Structural design in nature and in architecture

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Abstract

Structural design in architecture has always been influenced, at different levels, by structural design in nature. In order to increase the understanding of the relationship between structural design in nature and in architecture it is important to have a theory, allowing us to connect these two fields, and to create a basis for a comprehensive perspective. This article proposes a theoretical framework of structural design in nature and in architectural design. Structural design variables are developed and each design variable is examined in nature and in structural design in architecture. This enables us to find from which variables we can learn more from nature and to note possible future directions of structural design in architecture.

1 Introduction – structural systems and structural design

The structural system is one of the most important components of any entity in the universe, which has a physical dimension. Specifically, the main role of this system is to allow any entity to cope with physical loads, and to ensure the entity's performance. But generally this system can have other important roles – aesthetical, organizational and even cultural. The term "structural design" means: the art and science of creating a structural system in nature or in the artificial world. The term "architecture" relates mainly to the design of the built environment, but it can also relate to industrial design (airplanes, etc.). The term "structural design in nature" relates mainly to the way nature builds itself.

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2 Structural systems design in nature and in architecture

2.1 Structural systems design in nature

The structural systems in nature have a large gamut of variations. In spite of this it is possible to make a distinction between structural systems: A). structural systems in living systems which can be A1). Animals and human being. A2). botanic entities. B). structural systems in inanimate entities.

The design process of living systems, including the structural system design, is a living design process of growth and development. In plants and animated entities the structural system can be a rigid skeleton or an hydro-skeleton (fluid, gas or other material under pressure covered with an envelope - cell, bladder, lung, heart, fruit etc. A rigid skeleton is built from many hydro-skeletons because the cell itself is an hydro skeleton). Rigid skeletons can be divided into: exoskeleton (external) and endoskeleton (internal) [1],[2],[3],[4]. In non-living systems it is also possible to identify a process of design. The inanimate elements of the world are always being formed: Clouds, mountains, stones, stars, liquid or air bubbles, water streams, moisture drops, chemical liquids etc. – all these undergo a design process and changes of form [3], and all of them have a structural system. These systems can also be classified to rigid skeleton or hydro-skeleton systems.

In spite of the diversity in nature it is possible to identify "nature's school of thought" in relation to structural design. This is based on laws of survival and existence expressed by optimization and efficient use of resources and materials according to specific target and constraints. In relation to structural aspects the optimization is between the structural system needs and other system's needs.

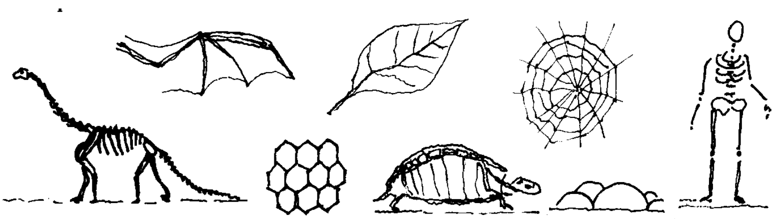

Figure 1: Examples of structural systems in nature.

2.2 Structural systems in architecture

The structural system is one of the most important architectural and structural component in architecture (including industrial products like furniture, cars, airplanes, ships etc.). This system usually functions parallel to other systems and together they create the whole architectural creation. During the planning and design process the architectural designer is the main entity responsible for the overall view of the project, taking into account many aspects, including the structural aspects. Usually there is a structural consultant besides the

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architectural designer, as one among other consultants. Contrary to nature, here it is possible to identify several schools of thought in relation to structural design.

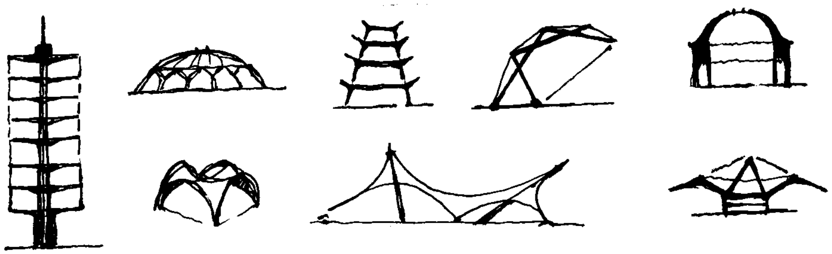

Figure 2: Examples of structural systems in architecture.

2.2.1 Structural design schools of thought in architecture

Understanding structural design schools of thought in architecture is connected to classification of architectural projects in relation to structural aspects.

1) Extreme structural projects - where the structural constraints are very restrictive and the designer "must go with nature" – this, in order to utilize the resources to their limit in an optimal way (large span projects, tall buildings, airplanes, ships, etc.). Usually in these projects the main target is to create structures, which are as efficient and light as possible, even if the price for this can be expensive because there is no other possibility. This school of thought is very close in many aspects to the "nature's school of thought".

2) Conventional structural projects - when the designer has relative freedom to choose his school of thought: on one side – a school of thought, in which structural considerations are the main generator of the architectural language and on the other side – a school of thought in which the structure has only the functional task to transfer loads from one place to another without any special influence on the architectural language/order (in a few cases the architectural language doesn't even fit structural considerations or structural efficiency). Between these schools it is possible to find other "middle streams".

2.2.2 Structural design school of thought in architecture - "Archistructure"

The school of thought, which takes into consideration the structural aspects and gives them, in many cases, a visual expression - in extreme structural projects or in conventional projects- can be called "the structural design school" or - "archistructure" (architecture and structure). In this stream, which can be identified throughout history, the structural design is one of the main generators of the architectural language. Here there is a strong correlation between form, loads and materials and in many cases the equation is - "architecture = structure and structure = architecture". The rational for this school of thought is based on one or a combination of the following aims: 1). to solve an extreme structural project 2). to express technological images and abilities 3) to create a minimalist design–light structure image and style 4). to express integrity between structure and architecture 5). to design a project which has mainly one functional

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engineering purpose (silo, bridge.) .6) to express an image which is closer to natural language.

2.3 Structural strategy and design variables of structural systems

Any structural problem in nature or in architecture, in any school of thought, can have many structural strategies (a structural strategy is a set of structural design variables). The preferable structural strategy is an outcome of not only the structural aspects (in many cases the structural requirements are in contrast with others). The human being already made use of many structural strategies that exist in nature (tension strategy, compression strategy etc.). If we want to check new directions in structural design in nature and in architecture it is important to analyze the structural design variables (and sub– variables), which are the main elements of the structural strategy.

3 Design variables of structural systems

The design variables (fig. 3) are the designer's freedom of choice and they will be used as a comparative tool between design in nature and in architecture. This can help to understand the situation of structural systems in architecture and nature and to identify what can be learned more from nature in relation to each variable. These variables are not necessarily independent and in many cases there is a mutual interrelations and influence between them.

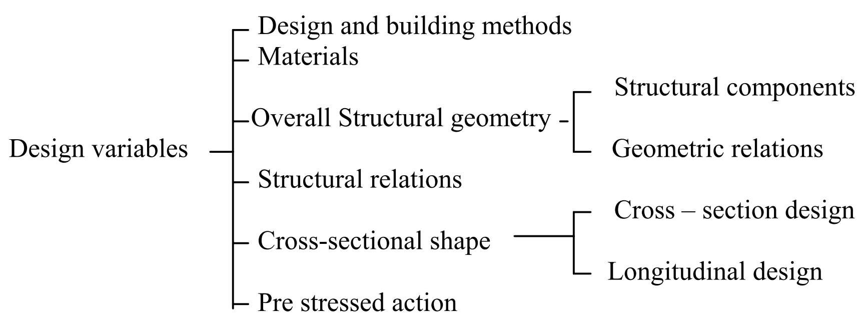

Figure 3: Design variables of structural systems in nature and in architecture.

3.1 Design and building methods – building technology

This variable relates to the "designer's decision" about design and building methods or building technology. In natural living systems, the design and building process (development process) relate to the creation of any entity from its beginning to maturity. This biological development usually begins after fertilization. All tissues and organs are composed of cells, which are the basic units of life. During the development process there are morphological changes of form and size and a differentiation of structures within the organism [1]. The entire process is an outcome of "the plan"- genetic information, which exists in

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any cell in the DNA, which contains the instructions for growth and management of living system. Because of this growing process the building method of most of the living systems, including the structural system, is a pneu- method or pneu-technology: a tensile - flexible envelope, which contains a filling (fluid, gas, tissue.) and behaves as a load-bearing structure. The cell - the basic unit of life, seed, embryo, snail – all these are pneu-systems [4], [3]. In this kind of development and design the systems, including the structural system, are growing together – in parallel and simultaneously. In plants, the development and the design process continue throughout all their life when the environmental influence is relatively very big [5].

Natural non-living systems also have a design process, which includes structural design element. Objects in the universe are being shaped and formed all the time, even if their life span is short or long. Clouds, oil bubbles, mountains, stones, stars, water streams, moisture drops, chemical liquids etc. – all these are changing their form irretrievably [3]. In this case the design process is: erosion, crystallization, chemical reactions etc., when the designers or the agents of the "meta–designer" are: winds, gases, sun radiation, gravity force, water and liquids, acids, earthquakes forces, chemical materials etc. In this case the design result is an outcome of physical laws.

The building methods of structural systems in architecture usually differ from nature's methods, especially in relation to living systems (There is more similarity to methods of non - living systems). The building methods in architecture are usually linear methods, where each system is erected linearly and in most cases not simultaneously. Usually structural components don't grow together with other systems, like in the case of living systems in nature. It seems that in this variable the human-structural design in architecture, can still learn a lot from nature, especially from the living systems development and building process.

Figure 4: Typical example of design and building method in living systems.

3.2 Materials

This variable relates to the designer freedom to choose materials and it has a strong connection to structural aspects like: deformation, deflection, strength, brittleness and others. Most living systems materials are organic materials and during their life they can be called " living" or "bio-materials" [6]. In contrast, inanimate systems have "non- living materials". Most biological materials have a central structural task, but usually they have other additional tasks. For this reason, these materials have optimization between functions [6]. This relates to living systems but the same logic can be related to the inanimate world. The

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materials selection in nature relates to many considerations, in order to achieve the entity's designation under different constraints.

In man made structural design, in addition to natural materials, there are also artificial materials with relatively high technology. From this aspect the future of artificial materials in structural design is unlimited relating to nature and new horizons are possible if we make careful use of materials as is found in nature and if we develop the new materials in a more natural way. In relation to materials selection - usually in extreme structural projects (like large span structures) the designer's freedom of choice is limited and only specific materials are suitable. In conventional projects it depends on the philosophical point of view. In "archistructure", usually there is more correlation between materials selection and structural aspects. (The aspect of efficient use of materials in nature and in structural design will be discussed later).

3.3 Overall structural geometry

The overall structural geometry (structural form) of any structure dictates the general scheme of the structure (macro geometry), and it can have a strong influence on the architectural image, forces flow, the structure's stability and other properties. This variable can be divided into: 1). structural components 2.) geometric relations between structural components. The overall structural geometry is structurally efficient if it creates minimum volume of less sever stresses. It is also important if there is a correlation between geometry and the material's properties. The relations between structural geometry and overall geometry have two important aspects: 1). the level of integration between the structural geometry and other systems 2). the level of visual expression of the structural system. These aspects can have many variations.

In nature, mainly in living systems, the overall structural geometry is an outcome of many considerations and the structural consideration is not always the main one, but one of the most important. Thus, natural structures usually don't have the best efficient structural geometry but an optimized one (the best efficiency under designation and constrains). In spite of this in many cases there is a correlation in nature between geometry, loads and materials. Also the level of integration between the structural geometry and other systems is relatively high (in many cases the structural systems fulfills other functions like liquids transmission etc.). In relation to visual expression of the structural system it is possible to find many variations of expressions but still the influence of the structural geometry on overall geometry is usually discernible.

In human-structural design the aspects of: structural efficiency, level of integration and visual expression of the structural system usually depend on the circumstances. In extreme projects there is less freedom of choice and the correlation between geometry, loads and materials is relatively high and also the structural efficiency. In conventional projects it depends in the school of thought. In many cases there is no tendency to create efficient structures and usually there is no visual expression of the structural system. In contrast, in "archistructure" it is possible to find strong desire to achieve an efficient structure. There is also a tendency to express visually the structural system (in many cases by visual

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separation). In spite of this, the level of integration of the structural system with other systems in relation to nature is not always high, as in nature. In this aspect more can be learned from nature where there is a unique integration between all systems.

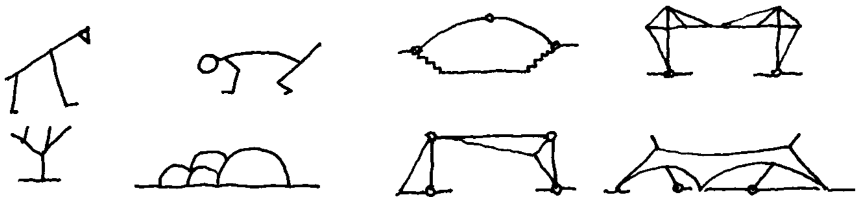

Figure 5: Overall structural geometry in nature and in architecture

3.3.1 Structural components

The structural components are the main structural elements of the structure's entity. In nature those elements are: shells, membranes, muscles, tendons, etc. In architectural design those elements can be: beams, columns, members, slabs, domes, arches, barrel vaults, rings, cables, fabrics, etc. The structural components in nature and in architecture can be classified as follows: 1). pointed elements 2). linear elements 3). surface elements 4). spatial elements. It seems that in structural design in architecture the human being succeeds in using most, and even all, structural component principles that exist in nature.

3.3.2 Geometric relations between structural components

This sub variable relates to the mutual geometric relations between structural elements–the spatial or planar angles. In structural design in architecture, the human being is using most of (or all) the geometric relations that exist in nature.

3.4 Structural relations between structural components

For a given form of a structure it is possible to have many kinds of structural relations between elements. These relations influence the degree of freedom, static determinacy, deformations, displacements, stability, stresses and others. The basic structural relations in space or in planar are:

a. Pinned relations – allow rotation of members but no other movements.
b. Limited pinned relations–allow rotation and partial movements of members.
c. Rigid relations – do not allow members to rotate or to move at all.

These relations are obtained by using different joints like: fixed, pinned, roller and others. It seems that in structural design in architecture the human being succeeds in using most of the structural relations that exist in nature. In "archistructure" even a visual expression is usually given to these relation.

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Figure 6: Structural relations in nature and in architecture.

3.5 Cross - sectional shape

This variable relates to the form of the micro-geometry shape: the cross- section. It contains two main sub-variables: a. The cross-section design b. The longitudinal design of the cross-sectional shape.

3.5.1 Cross-section design

This variable influences mainly the ability of the structural element to cope with bending, shear, buckling, torsion etc. In a given amount of material, a “clever” design of cross - sectional shape can obtain better structural performance by organization of material in space. In natural living systems it is possible to see that in most of the cases the organization of materials is an outcome of many considerations, where the structural consideration is one of the most important. Usually bio - materials are organized in a way that allows to cope with various structural aspects with the least materials and weight [6]. One of the most important indicators for this ability is a high moment of inertia (I). The expressions $I_{x,}$ $I_{y,}$ in respect to x, y -axes, for area A, are given in eqn (1) [7]:

$$I_x = \int_A y^2 \, dA, \qquad I_y = \int_A x^2 \, dA \tag{1}$$

It is possible to see many examples of living systems where this value is increased by spatial organization [6]. Other examples can be brought also from inanimate world in nature. In architectural design it is possible to find the same principle of material organization in the cross-section as in nature, using building materials like: steel, concrete, wood etc. It seems that in structural design we mostly use the cross-section principles that exist in nature.

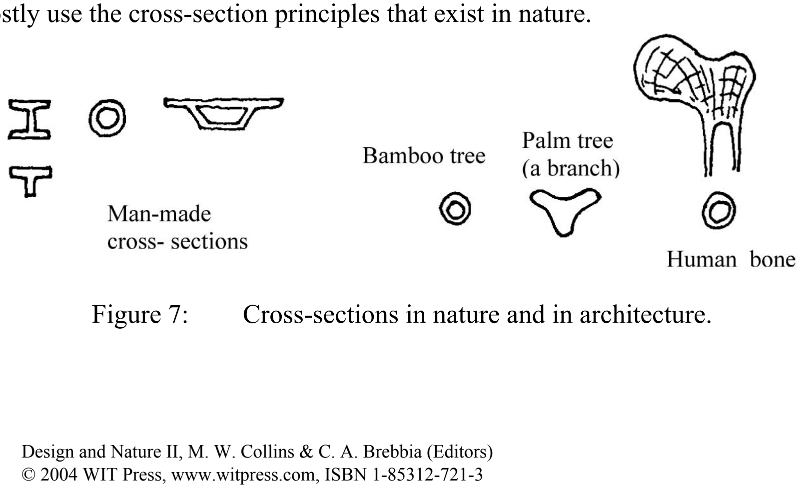

Figure 7: Cross-sections in nature and in architecture.

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3.5.2 Longitudinal design

This sub-variable expresses the material organization along the structural element. In nature it is possible to see that in many cases there is a general correlation between the internal stresses and the materials organization. Usually in a place where there is a big stress there will be a big amount of material. For example in a cantilever, loaded with equally distributed load (q), or single force at the free edge (p), the bending moment (M) becomes bigger with the distance x from the free edge, according to (eqn. 2,3 respectively):

$$M = qx^2/2 \tag{2}$$

$$M = px \tag{3}$$

In natural cantilevers it is possible, in many cases, to find a general correlation between the bending moment (which is very important in this case) intensity and materials organization (fig 8). In architectural design this correlation doesn't always exist, and in many cases the use of materials is not efficient and even wasteful. Mostly it is an outcome of practical reasons or a philosophical point of view. In comparison, the "archistructure" school of thought is very close to nature in this aspect and it is easy to distinguish a strong resemblance between nature and human structural design (fig. 8).

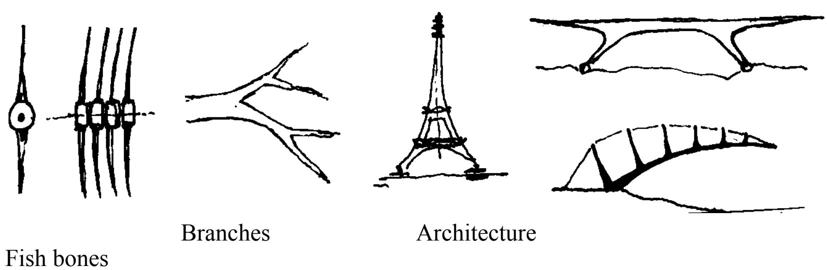

Figure 8: Examples of longitudinal design in nature and in architecture.

3.6 Pre-stressed action

Pre-stressed action can increase the structural performance of an element by creating stress before loading the element. After loading, the final stress in the element is much preferable than it was without the pre- stressed action. In nature, this principle exists for example in the botanic world. According to Gordon [8] the tree grows in a manner that the external layers of the trunk are pre stressed in tension and this improves the effective bending strength of the trunk by 50 % or so. In human-structural design pre-stressed elements are very common especially in structures, which are extensively loaded (large span structures - halls, bridges etc). It seems that in this aspect the human being is using the principles that exist in nature in a large gamut of versions.

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4 Conclusions and future directions – can we learn more from nature?

All the above can be used as a basis for a theoretical framework of structural design in nature and in architecture. In this first stage it is possible to find out several conclusions on the relations between structural design in nature and in architecture:

In general, the human being succeeded in using many of the structural principles that exist in nature. In cases of extreme structural projects the connection between nature and man-made creations is relatively high. In the cases of conventional projects, where there is more freedom of choice, it is more a question of a philosophical point of view. In "Archistructure" - the structural design school of thought- it is possible to find strong design resemblance to nature.

In spite of this, there are still a few design variables where the human structural design can get more inspiration from nature and even create new concepts:

Overall structural geometry (structural form) in nature has a relatively high level of Integration as well as strong visual design relations with other systems. This, because of the fact that the structural system is totally integrated with other systems and the whole system is acting as one "melted" system. In many cases the structural system fulfills other functions and it is very hard to separate it as an independent and disconnected system. More integration in architecture between the structural system and other systems can get inspiration from nature in this aspect. The unique integration, which exists in nature, is strongly connected with the building methods variable (to be discussed later).

An additional possible new direction of structural design in architecture is connected to materials. The research and development of new materials can suggest better mechanical properties. Adapting the natural approach of using materials as a limited resource in a way that reduces as much as possible the amount of materials and in an optimized way, can lead to a much more minimalist structural design and to lightweight structures (less mass) which will enable to overcome higher stresses. It is also possible that these materials will be produced as living materials with a friendly natural- environmental approach.

Another development, which is still futuristic, is connected to the "design and building methods" variable. A future possible direction of structural design in architecture can get its inspiration from the process of living systems in nature. The structural system, with other architectural systems, can be erected in a living process, with very small living elements- NTA – Nano–Tech Architecture. The cell will be the basic unit and all tissues will be built from it. During the development process there will be morphological changes and a differentiation throughout growth and replication. Finally, the total architectural creation will consist of thousands of billions of cells, when each cell will have a specific role. The entire process will be an outcome of "the plan" which will be made with the help of the ADNA – Architectural DNA. The designers will create the instructions, as part of the planning and design process, and they will be packed in a little seed. The technology of this process will be a pneu-technology' as in nature, in order to allow a flexible and parallel growth of all the systems. This process will have to be controlled with advanced means that will help to achieve the expected results. When architectural creation will achieve maturity the process of growth will stop and will remain "dormant". Later, it will be possible to continue the development process. This process can have many advantages including advantages in relation to structural integration, natural production of materials that were mentioned above.

It is important to note that nowadays there are already ideas to create new various products using nano-technology and DNA (for example [9], [10]).

As we have shown in this article, nature can still be a fertile source for structural design in architecture.

References

[1] Hickman, Cleveland P., Roberts Larry S. and Larson Allan. (9th ed*.). Integrated Principles of Zoology*. Mosby – Year Book, Inc. 1993.

[2] Dorit, L. Robert; Walker, Jr. Warren F; Barnes, Robert, D. *Zoology.* Saunders College Publishing. 1991.

[3] Otto, Frei. *Lightweight Structures*. Il 24. Institute for Lightweight Structure. University of Stuttgart. 1988.

[4] Schaur, Eda. Building Methods of Living Nature. *Natural Buildings.* symposium report. Il 27. Institute for Lightweight Structure. University of Stuttgart. pp 132-135. 1980.

[5] Raven, Peter, H; Evert, Ray, F; Eichoorn, Susan, E. (4th ed). *Biology of Plants.* Worth Publishers, INC. 1986.

[6] Nachtigall, Werner . Biomaterials and their Structural Arrangements. *Natural Buildings.* . symposium report. il 27. Institute for Lightweight Structure. University of Stuttgart. pp. 160-165. 1980.

[7] Schodek, Daniel L. *Structures*. Prentice – Hall, Inc. 2001 (4th ed.)

[8] Gordon, J. E. *The Science of Structures and Materials*. Scientific American Books, Inc. 1988.

[9] Berkeley Lab Research Review. Nanocrystals: the shapes of things to come. by Lynn Yaris. *Berkeley Lab Research review. Fall* 2001.

[10] Berkeley Lab Research Review. Legos for the Nano-age – the building blocks of nanotechnology. *Berkeley Lab Research review. Fall* 2001.

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