Similarities between "structures in nature" and "man-made structures": biomimesis in architecture

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Abstract

In this paper, we aim to reveal the similarities between "the structures in nature" and "man-made structures". These similarities can be observed from the very beginning of mankind, in many engineering and architectural designs. It can easily be seen that even though the scales, functions and processes encountered in nature are different, 'the design constraints' and 'the objectives' are the same in what man creates: functionality, optimization, and cost effectiveness (minimizing material and energy consumption). Thus, structures in nature exhibiting great lightness and yet rigidity with forms having capacity to endure internal and external forces in an optimum way are always a source of inspiration for many progressive architects and engineers.

Since 1998, the term 'biomimesis' (bios, meaning life and mimesis meaning to imitate) has been employed in the studies to provide clues and answers to what men need by observing and analyzing nature. In this paper, the structures that are found in architectural designs and structures in nature are examined through this new discipline. Within the scope of this study, the structures inspired by those in nature are categorized first according to their animate and inanimate nature, and then to their visual/formal similarities.

Five main categories, namely, tree-like structures, web-like structures, shell-like structures, skeleton-like structures and pneumatic structures are presented. The pioneering examples belonging to each category, chosen from different periods of architectural history are presented. Through the analysis of those examples, the visual similarities in man-made structures and structures in nature are discussed within the realm of biomimesis.
Keywords: biomimesis in architecture, formal/visual similarities, natural structures, architectural structures.

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1 Introduction

Man, since from the very beginning, has a tendency to discover and learn from his environment. In his observation/ learning/ designing process, he has experienced adaptation and he developed skills to provide his needs by imitating, interpreting, and using the opportunities of nature. Hence, similarities observed between man-made structures and the structures of nature are unavoidable.

These learning, adaptation and designing processes resulted in a new field of science: Biomimesis, to study nature's best ideas and then to imitate these designs and processes to solve "our" problems ranging from manufacturing to medicine, engineering to information technologies [1].

Although the biomimesis is considered as a formal field of science in 20th century, it has been long time that its principles and concepts have been recognized. The first concise examples dates back to medieval period, to Da Vinci's studies on mechanisms to medicine. The effect of nature can also be seen in many architectural examples from simple shelters to gothic cathedrals and today's high technology buildings.

The scales, functions, and processes that are observed in nature can be different, but constraints and objectives are very similar with what we have to provide in all the designs: functionality, optimization, and cost effectiveness. Therefore, it is not surprising that mankind has always admired biological structures and often been inspired by them, not only by their aesthetic attributes but also their engineering and design qualities and efficiencies.

When the interaction between nature and architecture is studied, it can easily be seen that the interventions between what architects design and what nature has, are very complicated, ranging from materials to construction techniques, from structural systems to aesthetics. In this paper, a categorization of structures in nature, based on their formal characteristics, is to be presented to illustrate the similarity between those structures and man-made ones through some benchmark examples of history of architecture.

2 Structures in nature

Nature exhibits a diverse variety of structures and in most cases the form and visual qualities of nature's animate or inanimate forms are tightly coupled with the structural system undergoing several internal and external loads. Therefore, in order to study the similarities between man-made structures and structures encountered in nature, certain categories explained in the next sections are introduced.

In the present study, the structures in nature are first classified according to their living nature- animate or inanimate and then according to their formal/visual characteristic. In this categorization "the structures produced by animals" can be included within the animate nature. The objects in non-living nature -from the atom through to molecules, crystals, rocks, mountains and waters, to stars and galaxies constitute a constructional family with characteristic forms and structural properties. The processes of formation determine their

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forms. The structural form adjusts itself due to the material properties and the composition of the material. Everything in nature is subjected to the laws of Universe. The structures in nonliving nature are analyzed and it is seen that, in their development only a few formation processes take place; the accumulation of masses, the movement of large masses, the flow of liquids and gases, the solidification of matter into solid bodies. Yet, those inanimate structures have extremely long life spans when compared with any animated form's life span.

(Figure 1 shows the images of inanimate structures for example heavenly body, earth pillars, snowflake, soap bubble and salt ion.)

Figure 1: Examples from inanimate nature.

However, animals, plants, and microorganisms are the living structures found in nature. They are able to assimilate and transmit forces with little expenditure of materials and energy even in their short existence period. It can easily be seen that the world of the animate nature is absolutely diverse, mobile, mutable and is miscellaneous when compared with inanimate nature.

Another important categorization of the structures in nature is related with their load bearing capacities as in the case of man-made structures.

One-dimensional [3] natural structures are usually lightweight elements. Such as tension-stressed fibers, hairs, sinews, muscles, intestines and compression and bending-stressed stalks, trunks, branches, bird feathers, bones. Membranes of cells, skins, intestines, and spider webs can be considered as **two-dimensional** structures resistant to tension, exhibiting membrane, or shell characteristics that are able to transmit forces through their surfaces. Structures composed of tension and compression-stressed elements, such as the wings of insects, bats, birds etc. are two-dimensional. Most structures in living nature are **three-dimensional** [3]. These include particularly tension-stressed cells, organs, hollow bodies and all mollusks. Many compression and pressure stressed structures, such as vertebral bones as well as the compression and bending-resistant skeleton systems of trees and bushes, the spongiosa inside bone and the three-dimensional skeletons of radiolarian are also included, in this categorization [3]. The bodies of many animals consisting of tension-, compression- and bending-resistant elements are also three-dimensional.

Figure 2 illustrates the dimensions of animate nature with the help of the images of, bird feather, radiolarian, fly wings and seashell.

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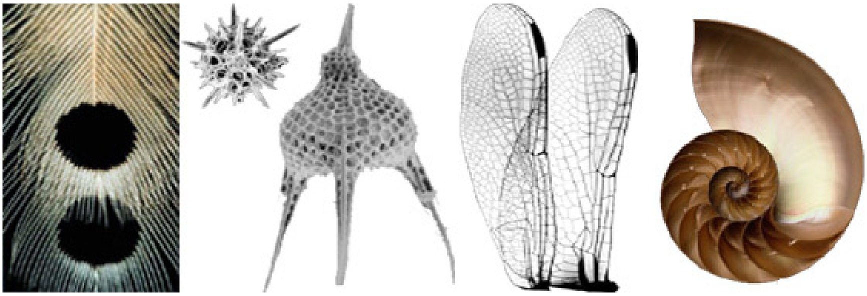

Figure 2: Images from animate nature.

The structures that are used in architecture are belonging to one of these categories depending on the forces that they are undergoing. In a building, the structural elements can vary from one-dimensional tension or compression members to plates and shells to support diverse variety of internal and external loads as the structures in nature. Any structure in nature and any man-made structure should withstand similar forces and loads. Thus, it is very natural to be inspired from the nature for design of new innovative structures.

2.1 Tree -like structures

When the structures are categorized according to their formal/visual characteristics rather than their load carrying capacity the first category appears to be the tree like structures. Throughout the history, tree has an important role in human life. It has always been a choice for man to provide many needs from warming to housing and more. The observations of tree like structures, led man to learn, both new constructional methods and a new inside into the structural systems that are observed in trees. When historical architecture is examined, a very deep and developed intuitive knowledge of construction becomes visible. The branched support tree-like structure can be first observed in the ribs of Gothic style. Today, tree-like structures are three-dimensional supporting systems used increasingly in steel, wood, and concrete buildings.

One of the pioneer examples of tree-like structures of its era, is Eddystone Lighthouse by John Smeaton which was constructed in Southwest of Plymouth in 1759. Smeaton's model was based on an English oak tree. Smeaton considered this tree as the one having the best configuration to resist the forces of nature as shown in Fig.3a [4]. Antonio Gaudi, who practically never journeyed anywhere, drew his inspiration from his ability to observe and reuse the countless details offered by nature. When one enters the crypt of Sagrada Familia in Barcelona, the four inclined basalt columns standing out, give the sensation of an organic and natural structure, like the trees in a forest Fig.3b. BCE Place (1987) was designed as a mixed-use complex in Toronto by Calatrava. The structure of the complex consists of 8 inwardly inclined steel supports bifurcated upward, eventually meeting to form pointed parabolic vaults

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spanning 14 meters across the interior space. Over a 30-by-3-meter regular plan, tree-like structures rise and support nine intersecting barrel vaults, creating a "forest" effect as illustrated in Fig.3c [5]. Rather than resorting to the imitation of these precedents, however, Calatrava reinterprets them as "forests" of structural "trees." The roof of the Stuttgart Airport Passenger Terminal (1996) in Germany designed by Meinhard von Gerkan is another contemporary example for tree-like structures. The huge sloping roof is supported by 12 very tree-like steel structures, in which the loads can be seen to be descending through an elaborate hierarchy from twigs to branches to trunks, all fundamentally in compression . More directly, the construction of the terminal roof is based on the structure of a tree, thus providing an unmistakable and individual feature for the Stuttgart Airport Fig.3d.

The number of examples of tree like structures in the history of architecture can be multiplied, but only four of them, which exhibits the main characteristics of their era, have been selected in order to clearly point out the similarity between those forms in nature and what man makes Besides those examples there are many other progressive architects who are influenced by the trees in their design consciously or not.

Figure 3: Examples of tree-like structures.

2.2 Skeleton-like structures

When the most of the animals and human beings are observed, each bone of skeleton and than the skeletal system itself, show how nature has sophisticated lightweight and rigid structures.

Since the main structural elements of the building is based on the spine, like in the animals and humans, it seems sensible that another less dominant structural piece should be based upon the ribs. In nature the spine and ribs work in conjunction with one another to provide support and protection. This idea seemed plausible for the buildings as well. The ribs provide support for the roof and create enclosure, in the form of a building. While designing the famous tower, Maurice Koechlin, assistant to the architect of the Eiffel tower, was inspired by the femur, the lightest and the strongest bone of the human body with self-ventilation property due to the porosity of the bone material, as shown in Fig.4a. Buildings designed and constructed similar to this bone optimizes the

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construction material, and they also provide firmness and flexibility in the skeleton of the construction. Again, Gaudi, in Casa Battlo (Barcelona 1905-1907), showed natural and organic forms which were no longer ornaments superimposed on the building, but constituted essential structural elements, as in the case of bone-shaped columns shown in Fig.4b. As a contemporary example, Nicholas Grimshaw's addition to Waterloo station which is originated from the human hand can be presented [6]. The cupped "hand" reaches across the track to make an enclosure of the space Fig.4c. Study of the conceptual sketch of the hand can easily reveal the influence of the skeletal structure to the structure of the building .

Figure 4: Images from skeleton-like structures.

Santiago Calatrava has also used features of an animal shapes and skeletal structures in the design of many of his bridge and building projects. He understands how a body varies in order to accommodate its various parts and forces through rib-like identical pieces which are less expansive to manufacture and yet have a high capacity to carry uniformly distributed loads when they are employed in man-made structures. Calatrava could possibly be considered the master of today's skeleton-like architecture.

2.3 Shell-like structures

Shells are among the most common and most efficient structural elements in nature and technology because of their high resistance, minimum material, large spans and sheltering characteristics. Examples of shells in the morphology of nature are particularly abundant. Eggs, seashells, turtles, skulls, nuts, and the nests of some birds and insects belong to this category as shown in Fig.5a [7]. Many great artists were inspired by the beauty, diversity and design of the shell, that they incorporated them into their masterpieces. Architecture has been profoundly influenced by the symmetry of these 'natural wonders' created by snails, clams, scallops, and other marine mollusks. Many scientists have faced the study of shell shapes from mathematical and geometrical point of views.

Discovery of the cement made possible the realization of the new architectural designs using thin shells in their structural systems. Moreover, the

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advent of concrete, as a new building material at the beginning of this century strongly influenced the philosophy of construction and the design of new domes.

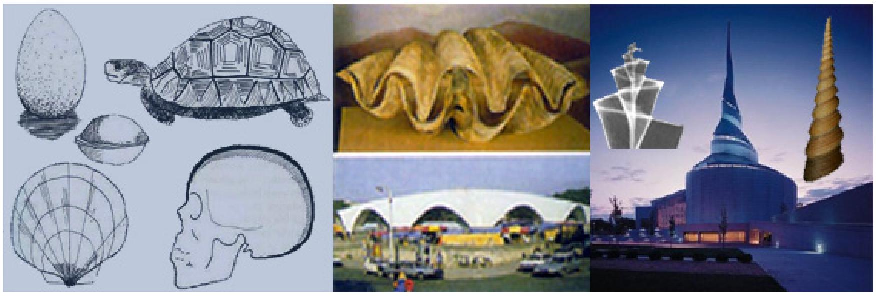

Figure 5: Shell- like structures.

In 1920's, the first examples of the reinforced concrete shells were introduced by Franz Dischinger and Walter Bauersfeld, evoking the comparison of these domes with the egg shells. The technology developed by Dischinger, Finsterwalder and Bauersfeld in 1930's was compatible with single arched structures. Following this, further developments in the analysis of these forms and their manufacturing processes made it possible to build more complicated forms such as double-arched saddles [8]. Later, many other engineers and architects, like Robert Maillart, Edouardo Torroja, Eugéne Freyssinet, Pier Luigi Nervi, Felix Candela continued to design and apply technically appropriate and elegant solutions to reinforced concrete constructions. Among them, Nervi and Candela brought some solutions to their designs, inspired by the structures in nature,

2.4 Web-like structures

In the categorization of structures found in nature, web-like structures have another importance in addition to their load carrying capacity that arises from their silk-like materials, as shown in Fig.6a. Spider silks appear to be stronger and more elastic than Kevlar, which is the strongest man made fiber[9]. Web-like structures exhibit membrane characteristic in their load bearing features. Moreover, their load carrying capacity is extremely high and yet the structure it self is a lightweight one. Tents, which are basically man made membrane structures, can be considered similar to those web-like structures in nature. Frei Otto in recent years is the pioneer architect who is studying the similarities in tents and web-like structures. He improved his new concepts by focusing his investigations on one of the principal forces which can be encountered in any structural system - tensile stresses. The modern tent is largely Otto's creation. Traditional tents were revived by him as a leading prototype for lightweight adaptable buildings as illustrated in Fig.6b.

Innovative structures with extreme lightness have been developed by Otto through his studies. Later, Otto's studies on tensional structures led

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contemporary architects like Horst Berger, and David Geiger, Kisho Kurokawa and many more to design many new web-like structures.

Figure 6: Web-like structures in nature and architecture.

2.5 Pneumatic structures

Another category of structures in nature can be considered as pneumatic ones which occur both in inanimate and animate nature. It can easily be found variety of forms of animate nature, plants, animals and human beings - their various life processes and conditions - were incredibly developed and built up through countless variations of a single construction principle, namely, the principle of the "Pneu" which is a system in which a tension-resistant, flexible envelope surrounds a filling [10]. The envelope and the filling together form a load-bearing structure."

Pneumatic constructions and their use of air as a supporting medium has become a part of architectural language, pneumatic technology is by no means, a newly established science. The study of air bubbles formed in liquids is undoubtedly nature's most relevant precedent in the design of pneumatic building construction.

Pneumatic constructions in architecture are called air halls. These are support systems consisting of a membrane that is supported by air pressure. Therefore, these structural systems are pre-stressed structural systems. As air is the supporting element, air halls are the lightest of all constructions dating back to 1783, to Montgolfier Brothers [11]. An air hole can be seen as a balloon under weak air pressure that is fixed to the ground.

The best of our present knowledge it was the English motorcar manufacturer Frederick William Lanchester who first recorded the idea of supporting tents by internal air pressure in 1917. But Lanchester's work and ideas did not attract any attention in the building field in his time[10].

Systematic research and development of the form finding processes of technical pneumatic constructions by Otto and his team result in progress in the development of new structural systems having roots in pneumatic forms in nature and allow the construction of many innovative building forms.

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Figure 7: Pneumatic structures in nature and architecture.

3 Conclusion

Architecture, inspired by nature and its laws, seeking to attain a "unity in multiplicity" comparable to that of existing in nature has became a worldwide wave.

As seen from the examples chosen from different periods of the history of architecture, man-made structures are deeply influenced by the structures in nature. Many progressive architects and engineers have been inspired by nature – by animate organisms or inanimate objects in nature-. This inspiration led some architects, such as Otto and Candela; establish institutes in order to research natural structures and patterns. Similarly, some architects like Calatrava has studied this subject as a doctoral research. All these names mentioned in this paper, contributed to design and development of new structures originated from the structures of nature.

The examples presented above and many other examples encountered in the history of architecture reveal that mimicking the nature, i.e. biomimesis in architecture has always been a part of architectural design and architects have found clues in nature for new designs and technologies. It is possible to conclude that in today's world and in future, the nature will always be a source for inspiration as in the past, in all the fields of science.

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