Inflatable Membrane Structures
Pneumatic Systems in Nature and Technology

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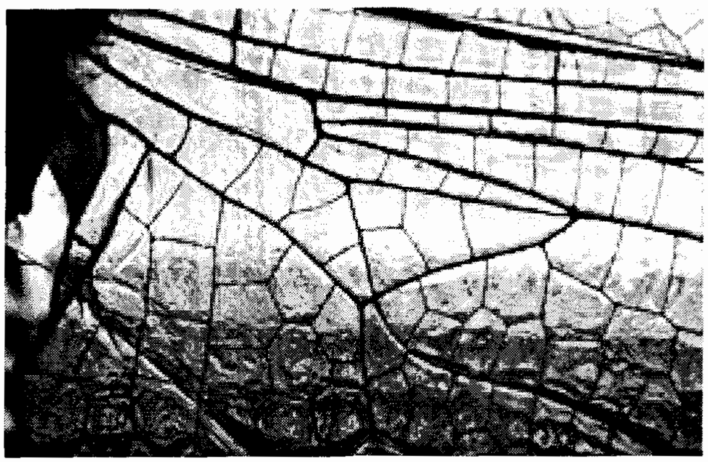


Fig. a. The Dragonfly Wing Membrane.

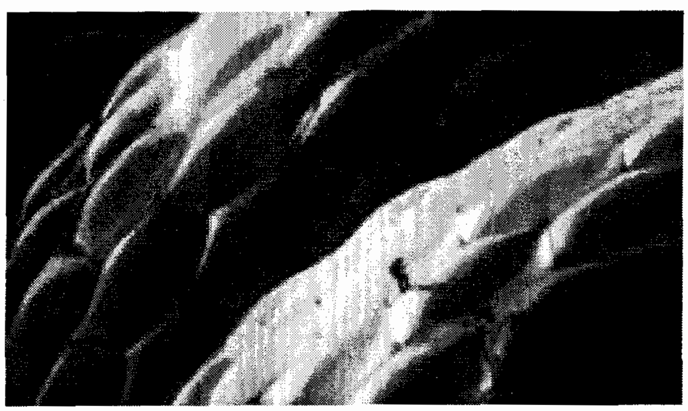


Fig. b. Eden Project. N. Grimshaw. Architects. A. Hunt. engineers. Membrane ETFE-Pillows.

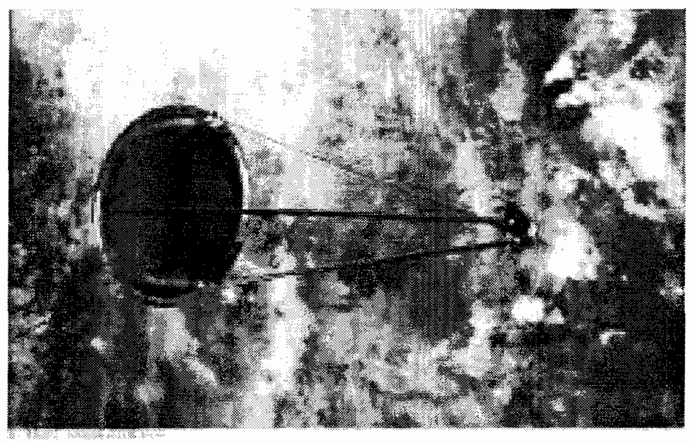


Fig. c. Inflatable Antenna Experiment – The Canopy.

ABSTRACT

Human technology has not yet equaled the highly complex and efficient construction principles of nature, as shown in the example of a dragonfly wing. Multifunctionality is a common principle of biological structures. Through the analysis of biological light weight structures and structure system using Finite Element Analysis and material analysis we can make quantitative statements regarding their constructive efficiency. This research focuses on the relationships between the structure system, (a tubular folded plate, a hydraulic system and a membrane) and the material of the dragonfly wing (nature) and makes the connection to new materials and smart structures used in engineering (technology).

The definition for light-weight construction is the optimization of the path of forces towards the reduction of the constructed volume. This research will examine to what extend adaptively affects the optimal geometry and efficiency of a structure. The goal is to define a set of structural principles, and to make those principles applicable for architects and engineers.

INTRODUCTION

From the scientific, architectural, aerodynamic and engineering standpoint the wing of the dragonfly is a perfect object to study because of its lightweight and yet rigid structure. The wings are in particular fascinating because of the minimal use of material (only 2% of the bodyweight). The basic structure of a dragonfly wing consists of a tubular *folded plate* (the veins) of primary bending members, secondary bending members and a chitin membrane that spans between the bending members. In addition, there is a hydraulic system of fluids that constantly flow through the bending members. The wing itself emerges from its chrysalis as a compactly folded structure. To deploy the wings, a fluid flows from the dragonfly's body out into the members of the wings. The hollow members respond to the growing pressure of the fluid by expanding outward and deploying the wings.

The veins (Fig.1) also stiffen the dragonfly's wing and support its cantilever, similar to the way spars or box-sections stiffen and support an aircraft wing. The stiffening is greater near the front of the wing, so that even crude up and down flapping of the wing tends to create lift and forward motion. The members themselves, as well as the majority of the dragonfly's body, are made of Chitin (Fig. 12). This particular material is a versatile compound that can either be rigid or flexible, thick or thin. From a morphological point of view the multilaminated procuticle of insects can generally be described as a natural composite material consisting of mainly chitin fibrils and other components embedded in a protein matrix (Vincent 1980).

HYBRID STRUCTURE
The smart structure of the dragonfly wing

Structural systems that have an embedded capability to sense external stimulus and respond to it depending upon predetermined criteria are commonly referred to as "Smart Structures." Smart structures positively affect the static as well as the dynamic characteristics of the system and minimize the weight of the structure. Smart Structures essentially consist of three components: nerve-similar sensors, which measure the external influences, a control system, which process the information, and muscle-similar actuators, which work against the outside forces. A perfect example of a smart structure in nature is the dragonfly wing. This active system is able to change the geometry and the physical properties accordingly to dynamic loads to optimize stress and deformation.

These changes can be local for example in the joints between the thorax and wing and/or global in the entire wing structure.

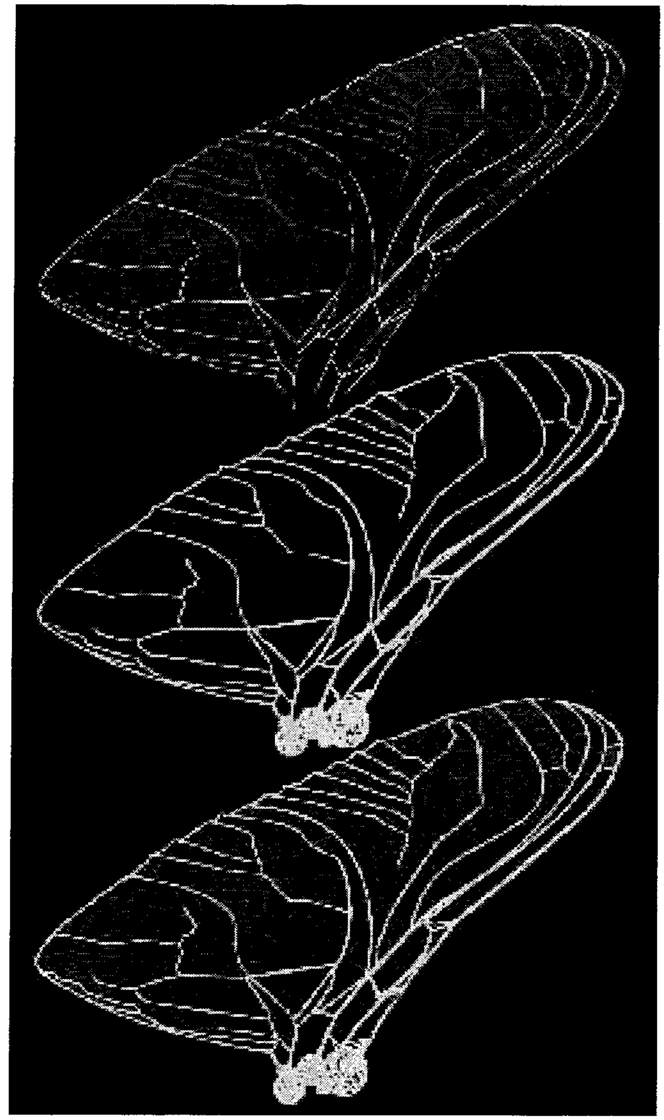
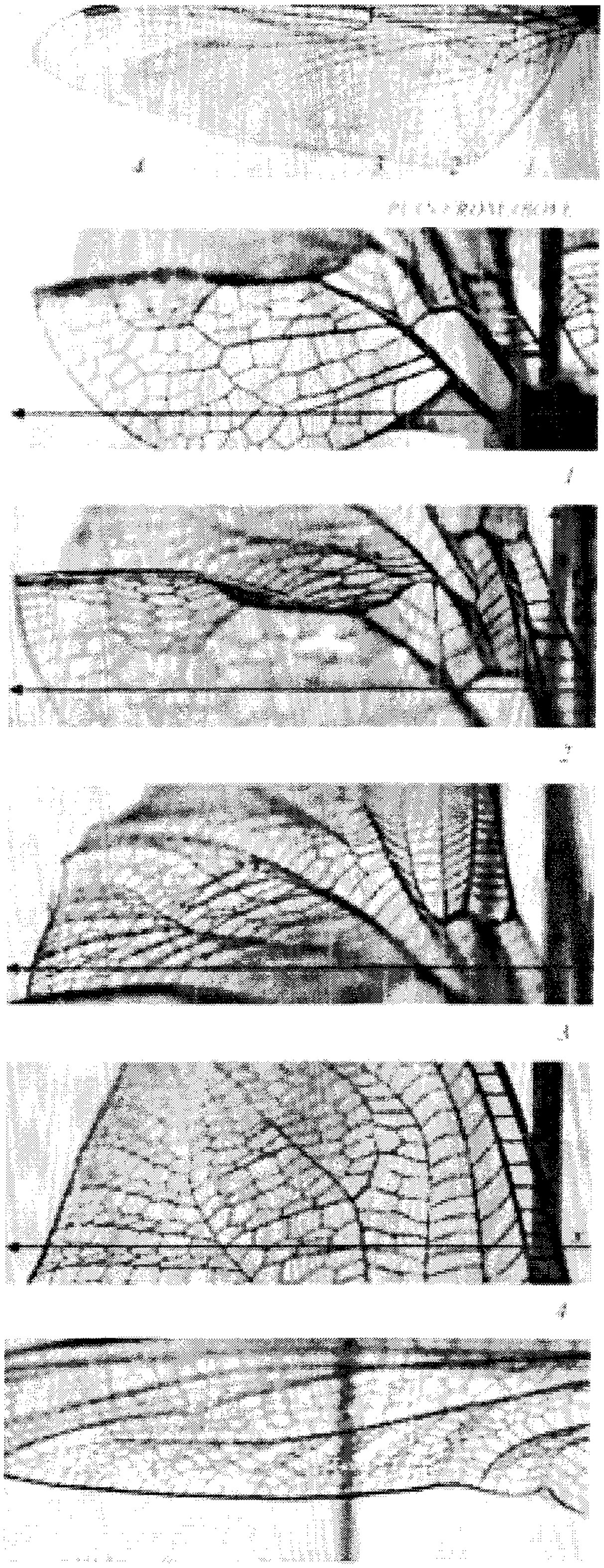


Fig. 1. Digital Model of Dragonfly Wing showing primary and secondary bending members (The Vein system) and the pentagonal cells.

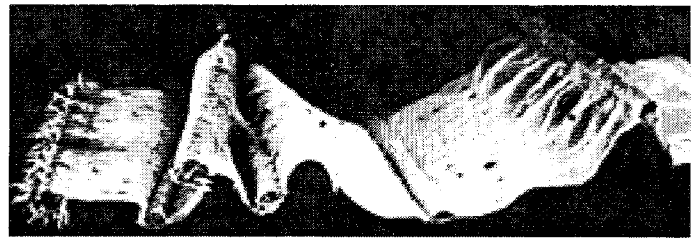
The Smart Joint
Attachment Tubular folded plate to the thorax

The motion of the wings is very complex. The attachment to the thorax and the musculature and structure of the thorax all contribute to the ability to fly.

The attachment itself is not a single joint, but a far more complex arrangement of smaller individual joints (Fig.6/7). Each main vein is attached to one of these joints. Individual muscle groups are able to control each individual member witch consist of a joint and a vein. This gives the ability to increase or decrease individually and actively the bending moments of each main bending member. Therefore the wing can be actively deformed under flight operation and decreases



Basic Structure Component: ***Tubular folded plate***
A. Primary bending members.
B. Secondary bending members.
Fig. 2. Axiomatic digital photography showing Membrane Corrugation of the wing.



C. Chitin membrane in between bending members.
Hydraulic System Primary and secondary bending members are filled with fluid.
Fig. 3. Cross-section wing [Prozess und Form. SF 230. pp.39].

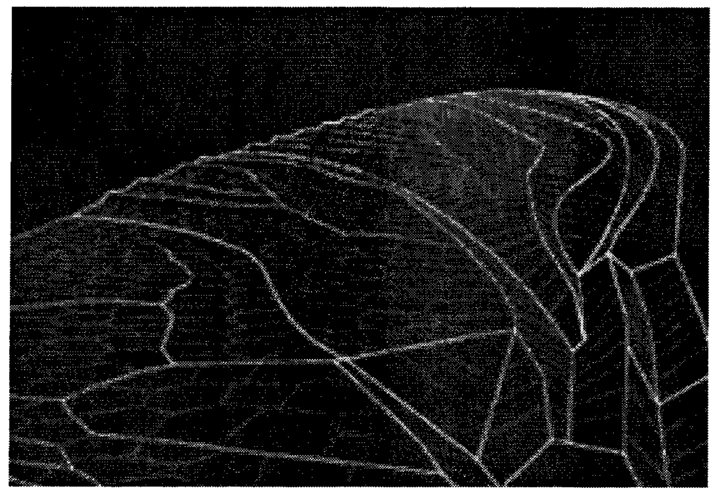


Fig. 4. Corrugation perpendicular, primary bending members.

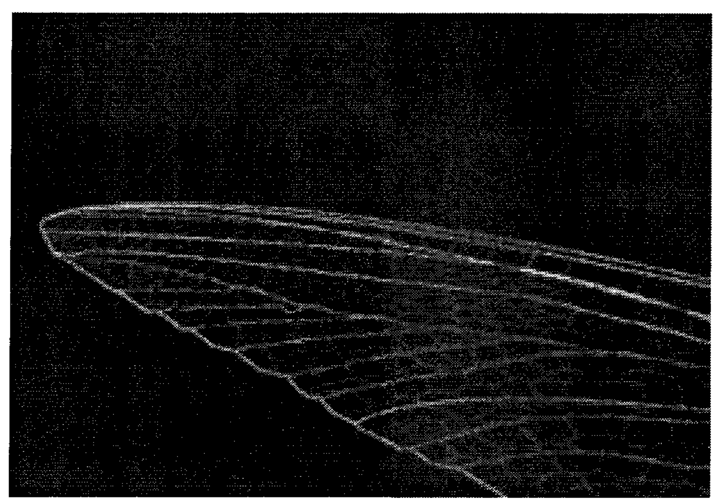


Fig. 5. Corrugation longitudinal, secondary bending.

the internal forces. The wing joint is able to response dynamic under dynamic loading.

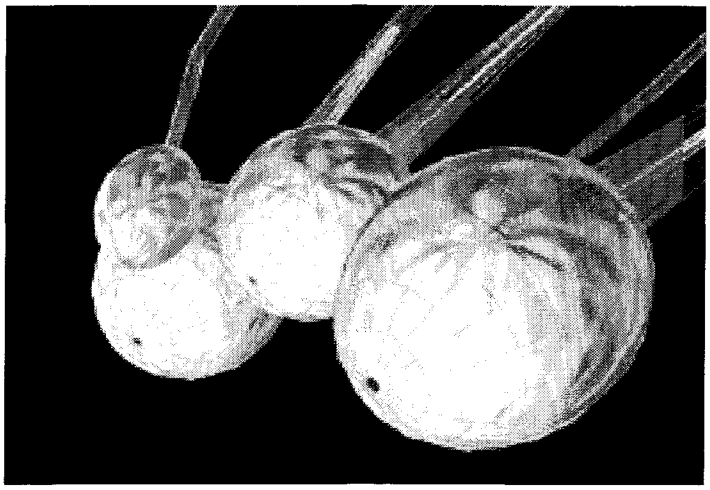


Fig. 6. Digital Model of Dragon-fly Wing Joint.

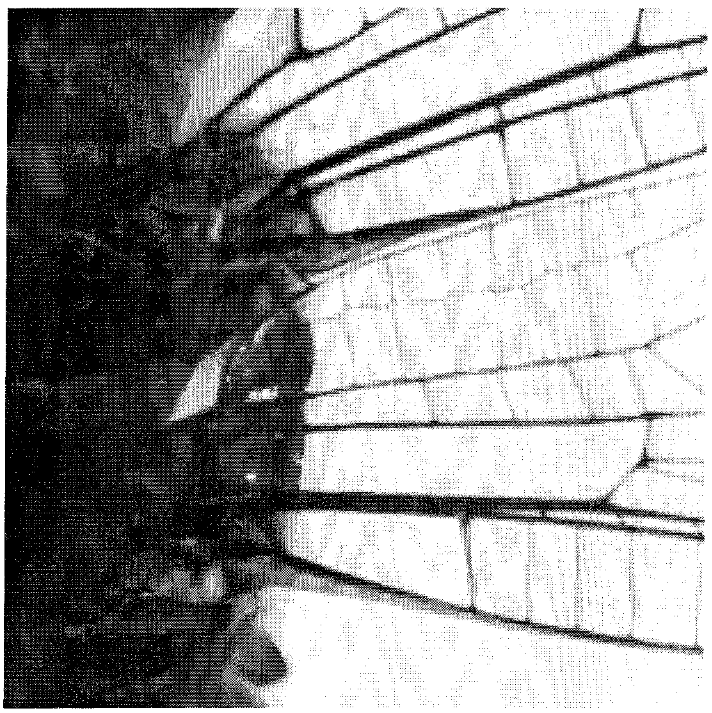


Fig. 7. Dragonfly wing.

Tubular folded plate

When the wings are fully deployed, they consist of hundreds of small polygons that interlock to provide structural rigidity to the wing. This system is similar to a intersecting folded plate. Since the entire wing's structure is hollow tubular members, its weight is dramatically reduced. Corrugations in the wing structure also contribute to its strength.

The corrugated rigid structure of the wing has (Fig.2) many folds in different directions. There are two major sets of corrugations. The primary corrugation system (Fig.4) extends in the long direction of the wing and mainly exists at the front. The secondary (Fig.5) set runs approximately at a forty-five degree angle. This set is mostly found at the rear and the outer half of the wing. This corrugation has been proven to produce a large bending rigidity than that of a non-corrugated structure of similar proportions and is even advantageous for the aerodynamic behavior of the wing.

The tubular vein-system combines the structural efficiency of bending rigidity hollow tubs with optimal material efficiency. Analogues with technical pneumatic hoses the main veins are braced with spiral wall reinforcing fiber-matrix material. [B. Kessel]

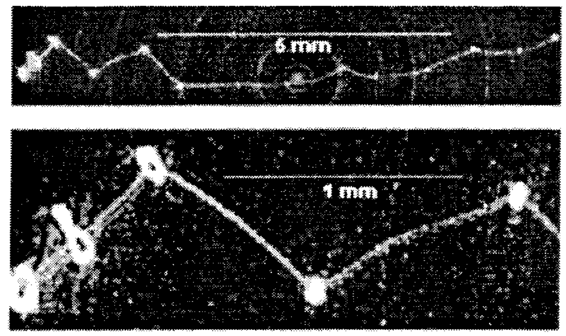


Fig. 8. Micro-computer-tomography of a dragonfly hind wing (Aeshna cyanea) demonstrating the special zig-zag-configuration of the veins in the anterior part of the wing. (taken from P. Kreuz, A.B. Kesel, H. Vehoff , A. Fery , W. Arnold, Fraunhofer Institute for non-destructive testing (IZFP)).

A non-destructive method to determine the geometry of small specimens is the micro-computer-tomography. The cross-sectional diagram (Fig.8) demonstrates the distinct zig-zag-configuration in the anterior part of a dragonfly hindwing (Aeshna cyanea, Anisoptera). [P. Kreuz ...]

The Membrane

Very little cuticle material is used to build the wings in order to reduce mass. The membrane combining the vein-network of a dragonfly wing (Anisoptera) is approximately 3-5 m thick. Nevertheless the special morphological construction and arrangement of the wing veins and membrane combined with the particular mechanical properties of the wing cuticle guarantees the stability and the aerodynamic function of this natural ultra light aerofoil (B. Kesel 1998).

Hydraulic System

Although very light, the efficiency of the wing itself increases during flight because the transfer of fluid decreases bending moment dramatically. This efficiency during flight is made possible by another aspect of the dragonfly wing's hybrid structure, the hydraulic system. As the dragonfly take flight, fluid from its body transfers to the wings venation (Fig.11)

Fig. 9/10. The wings of the insect are based on quadrilateral and pentagonal cells, braced against shear by a thin membrane.

system increasing their weight, and in turn making the body lighter.

This brings up the question of how structural systems might develop dynamic response to load under dynamic loading. This is analogous to consideration of weight distribution in modern-day aircraft design, where fuel tanks are located in the wings to increase their weight but the weight changes dynamically over the course of a flight as fuel is burned and redistributed between tanks.

MATERIAL CHITIN

The cuticle of arthropods: a multifunctional fiber-in-matrix material

The cuticle of arthropods can be interpreted as a greatly variable fiber-in-matrix material dependent on function and position. Its wide range of application extends from extremely

Cuticle – two main components:
- long-chained, highly crystalline poly-saccharid chitin
- multi-structural chitin which constitute the matrix material.

Material Properties:
- actively respond to external changes

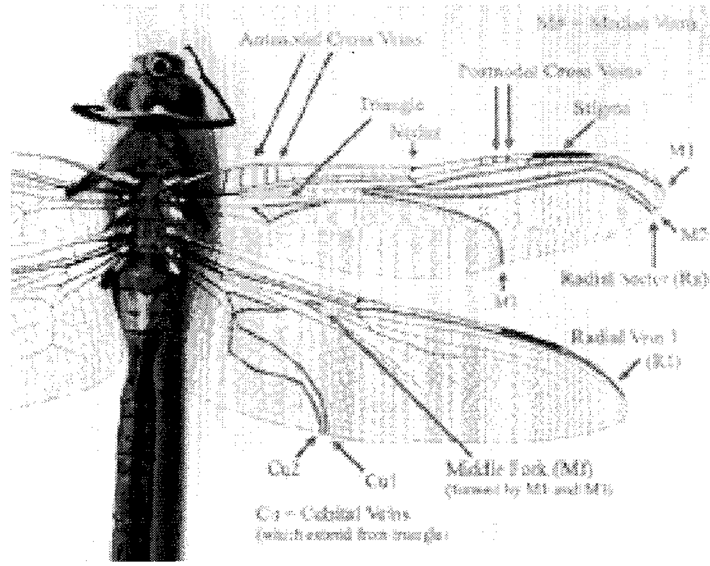


Fig. 11. Wing Venation (Taken from "A Glide to Dragonflies and Damselflies of North America" ... 2002 Gloria Mundi Press).

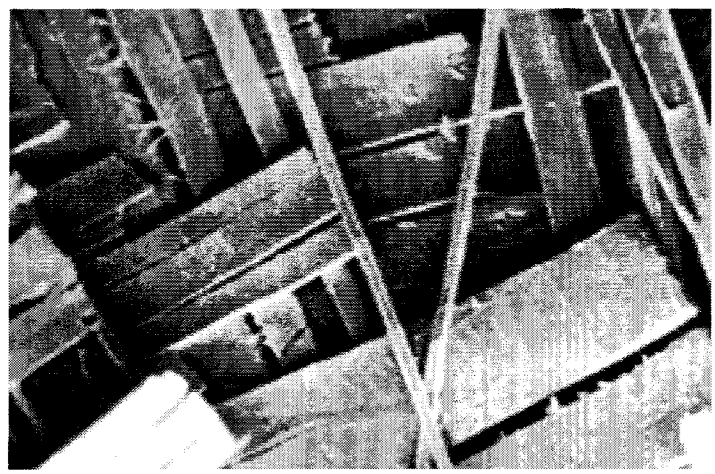


Fig. 12. Plywood-like orientation of the endocuticle of an elytron of a scarab beetle (taken from Neville 1993 "Biology of fibrous composites", Cambridge University Press).

- variable fiber-in-matrix dependent on function and position
- wide range of performance from extremely hard to elastic
- self-repairing, capable of identifying a failure and reacting accordingly

The cuticle always consists of two main components: a long-chained, highly crystalline poly-saccharid chitin and multi-structural chitin which constitute the matrix material. On a molecular level the mechanical properties of the chitin are determined by the bonding between the various proteins or between proteins and chitins or lipids. Furthermore, characteristics such as elasticity, rigidity and hardness are influenced by the long-chained polymer chitin. The rigidity or hardness of the fiber composite material chitin expands with increasing sclero-

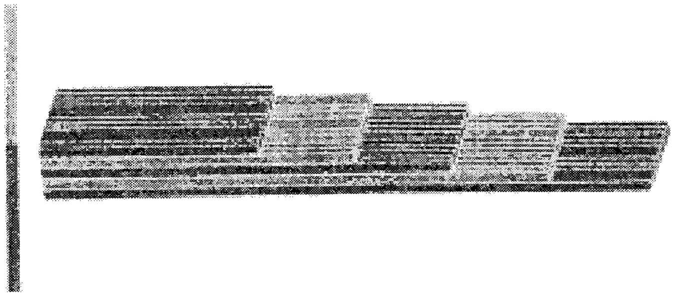


Fig. 13. Different layers in a "cuticle cube" (FEM, different orientations are coded by red and blue) hard biting tools (a task that requires extreme rigidity). to elastic joint membranes (which require extreme bending). This range of performance suggests that structural materials might also be considered in terms of the total dynamic range of properties possible for the component materials and the different organization of those materials into a structure.

tization of the matrix material. whereas the chitinous fibers themselves have a substantial influence on the elasticity.

Furthermore chitin fibers aggregate to form fibrils, which are arranged in variable fibrous compounds. The differing orientation of these fibrils in superimposed layers (Fig. 12/13) also influences the mechanical material characteristics. At the same time, the helicoidally orientation of the layers appears to be of greatest importance for the multi-functionality of the material. The catalogue of the mechanical characteristics of the material 'cuticle' at different hierarchical levels is based on simulation experiments using the finite element method.

NEW MATERIALS AND STRUCTURAL SYSTEMS

Smart materials are similar to the natural material chitin in there potential to be adaptable and self-repairing materials capable of identifying a failure and reacting accordingly. Potentially these 'adaptive' composite materials will be able to adapt themselves to particular external requirements, because do not have fixed properties. They are then able to actively respond to external changes such as temperature, radiation, loading or electrical current. Of particular interest is the reversibility of changes in property.

For about the last ten years, there has been an increase in the use of composite fiber materials made from glass, carbon, or aramide fibers (ex. Kevlar) in architectural and engineering applications. The benefits from these fiber-reinforced plastics are in their increased stability, minimal weight, and resistance to corrosion. Unexplored uses for composite fibers include not only the replacement of conventional materials like steel, aluminum or wood, but also uses particular to the new material. Especially in the case of structurally optimized building elements and systems, entirely new design possibilities are available. The idea of material and weight distribution according to the specific requirements means that material will only be placed where it is necessary according to the amounts required by structural statics and dynamics. It opens a new dimension in the field of material and structural optimization. Even a new technology of optimized connections of building elements can be developed from the adhesives used for plastics and aluminum in the airplane industry.

Inflatable Rigidizable Space Structure

Large hydraulic tubular space frames using inflated membrane shapes with diameters greater than 20 meters are already in use (Fig.14/16). Aperture diameters between 50 m and 100m for use in a space-based system like the Terrestrial Planet Finder and the Terrestrial Planet Imager, NASA (scheduled for launch in 2012/20) will be impossible without the use of very lightweight and volume-conformable systems. These structures are inflatable but extremely rigid after deployment.

Because the mass and stowed (un-inflated) volume of inflatable components is many times less than an equivalent solid structure, inflatable structures can significantly reduce the cost of future missions using these components (10 to 100 times less expensive).

Inflatable structures also have the potential to deploy much more reliably than the conventional mechanical systems used for deploying rigid structures. In addition, the small packaged

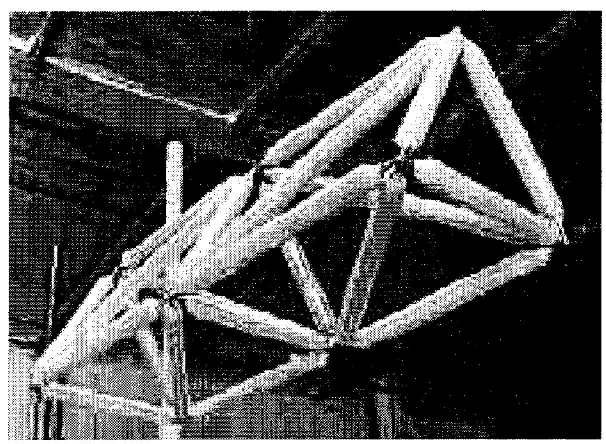


Fig. 14/15. IRSS Hydrogel Truss Mass < 2 Kg Compressive Load Capability = 290 lb; Damping = 15.5%. © L'Garde.

size of the inflatable components allows very large structures to be deployed in space with a single small launch vehicle.

This space truss prototype (Fig.14/15) is deployed un-inflated from a very small package. It inflates to a light, strong, and stiff space frame suitable for many space applications. Shortly after inflation the structure material rigidizes and internal pressure is no longer required.

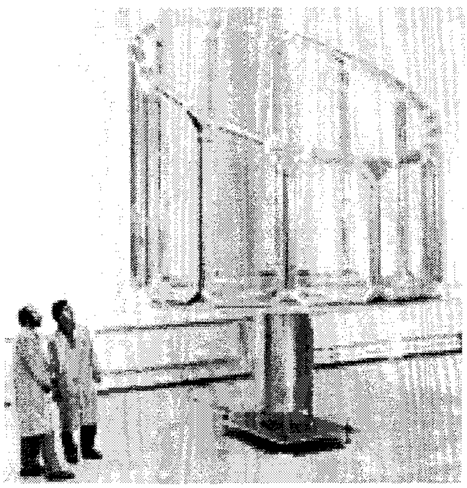


Fig. 16. Inflated space antenna ... Contraves Space AG.

The air cushion from the inflated space antenna by Contraves Space AG (Fig.156) is made out of thin film, inflated in space and hardens under UV-light. This is comparable with the dragonfly wing witch is also harden ones diploid.

Smart Pneumatic Structures in Architecture

An example for a smart pneumatic structure in architecture is the pneumatic exhibition building that was developed by Festo (Fig. 17/18) reacts to environmental influences like a living organism. 330 single air-inflated chambers and a computer create a self-controlled system which checks the pressure of each chamber at regular intervals and controls it in accordance with a weather station. Pneumatic muscles (elastic tension elements) are contractile hoses which – with the help of air pressure – are able to generate tension forces that can be controlled exactly.

CONCLUSION

The Dragonfly Wing is an example for the combination of a form-optimized structural system (smart structure) with an extremely light and flexible material (composite fibers). This creates an extremely low ratio between the loading capacity and the constructed volume of a structure.

The Dragonfly wing shows that 'smart structure' has a wealth of unexplored possibilities. Its 'adaptive' systems of one or more structural components are able to adapt themselves to particu-

Fig. 17. The pneumatic exhibition building © Festo AG Esslingen, Germany.

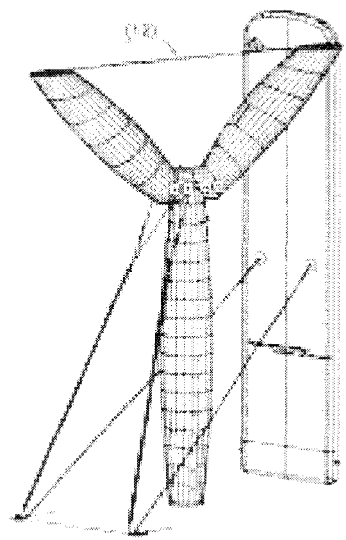


Fig. 18. Y-shaped column connected to a wall component and the pneumatic muscles (elastic tension elements).

lar external requirements, because each structural component has a dynamic range of properties. Taken together this range gives increased flexibility to the total system. This complexity is not yet reached in architecture ore engineering.

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