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The load-bearing duct: biomimicry in structural design

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The philosophical aspects of applying the principles of biomimicry are explored in a case study of structural design. Integrating structural engineering with services engineering can be regarded, to some extent, as taking principles from biological systems and applying them to large-scale conceptual design. The end-product discussed herein a so-called load-bearing duct, a functional naturally ventilated multi-storey office building that takes the applied loading efficiently both structurally and cost-effectively giving it the potential to be sustainable throughout its design life.

1. INTRODUCTION

Biomimicry, bionics or biomimetics is an emerging field that, among other things, proposes alternative ways of thinking about sustainable engineering solutions through, or inspired by, nature. Different engineering institutions and entities, depending on their field, describe biomimicry as a set of scientific[1] or design principles.[2] As its name suggests (bios and mimicry coming from Greek meaning life and imitation respectively) the aim is to mimic nature in order to provide efficient solutions to engineering problems.

Even though biomimicry as a scientific field is considered to be relatively new it has, in fact, been applied for centuries—Daedalus, who tried to mimic a bird flying in order to escape from King Minos's island of Crete, is well known in Greek mythology.[3] Before the industrial revolution and the development of applied mathematics and design codes for engineered structures, pioneering engineers and architects such as Antoni Gaudí searched in nature to find model solutions for their work. In those days, the absence of heavy machinery and other fuel-powered resources forced practitioners of the building industry to base their designs on what was achievable given the austere circumstances. This is precisely what natural models aim to do—use the available resources and materials to perform their function as minimum energy consumption systems. Later, the increased availability of fuel and technology sidelined biomimetic principles as these options seemed more expensive, at least in the short-term construction stage. Now that science and technology have reached a stage where the carbon-based economy needs replacing, because of source depletion and awareness of its environmental hazard, stakeholders are calling for new methodologies that will minimise resource consumption, provide cleaner power production and less environmentally impacting construction and manufacturing processes.

2. BIOMIMICRY IN BUILDINGS: POSSIBILITIES

2.1. Imitating shape, process and material

Biomimicry could offer sustainable alternative solutions to conventional design practice, as its basis is to reduce the energy consumed by the system by combining functions and reducing wastage. It can be applied not only to design the shape of the development but also to provide solutions in construction and operation processes, as well as in selection of the materials used.

2.1.1. Shape. Imitating shape and geometry from nature is probably the most well-known type of biomimicry in engineering. A number of structural systems that are considered great man-made achievements are in fact inspired by the natural environment. Suspension structures, such as long-span suspension bridges, share the same structural principles with spiders' webs. Membrane structures, such as modern stadia roofs and canopies behave very similarly to cell walls, gaining strength by being constantly in tension. The Pantheon in Rome is a biomimetic example, not in terms of its material but because of its structural behaviour, which is similar to that of a sea shell. Like seashells, the roof of the Pantheon gains its strength from its multi-dimensional curvature, which results in a structure not requiring extra reinforcing and hence being much lighter than conventional reinforced concrete spanning structures.

2.1.2. The process. Imitation of natural processes is also a key factor in biomimicry. Most of the environmental hazards the world is facing today are as a direct or indirect result of power generation and use. Natural ecosystems have existed as minimum energy systems[2] for millions of years, being driven primarily by solar energy. It is timely to determine whether the same principle could be applied to building structures, which themselves are artificial ecosystems where people live and work. Renewable sources could be incorporated into the method of construction, used for power supply, ventilation climate control and lighting.

2.1.3. Natural biochemical processes (materials). The industrial revolution and the use of fossil fuel power opened the gates to new synthetic materials that were more uniform and with better controlled properties than materials found in nature. Standardisation of building codes and market globalisation made these stiffer, stronger and more uniform materials major components of the construction industry. Because of this trend, however, millions of tonnes of non-biodegradable waste have been generated, which future generations will have to deal with. Fears of future consequences and turning points in technology have led some scientists to look back to nature for solutions. The idea is not merely to imitate the process at a macroscopic level but even the molecular level. An example is the silicon photovoltaic cell. Silicon is not found in the natural organic environment even though it is abundant in sand. The artificial harvesting of solar energy is quite expensive and inefficient when compared to photosynthesis in vegetation. The aforementioned scientists work in interdisciplinary groups and strive to imitate the manufacturing process of different natural materials that can restore themselves or can adapt to changes in their local environment—so-called 'smart' materials—or to understand and reproduce the natural mechanisms that harvest solar energy at a much higher efficiency rate.[2] Breakthroughs in this research field may have a tremendous impact on the way we design and build because the direct harvesting and conversion of solar energy to supply sufficient power to buildings is probably the most sustainable solution that is currently feasible and is also truly renewable.

2.2. Introduction to the case study

According to the Biomimicry Guild,[4] a biomimicry methodology exists that, when followed, produces a sustainable, environmentally friendly solution for a given problem, whether from engineering, administration or business. The first step of this methodology is to define the problem. For the current purpose, the design of an urban multi-storey office development is considered. The purpose and nature of the development imposes a series of constraints on the design brief such as adaptability, ventilation, natural lighting, visual appearance and accessibility. These constraints deal primarily with the functionality and operation of the development. There are also issues, however, of constructability and whole-life operation that relate to construction time and eventual cost, the latter being a factor determining the potential marketability of an innovative design.

2.2.1. Outline. For realisation, any design brief needs to be broken into component parts. For example, a multi-storey office building must perform certain functions (the 'parts') in order to serve its purpose. These functions include architectural, civil, structural, mechanical and marketability constraints. To begin with, the building has to bear its serviceability and ultimate design loads according to its specifications. The internal space must be adaptable to the needs of the client, provide a healthy environment for people to work in and be productive. It should provide easy access to all floors, as well as safe alternative emergency routes. Consideration should also be given to its cost and aesthetic benefits that may play a major role in its success as an office development. As an indication for success as a development, its marketability depends on the strengths or weaknesses of the solutions given the constraints outlined above.

Biomimicry does not always offer universal solutions. For example, the natural solution for wasps to maintain a constant hive temperature is to engage in strenuous activity.[5] This would not be acceptable in a house or an office, although humans act as buoyant (heat) sources in rooms and it is possible that their number and location within a room could play a role in maintaining a constant temperature. Nevertheless, the biomimetic solution in this case is not a universal concept for a multi-storey office development at this stage.

Local conditions and appreciation of the surroundings are key components for biomimetic conceptual design. With this in mind, it is not, therefore, possible to propose the conceptual design discussed later without reference to the local conditions. For the given development, a moderate to hot environment was assumed—hot enough to initiate solar chimney airflows and dry enough so that cooling by evaporation would not humidify the internal environment to a great extent. For best practice, biomimetic solutions should be as efficient natural systems tend to be, that is low energy-consuming systems. In order to achieve low-energy status, a system should be able to carry out multiple functions given limited resources, instead of having different systems working in parallel and potentially reducing energy efficiency. The next step is to consider which of the functions could be combined or integrated in a unified system. In the current study it was decided to explore the design challenge of combining a service, such as ventilation, with the structural design scheme. The other constraints will then be considered as feedback in the process to optimise the system developed initially. In conventional practice, the ventilation duct network hangs from structural members, assimilating the human 'nervous system' as it hangs from bones and muscle. Even though this existing practice can be considered as a biomimetic solution, it might not be the optimum solution for this case. As stated earlier, a solution found in nature may not be the global optimum. It has been shown that mechanical ventilation and other services are the cause of in excess of 40% of carbon emissions in the UK[6] and it is thought that one of its direct side-effects is the condition known as 'sick building syndrome' (SBS), discussed briefly in section 2.3. Conversely, a naturally ventilated and naturally lit building would reduce energy loads during the operation of the building and allow for more adaptability in space usage and reduce the risk of SBS.

2.3. Natural ventilation

Ventilation is a major issue for the serviceability of new building developments. Ventilation and air-conditioning of buildings has been dealt with in relation to spaces that require controlled environments through mechanical means. Mechanical heating, ventilation and air-conditioning (HVAC) systems are highly energy consuming, resulting in about 40% of the energy input in a given building. Moreover, this practice has given rise to SBS, mainly reported in deep-plan office blocks.[7] The causes of SBS are many-fold and include absence of adequate ventilation and natural lighting, low air quality, excessive mechanical air-conditioning and noise and fumes emanating from office equipment. SBS is suspected of causing sickness, fatigue and a general decrease in productivity of the workforce.

Recently, research has been undertaken to improve understanding of the airflow dynamics of natural ventilation in order for this to be applied and controlled in buildings.[8–10] Location, external climate, geometry and size are some of the key issues for natural ventilation and a good internal microclimate in general. What fluid dynamicists and service engineers are attempting to master is what termite colonies have been doing for epochs. Termites, regarded as pests due to the damage they cause to wood, are in fact great civil engineers when it comes to nest construction. *Macrotermes* termites build mounds that can reach heights of up to 7 m. These are covered by a compacted layer of earth material (soil, clay and dry fibres) that resembles reinforced concrete in terms of its structural behaviour and thermal capacity. This layer assists in climate control of the nest. Beneath these mounds, a complex subterranean infrastructure exists to serve the colony with water, food and storage facilities. The mound is designed ergonomically and the chambers are distinct and follow the patterns of the termite societies.[5] Additionally, termites adapt their building techniques according to local conditions and climate. *Compass* termites living in the Australian desert build almost planar mounds, where the long, planar, sides (approximately 3 m long) are orientated in the east–west direction with the height of these mounds being up to 5 m. With this orientation, the surface area under the scorching midday sun is minimised, while in winter the termites move to the eastern side in the morning and the western side in the afternoon for comfort. On the other hand, *Cubitermes* termites, which live in tropical conditions, build mushroom cap-like roofs on top of their mounds to deflect rainwater in order to prevent moisture weakening the structure.

Perhaps the most admirable achievements of some species are not their building techniques and adaptations, but their integration of structure and 'services'—mainly ventilation and, to a lesser extent, water supply. These are needed for a termite community, which at any instance can have approximately two million members. For some species, ventilation is carried out automatically, while the termites contribute only passively to the whole process; other species actively control ventilation by blocking/unblocking ventilation channels. Fig. 1 shows sections of two different structure/ventilation schemes. These are used by the species *Macrotermes Belicosus* in two different countries in Africa, the Ivory Coast and Uganda. Both schemes take advantage of the buoyant stream of hot air, rich in carbon dioxide and other gases, produced by the metabolic action of the dwellers, their respiration and by fermentation of fungi in the storage cells.[11] In Ivory Coast mounds (Fig. 1(a)), hot air rises and passes through an arm-sized horizontal duct to the buttresses and external ridges that contain a number of smaller ducts. These are porous and allow the gaseous exchange of carbon dioxide with oxygen-rich cooler air from the atmosphere. As it is cooler, the fresh air descends down small ducts that converge to another single larger duct, of similar size to the initial one, which leads to the cellar below the nest chambers. It then rises to replace the buoyant hot air, thus achieving ventilation and air circulation. This ingenious system combines the structure (buttresses) with a climate control service (ducts) in an integrated system. Weir[12] studied airflows in these termite mounds, observing hot air inflow during the morning and cooling by evaporation in the afternoon. Evaporation is an important factor not only for ventilation of the mound but also its structure, as moisture weakens the mound significantly.

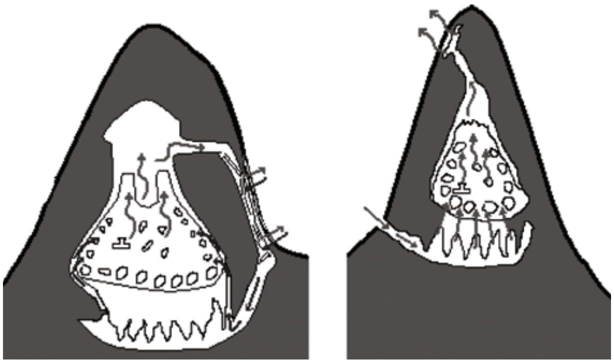

(a) (b)

Fig. 1. Schematics diagrams of termite mounds in (a) Ivory Coast and (b) Uganda, as described by Von Frisch[5]

The Ugandan system (Fig. 1(b)) has one opening near the top where hot air escapes to the atmosphere as it is displaced by cooler air entering through the cellar and the porous nest floor. The external envelope of the mound is very strong and provides the insulation necessary to allow buoyancy forces to drive a flow through the predetermined ducts and openings. Other families such as *Odontotermes* build high chimneys that are thought to assist in ventilation of the nests, probably making use of both wind and buoyancy forces.

By considering simplistically the relative scales of termites to humans in terms of size, equipment, technology and resources, what these insects create is beyond any man-made civil engineering structure. For man-made structures, natural ventilation schemes have been implemented successfully for residential purposes in one- or two-storey bioclimatic structures.[13] Smaller-scale projects (e.g. single rooms) are usually easier to design for natural ventilation because the effect of the driving forces that are responsible for flow dynamics are better understood and their influence can be controlled. Natural ventilation strategies do not have the switch-on/switch-off independence of an air-conditioning system, making them a good option for houses. As the number of occupants is much smaller (compared with, say, an office space), it is more likely that the comfort criteria of all will be met. This becomes more difficult to meet as the number of occupants increases. Conversely, natural ventilation schemes tend to be difficult to implement in multi-storey offices, which often consist of complex compartmentalised geometries and may be independent from each other, frequently accommodating different sections of companies or even different companies altogether. Even though a number of large-scale developments (e.g. 30 St Mary Axe in London,[14] the Commerzbank Tower in Frankfurt [15] and the ACROS Building in Fukuoka City[16]) have adopted natural ventilation strategies, they have done so in a more limited manner owing to the variability of the external climatic conditions. In these developments, backup air-conditioning systems exist that can be used locally and independently or by a central indoor climate administration system when conditions outside do not enable the desired flow dynamics in the building. This degree of control required by the client is clearly a key issue for any new development and needs to be taken into serious consideration. It should be noted, however, that the control provided by mechanical air-conditioning is only perceived and is actually no greater than the control provided by a well-conceived natural ventilation strategy. The problem with applying a natural ventilation strategy to an office block in which spaces tend to be compartmentalised and rooms become independent in that sense, is that airflows communicate nonlinear feedback between rooms and this is difficult to design for.

2.4. The natural model

Having defined the challenges of integrating structural design with natural ventilation, the biological literature was reviewed in order to find, essentially, a load-bearing duct. Preliminary research concluded that a potential and promising model from nature would be the trunk of a tree. Natural structures are quite unique as they are both 'built' (i.e. grow) and operated by solar energy. Indeed, trees may reach heights in excess of 100 m and raise water to the canopy in order to distribute nutrients to the whole structure naturally.[17]

As far as their structure is concerned, trees are the most abundant cantilevers in nature; they distribute internal stresses due to gravity and live loads with great efficiency as the size of the branches and trunk increases as stresses are transferred down towards the base (Fig. 2(a)). The structural properties of tree branches and trunks are quite similar to those of steel circular hollow sections (CHSs) commonly found in engineering practice. Instead of metal grains, longitudinal tree fibres on the perimeter of the section are aligned axially to the member (trunk or branch) in the direction of stress. In this way they are both efficient in resisting axial compression on the trunk due to gravity and provide an increased flexural rigidity (Fig. 2(b)). Increased flexural rigidity assists its capability to handle bending loads due to the self-weight of the branches and wind. Furthermore, the axial alignment of fibres serves another purpose—to carry water from the roots to the leaves for photosynthesis. With the longitudinal fibres aligned axially, water is distributed with increased efficiency as head losses due to cell wall crossings are minimised.

What is even more notable about trees is that they adapt to changes in the environment and local conditions. As mentioned above, other than supporting the tree and its branches, the trunk also provides the route for water to be extracted from the soil and distributed to the leaves where photosynthesis takes place. Water is drawn up due to the negative pressure created by the evaporation of water at the leaves during respiration. Simultaneously, (denser) water enriched with nutrients moves down, through the softwood centre of the trunk, to distribute nutrients to the rest of the tree.

In the design under consideration, air has to be circulated within the building and the natural forces involved are buoyancy forces, due to temperature differences, and wind. Buoyancy due to hot air rising is a consequence of both solar action and human activity, while wind is primarily a solar effect, its local magnitude and direction depending on the orientation and surrounding built environment. These natural forces must be made to have a similar effect as the development of negative pressure in tree trunks. The building's natural ventilation strategy thus becomes a direct analogy of the process of transporting water through a tree. By applying the trunk model to a building, a cylindrical shape is produced that has external atria—within the building, but around the circumference—resembling the longitudinal vertical fibres in a tree trunk and a shaft in the centre of the plan (Fig. 3). Air is heated in the atria (or solar chimneys), its density is thereby reduced and it rises. This causes air to be drawn from within the structure to replace it. Fresh air can also be drawn from outside by opening windows. External air from a higher altitude than street level is generally of better quality and top-down ventilation should be pursued.[18] The hot air rising could be allowed to leave from the top, with prevailing wind assisting this process (Fig. 4).

Expanding on the idea of top-down ventilation, the concept of introducing cool air from the top and allowing it to flow down is not unusual. It is similar to the concept of having heat sources on the floor, allowing hot air to rise due to density differences. Further examples can be found in nature including processes that take place in trees. In the proposed design, cool air could be drawn from the top and guided down the central shaded shaft. This flow could be reinforced further, if hot air rising in the lightwells could be cooled down at roof height. An option could be to have a roof garden on the top floor, enclosed by a dome-shaped roof, with green plants and possibly a pond covering the central shaft. During transpiration in green plants, carbon dioxide and other impurities harmful to humans are drawn in by the leaves releasing oxygen in return. Moreover, in order to draw water from the roots, heat is absorbed from the surrounding environment. The phase change that results in negative pressure within the tree cools the surrounding air in the process. In hot and dry climates, for example Arizona, the process can be developed further with vaporisers spraying water into the atmosphere; water droplets then extract heat from the surroundings and evaporate, reducing the temperature.[19] Cooler air is then driven down the central shaft and redistributed to the rest of the floors. Excess hot air is driven out from a vent on the top of the dome, assisted by wind conditions affecting the site. This top-down ventilation scheme would govern the number of floors. After studying the phenomenon of top-down ventilation, Gage *et al.* [18] derived a relationship between number of floors and parameters such as typical floor height, ratio of the

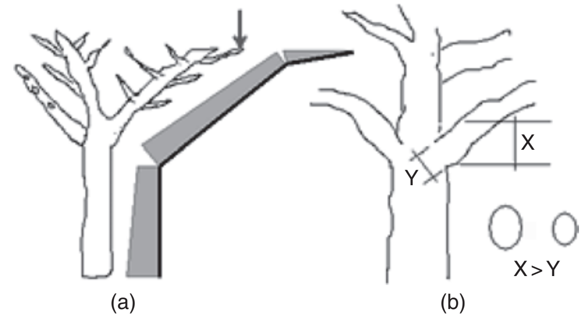


Fig. 2. (a) A tree and the induced bending moment on its structure due to its self-weight and other live loads; (b) Inclined branches take advantage of greater vertical cross-sectional area, thus increasing their flexural rigidity

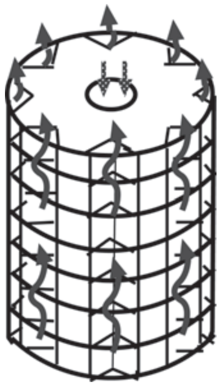


Fig. 3. The building structure behaving almost like a tree trunk as hot air rises through the atria to the top

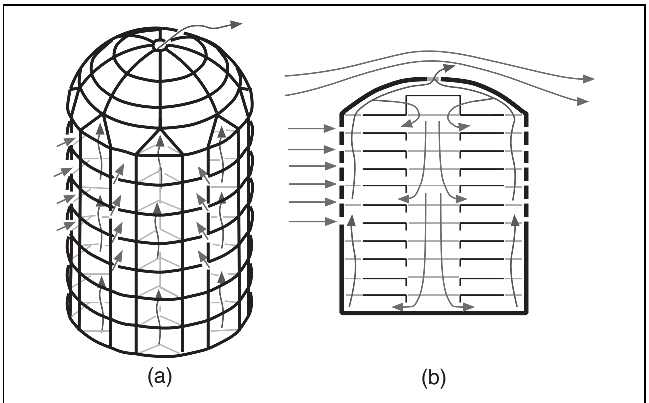


Fig. 4. (a) Global structural envelope indicating hot air rising through the atria and fresh air entering from the windows. (b) Section through the initial structure, indicating desired airflow directions by natural ventilation. Hot air rises to the top where it is either cooled by evaporation and filtered by green plants or escapes from the top. Cooled air is driven downwards through the central shaft, covered by a small pond/fountain. External air also enters from the sides where green plants are positioned close to windows such that they act as filters and wind buffers

cross-sectional area of the shaft with respect to the total floor area, number of air changes and average flow velocity. When the plan orientation was finished, typical values were used for the geometrical and physical parameters[20] giving a number of floors in the range of 10 to 13.

2.5. The structure

The preferred structural materials were selected as structural steel for the frame and steel–concrete composite floors. Steel-framed construction is faster than that of concrete as there is no need for formwork; further, structural members tend to be more slender and therefore enhance adaptability while significant prefabrication minimises waste. The vertical members acting as columns deliver gravity loads quite efficiently, but for lateral loads, such as wind and seismic loads, either the connections should be detailed in such a way as to become rigid or a bracing system must be included. Obviously having two systems for the load-bearing problem is really against the principle of biomimicry; moreover, such an inclusion would obstruct some views from the building. On the other hand, having many different types of highly detailed connections increases the cost of fabrication significantly.

To improve this scheme, inspiration from nature was again required. The question 'how can the structural/ventilation/lighting strategy be integrated?' was posed. A solution was offered from tree trunks growing in harsh environments, specifically from the formation of spiral grain in tree fibres as reported by Kubler[21] (Fig. 5(a)). With standard axially aligned fibres, water is carried to the leaves only from the roots directly beneath them. When the roots of a tree cannot progress or cannot reach the phreatic surface in a specific direction, the tree adapts and forms a spiral grain so that roots that have access to water and nutrients supply the tree all around and not just the branches directly on top of them.

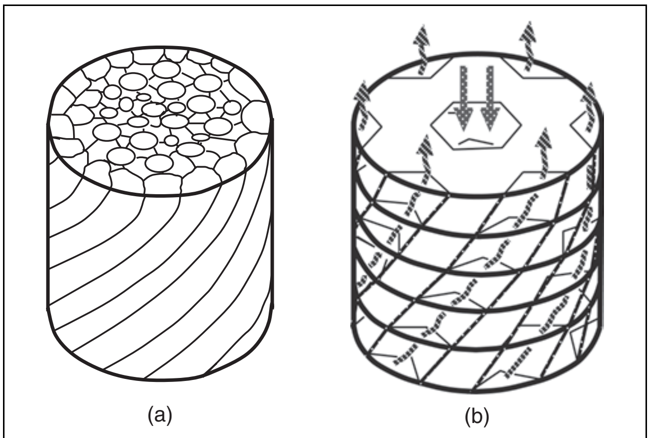


Fig. 5. (a) Sketch of a section of a tree trunk exhibiting spiral grain. (b) The 'spiral grain' analogy with a helical structural envelope. Hot air rises through the helical lightwells and cool air descends through the central shaft

This spiral grain, compared with the vertical alignment of fibres, makes the tree more flexible to bending. This is more suitable for harsh environments as it allows trees to deflect significantly without breaking under strong winds and to shed snow accumulating on branches. This is not, however, appropriate for the structure concerned since it would potentially compromise the serviceability limit state as the structural stiffness would be reduced. Notwithstanding this concern, a helical structure (Fig. 5(b)) where all floors have rotational symmetry makes the internal environment more uniform. This is the case in terms of both ventilation and lighting; it minimises the clear vertical depth of atria and, if it could be made stable, would become a more preferable design solution. The stability and stiffness issue could be resolved by superimposing the same helical structure, but in the opposite sense. This scheme essentially replaces stocky vertical columns with 'V' members having simple bolted connections, as shown in Fig. 6. The stability and strength is increased further by perimeter beams making the external envelope act as a vertical three-way braced barrel.[22] The global shape of an upright cylinder (Fig. 7) creates less wind flow separation when compared with a conventional office block, reducing both the drag force exerted on the structure and the deflected air stream down towards street level. It therefore becomes a robust structural system capable of redistributing internal forces in the event of an accident or impact and can be constructed efficiently as it would contain largely repeating fabrication details that are amenable to mass production.

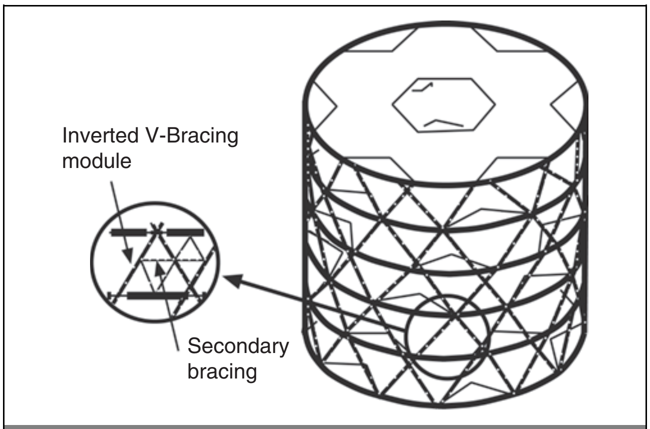


Fig. 6. External envelope forming a vertical three-way braced barrel; V-shaped columns also surround the central vertical shaft

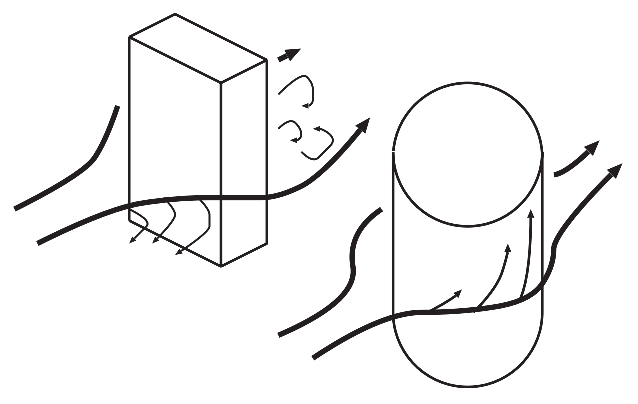


Fig. 7. Wind flow separation on two different buildings. On the left, a conventional rectangular building block will induce a greater wind flow separation causing a low-pressure region behind the building, thus increasing horizontal loads on the building. Wind streams would also be reflected down to street level from the front façade, creating an unpleasant environment outside the building. On the other hand, a cylindrical building would minimise wind flow separation and wind streams reflected down to street level

2.6. Internal space

Having devised the external structural envelope and ventilation scheme, the internal space is now considered. As the majority of buildings are compartmentalised, the floor plan should be modular and structurally efficient. Achieving appropriate and efficient use of space, modularity, adaptiveness and constructability are continual problems in building design. Wasps and bees offer a solution through evolution, based on a modular pattern that tessellates and uses minimum material perimetrically: the hexagonal wax and paper combs of bees and wasps respectively.

For the current design problem the model was provided by wasp paper combs. This tessellation pattern and the central shaft for access are the dominant features of this model in terms of internal space. The central shaft has two main functions: a top-down ventilation duct and an accessibility shaft for the lifts.

2.6.1. Tessellation. The main advantage of tessellation is that, by not leaving voids between shapes, it provides a feasible solution for flooring and tiling as well as structural design. The fact that tessellating shapes share perimeters is very helpful in framed structural design. What makes framed structural design powerful is the fact that the slab is supported on a regular beam grid that is a pattern of regular shapes (usually rectangles, see Fig. 8).

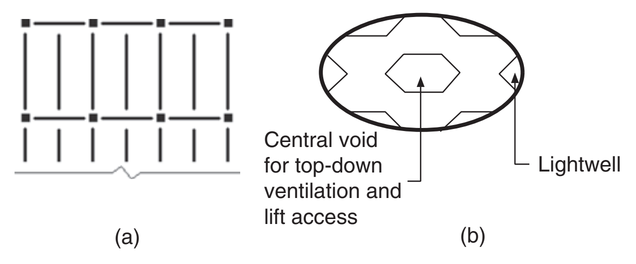


Fig. 8. (a) Structural framing grid exhibiting tessellation. (b) Hexagonal tessellation layout

Tessellation is mainly exhibited by regular planar shapes such as the triangle, the square and the hexagon. The latter is the polygon with the largest number of angles that tessellates. Hexagonal tessellation, as used by wasps, forms the basis of the internal space design. The floor plan comprises seven hexagons: one in the middle with six surrounding it. The pattern is enclosed by a circle that passes through the outermost vertices. The voids on the circumference of the space form the lightwells of the building, allowing natural light into the building and hot air to rise. The internal hexagon is also a void and serves as a top-down ventilation duct and access shaft. Each floor is identical but there is a rotational difference (offset) in each horizontal plane about the central shaft of 15°. The rotational pattern of the floors thereby repeats every four floors. In reality, since the floors have six-fold rotational symmetry, any angle of offset (in degrees) that is a divisor of 60 could be used.

2.6.2. Optimisation of internal space. In order to quantify the quality of the internal space, the floor plan of the building is now evaluated. As part of a biomimetic design, the internal space should avoid the 'deep-plan' condition that has been associated with SBS. This constraint dictates the maximum distance of any office worker from an opening such that the space cannot be characterised as deep-plan. Frankfurt planning authorities stipulate this distance as 10 m and is one of the key design features of the Commerzbank Tower.[15] For the current case, the maximum distance not to exceed the deep-plan condition is denoted n (measured in metres).

Owing to the regularity and symmetry of the internal space, optimisation can be simplified to a single variable x, which is the length of the side of a hexagon in the pattern. There are two main assumptions for this simplification (see Fig. 9).

(*a*) The internal shaft area is that of a circle whose circumference is tangential to the sides of the internal hexagon.
(*b*) There are six lightwells, each formed by the area enclosed by two adjacent hexagons and the circumference of the external envelope of radius R.

Hence the objective function to maximise the floor area without exceeding the deep-plan constraint is given by the difference of the areas of the two circles of radii R and r respectively, subtracting the areas of the six lightwells

$$\text{Max } A\colon A(x) = \pi[R^2(x) - r^2(x)] - 6A_t \tag{1}$$

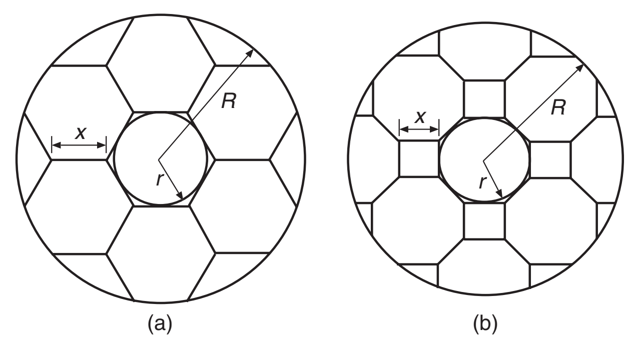


Fig. 9. Floor plans with (a) regular hexagonal tessellation and (b) semi-regular octagonal tessellation with key parameters

under the constraint

$$\frac{R(x) - r(x)}{2} < n \tag{2}$$

where the two radii R and r are functions of x

$$R = x\sqrt{7}, \qquad r = \frac{x\sqrt{3}}{2} \tag{3}$$

and A_t is the cross-sectional area of a lightwell evaluated as

$$A_t = \left[7 \arctan\left(\frac{\sqrt{3}}{5}\right) - \sqrt{3}\right] x^2 \approx 0{\cdot}6x^2 \tag{4}$$

By applying constraint (2) and substituting it into the objective function (1), the maximum effective area, A_{max} can be obtained from

$$\begin{aligned} A_{max} &= \left(\frac{2n}{\sqrt{7} + \sqrt{3}/2}\right)^2 \\ &\quad \times \left[\frac{25\pi}{4} - 42 \arctan\left(\frac{\sqrt{3}}{5}\right) - 6\sqrt{3}\right] \\ &\approx 5{\cdot}2n^2 \end{aligned} \tag{5}$$

To illustrate this result, if n were assumed to be 10 m, the effective or useful floor plan area is approximately 520 m^2. When this is multiplied by 13 floors, a total area of approximately 6800 m^2 results. Under this scheme, the ratio of the effective area of each floor against the actual building footprint comes to 68%. This can be improved further by decreasing the area of the lightwells or changing the tessellation pattern to a semi-regular one, consisting of octagon and a square. When this semi-regular tessellation is applied, the objective function (with eight lightwells this time) yields an effective area of $23{\cdot}3n^2$, almost four times greater than the regular hexagonal floor plan (It is worth noting, however, that the actual footprint of the semi-regular tessellation is in fact almost double the footprint of the hexagonal tessellation.) More importantly, it also increases the ratio of effective to actual area to over 83%. As with the hexagonal pattern, the floor plan also has rotational symmetry (four-fold), so the rotational difference in degrees of each floor can be any divisor of 90. The ratio for the regular hexagonal tessellation could be increased to 81% if the cross-sectional area of the lightwells is halved, which also makes it more efficient in terms of space.

For the purpose of this work, the floor plan with regular hexagonal tessellation was used. The plan consists of six hexagonal modules, within the circular structural envelope, surrounding the central shaft. Each module has three unobstructed views of the external environment, which allow natural light to enter and effectively counter SBS. Tessellation in plan ensures minimum use of structural material and optimum use of space available, as shown in Fig. 10. The rotational symmetry of each floor can be used to make the external envelope stiffer. Of course, if each floor is rotated 15° from the floor below, every fourth floor would have the same orientation as the first.

2.7. Accessibility

The problem of accessibility is solved in much the same way as wasps in the tropics solved theirs. Wasps build their hives suspended downwards from tree branches, building each comb horizontally and moving downwards—unlike human conventional construction that starts from the base and moves upwards. The explanation for the difference in method of construction lies primarily in the materials used and the way they behave structurally. The wasp hive is built from paper made of chewed wood, which is stronger in tension than in compression; thus a suspended tensile structure with such a material is more advantageous. On the other hand, conventional framed structures are primarily gravity–compression structures with heavier members at the base that are built first. The other reason for the absence of suspended buildings is the lack of tall and strong natural structures from which to suspend such buildings.

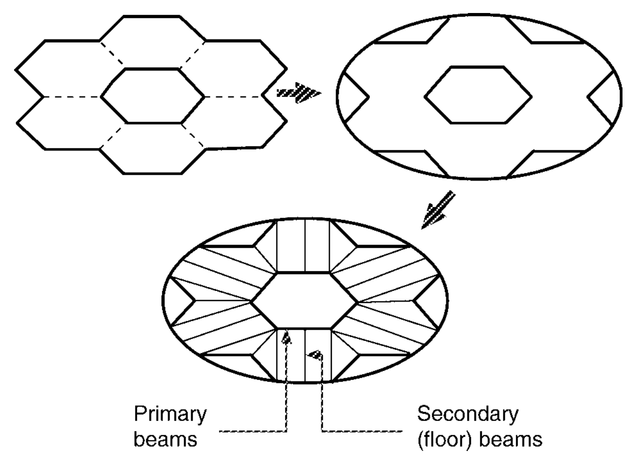


Fig. 10. The development of internal space. Each floor is rotationally offset by 15° to correlate with the external envelope, repeating itself every four floors

As in the case of termites, each wasp species adapts its building techniques to local conditions. The species *Polybia*, which inhabits the tropics, build vertical cylindrical nests with strong conical roofs in order to protect from heavy rainfall and winds, while the rest of the tubular envelope is stiffened by a stack of horizontal combs. The problem of accessibility of the combs is solved by allowing a hole in the centre of each comb, creating an access shaft throughout the height of the nest, which provides the minimum exit time from the furthest place inside the nest. The biomimetic design has lifts in the top-down ventilation shaft, which is also used for access. To cater for emergencies, when the central shaft may be compromised, two or more staircases can be fitted to follow the helical atria (see Fig. 11).

2.8. Testing the effectiveness

Testing the effectiveness of a building inspired primarily by biomimicry principles (Fig. 12) is not a straightforward task. Although there are methods to calculate carbon footprint and wastage of a developed project in order to assess its sustainability, these tests are mostly relevant to complete design proposals. Testing a concept is a rather more qualitative exercise. In this case the biomimetic conceptual design was tested against the ten laws of biomimicry,[2] with the following results.

(*a*) *Does it run on sunlight?* Solar energy drives natural ventilation and lighting, thereby reducing energy loads during the whole-life operation of the building. The use of solar energy could also be implemented during construction. The answer here is therefore partly yes.

(*b*) *Does it use all the energy it needs?* As a continuation of the previous point, the building cannot totally provide its own

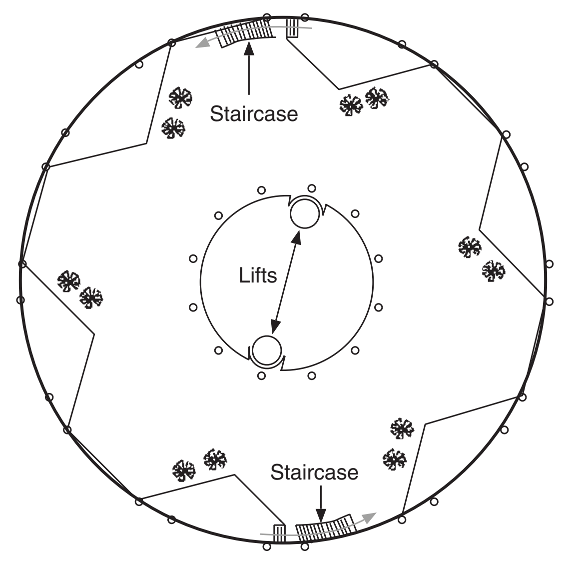
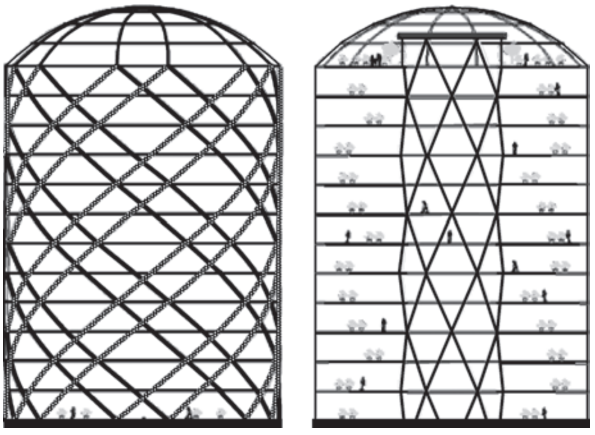


Fig. 11. Typical floor plan indicating the positions of lifts and staircases

energy needs. Adaptations on the building's external envelope or structure could harvest, store and provide energy when needed. These include novel technologies such as photovoltaic cells and wind turbines or the more common thermal masses. The thermal mass is a direct biomimetic concept coming from the behaviour of reptiles warming in the sun prior to moving. Furthermore, research is currently being undertaken[23] on a new technology that mimics the process of photosynthesis to yield a much higher efficiency for the conversion from solar to other useful forms of energy. If this research is successful, then any building or system incorporating this technology will be able to cover its own energy needs. Until then, the answer to this question is no, even though steps are being made to address the shortcomings.

(*c*) *Does it fit form to function?* The structure, other than being a strong, stable, load-bearing system, provides an adaptable, largely columnless and yet modular open office space that is naturally ventilated and lit. The answer is therefore yes.

(*d*) *Does it recycle everything?* Construction materials (steel, aggregates and concrete) can be mostly products of recycling. Air is also recycled naturally, while adaptations of the 'Living Machines' of living technologies[24] could be used to recycle greywater and water plants, thereby minimising fresh water consumption. Finally, future technologies, including so-called smart, environmentally friendly materials that can adapt to different situations, would not require high energy input for production and would be recyclable. This would essentially turn this answer to a definite yes.



(a) (b)

Fig. 12. The final conceptual design: (a) front view; (b) section

(*e*) *Does it reward cooperation?* Materials used in both the construction and operation of such a development should be from industries that use each others by-products (industrial symbiosis[25]) instead of using more virgin material that creates more waste. The building management should follow a strategy to reduce wastage in resources. During operation, cooperation is rewarded through the implementation of a natural ventilation strategy. Studies show that higher percentages of people are satisfied in natural ventilation schemes, rather than when air-conditioning is involved.[26] All the above indicate that certain design choices could make the answer yes.

(*f*) *Does it bank on diversity?* Even though the building has been specified for office use, there is scope for commercial, residential, educational or even mixed use. The plan layout provides both continuity and modularity if necessary, without compromising global strategies such as natural ventilation and natural lighting. The answer is therefore yes.

(*g*) *Does it utilise local expertise?* Local experience and its appreciation is vital for any biomimetic design. The natural ventilation strategy strongly depends on it, while findings from the 30 St Mary Axe development[14] indicated that the direction of helical atria should reflect the prevailing wind direction. Further adaptations of façades and shades can make it an exact match for a given local environment. The answer is therefore yes.

(*h*) *Does it curb excesses from within?* This mostly affects the operation of the building as most of the energy consumed by a building is during its use. Natural ventilation and light should reduce energy bills of the post-construction phase, while recycling of greywater would reduce water consumption to a minimum. Furthermore, during construction, frame prefabrication would ensure minimisation of construction waste, a higher achieved quality and a resulting reduction in total construction time. The answer is therefore yes.

(*i*) *Does it tap the power of limits?* The development is an optimisation of the combination of open plans, natural ventilation and lighting, rather than trying to maximise each separately. The result is a medium-sized building standing against unsustainable deep-plans and futuristic green skyscrapers. The answer is therefore yes.

(*j*) *Is it beautiful?* This clearly has a subjective answer. To some, the building looks more like a cigar casing or even a buckling cylinder.[27] Its curved external envelope, combed interior and helical lightwells, all being natural shapes coexisting in harmony and performing their functions could, however, lead to a yes.

As a concept, biomimetic design is successful in producing a naturally ventilated, user-friendly, adaptable and modular workspace. Services and interior layout are totally integrated with the structural system, which is simple, repetitive and modular. All these characteristics, other than producing a stable, strong multi-functional structure, reduce costs and save time. Scheduling of steel members can be done easily and quickly, with repeated connection details that can be mass produced; everything—except the production of concrete for the slabs, prefabricated and assembled on site—minimising wastage significantly.

3. CONCLUDING REMARKS

For this concept to become a proper design solution ready for realisation, a long and difficult journey lies ahead that would include model testing, structural analysis, mathematical and computational modelling, fluid dynamics experiments and whole-life costing. A good ecological solution that would be so costly as to compromise the welfare of the current generation is not really sustainable; care must therefore be taken when costing or comparing costs, making sure that whole-life costs are considered in any comparison. Nevertheless, the design concept proposed could form the basis on which an optimal structural design could be developed, incorporating more services such as electrical and hydrological, as well as proposing new structural systems based on tensengrity.[28,29] This natural phenomenon, when used in compression structures, reduces or even eliminates geometric limitations against instability found in conventional compression members. Breakthroughs into the potential application of tensengrity in structural design as well as the integration of other services will clear the way for an efficient and optimum structural design that is truly sustainable. Another point that has scope for further exploration is the potential use of tessellation and the possibility of modular building on a micro (internal space) or macro scale (global structure as a module). An example of the macro scale would be when six buildings are brought together in a hexagonal manner to create a larger development (Fig. 13). Obviously, changing constraints should be considered such that any serious compromises of natural ventilation and lighting strategies are minimised; nevertheless, this development could be part of a viable expansion programme. Accessibility within each module (building) would be as before, while connection between modules would exist every four floors due to the helical structure of each module (Fig. 13(b)).

This article is not entirely concerned with sustainable and biomimetic office buildings, but rather the potential use of biomimicry as a tool in conceptual engineering design. The conventional conceptual design philosophy dictates that a client, as the first link in the chain, interacts with an architect to set the objectives of the project. The architect develops the concept, which is then passed to a structural engineer for detailed structural design. Geotechnical issues, services, façades and other issues are dealt with sequentially; as a result, each link does not produce the optimum solution but rather a suboptimal solution based on the decisions or solutions taken by the previous link in the chain. In the whole process, there is very little feedback, usually related to issues not initially considered.

The situation can be considered to worsen because each practice seems to overtake the holistic approach with each link in the chain considering its part to be the most important. The diversity of biomimicry indicates that different stakeholders should work synergistically to produce sustainable solutions. To achieve this, university courses and professional training schemes for architects and engineers should include some background of each other's practice. The objective of such an inclusion in training schemes is not to create multi-tasking engineers that can do everything by themselves, but well-rounded professionals that can communicate with colleagues of different disciplines at a higher level in order to deliver more sustainable solutions in design and construction.

Nature offers a myriad of organisms and ecosystems to inspire biomimicry to develop solutions to applied human problems, from project management to methods of construction, manufacturing and materials. This is because natural organisms generally exist as low-energy systems, part of a greater ecosystem that bases its survival on the synergistic cooperation and coexistence of the species in the ecosystem. When one component is removed from the ecosystem, it will either try to adapt to the change or it will not survive and a new chain of events will be initiated—usually when the change is catastrophic. This is why solutions from nature are not always applicable—nature's most common solution for harsh environments and extreme weather conditions is usually extinction. With the human population set to continue increasing radically over the next few years, a solution involving extinction should not be an option. Furthermore, scale effects may limit the ability to replicate exactly a natural system (e.g. achieving dynamically similar flows at different scales). Nevertheless, with current technological and scientific advancements, truly sustainable solutions can potentially be realised soon.

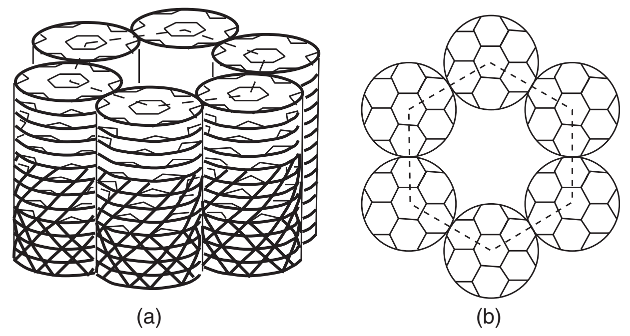


Fig. 13. (a) Three-dimensional model of potential tessellation of the proposed building forming a hexagonal footprint. For the first four floors the external bracing is indicated (removed for the top floors to indicate internal space). (b) Plan of a floor where modules communicate

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