diptera, Syrphidae).

2.5. Model characteristics of the fly wing

Cross-section of pipe elements, 3.63E − 02 mm; thickness of the wall, 1.06E − 02 mm and thickness of the membrane (shell elements), 1.2E − 03 mm. Loading, 4.5E − 06 N/mm^2 (static loading with animal's own weight with reference to wing area) and Young's modulus for chitin, 6.1 GN/m^2 (isotropic; Poisson's ratio = 0.25).

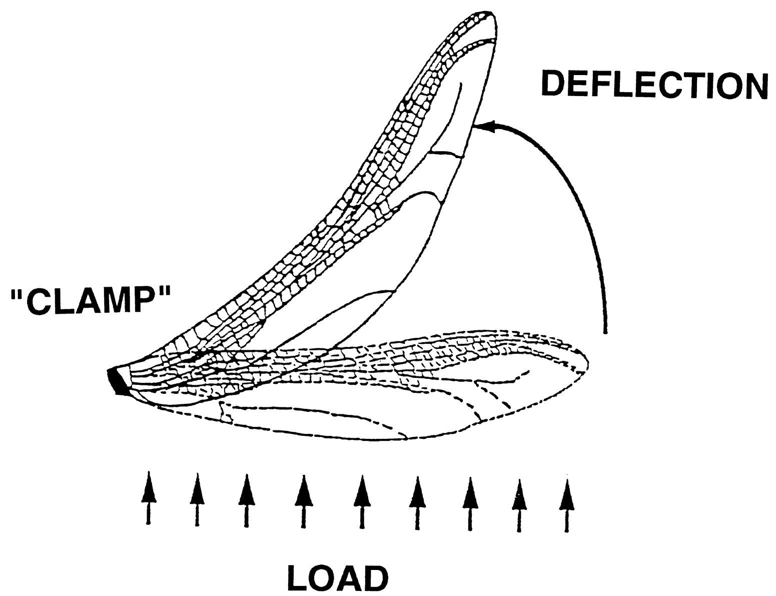

Fig. 3. Deflection of the two-dimensional model under perpendicular loading from below. A loaded (solid line) and unloaded (dashed line) wing model are shown. The insect would be unable to fly with such an aerofoil.

3. Results

3.1. Model I

Under the described conditions, the calculated model I reacts by deflecting strongly in a longitudinally direction (loading direction, Fig. 3). Although no longitudinal torsion occurs the stability of this simplified model is obviously insufficient and would make flight impossible. In addition, with a vein mass of 6.924 mg the model wing is much too heavy (original forewing of *Aeshna cyanea*: 3.77 mg; $n = 10$).

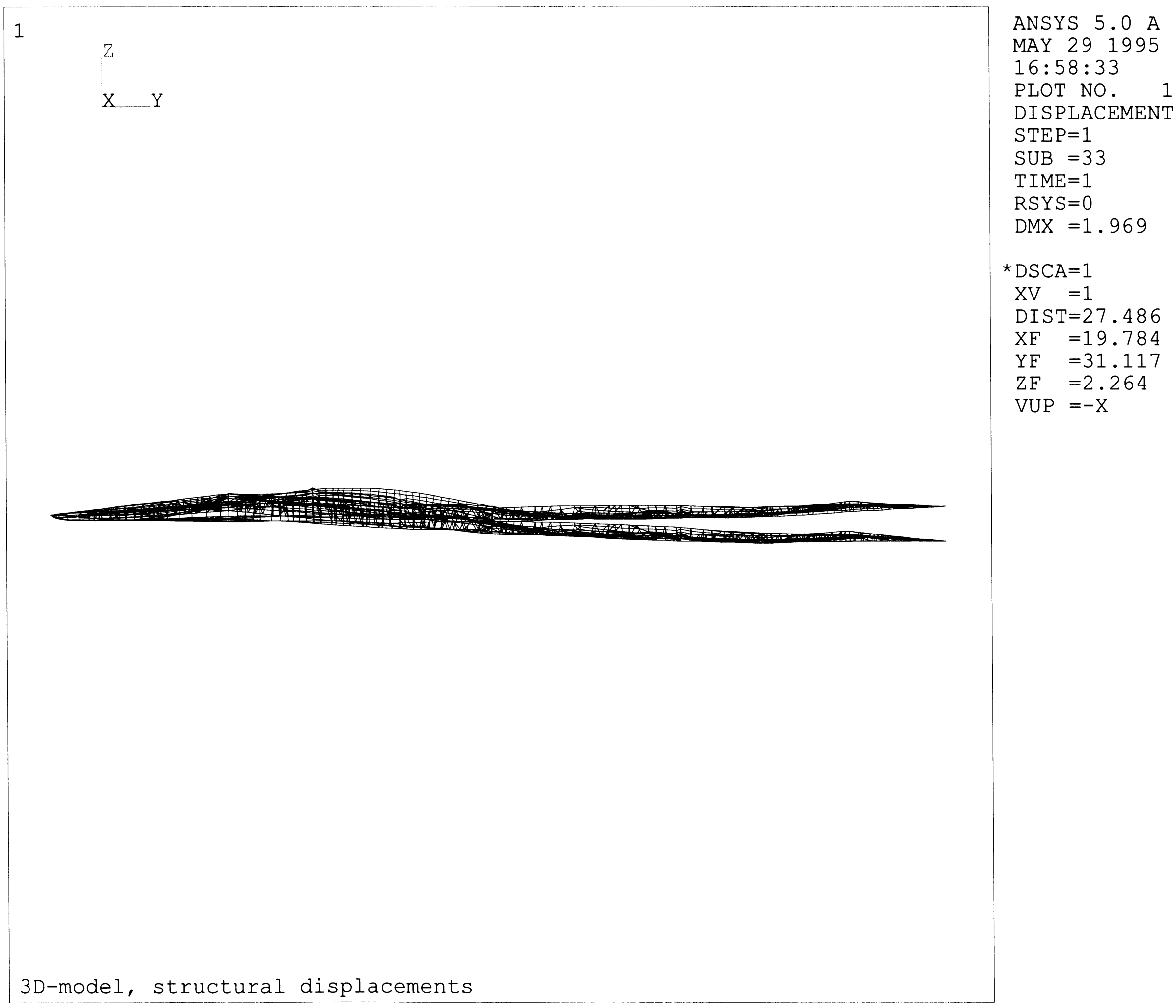

Fig. 4. Integrating vein topology clearly reduces model deflection (factor 20) under animal weight loading (compare Fig. 3) (after Kesel et al. [12]).

3.2. Model II

Given the same load, the 3D-model is much more stable than the two-dimensional one and, with the same amount of material, a 95% reduction of wing deflection is achieved (Fig. 4).

3.3. Model III

In model III a reduced use of material is achieved by integrating the real diameter and thickness of the veins into the model. This leads to a material reduction of ca. 70% compared to model I and model II (vein mass, 1.74 mg). However, a model with so little material is

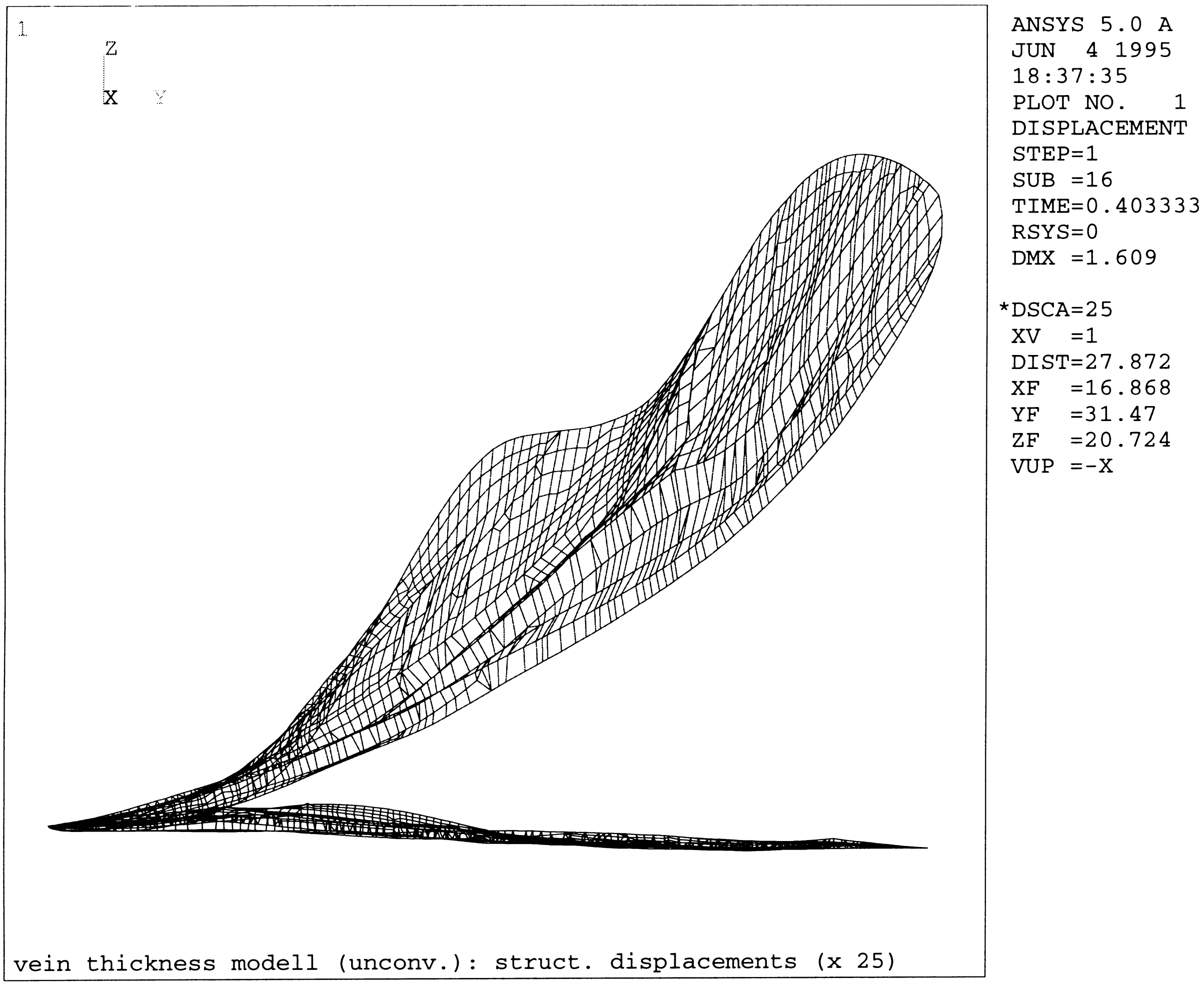

Fig. 5. The reduced amount of material (integration of real diameters and thicknesses in the smaller veins) leads to a structural weakness. The 'wing' reacts with typical buckling failure in the posterior area. The critical buckling load is only 40% of the original load.

virtually incapable of flight, because its load bearing capacity is also greatly reduced. This is not so much due to wing deflection, but to material failure and typical buckling effects. Local high tension values appear particularly in the posterior 'homogeneously' modelled section. This area is not sufficiently stiff, and displacement pictures clearly show that it folds towards the leading edge of the wing (Fig. 5). In this wing model the critical buckling load is 40% of the original load.

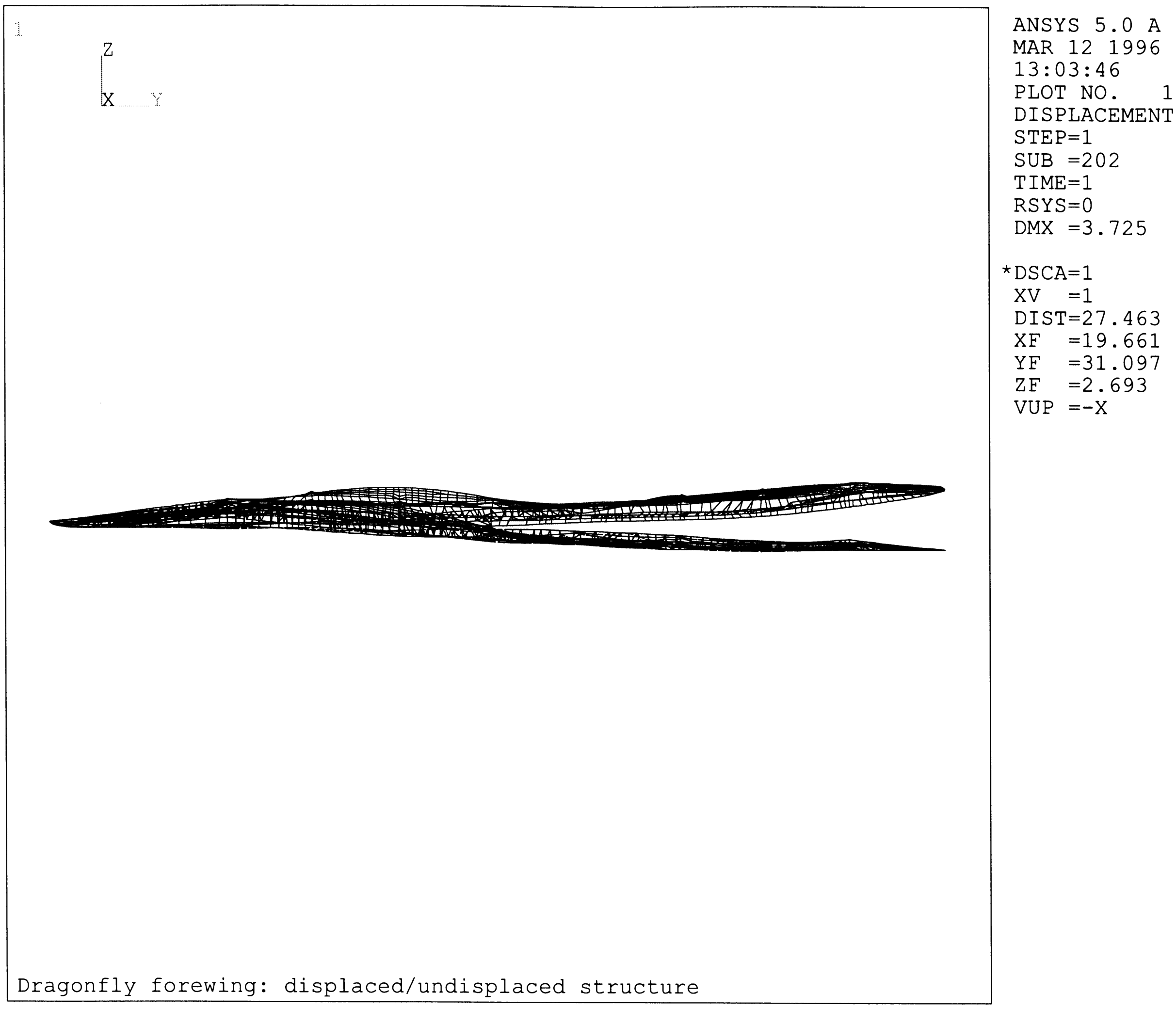

Fig. 6. Deflection of a completely modelled wing (viewed obliquely from above). The wing gains rigidity in the longitudinal and transversal directions by integrating the veins of the posterior wing areas (compare model III). (For clarification, the deflection has been enlarged eight times).

3.4. Model IV

Due to realistic modelling of the distal wing areas, the buckling which leads to the structure collapsing in model III, can be avoided. Deflection in the transversal direction is greatly reduced, but asymmetrically as in model III. Maximum deflection occurs at the trailing edge and not at the wing tip. The leading edge is more resistant to deflection (Fig. 6).

By incorporating the complete vein network, the total mass of the model is increased to 2.024 mg (29.2% of the initial mass compared to model II). Thus the model has ca. 70% less mass than the original initial wing. However, the main veins of a real wing are filled with

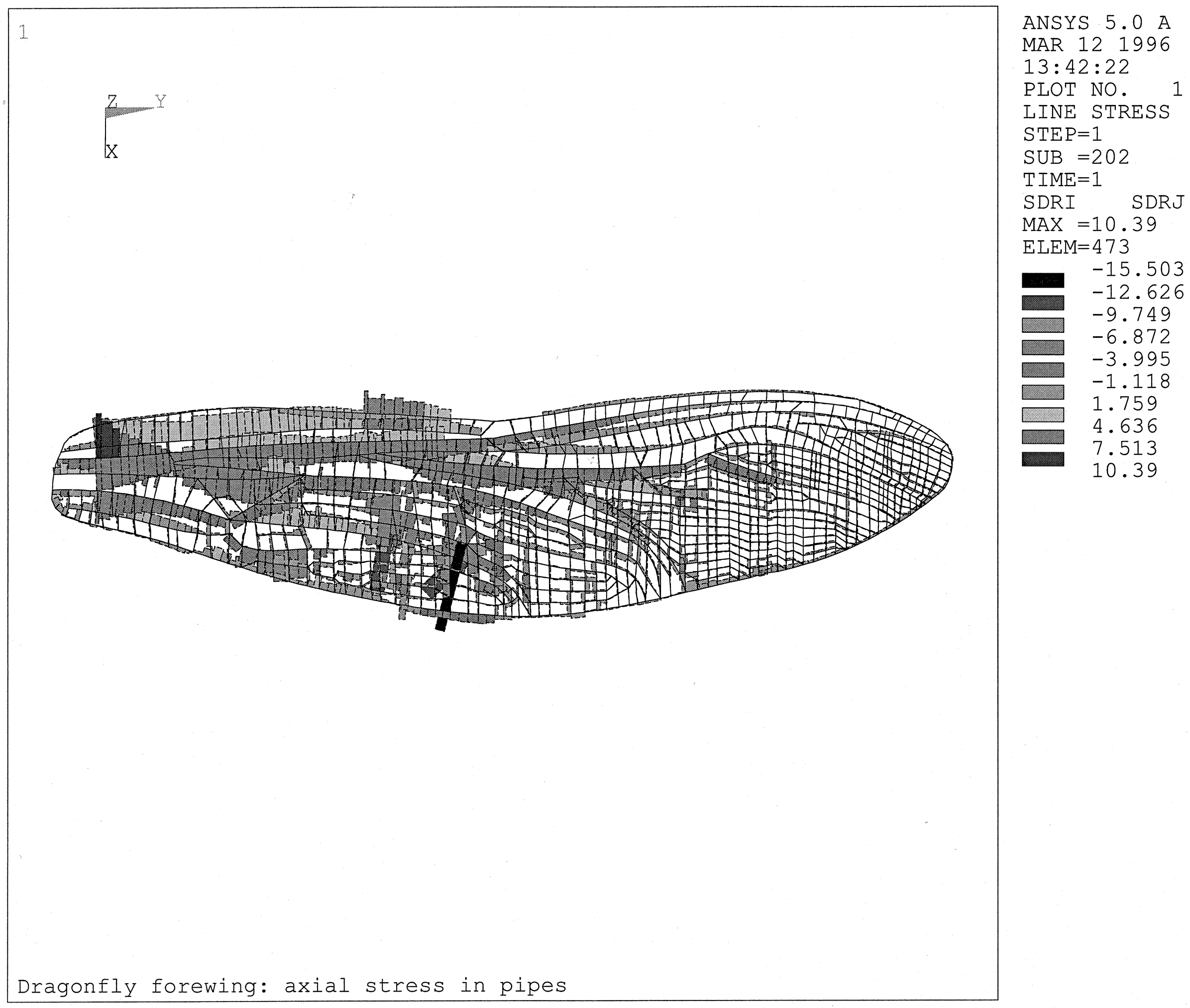

Fig. 7. Axial stresses in pipe elements of model IV under loading. Two stress maxima, one at the base induced by modelling artefacts and one in the middle of the wing induced by the geometry of the very complex nodal structure, are visible.

haemolymph which add up to 30% to its total mass. Furthermore, the membrane mass, amounting to ca. 1 mg, was generally ignored, so that the mass of the calculated model is very similar to the mean mass of 3.77 mg measured for the original wing.

The analysis of stress distribution in this model is particularly interesting (Fig. 7). It shows maximum values at two positions. As a result of the membrane strengthening necessary at the 'joint', modelling artefacts appear, so that the model is incorrect at this point, and the results thus obtained are irrelevant. The high stress values around the centre of the leading edge are caused by the conspicuous wing geometry in the nodal area.

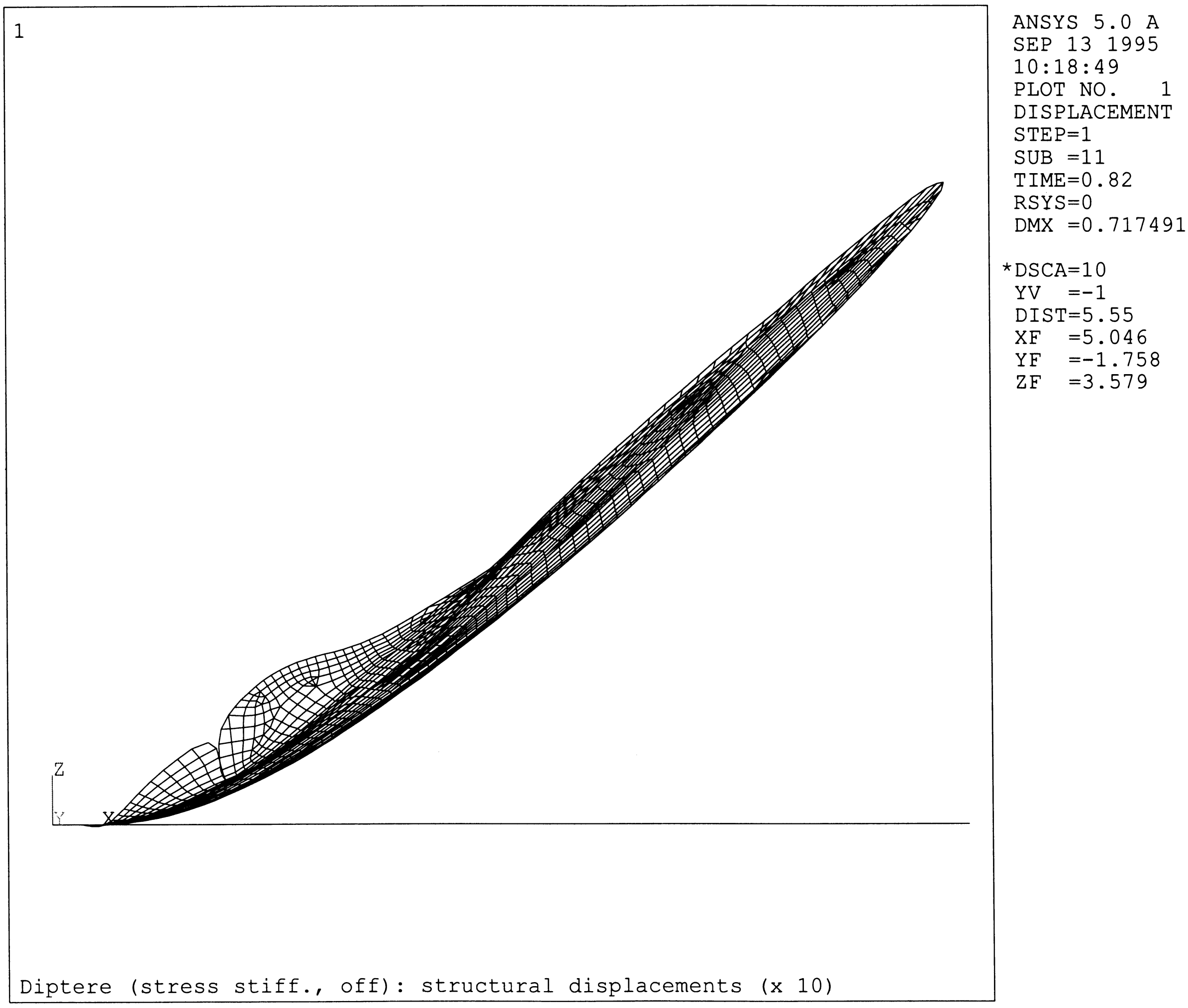

Fig. 8. Deflection of the Diptera (*Episyrphus balteatus*) 'wing without stress-stiffening' under loading. Only 82% of the required load was applied. (Deflections are shown increased by the factor 10.) (From Kesel et al. [13].)

3.5. Stress stiffening effects

Analyses have shown that stress stiffening effects have no great influence on the stability of the dragonfly wing. However, calculations for the fly wing have shown that it was significantly affected by stress stiffening. The model without stress stiffening effects invoked collapse under 82% of the required load (Fig. 8). The model accounting for stress stiffening effects reacted more rigid under loading. The wing showed only slight deflection (Fig. 9).

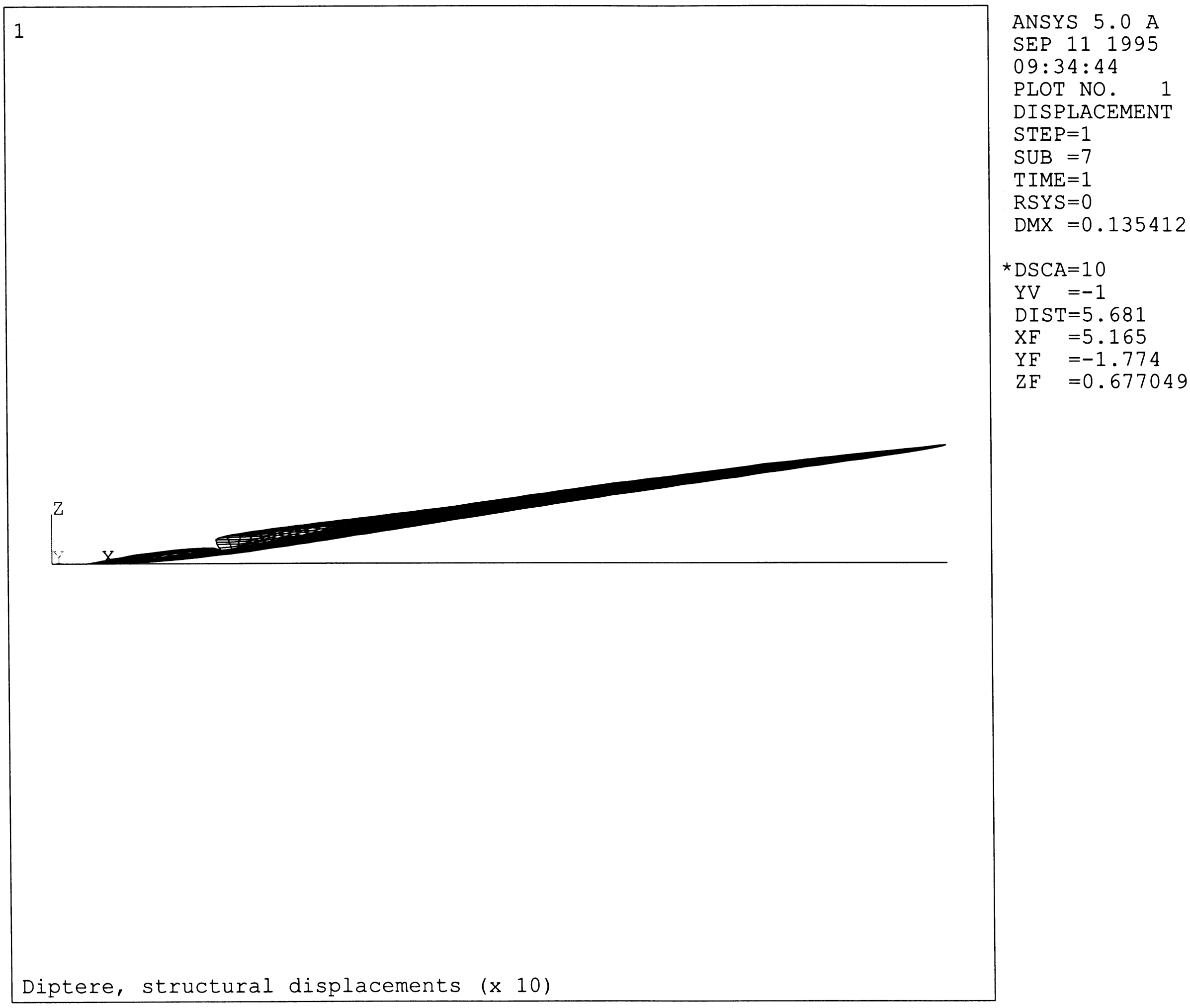

Fig. 9. Deflection of the 'wing with stress-stiffening' under loading proved to have considerably more load bearing capacity. (Deflections are shown increased by the factor 10.) (From Kesel et al. [13].)

4. Discussion

4.1. Stabilizing effects of wing configuration

Model calculations show that the stability of this ultra light wing is mainly achieved by its 3D configuration. The wing can be defined as a pleating structure characterised by the presence of stiffening edge beams along the folding lines. The profile of this folding structure is maintained by the edge beams. Thus greater structure stability is achieved with the least possible material expenditure. Analyses of simple mechanical models support these results. Due to an angular configuration, deflection can be reduced by the factor 113 by slightly increasing (ca. 10%) the material expenditure [14].

In addition, the results of model IV indicate the stabilizing influence of the vein network in the posterior section of the wing. To prevent the system from buckling and thus failing down under loading, the entire vein and membrane system (Fig. 6) has to be considered. The 'stiffening ribs' in the posterior wing area reduce the danger of collapsing. The longitudinal veins bending towards the rear edge and stiffening that wing section [15] are not sufficient to stabilize the whole structure.

The asymmetrical reaction of the model under loading, despite the 'stiffening ribs', leads to a torsion of the wing around its longitudinal axis. This torsion is caused by the interaction of wing geometry, distribution of material, material constants and external aerodynamical forces. From an aerodynamical point of view, a propeller like torsion is actually required [3, 5, 9]. Accordingly, the static behaviour of the modelled structure corresponds to the dynamic demands of the wing.

4.2. Aerodynamical effects of the wing configuration

Analyses of the aerodynamic characteristics of the dragonfly wing have shown that at least two effects overlap. On the one hand the profile is cambered, on the other hand, the camber is overlain with folds and ridges. Within the range of Reynolds numbers (10^3 to 10^4) relevant for insect flight, a cambered plane creates a more suitable lift–drag-relationship, i.e. it is aerodynamically more suitable, than a flat one [16, 17].

The extra folds and ridges on the dragonfly's wing provide not only more stability, but in addition have a positive aerodynamic effect. Visualisation experiments as well as measurements of lift–drag relationships show that, under stationary conditions, the zig-zag profile prevents flow from tearing off prematurely, thus enhancing lift [18–20].

4.3. Stress stiffening

The integration of stress stiffening effects in the fly wing model has shown that this material distribution (large thin membranes) is able to stiffen under the influence of loading and can bring more stability. The actual extent of a comparable mechanical behaviour in chitinous membranes has not yet been determined. The first signs of this have been found during experiments on the orientation in space of long-chained chitin molecules [21]. It was found that fibrils of chitin brace the membranes diagonally, which increases the bending and torsion resistance of neighbouring veins [9]. Thus, the membranes lying between the veins play a crucial role in stabilizing the wings.

4.4. Additional structure stabilizers

Stress analyses of model IV indicate that this system will collapse under the load of flapping flight (Fig. 7) which is largely enhanced comparing the loading under gliding. A real wing must therefore possess further stabilizing structures which have either not been included in the model, or have not yet been recognised. The membrane and its mechanical characteristic is one, but electron-microscopic studies have shown the presence of other stabilizing elements. The mechanics of the latter have still to be studied and then integrated into the model. One of these structures is the nodus which may be interpreted as a damper. It appears to dissolve critical stresses along the longitudinal axis of the wing, thus preventing the structure from collapsing.

Analysis with the finite element method have clearly demonstrated that the distribution of stabilizing material is of utmost importance for the mechanical load bearing capacity of a natural construction. In particular the corrugated 3D-configuration of the wing ensures its functionality [12, 22]. One cannot expect a spectacular increase in stability by integrating more constructional elements into the model, but one will have gained a better understanding of individual constructional elements and their effectivity. In the process of qualifying such effects, the finite element method is an ideal tool since it enables one to vary individual parameters of a (model) construction.

5. Summary

This study analysed the mechanical load-bearing capacity of a light-weight plane, the insect wing (based on the forewing of *Aeshna cynea*, Odonata). Three-dimensional data obtained by probing a wing surface, served as a basis for constructing a numerical model using the finite element method.

Simplified interpretations of various wing aspects were used to construct the model: the joint became a clamp, the veins a framed structure. The wing veins were implemented as pipe elements, the membranes as shell elements. Chitin was defined as an isotropic material.

The following results were obtained from a non-linear analysis carried out in several stages:

(1) The aerofoil wing is stabilized primarily by its 3-dimensionally folded configuration. Compared to the flatter 2-dimensional model, deflection in this model is reduced by the factor 20. Thus, more stability is obtained with least possible material, similarly to technical corrugated light weight structures.

(2) The secondary veins of the posterior wing section play an essential role in the stability as a whole. They greatly reduce the danger of buckling and structure failure.

(3) Nonlinear characteristics such as stress stiffening are very important for structure stabilizing of insect wings with large areas of membrane (e.g. Diptera). An appropriate orientation of the long-chained chitin molecules is prerequisite for such an effect.

(4) A series of small details, as for example the nodus localised on the leading edge of the wing, help in stabilizing the wing. Preliminary modelling with this detail suggests that it has a mechanical damping function.

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Antonia B. Kesel, born 1962 in Saarbrücken, Germany. Studied biology (Zoology and Biophysics) at the University of Saarland, Germany. Since 1988 co-worker on the project of the Deutsche Forschungsgellschaft "Locomotion in fluids". 1989 Masters degree on "Neurophysiological aspects of fish locomotion". 1993 PhD on "Aquatic locomotion" (studies on muscle physiology, movement dynamics and biomechanics in fish). 1993 till 1995 postdoctoral in Sonderforschungsbereich 230 "Natural Constructions" with

regard to the functional morphology and biomechanics of invertebrates and grasses (Poaceae). Since 1996 assistant lecturer in the Zoology Department of the University of Saarland, Saarbrücken, Germany. Field of research: Biomechanics (statics and aerodynamics of insect wings; structural stability in the axes of plants).

Ute Philippi, born 1963 in Saarlouis, Germany. Studied Biology with emphasis on Zoology and Technical Mechanics at the University of Saarland, Germany. Since 1985 co-worker in Sonderforschungsbereich 230 "Natural Constructions". 1989 Masters degree; Thesis on "Allometrical and biomechanical analyses on carapaxes of Carcinus maenas". 1993 PhD on "Investigations of the constructional morphology and biomechanics of the sea urchin shell using the finite element method". Currently, she is working as an independent with the Department of Zoology of the University of the Saarland, on finite element studies of insect wings and blade of grasses.

Werner Nachtigall, born 1934 in Saaz. Studied biology and physics in Muenchen, Germany. Since 1968 Head of the Zoology Department of the University of the Saarland, Saarbrücken, Germany. Numerous publications about aspects on animal movements, especially on insect and bird flying.