



Biodynamics

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Since its inception, the Emergence and Design Group has collaborated with Professor George Jeronimidis at the Centre for Biomimetics of Reading University and Professor Birger Sevaldson at the Institute of Industrial Design at the Oslo School of Architecture. The focus of research is living nature's capacity to provide versatile models for design. Here, Professor George Jeronimidis examines natural dynamic systems, material behaviour and adaptation, and presents the case for implementation of these models in architecture and engineering.

The developments in smart materials and responsive buildings are at the forefront of scientific and technical advances in engineering and have stimulated a renewed interest in biology and biomimetics.¹ Whilst there have been a number of interesting architectural applications of advanced materials in architecture, we cannot say that intelligent buildings exist. Environmentally responsive systems for buildings have certainly made rapid advances in the last decade, but they function as a collection of devices such as louvres and shades, controlled by a central computer that receives data from remote sensors and sends back instructions for activation of mechanical systems.

This is essentially a 19th-century concept, even if human decision-making has been replaced by computational decision-making. Natural systems are quite different. Most sensing, decision-making and reactions are entirely local, and global behaviour is the product of local actions. This is true across all scales, from small plants to large mammals. When we run for the bus, we do not have to make any conscious decisions to accelerate our heartbeat, increase breathing rate and volume, or to open our pores to regulate the higher internal temperatures generated. Plants, lacking a central nervous system and mammalian brains, make growth movements to orientate themselves to the sun or to correct their inclination.

In order to abstract engineering principles for use in architecture, we must first recognise that we are studying material systems in which it makes little sense to distinguish between material and structure. Further, we must recognise that all

natural material systems involve movement – both local and global – to achieve adaptation and responsiveness. There has been little systematic engineering study of dynamic systems in nature, and in particular of the way in which many biological material systems achieve movement without muscles.

Geometry and Fibre Material Hierarchies

In the morphogenesis of biological organisms, it is the animation of geometry and material that produce form. Dynamic capacity, the ability to move, is created by the same factors. Geometry and material hierarchies produce dynamics. Biodynamics are achieved by a system of pre-tensioning and variation of turgor pressure² in differentiated geometrical arrangements to produce different kinds of movements. Many animals with flexible skins, such as worms and sharks, use hydrostatic skeletons where the prestressing of fibres in tension is balanced by compression in a fluid. Similarly, nonlignified plants are entirely dependent on control of turgor pressure inside their cells to achieve structural rigidity, prestressing the cellulose fibres in the cell walls at the expense of compression in the fluid. Trees prestress their trunks, too, with the outermost layers of cells being prestressed in tension to offset the poor compressive properties of wood.³

Biology makes use of remarkably few materials, and nearly all loads are carried by fibrous composites. There are only four polymer fibres: cellulose in plants, collagen in animals, chitin in insects and crustaceans, and silks in spiders' webs. These are the basic materials of biology, and they have much lower densities than most engineering materials. They are successful not so much because of what they are but because of the way in which they are put together. The geometrical and hierarchical organisation of the fibre architecture is significant. The same collagen fibres are 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.

Fibre composites are anisotropic, a characteristic that can provide higher levels of optimisation than is possible with isotropic, homogeneous materials, because stiffness and strength can be matched to the direction and magnitude of the loads applied. It is growth under stress; the forces that the organism experiences during growth produce selective deposition of new material where it is needed and in the direction in which it is needed. In bone, material is removed from the under-stressed parts and redeposited in the highly stressed ones;⁴ in trees a special type of wood, with a different fibre orientation and cellular structure from normal wood, is produced in successive annual rings when circumstances require it.⁵ Thus biology produces a large number of patterns of load-bearing fibre architectures,

Opening spread
The bony lamellae of the femur, made of compacted collagen fibres and minerals. During self-formation a matrix is laid down in lamellar, sheet-like form which is mineralised by calcium phosphate crystals.

Opposite
Section through the stem of a buttercup showing the oval vascular bundle at the centre that contains xylem vessels and supporting tissue.

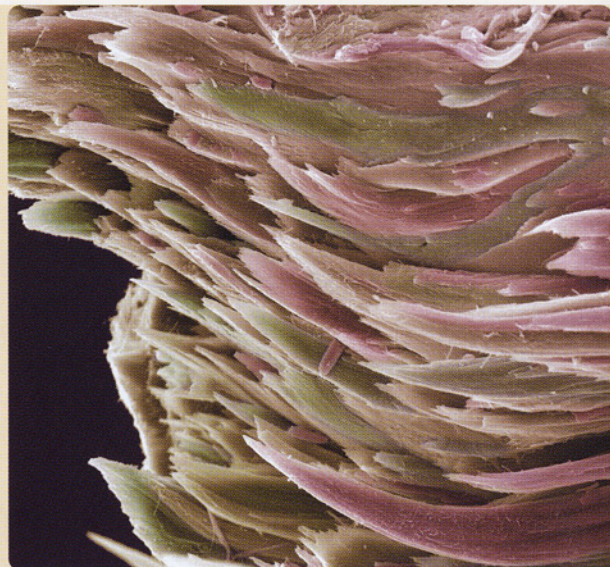




Above left
Ripe seed capsule of the field poppy, showing the release of seeds by the self-organised process of dehiscence (dehydration and splitting).

Above right
A freeze-fractured tendon revealing the parallel structure of collagen fibres of varying size. The parallel organisation produces a structure that is flexible but inelastic and able to resist tension.

Opposite
Human collagen-fibre bundles made up of three long polypeptide chains that self-assemble into triple-helix fibrils, extensively cross-bonded to form a strong inextensible structure.



each a specific answer to a specific set of mechanical conditions and requirements.⁶

Fibres are most efficient when they carry pure tensile loads, either as structures in their own right or as reinforcement in composite materials that are used as membrane structures in biaxial tension.⁷ Fibres perform poorly in compression because of buckling, even when partially supported laterally by the matrix in composites. In nature there are a number of available solutions to this problem: prestress 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; or 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.

Movement Without Muscles

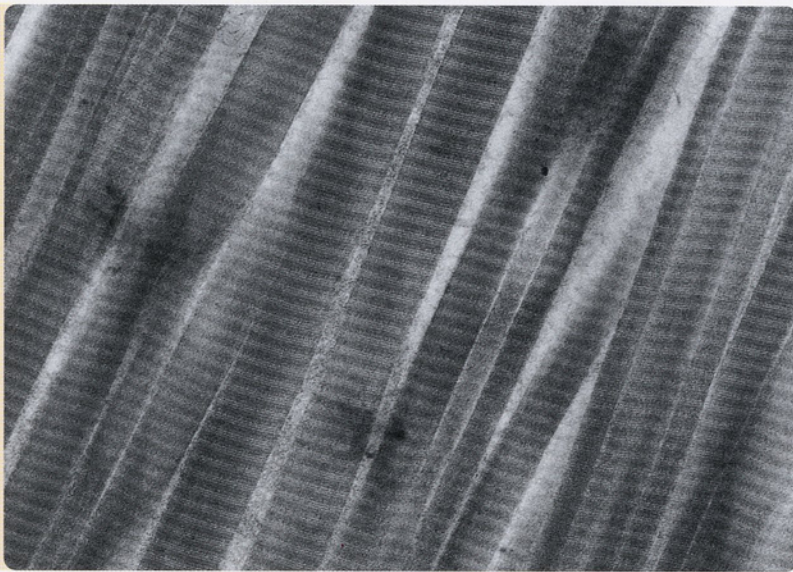
Many plants are capable of movement. Slow movements often pass unremarked, even though they are very familiar, such as those seen in the petals of flowers that open and close, the tracking of the sun by sunflowers, the convolutions of bindweeds around supporting stems and the snaking of roots around obstacles. Rapid movements are more visible, such as the closing and drooping of leaves when *Mimosa pudica* is touched. Very rapid movements, too fast to be seen, are exceptional, but do occur in the closing of the leaves of the Venus flytrap. And the most common of all movements is 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.

Movements that are reversible in plants are produced by pressure changes within special cells. These parenchyma cells are flexible in bending but stiff in tension; when a cell takes in water, the pressure exerted on its walls increases, and the cell increases in size due to the elasticity of its walls. If the pressure of neighbouring cells increases at the same time, the tensions result in deformations of the whole tissue, which causes movement of part of the plant. The arrangement of cells of different sizes and orientations constrains the movement in the direction that is needed. When the osmotic pressure⁸ within the cells slowly decreases, the movement is reversed. A common example of this mechanism is the daily lifting and lowering of leaves in a day/night cycle.

These material 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 capable of generating very high stresses.

The same mechanism is used within the tissue of the leaf, where the stomata regulate the respiration of the plant. Stomata open when the air is humid, and close when it is dry. The mechanism is differential pressure in an asymmetrical arrangement of cells. The outer and inner walls are much thicker than the lateral walls, and so have greater resistance to deformations. The thinner areas are more easily stretched. The asymmetry of the cell's structure and of the wall thicknesses directs the movement caused by the pressure changes. There are two controlling cycles, of water and of carbon dioxide, which at times may compete, as carbon dioxide can limit photosynthesis. Light stimulates the stomata to open, and they close at night except in very arid



Notes

1 GR Tomlinson and WA Bulloch, 'Smart Materials and Structures', *Proceedings of the 4th European and 2nd MIMR Conference*, Harrogate, July 1998 [Institute of Physics, Bristol].

2 When plant cells take in water by osmosis they start to swell, but the cell wall prevents them from bursting. Plant cells become 'turgid', which means swollen and hard. Turgor pressure is liquid or hydrostatic pressure, and turgidity is what makes the green parts of the plant 'stand up'.

3 RR Archer, *Growth Stresses and Strains in Trees*, Springer Verlag (Berlin), 1986.

4 JD Currey, *The Mechanical Adaptation of Bone*, Princeton University Press (Princeton, NJ), 1984.

5 Archer, op cit.

6 AC Neville, *Biology of Fibrous Composites*, Cambridge University Press (Cambridge), 1986.

7 M Elices (ed), *Structural Biomaterials*, Princeton University Press (Princeton, NJ), 2000.

8 The pressure created when water flows by osmosis through a semipermeable membrane into a chamber containing a high concentration of solutes.

9 H Kobayashi, B Kresling and JFV Vincent, 'The geometry of unfolding tree leaves', *Proceedings of the Royal Society of London*, 1998, pp 147-54.

10 JA Trotter and TJ Koob, 'Collagen and proteoglycan in a sea urchin ligament with mutable mechanical properties', *Cellular Tissue*, 1989, pp 258, 527.

climates where the cycle is reversed to prevent water losses.

If the pressure change cannot be reversed, the pressure builds beyond the ability of the tissue to resist the force. The tissue will rupture in the weakest area. Weak areas are carefully placed, so that the orientation and speed of the rupture is controlled. This mechanism is designed for the explosive movements or catapult actions of some fruits.

The fruits of all *Impatiens* plants have specially formed weaker tissues along which the ruptures will propagate, severing the longitudinal connections between the carpels, which instantly roll up and catapult the seeds away. The squirting cucumber, *Ecballium elaterium*, uses the same mechanism to discharge its seeds at such high velocity that a distance of up to 10 metres is achieved. Similar mechanisms can be seen in operation when leaves emerge from buds and deploy to catch sunlight. The packing of the maximum surface area of material in the bud and expanding it rapidly and efficiently is the result of very clever folding geometry, turgor pressure and growth.⁹

Variable-Stiffness Material Systems

Evolutionary adaptive mechanical design in natural material systems occurs at the level of the species, in response to a set of inputs on the developing organism. The inputs include loads and environmental pressures that interact with the genetic information available. Evolutionary time is very long, but evolutionary adaptation can be successfully modelled in computational processes and is useful in design strategies for the development of architecture in series, types

and populations. There are two other aspects of biological adaptation that occur over much shorter time scales, which involve individuals rather than whole species and are thus more observable.

Thigmomorphogenesis is the changes in shape, structure and material properties that are produced in response to transient changes in environmental conditions. Tropisms of various kinds are also observable, such as heliotropism in sunflowers. These are all growth movements, slow adaptations to changes in specific conditions. The formation of reaction wood in trees, needed to straighten a trunk towards the vertical when it has experienced inclined growth or to offset loads from prevailing winds, and the mechanism of bone remodelling are perhaps the best known and best documented examples. Fibre orientations, structural capacities and properties of materials are modified by slow movements within a material; these are not yet available in industrial materials, but it is clear that this should be the goal of longer-term research.

There are many instances in engineering where variable-stiffness materials and structures would be beneficial. For example, this is particularly true for vibration control, and in applications where it would be beneficial to alter the shape of a rigid structure, or an element of structure, and then restiffen it. Potential architectural applications are structures that could be reconformed for change of load or condition, and portable structures that could be soft for transportation, rigid in deployment and soft again for relocation.

There are several examples of this in biology that offer interesting models that are more immediately achievable. The most interesting is the variable-stiffness collagen found in many marine animals.¹⁰ It is found in sea cucumbers and also at the base of spines in sea urchins. In this system, the collagen fibres are embedded in a matrix that can be changed from rigid to nearly liquid. In the liquid, low-stiffness state the collagen fibres act as uncoupled elements and do not have any reinforcing effect. When the matrix is hardened by the release of calcium ions, 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; the sea urchin softens the anchorage of its spines when it wants to move and can relock the system in a new location.

The study of biodynamics offers models for dynamic material systems and for adaptation. Scale has to be carefully considered if principles are abstracted from biodynamic systems for use in architecture. Forces increase exponentially when differential pressure systems are enlarged. The geometrical organisation and fibre patterns are scaleable, and with 'muscle-less' movement and stiffness variability suggest a means of achieving significantly advanced architectural material systems. ▴