



Bioinspiration For Engineering And Architecture

Materials—Structures—Function

George Jeronimidis

Centre for Biomimetics University of Reading University, Reading, UK

1 Introduction

Biology has had to solve engineering problems since the appearance of life on earth. Design and function in plants and animals have been optimised under evolutionary pressures over millions of years, a small step at a time. These long lead times do not fit easily with the more frenetic pace of the engineering world of today but to dismiss on these grounds the solutions that nature has arrived at would be foolish and arrogant. Time-scales may be different but design constraints and objectives are very similar: multi-functionality, optimisation and cost-effectiveness. Therefore, it is not surprising that mankind has always admired biological structures and often been inspired by them, for we can appreciate their aesthetic attributes as well as their engineering and design content. Some early examples of engineering structures which borrowed ideas from nature include the Eiffel Tower¹, Crystal Palace² and all manner of primitive and rather ineffectual flying machines³. More recently, the architectural community has looked at fresh approaches for the design of functional buildings, often taking inspiration from biology³⁴⁻³⁵.

Biomimetics or, bio-inspiration, is likely to play an increasing role in design because of all the current issues concerning sustainability, carbon foot prints, energy efficiency, etc. Its purpose is to look at what biology has to offer in terms of materials, hierarchical organizations into structural components, design and processing. A useful definition of what biomimetics is, and what the objectives are, is the one coined by Prof. J.F.V. Vincent - "the abstraction of good design from Nature"⁴. What biomimetics actually means is more a matter of personal belief than a rigid dogma, "...it means just what I choose it to mean, - neither more nor less". More important is to capture the very essence of biomimetics which is its multidisciplinary. In the words of the French naturalist Buffon: "...Nature, on the other hand, takes every single step in all directions; in going forward it spreads sideways and extends above; it travels in all three dimensions and fills them all at the same time; whereas mankind reaches a point, Nature embraces the whole volume."⁵. In abstracting ideas from biology and turning them into practical engineering and architectural solutions, all disciplines have something to contribute. Success can only come from their integration.

2 The Materials Of Biology

Looking at the basic materials, i.e. the chemical substances used by organisms to provide the properties needed for the various mechanical functions it is interesting to note that there are comparatively few, far fewer in fact than what is available to the engineering community. They do not have any especially outstanding characteristic and, compared to many engineering materials, none of them has a particularly high Young's modulus, tensile

strength or toughness. In other words they cannot be classed as “high performance materials”, although they do have much lower densities than most. They are successful not so much because of what they are, but because of the way in which they are put together. Here is perhaps a first biomimetic lesson: extremely successful engineering solutions do not require esoteric and expensive materials. The De Havilland Mosquito bomber of the last war is a good example of how far you can go with “primitive” materials such as wood but with a great deal of ingenuity, design skills and creative thinking.

The bulk of the mechanical loads in biology are carried by polymer fibres such as cellulose (plants), collagen (animals), chitin (insects, crustaceans) and silks (spiders’s webs). The fibres are bonded together by various substances (polysaccharides, polyphenols, etc.), sometimes in combination with minerals such as calcium carbonate (mollusk shells) and hydroxyapatite (bone). The way in which fibre architectures are organised and the degree of interaction between them does provide the means of tailoring properties for specific requirements. It is the same collagen that is used in low-modulus, highly extensible structures such as blood vessels, intermediate modulus tissues such as tendons and high modulus, rigid materials such as bone. Direct measurements of the intrinsic mechanical properties of the smallest building blocks, the microfibrils, are virtually impossible. Some of them can be inferred from measurements on tissues containing them or predicted from theoretical considerations⁶⁻⁹.

It is a fact of life that nearly all load-bearing materials in nature are fibrous composites of some kind or another. It is very much a case of CRU, i.e. Composites Are Us. The reason for this is probably that the synthesis of long polymer chains based on carbon, oxygen, nitrogen and hydrogen makes use of readily available chemicals and can be controlled by enzymes at low temperatures. If the building blocks are long macromolecular chains, their aggregation into microfibrillar structures and beyond is the next logical step, especially when it is helped and stabilised by crystallisation and interactions between chemical side groups. The man-made counterparts of these biological fibrous materials are high-performance fibres such as nylon, aramid and highly-oriented polyethylene. Nylon is particularly interesting because its synthesis was the result of a research effort to find an alternative to natural silk -an early example of biomimetic thinking.

The use of fibres for making structural materials offers a great deal of scope and flexibility in design but it also presents a few problems. As a consequence of using fibres and fibre-reinforced materials, anisotropy of physical and mechanical properties and heterogeneity have to be accepted. If properly exploited, they can provide higher levels of optimisation than would be possible with isotropic, homogeneous materials because stiffness and strength can be matched to the loads applied, not only in magnitude but also in direction. In biology this is extremely common and happens as a result of “growing under stress”. The magnitude and direction of the loads that the organism experiences as it develops provide the blueprint for the selective deposition of new material, where it is needed and in the direction in which it is needed. The best known examples of this are the “adaptive” mechanical design of bone and trees. In bone, material can be removed from the under-stressed parts and re-deposited in the highly stressed ones¹⁰; in trees a special type of wood, with different cellulose microfibril orientation and cellular structure from the norm, is produced in successive annual rings when mechanical circumstances require it¹¹.

There is little doubt that growing a structure by producing and organising fibres under the control of the loads that it has to carry is extremely effective, albeit slow. Numerous patterns of load-bearing fibre architectures are found in nature, each one of them being a specific answer to a specific set of mechanical conditions and requirements¹². In a sense there are no general design solutions in biology but individual ones, governed nevertheless by common general principles. In engineering this process is replaced by stress and structural analysis which is not always accurate and often very complex. In recent years, numerical techniques based on Finite Elements have provided new tools to simulate the adaptive design of nature and this approach has proved to be very successful^{13,14}.

A major problem with fibres is that they are most efficient when they carry pure tensile loads, either as structures in their own right (ropes, cables, tendons, silk threads in spider’s

webs) or as reinforcement in composite materials used as membrane structures in biaxial tension¹⁵. Being slender columns, fibres cannot carry loads in compression because of buckling, even when partially supported laterally by the matrix in composites. In the case of polymer fibres, micro-buckling at the microfibrillar level within the fibre results also in very poor compressive strengths. This problem is common to both man-made and biological composites. To this day, the main issue which plagues the design of composite structures is their low compressive strength which limits the exploitation of their high specific modulus and strength in tension. Since nature had no alternatives to fibres as building blocks, it had to find ways of offsetting the low efficiency of fibres in compression in order to expand life beyond the limits of squidgy invertebrate species or aquatic environments. There are four solutions available in nature to this problem: pre-stress the fibres in tension so that they hardly ever experience compressive loads; introduce high modulus mineral phases intimately connected to the fibres to help carry compression; heavily cross-link the fibre network to increase lateral stability, and change the fibre orientation so that compressive loads do not act along the fibres.

3 The Structures Of Biology: Hierarchies

As Jim Gordon, the unforgettable author of *The New Science of Strong Materials and Structures*, was fond to say, when one is dealing with very heterogeneous fibre-reinforced composite systems, the distinction between materials and structures becomes one of convenience rather than of fact^{16,17}. This distinction becomes even more elusive in biology because between the polymer macromolecular chains (at the nanometre level) and the functional organ (at the millimetre or metre levels) there is a multiplicity of structures which represent different levels of aggregation of the load-bearing materials. These hierarchical organisations are the rule rather than the exception in all biological composites. They are probably the result of growth by successive deposition of fibres and other materials. They are difficult to analyse because of their complexity but, by varying the degree of interaction between sub-elements within a hierarchical level and between levels, stiffness, strength, toughness, etc. are modulated, tailored and optimised for specific requirements^{18,19}. This kind of integrated sub-structuring is a common theme in biology, far more subtle and extensive than in any man-made material or structure.

Familiar biological materials such as tendons, bones, muscles, skin and wood provide amazing arrays of hierarchies spanning in typical dimensions from 10⁻⁹ metres at the molecular level, to typically 10⁻³ - 10⁻² at tissue level and 100 and beyond at the organ level. In trees, for example, the representative diameter of the various substructures covers a range from 10¹ metres (trunk of sequoia) down to 10⁻⁸ metres (diameter of cellulose protofibril) i.e. ten orders of magnitude with perhaps eight hierarchical levels: organ (trunk), tissue (wood), wood cell, laminated cell walls, individual walls, cellulose fibres, microfibrils and protofibrils.

It is true that all engineering materials, metals, plastics or ceramics, have also micro-structure but, in general, their Representative Volume Element (RVE) is very small compared to the linear dimensions of the structures or structural components they are used for. In a metal, the grain size may be of the order of 10 μ m; hence, a volume of 0.1 mm³ will contain 10⁵ grains. Even if the grains have different orientations, with different properties in different directions, owing to anisotropy of their crystalline structure, the average value of the property over the RVE can be considered constant throughout the material. In more heterogeneous materials such as glass or carbon fibre-reinforced composites, with typical fibre diameters of 5-10 μ m the RVEs are of the order of a few mm³. It is interesting to note that the man-made polymeric fibres such as aramid, and high-oriented polyethylene do have a few hierarchical structures within the fibre itself (highly oriented polymer microfibrils); because of them, they do share the same benefits and drawbacks of biological fibres: high tensile strength, high modulus, high fracture strains but poor compressive properties.

4 Functional Integration And Design

One might define a good engineer as someone who is capable of extracting maximum performance at minimum cost from the materials he has available and achieve a design that is “fit for purpose”. This has been a recurrent theme in engineering courses since the subject became academically acceptable as a discipline and, together with creativity, they are the yardsticks by which we judge success or failure. All too often, the problem is not with the aims but with the methods we use to achieve them. I refer in particular to the fact that our traditional approach to design has been severely limited by the labels that we often attach to ourselves, or that others have seen fit to identify us with: engineer (mechanical, structural, civil, materials, medical, aeronautical, transport, electrical, electronic, software...). In the same way as in nature the boundary between materials and structures is blurred, the study of biological systems to understand those aspects of design that might be useful for our purposes requires an integration of all the disciplines above. The main reason for this is that biological structures are often multifunctional, in the sense that they often perform more than one task. If we do not understand what the various functions are, and how they are controlled and integrated, it will be difficult to extract any useful lesson. There is also the risk of being blinded by admiration at what nature does, accept that “all is for the best in the best of possible worlds”, and either leave it at that or turn it into a religion.

It would be difficult to argue that multifunctionality is a route to optimisation. The recently emerging disciplines of smart materials and structures are at the forefront of scientific and technical developments in that direction and in doing so they have stimulated a renewed interest in biology and biomimetics²⁰. Rather than present a series of recipes of how nature can inspire engineering, the examples which follow will illustrate better some of the features of multifunctional design in biology, focussing on what I believe are the main lessons to be drawn from an engineering perspective.

4.1 STRUCTURAL OPTIMISATION

In this respect there is nothing special about biological systems other than the fact that the solutions it has arrived at are the logical conclusion of the problems with fibres mentioned earlier. There are rules which govern the efficiency of materials in a structural context^{16,17,21-23} and the answers we observe in nature appear to follow them, probably better than we do ourselves. If fibres are good in tension and bad in compression (and hence in bending), use them in tension either by pre-stressing them or by stabilising them laterally using ceramic materials of high modulus or extensive cross-linking with suitable matrices.

All these tricks are used in biology. Many animals with flexible skins (worms, sharks, tunicates) use hydrostatic skeletons where the pre-stressing of fibres in tension is balanced by compression in a fluid (mostly water and hence not expensive). Similarly, non-lignified plants are entirely dependent on control of turgor pressure inside the cells to achieve structural rigidity, pre-stressing the cellulose fibres in the cell walls (typically up to 200 MPa) at the expense of compression in the fluid. In bones, mineralisation of the collagen with hydroxyapatite increases the modulus of the collagen-mineral composite fibres and hence their buckling resistance; what is particularly interesting in this system is that the collagen microfibrils have all the chemistry needed for mineralisation already there, but the mineral is deposited only when needed. Trees pre-stress their trunks too, with the outermost layers of cells being pre-stressed in tension to offset the poor compressive properties of wood¹¹. Trees are also good examples of design compromise, where the advantages of a cellular material for specific bending stiffness lead to low compressive strength (partly because of fibre properties, partly because of the cellular structure) which, however, can be moderated by pre-stressing fibres and cells in tension where it matters.

An important feature of biological structures which is sometimes forgotten and which stems directly from the rules mentioned earlier, is that very often optimisation can be more effective if carried out on shape rather than material properties, especially in bending structures. There is a great deal to be gained in this manner (I is cheaper than E, as is well known), more so with the added mechanism of tensile pre-stressing available, as demonstrated by leaves, for example².

4.2 MOVEMENT WITHOUT MUSCLES

We are all familiar with the fact that many plants are capable of movement, sometimes slow (as in the petals of flowers which open and close, the tracking of the sun by sunflowers, the convolutions of bindweed's around supporting stems, snaking of roots around obstacles), sometimes visible to the eye (as in the drooping of leaves when *mimosa pudica* is touched), exceptionally very rapid, too fast to be seen (as in the closing of the leaves of the venus flytrap). In the same category one must also add the shedding of leaves in the autumn which is not a passive mechanism but an active one. In all these examples, movement and force are generated by a unique interaction of materials, structures, energy sources and sensors. The materials are the cellulose walls of parenchyma cells (non-lignified, flexible in bending but stiff in tension); the structures are the cells themselves and their shape with the biologically active membrane that can control the passage of fluid in and out of the cells; the energy source is the chemical potential difference between the inside and the outside of the cells; the sensors are as yet unknown. These systems are essentially working as networks of interacting mini-hydraulic actuators, liquid filled bags which can become turgid or flaccid and which, owing to their shape and mutual interaction translate local deformations to global ones and are also capable of generating very high stresses. The average content of cellulose fibres (metabolically expensive) rarely exceeds 20% by weight and the pressures that can be generated can be as high as 20 bar.

Similar mechanisms can be seen in operation when leaves emerge from buds and deploy to catch sunlight. How to package the maximum surface area of material in the bud and to expand it rapidly and efficiently is the result of very clever folding geometry, turgor pressure and growth^{24,25}.

5 Variable Stiffness Systems

There are many instances in engineering where variable stiffness materials and structures would be beneficial^{26,27}. This is particularly true in vibration control, for example, and in applications where one would like to alter the shape of a rigid structure, or element of structure, and then re-stiffen it (conformable wings, portable soft-rigid-soft structures). There are several examples of this in biology but only two will be mentioned: muscle, which operates in a very integrated fashion at all levels of hierarchy²⁸, and variable stiffness collagen which is found in many marine animals²⁹.

Muscle is the archetypal variable stiffness device and to work, as it does, requires a very high level of functionality and integration. At the molecular level there is the chemical specificity and organisation of the sliding actin-myosin filaments mechanism; at the chemical level there is the transport of energy through ATP via specifically designed diffusion pathways; at the structural level there is the collagen fibre structure which confines partially the system against volumetric expansion and transmits the forces to the tendons³⁰. It is an ideal example for biomimetics and indeed, without replicating all the features of muscle, a great deal of progress has been made in developing "artificial muscle systems" based on active polymer gels.

Variable stiffness collagen can be considered a less sophisticated alternative to muscle. It is found in sea cucumbers (sea slugs) and also at the base of spines in sea urchins, for example. In this system the collagen fibres are embedded in a matrix the state of which can be changed from virtually liquid-like to rigid. In the liquid state (low stiffness), the collagen fibres are acting as uncoupled elements, and do not have any reinforcing effect. When the matrix is rigidified (by the release of calcium ions which act as labile cross-links between the polymer chains of the matrix) the efficiency of load transfer between matrix and fibres increases and the composite becomes rigid. The sea cucumber goes soft when threatened and flows away, literally, from its predator; the sea urchin softens the anchorage of its spines when it wants to move (requiring less energy to do so than if it were in the stiff condition) and the re-locks the system in place.

6 Integrated Mechanical Sensors

One of the most interesting aspects of multifunctionality and integration in biology is the way

in which receptors detect and amplify mechanical strains and displacements are used (mechanoreceptors). They do exist in all creatures, plants and animals although very little is known about them, except in the case of insects, arthropods and crustaceans³¹. These species have exoskeletons which, in their rigid state, are stiff laminated composite structures made of chitin fibres embedded in a highly cross-linked matrix of proteins and phenolic substances. The exoskeleton acts also as the load, strain or displacement detector via specialised organs, called sensilla, parts of which are local modification of the laminated structure of the exoskeleton to amplify the strain information for the detector organ connected to the nerve cell. These local modifications are a combination of changes in thickness, material stiffness and fibre orientation. They function as strain concentrations and mechanical signal amplifiers. To all intents and purposes they are the equivalent of drilling holes into structural elements and strain gauging the regions near the holes to get an amplification of the remote state of strain of the structure. Since even in small spiders there can be several thousands mechanoreceptors, an intriguing question is to ask what level of compromise can be achieved between the mechanoreception function and the loss of structural integrity. As it turns out^{32,33} the orientation of the chitin fibres in the hole regions follows the contours of the hole and the fibres do not terminate abruptly at the hole edge, as might be the case for drilled holes. The result of this is a lower stress concentration, sufficiently lower, one presumes, to maintain high levels of structural integrity in spite of the perturbations. Bearing in mind that in flying insects, for example, the mechanoreceptors are located in groups near the root attachment of what is essentially a wing spar, there are perhaps lessons to be learned from the remarkable effectiveness and optimisation of such systems.

6.1 ADAPTIVE MECHANICAL DESIGN

Adaptive mechanical design in biology deals with the design output arising from a set of inputs on the evolving or growing organ or organism. The inputs can be external and internal loads, environmental changes, etc., which are superimposed on the genetic information available. As was mentioned earlier, the evolutionary time-scale is a long one and what we observe now is the result of all these inputs over long periods of time. The study of fossils does help in retracing the design steps backwards but, all too often unfortunately, not all the relevant information is available. Two other aspects of adaptive mechanical design which occur over much shorter time-scales (and hence more observable) and which involve individuals as opposed to whole species, are thigmomorphogenesis (i.e. the changes in shape, structure, material properties, etc., as a result of transient changes in environmental conditions) and the various forms of tropism (such as heliotropism in sunflowers and bone-remodelling, mentioned earlier). These effects are closely related to growth and they offer good examples of modifications in the design directed to solve specific sets of conditions. The formation of reaction wood in trees, needed to straighten a trunk towards the vertical or to offset loads in specific directions (prevailing winds, inclined growth) and the mechanism of bone remodelling are perhaps the best known and best documented examples. What they show is that the intrinsic design flexibility due to fibres and fibre architectures, hierarchies and the modulation of interactions between them, together with growth, converge to the specific solution needed for the specific situation which has arisen. Fibre orientations change, structure and properties of materials are modified, shapes are altered; all in order to adapt the design solution, albeit temporarily to the changes in circumstances. These examples and others, when carefully investigated offer one of the most effective means of developing ideas taken from the biological context into engineering.

7 Conclusions

As well as the significant benefits that the engineering community can derive from looking at nature, and which have been discussed only too briefly in this paper, it is important also to recognise the valuable contribution made by engineers of all kinds in helping biologists to unravel the design principles behind the biological world. It is only the synergy between these disciplines that will provide the means of increasing our understanding of what nature does and how, and to take full advantage of what is on offer, being aware of advantages as well as limitations. If we succeed in this, it will be for the benefit of both engineering and biology.

8 Endnotes

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