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Design and construction principles in nature and architecture

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Abstract

This paper will focus on how the emerging scientific discipline of biomimetics can bring new insights into the field of architecture. An analysis of both architectural and biological methodologies will show important aspects connecting these two. The foundation of this paper is a case study of convertible structures based on elastic plant movements.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Architects and master-builders have been using nature as a source of inspiration long before the terms bioinspiration or biomimetics were introduced. The eras in which architects transferred the variety of natural shape and form directly into their work alternated with those of strict geometrical order. After a period of technological functionalism and subsequent post-modern architecture, today's aesthetic understanding is focused once more towards movement and flowing spaces which reflect forms found more or less directly in nature. Which new findings can this young scientific discipline biomimetics offer architecture? New options can only result from an in-depth analysis and comparison of architecture and nature, both from a broader and deeper perspective as well as on a functional and methodological level. Not only architects show a deep interest in this discussion, also biologists are actively pursuing their interest in architectural design (Gould and Lewontin 1979).

Architectural design and biological evolution are non-deterministic processes. In biological evolution and architectural design, evaluation criteria and development targets are created and are part of a process subject to constant change and adaptation. In this respect, biology and architecture differ from most engineering sciences, which usually concentrate on the optimization of clearly defined individual functions with fixed boundary conditions and target functions. In architecture, a quantifiable optimum is, at its best, only possible with some technical or economical parameters (e.g. optimization of energy or material consumption), but it does not allow for an integrated assessment of important features such as aesthetic, spatial, urban or social qualities, which are vital for successful and sustainable architecture.

During the course of evolution, biological organisms adapted their character through selection and interaction to meet constantly changing environmental conditions by developing multifunctional solutions. The result is a compromise satisfying partially conflicting requirements (Rowe and Speck 2004, Speck and Rowe 2006). In this context, it is worth mentioning that living beings carry an 'evolutionary burden' because evolutionary innovations always build on inherited structures (the 'bauplan') and their respective functions. The 'bauplan' and the fact that living beings have to 'function' successfully during all phases of evolution confine the potential of natural selection as an optimizing agent. A comparable situation can be found in architecture, where a building plan based on static constraints

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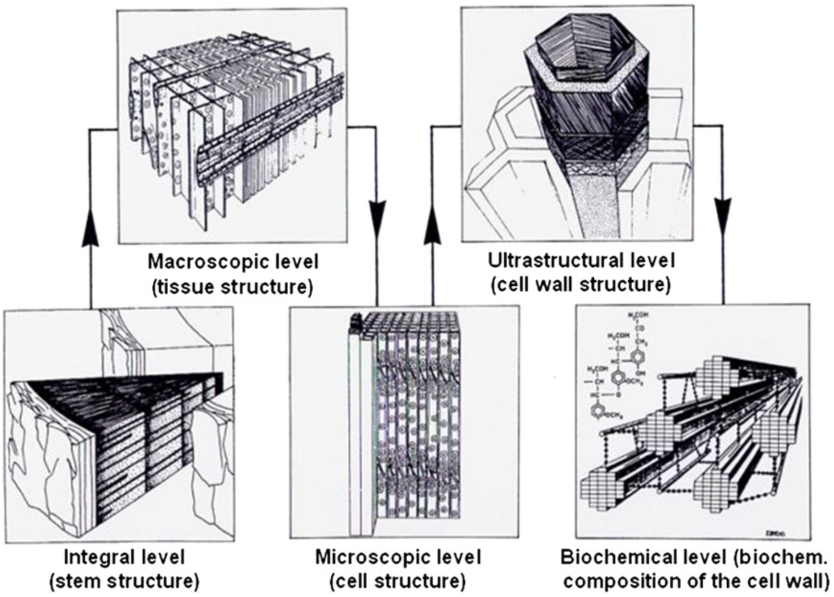

Figure 1. Five different structural hierarchical levels of plant stems covering up to 12 orders of magnitude, shown as an example in a pine stem and a tracheid. Adapted from Speck and Rowe (2006).

confines the degree of freedom of further architectural embodiment. Therefore, similar to architectural design, evolutionary adaption in nature is limited by 'architectural' constraints predetermined in the 'bauplan' of the biological organism (Gould and Lewontin 1979).

The requirements modern buildings have to fulfil today are very complex, often contradictory, and during their life cycle need to be adapted for utilization, economical and ecological reasons. In the last decades, emerging ecological demands have been a driving force in the development of highly evolved building technologies including material development and automation. Nonetheless, these technologies are still handled as isolated components which are integrated into otherwise traditional building concepts.

Holistic approaches for new structural, functional and ecologically efficient buildings may be expected from a more interdisciplinary approach. A very important aspect will be an effective exchange of research between the disciplines, not only on the level of scientific knowledge but also on a methodological level. Biology is in this respect of particular interest for architects and civil engineers, since it delivers not only isolated phenomena but also new technical and methodological strategies.

2. Design and construction in nature and architecture

In addition to the initially drawn parallels, fundamental differences between architecture and biology can also be identified. Taking these differences into consideration can lead to a change in perspective and to an expansion of possibilities for architects and engineers.

If we restrict ourselves to considering structures in biology and architecture, it becomes apparent that, in respect of structural design, they have diametrically opposite principles. Architecture and civil engineering define construction in two categories: 'material' and 'structure'. In today's practice, the design of a structure is a hierarchical process. It starts with the choice of a load-bearing system. This is based on a limited canon of options (e.g. beam, truss, wall, slab, arch, etc) that are primarily classified through analysis as well as construction methods. Such support systems are realized in very similar forms but using different materials which are selected during the second stage (e.g. steel, timber, masonry or concrete, etc). Natural constructions, however, arise from an almost infinite diversity through mutation, recombination and selection. They show a hierarchical structure on usually five to seven levels that may span up to twelve orders of magnitude (Dunlop and Fratzl 2011, Fratzl and Weinkammer 2007, Milwich *et al* 2006, 2008, Speck and Rowe 2006). A conifer stem shows (at least) five different structural hierarchical levels (figure 1). On each of these hierarchical levels, which cover up to twelve orders of magnitude, the different functionally important properties of the stem (including mechanical properties such as stiffness, damping and prestressing; water and assimilated transport; nutrient storage; adaptive growth by reaction wood, self-repair; heat insulation, etc) may be varied (Speck and Burgert 2011). Mechanical properties for example can be influenced on the biochemical level by the cellulose-to-lignin ratio, on the ultrastructural level by the angle of cellulose microfibrils, on the microscopic level by the cell wall thickness (mainly the thickness of the S2-layer) and the distribution of pits, on the macroscopic level by the ratio of early wood to late wood, and on the integral level by the amount of secondary wood.

From the macroscopic organism down to the smallest molecular components, each structural element consists of smaller sub-structures made up of similar building components. A separation into 'material' and 'structure' categories is therefore not possible (figure 1). The same


(*a*) (*b*)

Figure 2. (*a*) Geodesic Dome Montreal 1967, Buckminster Fuller (photo: Philip Hienstorfer). (*b*) Grid Shell Frankfurt MyZeil, Architect: M Fuksas, Rome; Engineer: Knippers Helbig Advanced Engineering (Knippers and Helbig 2007, 2009; photo: Christian Sauter).

applies to the terms 'structure' and 'form', which are of great importance in architecture. The various functions of a thermal envelope, spatial separation, building services, load transfer, etc are assigned to different components. Consequently, the load-bearing 'structure' and the space-shaping 'form' of the building are functionally separated. In an architecture that is driven by formal aesthetics, the geometric 'form' is often not even related to the geometry of the 'structure'.

In natural structures, however, the basic building components not only support the structure but also carry substances that catalyze chemical reactions and recognize molecular signals. The 'form' arises from functional requirements that are met by a 'structure' which is often composed of a single basic substance.

From an engineering perspective, the analysis of natural structures demonstrates that they essentially consist of a small number of mostly light elements (C, H, O, N, P, S, P, Ca, etc) and only a few polymeric substance groups (proteins, polysaccharides, lipids, nucleic acids, etc) exist (Dunlop and Fratzl 2010, Fratzl and Weinkammer 2007, Jeronimidis 2000a, 2000b, Milwich *et al* 2006, Speck and Rowe 2006). Individual cells form tissues that are combined to create 'organs' with different functions. Natural structures are often not isotropic but consist of fibres such as cellulose or collagen with direction-dependent properties. By combining different trajectories and the packing density of fibres, a number of finely tuned structural properties is achieved. In addition, chemical and structural heterogeneities play an important role in allowing local adjustments to be integrated. The continuous external skeleton (exoskeleton) of insects, for example, is made from chitin fibres (polysaccharides) which are embedded in a protein matrix. The chemical, structural and mechanical properties of such a composite material may vary to a large extent and thereby allow for local functional adaptations in different areas of the insect's body. Natural constructions, therefore, consist of only a few basic components which are geometrically, physically and chemically differentiated. In this respect, they are fundamentally different to most architectural constructions. These consist of highly differentiated material and functional components (e.g. steel for the structure, glass for the envelope and different plastics for the installations, etc), which, in themselves, are geometrically simple and can be assembled by being added to each other to build up the desired construction.

The question arising at this point is whether the morphological form and function principles of nature which have developed over 3.8 billion years of evolution can be used for structural, functional and ecologically efficient building structures.

2.1. Paradigm shift in building construction

The use of as many equal building parts as possible, arranged and joined in the simplest possible manner was paradigm until a few years ago. This has dramatically changed in the last decade through the introduction of computer-aided manufacturing processes.

The following example may illustrate this. The American visionary inventor Buckminster Fuller worked intensively for over 50 years on the geometrical laws of geodesic domes (cf Hays and Miller 2008). One of his many aims was to develop topologies for spherical shell structures that allowed the use of as many identical beam and node elements as possible. He accomplished this by dividing a sphere into twenty identically large spherical triangles (icosahedron), which were subdivided into a regular triangular mesh. At the corner points of the large spherical triangles, special nodes joined by only five members, an irregularity because all the other nodes are supported by six members (figure 2(*a*)).

For modern computer-aided manufacturing CAM techniques, such considerations are obsolete; it is not important whether the milling geometry of a joint is changed or not; it has no influence today on the production process. In recent years, numerous lattice shells were constructed, consisting of many thousands of different rods and nodes, without significant additional expense. This provides greater freedom in the design process: Buckminster Fuller and other designers of his time were still limited to regular geometries such as the dome or barrel. Today's lattice shells, however, can adapt to almost any geometry, driven by functional or aesthetic requirements (figure 2(*b*)).

During the mid-1990s such lattice shells, composed of steel rods and glass plates, took over an important model role

(*a*) (*b*)

Figure 3. (*a*) ICD/ITKE Research Pavilion 2010, University of Stuttgart (photo: Roland Halbe), (*b*) digital fabrication of plywood strips (photo: University of Stuttgart).

in the steel construction industry in terms of developing a digital design and production chain. Other building techniques including concrete and timber construction are gradually reaching similar innovative results.

A fitting example is the research pavilion built by the members of the Institute of Computational Design (ICD, Professor Achim Menges) and the Institute of Building Structures and Structural Design (ITKE, Professor Jan Knippers) of the Faculty of Architecture and Urban Planning at the University of Stuttgart with the help of many students in 2010 (Menges *et al* 2011, Lienhard *et al* 2011). The structure is entirely based on the elastic bending behaviour of 6.5 cm thick birch plywood strips. The strips were robotically manufactured as planar elements and subsequently connected to coupled arch systems as shown in figure 3. A radial arrangement and interconnection of the self-equilibrating arch system lead to the final torus-shaped design of the pavilion. Due to the reduced structural height, the connection points locally weaken the coupled arch system. In order to prevent these local points from reducing the structural capacity of the entire pavilion, the locations of the weak connection points between the strips had to be varied along the entire length of the structure which resulted in 80 different strip patterns being constructed from more than 500 geometrically unique parts. A continuous computer-aided process for design, simulation and manufacturing was implemented to realize this structure.

Although neither the design nor the construction of this pavilion was inspired by biological role models, it inevitably is reminiscent of natural structures, because the seemingly innovative principles used here are frequently found in nature. These principles are the homogeneous nature of the construction using a single textured material, the parametric differentiation of the plate geometry with a uniform basic typology and the shaping of large elastic surface deformations.

This example shows that digital simulation, planning and production processes open up new methods of approaching natural role models. Today, the technical requirements for a transfer of knowledge from nature into construction engineering are much more prevalent than those even a few years ago (Fratzl 2007, Masselter *et al* 2011, Masselter and Speck 2011, Milwich *et al* 2006, 2008, Pohl *et al* 2010). Therefore, the study of biomimetics for architects and engineers is even more relevant today than ever before.

2.2. *Natural design principles in architecture*

An important characteristic of natural systems is a multi-layered, finely tuned and differentiated combination of basic components which lead to structures that feature multiple networked functions (Dunlop and Fratzl 2010, Fratzl 2007, Fratzl and Weinkammer 2007, Jeronimidis 2000a, 2000b, Masselter and Speck 2011, Milwich 2008). Such design principles have so far virtually never been used architecturally; if at all, only in a very basic form (Godfaurd *et al* 2005). They can be classified as follows.

- *Heterogeneity*: natural constructions are characterized by a geometric differentiation of their elements. As described above, the introduction of digital design and manufacturing processes increases the possible level of geometric differentiation in building structures and facilitates the transfer of natural morphologies into architecture. Additionally, natural structures are characterized by local adaptations of their physical or chemical properties. Material research is currently concerned with gradient materials, such as the targeted control of porosity in concrete, trying to match the opposing properties of thermal conductivity (high porosity) and mechanical load bearing (low porosity) to meet local requirements. The introduction of gradient materials in construction practice is still pending.
- *Anisotropy*: many natural constructions consist of fibre-reinforced composite materials. Similarly modern high-performance materials are increasingly based on the principle of anisotropic fibre reinforcements. Current developments are concerned with the manufacturing methods for producing a demanding arrangement of stress-related fibres, especially around load concentrations at branching points (cf Fischer *et al* 2010,

Figure 4. Folding Bridge Kiel 1998. Architect: von Gerkan Marg and Partner; Engineer: Schlaich Bergermann and Partner (photo: Klaus Frahm).

Masselter and Speck 2011). Therefore, many valid suggestions can be expected, resulting from the study of natural role models.

- *Hierarchy*: biological structures are characterized by a multi-level hierarchical structure from nano- to macro-scale, each level consisting of similar molecular components, but giving rise to different and, to some extent, independent functional properties and adaptions (figure 1).

  In contrast, building structures show a very different understanding of hierarchy: they consist of a static system (e.g. optimized for maximum efficiency) using components (e.g. girders with an optimized cross section) made of different materials (e.g. optimized for maximum strength or processability).

  The natural conception of hierarchy still remains virtually unexplored in architecture and civil engineering so far. Current approaches for highly loaded structures are moving away from static systems with a few specific structural elements, towards structures with increased redundancy, but the advantages and possibilities offered by implementing a multi-level hierarchical construction as found in living beings are still not being taken into consideration.
- *Multifunctionality*: botany fibres simultaneously serve mechanical and diverse physiological functions. Current research is focusing on integrating monofunctional components into multifunctional material systems, such as the integration of sensors and actuators in adaptive composite structures for aircraft, or elements for generation, transmission and storage of energy in facade elements. Systems which reflect natural structures in terms of uniform texture with a variety of functions are unknown in architecture and engineering so far.

This classification is, of course, not complete. It could be widely increased by describing principles such as redundancy, adaptability, etc.

3. Case study on convertible structures

Based on selected functionality, namely the movement of structures, it will be analysed how biomimetics can be used in specific design questions.

Questions regarding this issue came to light during the first author's many years of work on kinematic structures, such as the three-field Bascule Bridge in Kiel Horn, Germany (figure 4), where he was employed as a project manager responsible for design for Schlaich Bergermann and Partner. The bridge is moved through a complex cable system of numerous ropes, winches and rollers, and simultaneously each change to the construction's position had to be stabilized to counteract wind loads from all directions (Knippers and Schlaich 2000). The architectural intent was to incorporate not only the mechanics but also the aesthetics of the surrounding harbour cranes and transfer it to the bridge construction. This bridge, however, is a unique item; it was planned and built without any reference projects or prototypes. This is also the case for the majority of structures in architecture. It is a major contrast to industrial machinery and, for example, the surrounding cranes which are usually developed with extensive test runs and prototypes of various scales. This approach often leads to problems in practice which can only be solved by tedious experimentation on the finished object.

The arising question is how one can reduce the complexity of movable building structures. This leads almost automatically to the study of natural role models. Botany in particular provides the most radical answer which stands in total contradiction to the technical solution as shown in figure 4. Many plant organs move without any specific mechanical elements but through the locally adapted and adaptive flexibility of their components. One can distinguish between autonomous and non-autonomous movements. Active autonomous movements are characterized by motor organs, e.g. pulvini driven by a change of turgor pressure. Passive autonomous movements occur by changing physical circumstances, e.g. bending through desiccation. Non-autonomous movements are mostly reversible deformations caused by the release of stored elastic energy following an external trigger or by direct application of mechanical forces (Burgert *et al* 2007, Burgert and Fratzl 2009a, 2009b, Dawson *et al* 1997, Elbaum *et al* 2007, 2008, Fratzl *et al* 2008, Lienhard *et al* 2009, 2010, 2011a, 2011b, Martone *et al* 2010, Melzer *et al* 2010, Poppinga *et al* 2010a, 2010b, Schleicher *et al* 2010, 2011, Vincent *et al* 2011).

If and how such plant movements can be used technically was investigated by developing the elastic kinematics for a facade shading system (Lienhard *et al* 2009, 2010, 2011a,

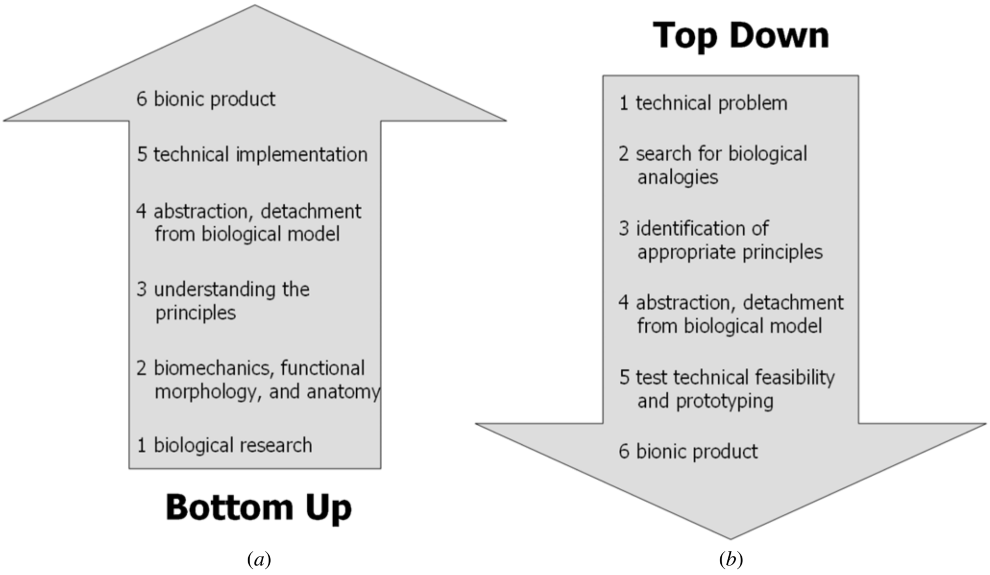

Figure 5. Process sequences in biomimetic research. (*a*) Bottom-up process of biomimetics (biology push). (*a*) Top-down process of biomimetic research (technology pull).

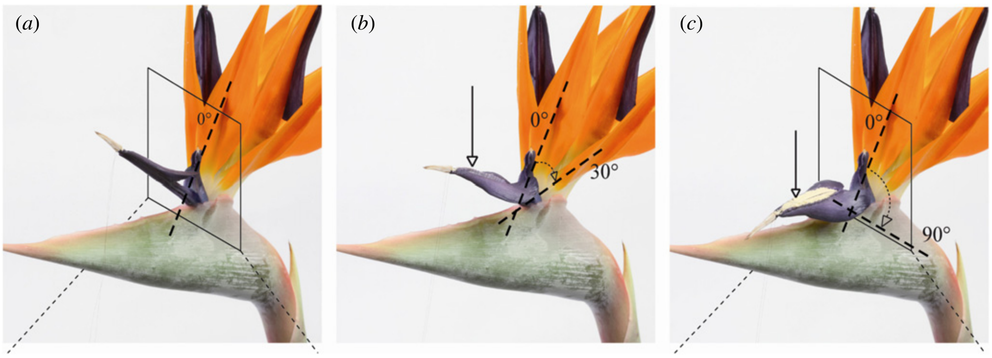

Figure 6. Elastic deformation of the kinetic system in the *Strelitzia reginae* flower. When mechanical force is applied (as indicated by an arrow), the sheath-like perch opens (adapted from Lienhard *et al* 2011b).

2011b). This exemplifies a top-down process of biomimetics (figure 5). Screening various plants identified the movements of the 'bird of paradise' flower (*Strelitzia reginae*) as a suitable kinematic principle. The *Strelitzia*'s flower features two adnate petals that form a perch for pollinating birds. When a bird sits on this perch to sip the nectar, its weight causes the perch to bend down. In a simultaneous movement, the petal lamina exposes the anthers and the style that are otherwise hidden and kept safe (figure 6). This bending actuates a lateral unfolding of the wings (lamina) (Poppinga *et al* 2010a, 2010b).

From an engineering perspective, the arrangement of fibre-reinforced ribs, lamina and wings, which the perch consists of, initially appears to be quite a complex design. A gradual abstraction, described in detail in Poppinga *et al* (2010a, 2010b) and Lienhard *et al* (2010, 2011a, 2011b), transforms the elastic kinematics into a simple mechanism which consists of a thin shell element attached to a beam (figure 7).

The equilibrium path of the shell element is a non-symmetrical bending motion, triggered by torsional buckling which is induced by uniaxial bending of the attached beam. This torsional buckling phenomenon is well known to engineers. However, in structural design, it is usually considered as a failure, which needs to be prevented through design countermeasures and static verification. Nature, however, exploits this principle and uses it actively to mobilize certain functions.

Based on the first physical models and numerical simulations, a prototype facade shading system called Flectofin® was developed (figure 8) and registered for a patent (Lienhard *et al* 2010, 2011a, 2011b, patent application). The Flectofin® lamellas consist entirely of fibreglass-reinforced plastic, which offers high tensile strength combined with low bending stiffness, allowing for large elastic deformations.

Because the system functions without a straight turning axis but with a bent backbone, it can also be adapted to facades with curved geometries. This represents a significant expansion of possible future applications. Another important advantage is the shading system not having any maintenance-intensive parts such as sliding joints or hinges. This reduces costs for maintenance and care. Presumably, this mode of

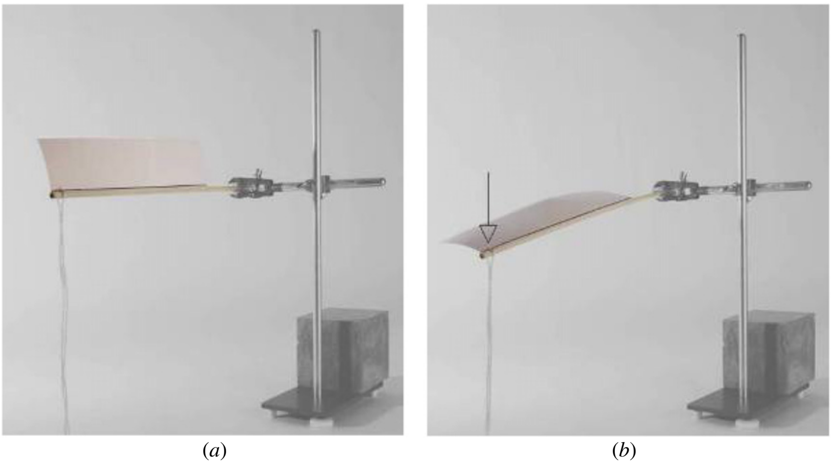

Figure 7. Simple physical model as a first-level abstraction of the kinematic system in the *Strelitzia* flower (adapted from Poppinga *et al* 2010b). Courtesy of WIT Press from the book C A Brebbia (ed) 2010 *Design and Nature V* pp 403–10.

Figure 8. Prototype of the façade shading system based on the Flectofin® produced in collaboration with the industrial partner Clauss Markisen (adapted from Lienhard *et al* 2011b).

function will also increase the durability of the biomimetic facade shading system.

3.1. Biomimetics in the architectural design process—design of the thematic Pavilion EXPO 2012

The opportunity of introducing such systems on a larger scale in an architectural design will be presented at the Thematic Pavilion at EXPO 2012 in Yeosu, Korea (figure 9). A kinematic media facade with 108 individually controllable fins is planned on the pavilion side facing the expo. The design is the result of an open design competition which was won by Soma architects (Vienna, Austria). The technical concept of the kinematic fins comes from Knippers Helbig Advanced Engineering, Stuttgart, New York. The facade can adapt to light conditions and physical building conditions and allows the artistic staging of special lighting effects. It has a total length of 140 m and a height of between 3 and 14 m, and is designed to withstand the very high wind speeds on the Korean coast.

It was initially attempted to scale Flectofin® to the size of this façade. However, this proved to be difficult in its original configuration. On the one hand, it did not fulfil all aspects of the architectural design; on the other hand, without additional structural reinforcement, it does not offer enough stability to withstand the high wind loads. Inspired by the research on plant movements, another kinetic system has been developed (figure 10). The facade is made of slightly curved plates which are supported by two hinged corners at the top and the bottom. In the other two corners, a small compressive force is applied in the plane of the fin, which leads to a controlled buckling. This principle shows locally smaller strains than the Flectofin®

Figure 9. Thematic Pavilion EXPO 2012, Yeosu, Korea; architect: Soma architects, Vienna; Engineer kinetic façade: Knippers Helbig; Stuttgart, New York (visualisation: Soma/isochrome).

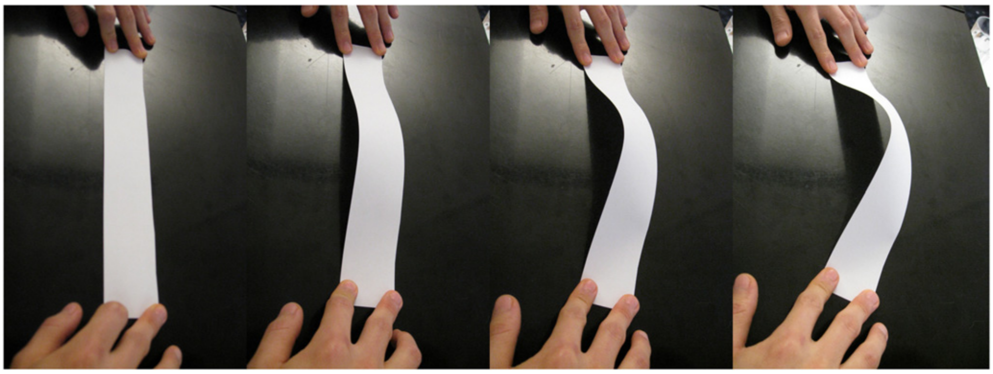

Figure 10. Kinematic principle of the Yeosu façade (photo: Knippers Helbig).

but does not open completely. It perfectly matches the initial design intentions of the architects and offers a favourable ratio of structural stability and actuation energy (figure 9).

The elastically deformable fins are made of fibreglass-reinforced plastic. They are up to 14 m high, 1.25 m wide and only 9 mm thick with an additional stiffener on the side with less-elastic deformation (the right edge in figure 10). When open, the curved geometry, together with the residual stress state, results in a very rigid system that deforms only a few millimetres under high wind loads. In its closed state, the adjacent plates are clamped together so that the facade can withstand even the strongest storms without damage.

4. Conclusion

Both the Yeosu shading system and the Flectofin® movements are made possible via elastic deformations that are associated with correspondingly large strains. Both cases show nonlinear deformation which, from a structural engineer's perspective, is considered to be a stability failure, and usually needs to be prevented by sophisticated nonlinear analysis and bracings or reinforcement. Even though the principle of the Yeosu facade does not follow the abstraction of a plant movement directly, the underlying idea was inspired and derived from the observation and analysis of natural role models.

This encouraged the search for solutions outside the traditional methods of design and construction and going beyond preconceptions, such as avoiding disproportionately growing deformations and stability failure modes.

The two examples show that a linear understanding of biomimetics, as illustrated in figure 5, may only be sufficient if the focus is on the abstraction of single functions as found in technical products such as the shading system Flectofin®. In architectural tasks, such as the design of the facade in Yeosu, however, differing requirements between the aesthetics and functionality have to be met in a given set of defined boundary conditions. In addition, the biological role models very often have to be scaled up to a large size, which leads to increasingly difficult functional requirements.

In the context of architecture or building structures, a linear abstraction process is therefore difficult to maintain. Instead, an expanded definition of biomimetics is required: the analysis of natural form and function principles have the potential to stimulate architects and engineers to fundamentally new strategies in architectural design and technical implementation.

Acknowledgments

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