ARCHITECTURAL BIONICS IN CIVIL ENGINEERING

АРХИТЕКТУРНАЯ ВIОНИКА V СТРОИТЕЬСТВЕ

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Abstract: *Historical view and the present state of the problem. Basic mechanisms in architectural bionics. Armors of turtles. Principles of analogy and homology. Structural forms of living nature. Mathematical aspects of the optimal shape structure design. Applications in civil engineering. Conclusion. References.*
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1. Introduction

During past three decades we have witnessed a new trend in architecture - the inspiration by natural forms, such as marine shells (Fig. 1), [17], radiolarian, and turtle shells. In the past, humans often consciously or intuitively looked for the inspiration in wildlife for their architectural activities. After thousands of years of testing the effects of different loads and their combinations, as well as the use, natural forms are perfectly adapted to their environment. Probably this is the reason why ancient human dwellings resembled to beavers, termites, or bird nests.

Figure 1: Marine shell

Already Democritus and Vitruvius argued that the first vertical stone - prehistoric menhirs were erected by man and replicated the idea of tree, embodied in the pillars of Egyptians, Greeks and Gothic cathedrals

Brunelleschi based his construction of the dome of Santa Maria del Fiore temple on the shape of egg shell, which is interesting not only because of its geometry but also because of its internal structure. By its shape it is a two-focus of a parabola. This geometric object can result from the rotation of parabola around its axis of symmetry (Fig 2a, 2b) [1], where F1, F2 are the focal points of the curve, c is the distance between focal points, F/2 is the distance from the first focal point, P is the distance of the apex of curve to the directrix , r1, r2 are diameters; D is so-called large diameter.

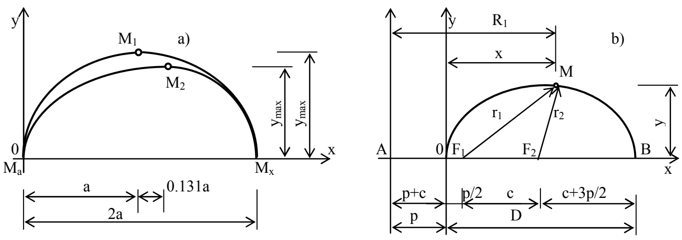

Figure 2: Geometry of parabola with two focal points

The equation of the curve is given in the form

$$y = \sqrt{3x(2-x)\left(1-\beta^2/(x+1)^2\right)} \qquad (1)$$

where $\beta = c/a$, a is the half the large axis, c is the distance between both focal points. B is the coefficient characterizing the shape of the curve, $\beta \in$<0.76 - 0.86>, the value of 0.76 - 0.80 is characteristics for hen eggs and 0.8. - 0.85 for birds' eggs [1].

The Russian wooden churches reflect the harmony of tall firs and their domes the structure of pine or fir cones.

Architectonic bionics is the division of technical bionics devoted to discovery of laws of nature objects shapes and forms and application of these laws in architectural construction. This is a brand new approach in theory and practice of architecture. Technical bionics examines principles of construction of nature objects and applies these results in engineering tasks. Such approach is fully justified, as in the nature there are no strict barriers between the living and inanimate. The world is integrated into one single unit by laws of nature, creating the possibility of unification in natural sciences.

Work of D'Arcy Thomson "The genus and form" [2], devoted to the issue of creation of forms in the nature, taking as an example the smallest aquatic organisms - radiolarian, diatomite and jellyfish, represents a big accomplishment in the field. French architect Robert Le Ricolais (cited R. Motro [3] and ZS Makowski [4]) studied mechanical properties of radiolarian *Tuscaretta Globosa* and applied results to construction of geodesic domes.

Significant contribution to the theoretical thinking in engineering research was made in the 17th century by Galileo Galilee, who studied mechanics of plant stalks and derived the theoretical formula for calculating the beam, which was used by engineers until 19 century [5].

Biologists Malpighia, Senebrier and Müller were studying the structural characteristics of living organisms. S. Schwendener also studied "plant architecture" with application to shape design. All this research contributed to formation and development of and another scientific discipline named Biostatics by Lebedev [1], with the goal to further study and examines architectural structures in nature.

2. Basic mechanisms of architectural bionics.

It is useful to express the relationship between the shape of the projected artificial structure and nature shape in form of their analogy and homology.

The analogy means that the same function is fulfilled by originally different structural features. As an example, a thorn of the thistle *Crataedus* originated from a deformed branch, but the thorn of the thistle *Berberis* is a transformed leave (both have the same function - the protection) [1, 6]. We can draw analogies between the elements of architectural structures and forms in nature and we can also find related shapes: cable roof structure and spider web, dome on the building and anthills, etc. Analogies may appear at the level of the shape, but also at the level of functions (humans dwelling - bird's nest). In making an analogy we search for the match [N. Bohr], we search for the expression of the general law in a specific situation.

Homology is a different way of expression of natural laws. In biology it means that similar forms with the same origin and construction fulfill different functions. As an example, fins of the whale, bat wings and human hands have the same structure and origin, but perform different functions. In terms of technical bionics, homology is a manifestation of similarities, based on the common relationship. In search of homology we focus on establishing links between human activity and activity of living organisms. We can make an example of ropes, whether used as a load-bearing structure roofing systems, bridges, structural elements or aerial high-voltage wires. Their origin can be traced to the spider webs, lianas or processed flax fiber. Thus, these and alike structures created different, homologous, functions. As said above, fin of the whale and bat wings are homologous to the human hand. They originate from the same structures on the skeleton, but their functions diversified so much that there is virtually no remaining similarity between them [7].

The main difference between these two principles is that homology principle operates in “family” lines and the principle of analogy is characterized by structural and functional similarities between non-related phenomena. It should also be noted also that they do not contradict each other.

3. Creation of forms - growth and development

Close examination of analogies allows us to further clarify some issues concerning the design of the shape of structure. Evolution theory shows us that organic forms progressively improved during the process of evolution as a response to the change of environment (although with different deviations) [8], or new organisms appear that are better adapted to their surroundings and the conditions of existence. This improvement is accompanied by a very functional transformation. It is not simple "piling" of individual functional elements, but the quality change in the transition to a lesser extent of "uncertainty".

Operation with the structure and the geometry of the form (integration, or differentiation, if necessary) are of the special importance, as they lead to homeostasis, and help to implement the optimal energy exchange in the process of growth and development in the presence of exogenous factors such as gravity, a temporary mechanical loads (snow, wind, rain, seismic effects, changes in radiation, meteorological disturbance.

Principle of interaction is crucial in terms of tasks imposed on the optimal design of the shape. In this case we can speak of "two cones”, the cones of stability and development. This principle is well known in nature (in plant kingdom) - tree trunks and tree crowns, stalks of plants, etc... The first cone - cone of stability is a reaction to external load effects (gravitational forces, self-gravity, and wind). The second cone is the growth into space - a dynamic cone (Fig.3), in the Fig 4 [17] is the application to of this principle to the construction water tower.

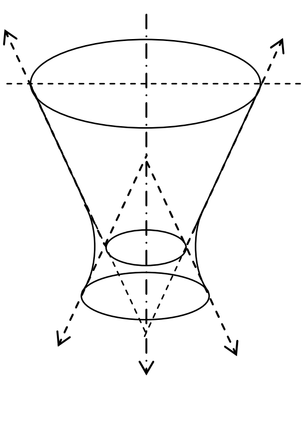

Figure 3: Principle of two cones

Figure 4: Water tower

Another element describing the evolution of the nature is so-called principle of spiral (thin stalks of plants, snails, etc.). We encounter predominantly in the nature the logarithmic spiral - spiral with an increase in radial dimension (Fig. 5), [20]. This is dynamic type of spiral and it provides room for free growth and at same time the economics of energy and building material, e.g. [1].

One of necessary means for the existence and the development in nature is structuralisation of the space. It integrates a number of principles. One of them is the principle of "space in space" in order to create a transitional climatic environment.

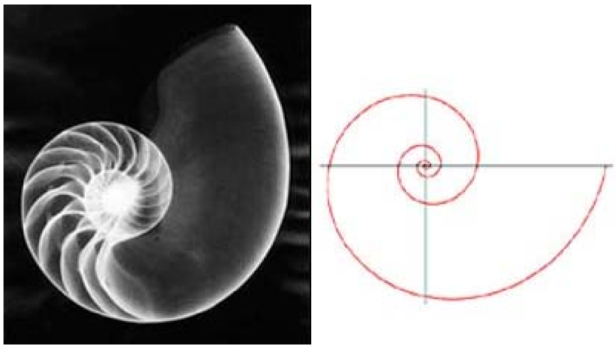

Figure 5: Principle of spiral - Nautilus shell as an example of logarithmic spiral.

As an example we can consider the medical academy in Ulm (author F. Otto), or known "cities under the dome" built in areas of the Arctic Circle (by B. Fuller).

In the optimal design of construction one can also use principle that we often encounter the nature and that is the "repetition of the same element type and shape”, which is routinely found in living organisms, which recalls building objects from the standard prefabricated parts. One of the fundamental elements of living nature is a cell. We will find it in plants, as well as in animals.

In terms of observation of nature, we should notice the structural genius of combinational art of the creator. Some natural forms are geometrically ideally regular, especially those encounters in an environment with stable physical parameters - in the depths of the seas and oceans. As pointed out by R. Le Ricolais [3] or Z.S. Makowski [10] for the class of radiolarian, one could find the structure of octahedrons (composed of equilateral triangles), dodecahedra (composed of regular pentagons), or icosahedra (assembled from 20 equilateral triangles).

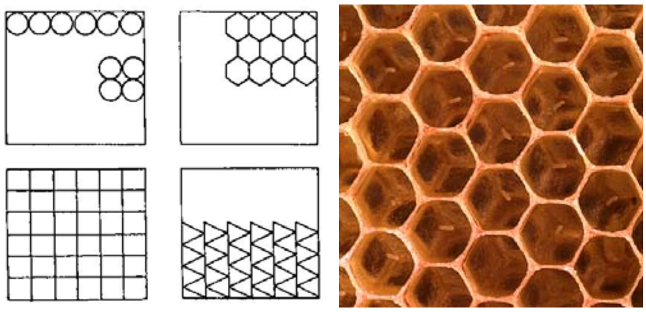

Figure 6: Composition from regular polygons. Structure of the honeycomb.

The shape of the regular hexagonal prism is very important in practice and also very economic in terms of optimal shape design. This building block is encountered in honeybee comb (Fig. 6), [20], or in plant vessels. Regular hexagons provide economical base filling of the base area, e.g. [1]. These structures are used successfully for grid domes (often combined with pre-stressed elements), as in the example of the roof of chemical plant in Baton Rouge, USA [10]. In architecture, these types of domes are known as Fuller domes. One can obtain an interesting structure by assembling semi-regular polyhedron, such as dodecahedral diamonds (12 planes, 24 edges and 14 vertexes), or Kelvin polyhedron (with 14 planes), consisting of six squares and eight regular hexagons. The latest ensures the optimal thermal regime for the living organism. It respects “appropriate” relationship between the size of surface and the volume delimited by this surface. The radial stress increases the stiffness of the structure. All the above mentioned elements enable the optimal design of spherical (or close to spherical) systems.

4. Natural construction forms from the viewpoint of bionics.

In the nature we encounter various types of structural forms that react differently to the external stimuli because of their different physics-chemical properties. These properties include strength, flexibility, resistance to water, toughness, and alike. As an example, stalks of grasses are characterized by its flexibility, trees by their strength, etc.

Natural materials are in most cases composed from several tissues with different mechanical properties, thermal conductivity, density, etc.., therefore, from a mechanical point of view, they can be classified as composite materials.

One should also notice that all these tissues are assembled into a single system designed to work as one unit, although they each have different physical properties. This phenomenon can be illustrated on the example of the lignification process of cell membranes, in which the mechanics of tissues and its spatial distribution changes. J. Gordon, researcher in the field of material science, [1] claims "that the main defaults of the structural material are its low strength and toughness, which are ultimately absolutely necessary, as well as lack of viscosity, in other words - the lack of resistance to the spreading of cracks."

Important progress has been achieved in the research of natural stalk structures, their patterns, and principles of construction that can be used in construction. Research and application of construction principles of plants vertical forms can diverge into two different directions: through the structural design - changes of the form in vertical direction, or through the use of mechanical adjustment (achievement damping effects, suspension, etc. [11, 12]).

When building at extreme conditions, such as in the areas of strong winds, or seismically active areas, it is useful and necessary to evaluate and compare how the suspension, shock absorption, with similar forms found in the nature. Analogies can be made with human spine, tree trunks or plant stalk.

Figure 7: Draw-strut frame system (Frei Otto)

Figure 8: Lecture hall

The push-pull coupled system (or so-called draw-strut frame system) (Fig. 7), [1], [19-20] was used by F. Otto in the construction of the bell tower (structure similar to the construction of the human spine)

Another important form found in the nature is the shell, similar to the shape of eggshell with an even distribution of tension in the cross-sectional thickness in cases, where the observed geometry and loading fulfill some requirements - see [13]. In addition to continuous models, one can encounter curvilinear rib systems with shell elements. An example of such a structure is the lecture hall in Illinois (USA), by of Harrison &; Abramowitz, with the surface resembling to the shape of tree mushroom, Fig 8 [20].

An important consideration to optimize the spatial structure (shell) is to take into account the relationship between the volume and covered surface area. Taking the analogy of shells the relationship can be expressed as follows [1]

$$S = K.V^n \qquad (2)$$

where S is the surface, V is volume, K is a coefficient characterizing form (form-factor) and n is called the rate of form change. The detailed analysis of Eq. (2) showed that n = 0.618 for almost all species studied aquatic shells and was close to "golden section" $1/\sigma_\rho$ [1].

In the last case we will analyze the lattice and rib systems, e.g. [10.13]. Redistribution of functions between carriers and non-load bearing elements is their characteristic feature. Strongest material is concentrated at the main stress/tension trajectory. Grills with ribs are positioned on the curvilinear or curved surfaces. One can imagine the lattice structure as a combination of intersecting beams. The direct analogy of this system in nature is the blade of a plant leaf with clearly expressed veins as depicted in Fig. 9, [21].

Figure 9: Veins of the leaf of tree

Another type of structure is vasculature of *Victoria Regia* flower [14], in which the principle of division of material along the main lines of tension is followed (Fig. 10), [20]. Similar orientation of the beams can be found in the factory Gatti (Rome, P.L. Nervi).

Figure 10: Vasculature of *Victoria Regia* flower and application of this principle in roof construction.

Different lattice structure, based on the penetration Mitschell beams, can be found in human femur [1]. In this beam structure, short beams follow the direction of major stress. The presence of Mitschell beam provides a relatively high strength and load-bearing capacity of the structure.

5. Mathematical aspects of optimal design

Let us address now some of the mathematical aspects of optimal design. From the numerical (or algebraic) point of view the problem of optimal design is based on minimizing the weight of the proposed structure [15-17]. From a mathematical point of view the objective function $W(\boldsymbol{x})$, (or $-W(\boldsymbol{x})$), if the problem does not relate to finding a minimum weight) needs to be minimized in the space of design variables $x = (x_1, x_2, ..., x_n)^T$ with restrictive conditions

$$g_i(x) = 0 \; i \in E \quad (3)$$

$$g_i(x) \geq 0 \; i \in I \quad (4)$$

For geometrical illustration we will consider design space θ_2 whose elements are the design variables x_1, x_2 (Fig. 11) with numerous upper and lower boundaries for permissible values that depend on permitted amplitudes of tensions and relocation amplitudes for each design load.

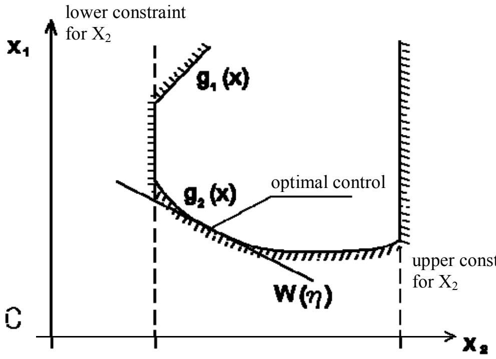

Figure 11: Two-dimensional space with limiting conditions

As follows from the above, there is a number of limiting conditions in the calculation. The function $W(x)$ is also called the target function.

The prevailing (dominant) boundaries/ limiting conditions create a complex surface shape of the borders/limits, where every surface, represents a segment - the individual limit.

As seen in the Fig. 11, two opposite boundaries are mutually parallel, which is the direct indicator of the maximum and minimum limits of the design of this variable. Selection of the initial parameter $\boldsymbol{x}^o$ plays an important role in design of then structure. If it is chosen outside the boundaries, such parameter is *a priori* unacceptable.

Fig. 11 shows that the optimal design is related to finding the "touch" point on the boundary area. One needs to choose first the appropriate starting parameter x_0 and then the "way" to the point $\boldsymbol{\eta} = \boldsymbol{x}$, which represents a set of parameters for the optimal design.

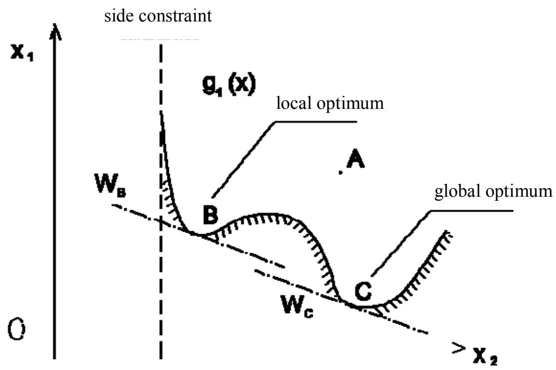

Figure 12: Local and global minimum

Another problem (as an example in 2D space of parameters) will occur if the area contains a number of possible boundaries "touch" points, i.e. the values of $W(x_i = \xi_i)$, represent a set of local minima, therefore it is difficult to decide the "way" to find $\boldsymbol{\eta} = \boldsymbol{x}$, where $W(\boldsymbol{\eta}) \leq W_i(x_i = \xi_i)$, Fig. 12.

It can be shown that the local minimum coincides with global minimum when the space is convex [15]. But not all spaces are convex. The analytic way to find local minimum is Kuhn - Tucker conditions of adequacy. This represents an important method for obtaining the optimal design.

Let us suppose that we solved the problem of optimal shape design in terms of minimum weight. However, there is another important element - the aesthetics of the design, with witch we are yet unable to cope using mathematics.

6. Conclusions

Bionics is a frontier science that systematically acquires and applies knowledge about living organisms and their structures and functioning in the development of new technologies. In the last past 50 years architecture was also influenced by bionics. This relatively young interdisciplinary science was primarily a product of qualitatively new development in biology. People naturally always have observed the nature that surrounded them, and found the inspiration in it. Imitation of natural structures (also in the building engineering), can be found in the aviation and construction much earlier than bionics emerged as a science discipline. Let us remind the legendary Leonardo da Vinci and his flying machine inspired by the bat in the early 16-century, or "Crystal Palace" in London from the years 1850-51, where the author of the buildings, Sir Joseph Paxton, was inspired by studying leaves of *Victoria Regia* - giant water lily with leaves measuring up to two meters in diameter. It is unforgettable not only as the architectural construction, but also as a new method of construction using panel assembling [8].

Application of the laws of nature and inspiration by the living forms in civil engineering, architecture and technology as such proved itself to be fully justified. So finally we can confidently conclude that the future of technology will learn from the nature.

7. References

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