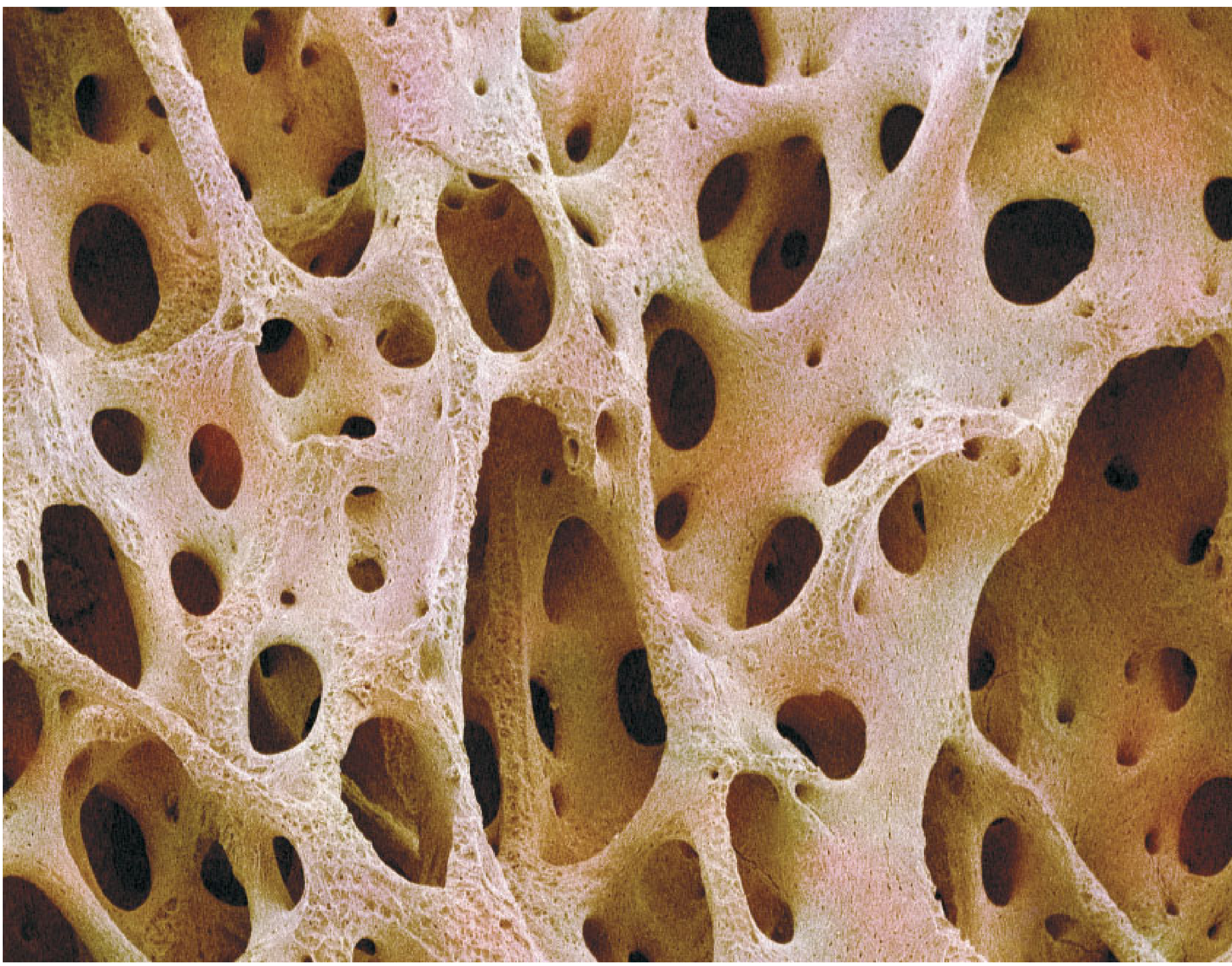
Self-Organisation and Material Constructions

Cellular biological materials have intricate interior structures, self-organised in hierarchies to produce modularity, redundancy and differentiation. As Michael Weinstock explains, the foam geometries of cellular materials offer open and ductile structural systems that are strong and permeable, making them an attractive paradigm for developments in material science and for new structural systems in architecture and engineering.



Spongy bone tissue
Scanning electron micrograph of cancellous (spongy) bone tissue. Bone can be either cortical (compact solid) or cancellous, with cortical usually forming the exterior of the bone and cancellous tissue forming the interior. The cellular structure is highly differentiated, formed by an irregular network of trabeculae, or rod-shaped fibrous tissue. The open spaces within the tissue are filled with bone marrow.

In recent years, new strategies for design and new techniques for making materials and large constructions have emerged, based on biological models of the processes by which natural material forms are produced. Biological organisms have evolved multiple variations of form that should not be thought of as separate from their structure and materials. Such a distinction is artificial, in view of the complex hierarchies within natural structures and the emergent properties of assemblies. Form, structure and material act upon each other, and this behaviour of all three cannot be predicted by analysis of any one of them separately.

The self-organisation of biological material systems is a process that occurs over time, a dynamic that produces the capacity for changes to the order and structure of a system, and for those changes to modify the behaviour of that system.[1] The characteristics of self-organisation include a 3-D spatial structure, redundancy and differentiation, hierarchy and modularity.[2] Studies of biological systemic development suggest that the critical factor is the spontaneous emergence of several distinct organisational scales and the interrelations between lower or local levels of organisation, the molecular and cellular level, and higher or global levels of the structure or organism as a whole. The evolution and development of biological self-organisation of systems proceeds from small, simple components that are assembled together to form larger structures that have emergent properties and behaviour, which, in turn, self-assemble into more complex structures.[3] The geometry of soap foams is a model for the cellular arrangements at all scales in natural physical systems.

Natural Constructions

Natural materials develop under load, and the intricate interior structure of biological materials is an evolutionary response. At the level of the individual, there is also an adaptive response as, for example, bone tissue gets denser in response to repeated loads in athletic activities such as weightlifting. Bone is a cellular solid,[4] a porous material that has the appearance of mineralised foam, and its interior is a network of very small and intricately connected structures. When bone becomes less dense, due to age or prolonged inactivity, it is the very small connective material that vanishes, so that the spaces or cells within the bone become larger. The loss of strength in the material is disproportionate, demonstrating the importance of the microstructure: larger cells make a weaker material.

Cellular materials are common at many scales in the natural world, for example in the structure of tiny sea creatures, in wood and in bones. What they have in common is an internal structure of 'cells', voids or spaces filled with air or fluids, each of which has edges and faces of liquid or solid material. The cells are polyhedral, and pack all the available arranged space in a 3-D pattern. Foam has cells that are differentially organised in space, whereas honeycombs are organised in parallel rows and tend to have more regular, prism-like cells. In all cellular materials, the cells may be either regular or irregular shapes, and may vary in distribution.

D'Arcy Thompson[5] discussed the mathematical expressions for the shapes of growing cells in 1917, arguing that new biological structures arise because of the mathematical and physical properties of living matter. His chapter on 'The Forms of Cells', when read in conjunction with the 'Theory of Transformations', has been extended today to patterning and differentiation in plant morphogenesis. The problem of mathematical descriptions of foam has a long history ,[6] but it can be observed that foam will comprise a randomised array of hexagon and pentagon structures.[7] Diatoms and radiolara are among the smallest of sea creatures, and the intricate structures of their skeletons have fascinated, among others, Frei Otto and his biologist collaborator JG Helmke. It has been argued that the formation of these tiny intricate structures is a process of mineralised deposits on the intersection surfaces of aggregations of pneus or bubbles.

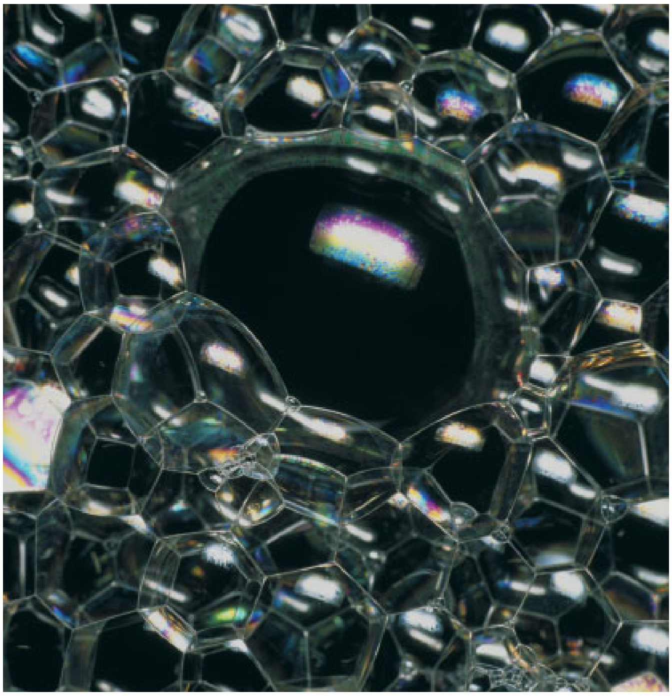
The Construction of Materials

In the industrial world, polymer cellular foams[8] are widely used for insulation and packaging, but the high structural efficiency of cellular materials in other, stiffer materials has only recently begun to be explored. Comparatively few engineers and architects are familiar with the engineering design of cellular materials, and this has contributed to the slow development of cellular structures in architecture.

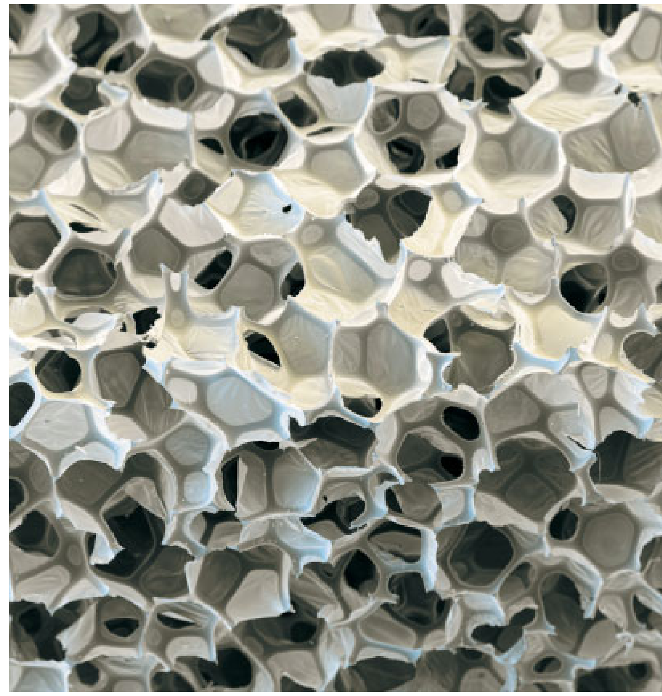
Industrial and economic techniques do exist for producing foams in metals, ceramics and glass. Foamed cellular materials take advantage of the unique combination of properties offered by cellular solids, analogous properties to those of biological materials, but they do not share their origin. They are structured and manufactured in ways that are derived from biological materials, but are made from inorganic matter. The production processes for metal foams and cellular ceramics have been developed for the simultaneous optimisation of stiffness and permeability, strength and low overall weight. This is the logic of biomimesis, abstracting principles from the way in which biological processes develop a natural material system, applying analogous methods in an industrial context, and using stronger materials to manufacture a material that has no natural analogue.

The ability of some materials to self-organise into a stable arrangement under stress has been the founding principle of structural form-finding in the physical experiments of Gaudí, Eisler and Otto. 'Organisation' here refers to the reordering of the material, or the components of the material system, in order to produce structural stability.

Biomimetics is essentially interdisciplinary, a series of collaborations and exchanges between mathematicians,



Soap bubbles
A naturally produced foam of soap bubbles, demonstrating the differentiation of polyhedral cells in an intricate geometry of foam architecture, including the basic Plateau rules for the intersection of three films.



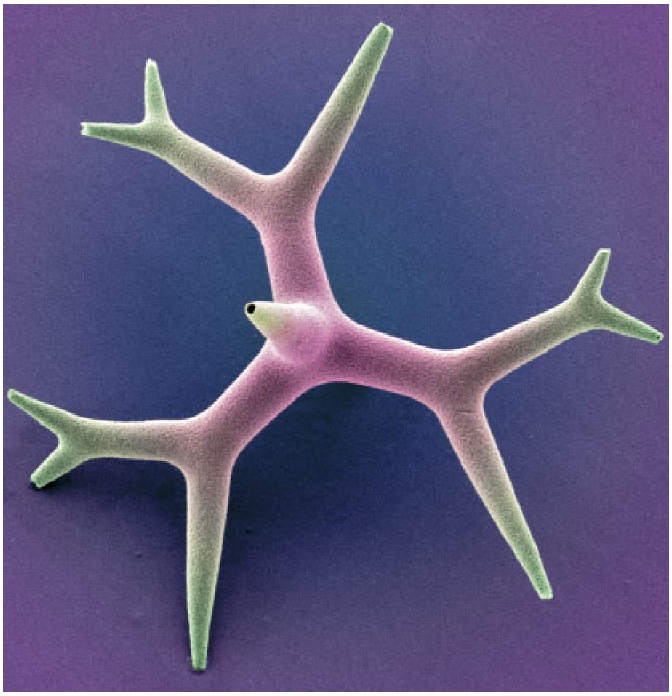
Polyurethane foam wound dressing
Scanning electron micrograph of polyurethane foam, showing the porous structure of differentiated open and partially closed cells. Magnification x 20 when printed at 10 centimetres wide.

physicists, engineers, botanists, doctors and zoologists. The rigid boundaries between the inherited taxonomy of 'pure' disciplines make little sense in this new territory. Similarly, the traditional architectural and engineering ways of thinking about materials as something independent of form and structure are obsolete.

New research into the molecular assembly of structures and materials in what were previously thought to be homogenous natural materials has led to 'biomimetic' manufacturing techniques for producing synthetic materials, and new composite materials are being 'grown' that have increasingly complex internal structures based on biological models. The fabrication of composites relies on controlling structure internal to the material itself, at molecular levels. Here, processing is the controlling parameter and growth is more than a metaphor. 'Grown' materials are layered, molecule by molecule, to create distinctive micro-structures in thin films, making new combinations of metal and ceramic that are produced by design rather than 'nature'. New composites such as flaw-tolerant ceramics and directionally solidified metals might seem to be a long way from the materials available to architects, but they are already in use in many other fields.

Other 'designed' materials, such as polymers and foamed metals, are already being used in many aerospace, maritime and medical applications. Polymers also have unique combinations of properties not found in 'natural' materials, being lightweight, very flexible and mechanically strong. In tandem with their electrical and optical properties, this makes them highly suited to military applications. In aircraft fuselages and body armour they offer high strength for low weight, providing structural stability and flexibility.

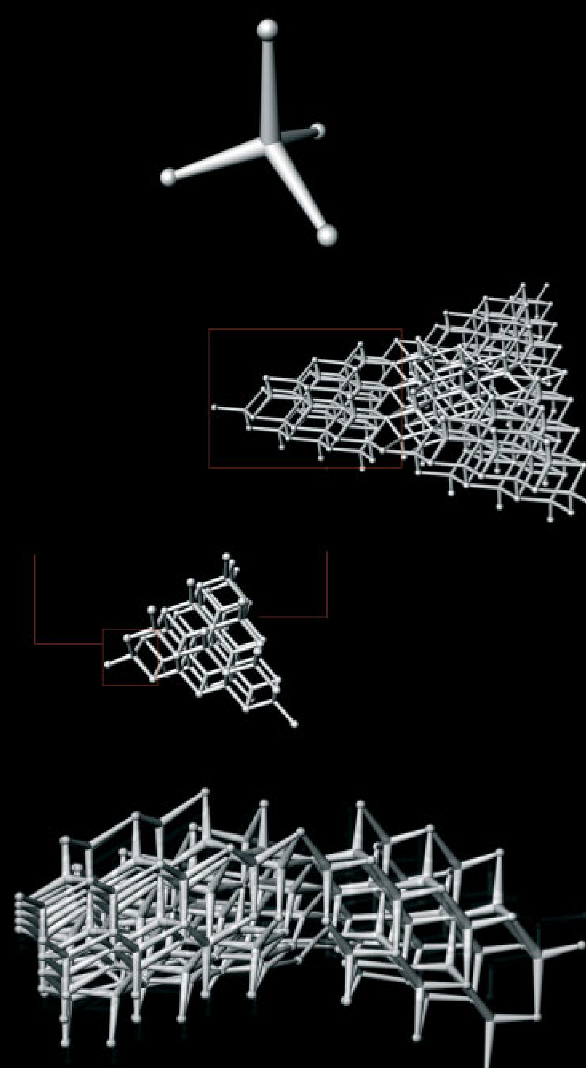
Simple polymers, such as the ubiquitous plastics like DuPont's Corian, are homogenous materials, similar in density and strength in all directions. Complex polymers need not be homogenous, and can be produced with surfaces that have different properties from the polymer interior. Complex polymers are useful for films and surfaces with multiple layers, each with distinct and differentiated functions. Manufactured by mimicking and adapting the self-organising behaviour and complex functions of natural polymers, very strong transparent or translucent films can be produced with a water-repellent and self-cleaning surface for facade systems. The process, known as 'free living radical polymerisation', can produce honeycomb structures at a molecular level, although the controlled formation of the honeycomb morphology at larger scales is still

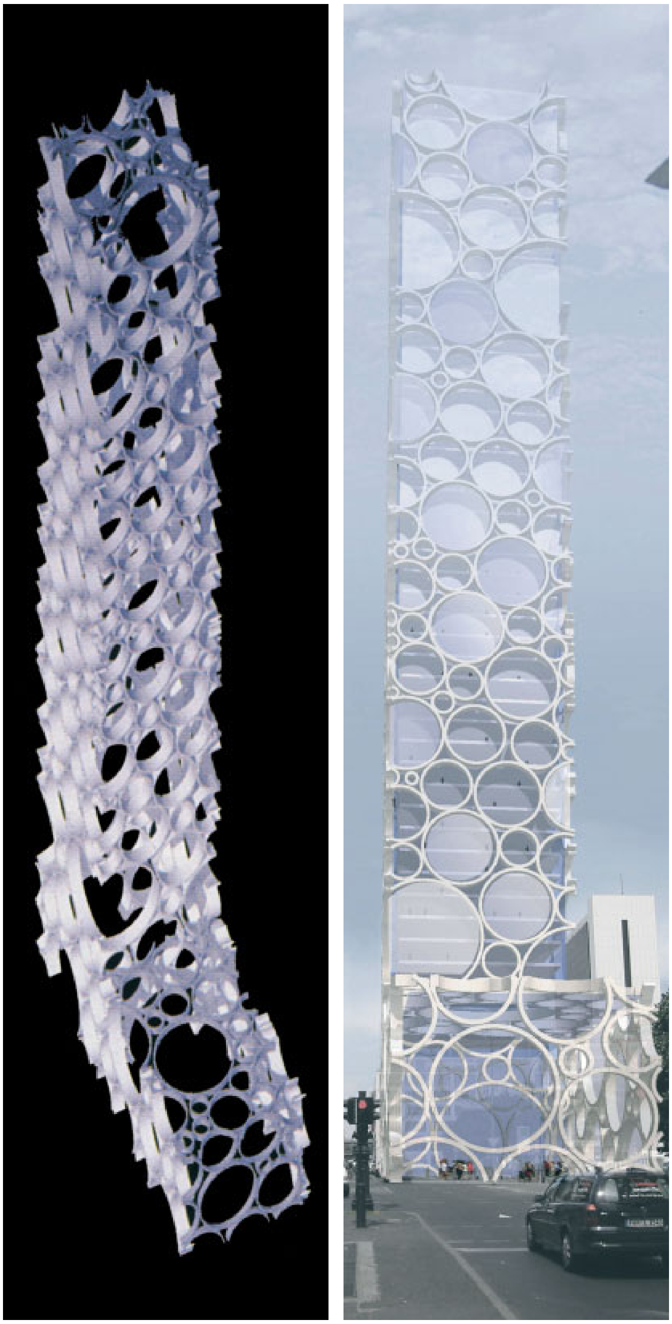


Sponge spicule
Scanning electron micrograph of the endoskeletal component of a sponge made of calcium carbonate. When assembled, the skeleton forms either a mesh or honeycomb structure. Magnification x 210 when printed at 10 centimetres wide.

The process, known as 'free living radical polymerisation', can produce honeycomb structures at a molecular level, although the controlled formation of the honeycomb morphology at larger scales is still in the research, rather than production, phase.

Thomas Von Girsewald and Juan Subercaseaux, centroidal Voronoi tessellation and boundary optimisation in close-packing systems, Emergent Technologies and Design programme, AA Graduate School of Architecture, 2005
Geometric logics were identified from a physical soap-film model and, based on the geometric fundamentals of Plateau's laws extended into three dimensions (three relaxed soap bubbles can only meet at an angle of exactly 109° 28' 16"), a four-segment tetrahedral dihedral angle component was digitally designed. The component was nested inside a layered triangular organisation generating a parametrically deformable triangular tile with regular pentagonal dodecahedra (12-sided) interior cellular partitions. This tile was aperiodically distributed into a larger equilateral configuration with a total population of 152 nested component features. The parametric system permits the manipulation of one single input point to produce an automatic reconfiguration of 114 primary components, maintaining the coherence of the cellular partitions while relocating the respected individual centroid.





SMO Architektur and Arup, Bubble Highrise, Berlin, 2002
Experimental design from which the design approach to the Watercube was evolved. The structure is produced by running a packing algorithm to fill a notional high-rise volume with differentiated spheres, which are then cut at the surface intersection.

in the research, rather than production, phase.

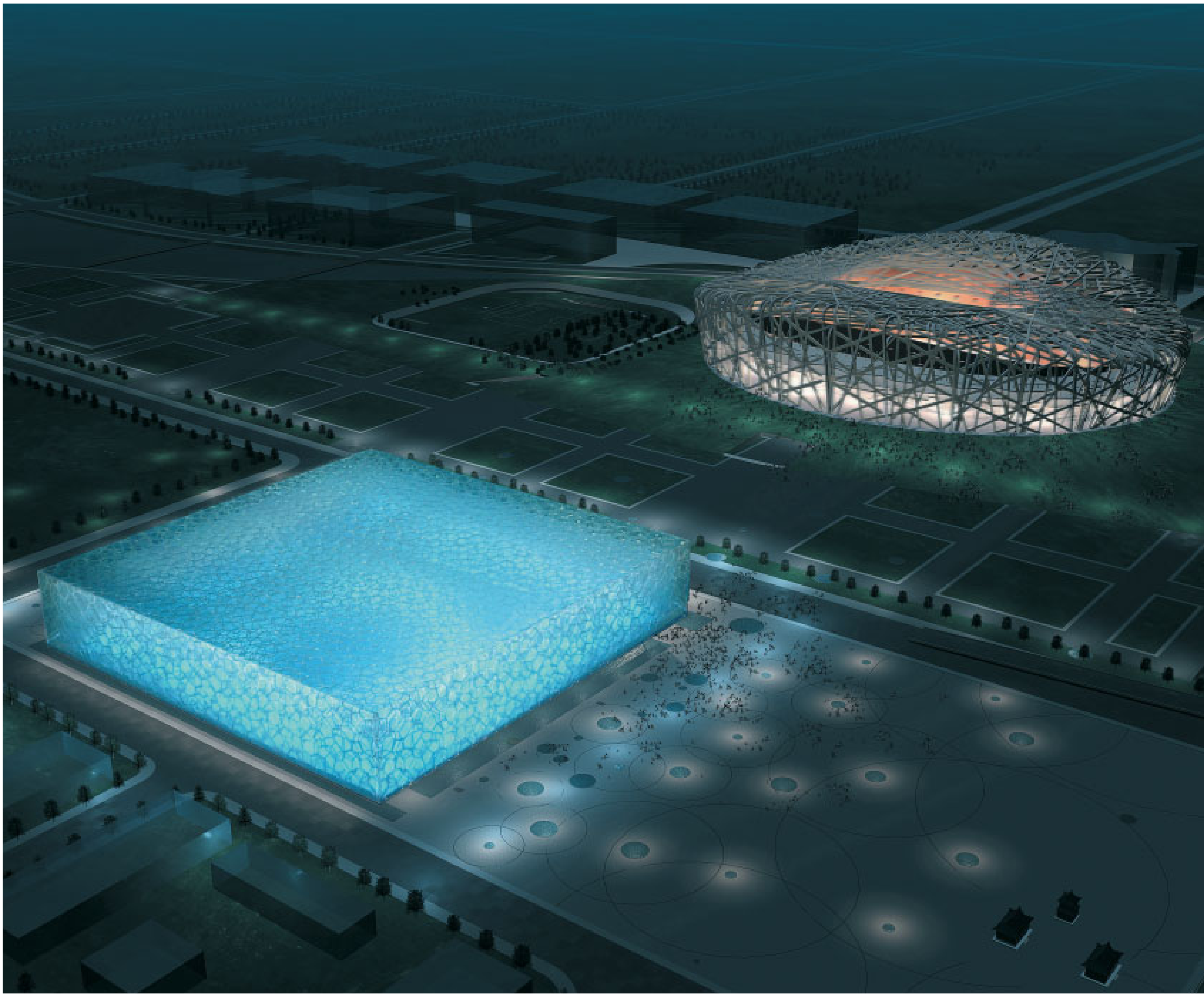
Kevlar is perhaps the best-known manufactured organic fibre and, because of its unique combination of material properties, it is now widely used in many industrial applications. It has high tensile strength (five times that of steel), low weight and excellent dimensional stability, and so has been adopted for lightweight cables and ropes in many marine and naval applications. Kevlar has high impact resistance, so it is the major fibre constituent in composite panels in military and civil aircraft, and in sporting equipment such as canoes, skis, racquets and helmets. However, it has yet to be used widely in architectural construction.

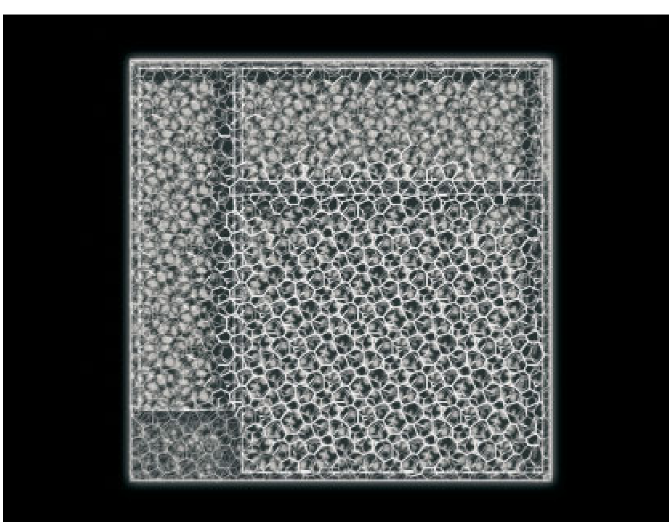
Liquid crystals have the flow properties of a conventional liquid, and the molecular structure of a solid crystal. This is a phase change occurring between the crystalline and isotropic liquid states. Kevlar is produced, in part, by manipulating the liquid-crystalline state in polymers. Spiders use the low viscosity in the liquid crystalline regime for the spinning of their silk. Spider silk is as strong as Kevlar, which means that it has superior mechanical properties to most synthetic fibres and can stretch up to 40 per cent under load. This gives it an unusual advantage, in that the amount of strain required to cause failure actually increases as deformation increases, an energy-absorbing ability that allows the web to absorb the impact of flying prey.

Self-organising materials, such as liquid crystals, natural polymers and copolymers, found their first applications in biotechnology, sensor development and smart medical surfaces, and more recently in maritime, automotive and aerospace applications, but they have the potential to produce new structures and systems for advanced architectural engineering.

There is new interest within the material sciences and industry in the use of ceramics as a structural material. Ceramics are very light, but their compressive strength matches, or exceeds, that of metals. They are hard and durable, resistant to abrasion and noncorroding as they are chemically inert. Ceramics are good insulators (both electric and thermal) and can resist high temperatures. However, they have one major disadvantage: their lack of tensile strength. The solution to this problem is being sought in biological models – the forming of complex structures internal to the material – and as new production facilities come online ceramics may become the most ubiquitous of new materials for built structures. Cellular ceramics are porous and can now be manufactured in various morphologies and topologies, ranging from honeycombs and foams to structures woven from fibres, rods and hollow spheres. Substitutes for human bone and the coating of orthopaedic prostheses are produced by similar methods.

Injecting a stream of gas bubbles into liquid metals is the basic technique for producing foamed metals, but preventing





PTW Architects, CSCEG Design and Arup, 'Watercube' National Swimming Centre, Beijing, due for completion 2007
Competition model showing overall scale: 177 x 177 metres (581 x 581 feet) and more than 30 metres (98 feet) high, with an entirely column-free interior space.

Watercube digital structural model. The mathematics of foam geometries are used to produce the structural array, ensuring a rational optimised and buildable structural geometry.

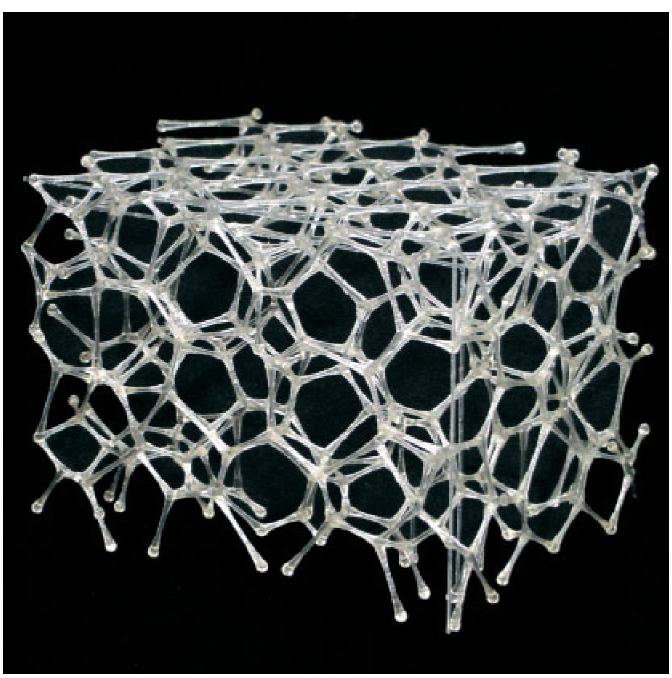
the bubbles from collapsing is difficult. Adding a small quantity of insoluble particles to slow the flow of the liquid metal stabilises the bubbles in the production of aluminium foam sheets, produced with open or closed cells on the surface. Aluminium foams can be cast in complex 3-D forms, are stronger and more rigid than polymer foams, can tolerate relatively high temperatures, and are recyclable and stable over time. They are very light, nominally about 10 per cent of the density of the metal, and are currently used as a structural reinforcement material, particularly in aerospace applications, though they have not yet reached their full potential in lightweight architectural structures.

Closed-cell aluminium honeycomb is widely used as the core material of panel structures, conventionally with other materials as a surface. This is no longer strictly necessary, as new advanced processes produce 'self-finished' surfaces of high quality. Cellular metals including, but not exclusively, aluminium, are being deployed for applications such as acoustic absorption, vibration damping and innovative thermal regulation. As the frequency and range of applications increases, data accumulates for the relationship between the topology of cells in the foam and the subsequent performance of the cellular material, so that improved and optimised cell topologies can be produced.

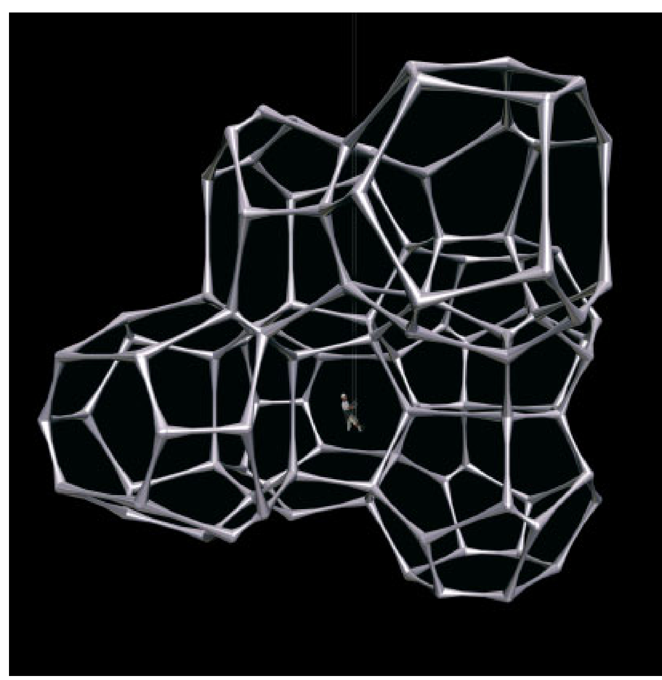
Another new open-cell foamed material, made of a glass-like carbon combining properties of glass and industrial carbons, can be used for biological 'scaffolding'. Reticulated vitreous carbon has a large surface area combined with a very high percentage of void spaces, is sufficiently rigid to be self-supporting, and is biologically and chemically inert. Cellular glass structures are used in medical applications for bone regeneration. The bioactive glass acts as a scaffold to guide the growth and differentiation of new cells, and this requires an open-cell structure that is highly interconnected at the nanometre scale. The cells must be large enough to allow the bone tissue to grow between the cells, yet fine enough so that the 'bioglass' material can be absorbed into the bone as it is replaced by living tissue.

Material Constructions

Design and construction strategies based on space-filling polyhedra and foam geometries offer open structural systems that are robust and ductile. Control of the cell size, the distribution and differentiation of sizes within the global structure and the degree and number of connections are variables that can be explored to produce strength and permeability. SMO Architektur and Arup designed the Bubble Highrise by packing a notional structural volume with bubbles of various sizes, then used the intersection of the bubbles and the exterior planes of the notional volume to generate a structure that gives entirely column-free interior spaces. The 'Watercube' National Swimming Centre, Beijing, to be finished in 2007, was



Watercube resin model.



Watercube digital model of cell cluster.

designed by PTW Architects and Arup using a structural design developed from Weaire and Phelan's soap bubbles arrays. Despite the appearance of randomness, the elements of the structure are highly rational and so economically buildable. The Watercube is an enormous building, 177 metres (581 feet) on each side and more than 30 metres (98 feet) high. The network of steel tubular members is clad with translucent ETFE pillows. Over such a wide span of column-free space, the need to minimise the self-weight of the structure is paramount, as most of the structural work involves ensuring the roof can hold itself up.

The steel tubes are welded to round steel nodes that vary according to the loads placed upon them. There is a substantial variation in size, with a total of around 22,000 steel members and 12,000 nodes.

There is a total of 4000 'bubbles' in the Watercube, the roof being made of only 7 variant types (of bubbles) and the walls of only 16 variations, which are repeated throughout. The geometry was developed by extensive scripting, using the Weaire and Phelan mathematics, with a further script required for a final analytical and geometrical correct 3-D model. Scripts that run in minutes can deal with the tens of thousands of nodes and beam elements, and scripting was also used to develop structural analysis models and models from which drawings were automatically generated.

The ETFE cushions make the building very energy efficient, and sufficient solar energy is trapped within to heat the pools and the interior area, with daylight maximised throughout the interior spaces.

Conclusion

A systematic change is on the horizon, whereby the boundary between the 'natural' and the 'manufactured' will no longer exist. The complex interaction between form, material and structure of natural material systems has informed new 'biomimetic' industrial processes, generating new high-performance materials. New processes are having a compelling impact on many industries, and new materials are radically transforming aerospace and maritime design and medicine. Cellular materials, especially metals and ceramics, offer an entirely new set of performance and material values, and have the potential to reinform and revitalise the material strategies of architectural engineering and construction.

At the scale of very large architectural projects, the emphasis on process becomes not only the significant design strategy, but also the only economic means of reducing design data for manufacturing. Biomimetic strategies that integrate form, material and structure into a single process are being adopted from the nanoscale right up to the design and construction of very large buildings. Δ

Watercube physical prototype; cells and ETFE cushions fabricated for the testing of environmental and structural behaviour, and confirmation of production logics.

Notes

1. Stuart A Kauffman, *The Origins of Order: Self-Organization and Selection in Evolution*, Oxford University Press (Oxford), 1993.
2. 'A combination of emergence and self-organisation is often present in complex dynamical systems. In such systems, the complexity is huge, which makes it infeasible to impose a structure a priori: the system needs to self-organise. Also, the huge number of individual entities imposes a need for emergence.' Tom De Wolf and Tom Holvoet, 'Emergence and self-organisation: a statement of similarities and differences', *Proceedings of the International Workshop on Engineering Self-Organising Applications 2004*, Belgium.
3. Francis Heylighen, 'Self-organisation, emergence and the architecture of complexity', *Proceedings of the 1st European Conference on System Science*, 1989.
4. The structure and properties of cellular solids such as engineering honeycombs, foams, wood, cancellous bone and cork have similarities of behaviour and can be exploited for engineering design. Case studies show how the models for foam behaviour can be used in the selection of the optimum foam for a particular engineering application. See LJ Gibson and MF Ashby, *Cellular Solids: Structure and Properties*, Cambridge University Press (Cambridge), 1997.
5. D'Arcy Thompson, *On Growth and Form*, Cambridge University Press (Cambridge), 1961, first published 1917.
6. Plateau's observation in 1873 that when soap films come together, they do so as three surfaces meeting at 120 degrees, and Lord Kelvin's 1883 challenge of subdividing a 3-D space into multiple compartments or cells.
7. D Weaire and R Phelan, 'A counterexample to Kelvin's conjecture on minimal surfaces', *Philosophical Magazine Letters,* Vol 69, 1994. See also D Weaire, 'Froths, foams and heady geometry', *New Scientist,* 21 May 1994.
8. Denis Weaire and Stefan Hutzler, *The Physics of Foams,* Oxford University Press (Oxford), 2001.