Performance Driven Structural Design: Biomimicry in Structure

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Since last century one of the iconic dichotomy that divides architectural designers into two groups are performance and appearance. It is to our benefit to reconcile the performance-appearance debate and to provide an unambiguous definition of the related notions. And natural organism and system is a great model to follow. Biomimicry is the study of emulating and mimicking nature, where it has been used by designers to help in solving human problems[1] Biomimicry as an emerging field since late 1980s has been looking at advanced technologies derived from bio-inspired engineering at the different levels; however, the research of biomimicry application in the structure design field is lagging behind other design-related fields, such as product design and material design. The paper is to provide a framework to answer the question: How do we make biomimicry concepts practical in the context of structural design and from what key perspectives? And to address how performance and appearance could be blended into one and measured and verified as a whole. This paper will address two important factors influencing structure performance: form-pattern making and the properties of materials. Numerous case studies will be used to demonstrate a variety of strategies corresponding to different levels of performance-driven structure design based on bioengineering. This paper aims to integrate material science and biology study into the research of architectural structure design.

1. INTRODUCTION

As pointed out by one of the greatest physicists of this century, Freeman Dyson: "It has become part of the accepted wisdom to say that the twentieth century was the century of physics and the twenty-first century will be the century of biology… Biology is also more important than physics, as measured by its economic consequences, by its ethical implications, or by its effects on human welfare."[2] In the natural ecology system, performance is the overarching goal of all independent parts and the system, all organisms and structures; it is also the underlying measurement to determine the opportunity for survival and evolvement. Biomimicry argues that nature is the best, most influencing and the guaranteed source of innovation for designers, as a result of nature's 3.85 billion years of evolution, as it holds vast experience in solving problems of the environment and its inhabitants.[3] Architects have been looking to nature for solutions to their complicate condition about needs for more innovative structures, and they have started to benefit from mimicking the forms, shapes from nature to create more efficient and resilient structure to fit different programmatic needs.

2. KEY FACTORS FOR STRUCTURAL PERFORMANCE

2. 1. DEFINITION OF PERFORMANCE

Performance-driven design is based on understanding that architectures or structures unfold their performative capacity by being integrated in a system, which could be a single building or a nested group of buildings.[4] The relationship between building's primary framework-structures and external environment factors is set on a spatial organizational level, materials and patterns of individual elements are secondary. When we define the performance of building's primary organization we should take into consideration material-specific exterior-to-interior relations, as well as the order and hierarchy of form – to function extension, and all those above live within a dynamic environment.

In reality, the majority of today's designs are perceived and achieved as discrete objects, and performances of the building have been divided into separate categories and measured by separate metrics: energy performance, material performance, structural performance, aesthetic performance and occupancy satisfaction are designed and measured individually. One of the most fundamental consequences of the dominance of isolation and individual measurement is that the building performance could only be locked in the stringent definition between the natural versus man-made, quantitative versus qualitative. Unlike in the nature, the efficient, safe and aesthetically pleasing structure can be found everywhere and the attributes are always regarded as a whole. The challenge of learning from nature, however, is to quantify these understand of the natural form and derive the structural behavior from it and modify, adapt to buildings. "These organically-inspired structural systems typically exhibit intersecting aesthetic qualities which are not necessarily intuitive."[5] In some projects, individual performance metrics have been blended better than in others; two approaches within

Figure 01: Munich Olympic Park Figure 02: Casa Batlló Figure 03: Spider web

structural design have particularly shown a promising model for how performance could serve as a linkage among all concerns, including energy, functionality, stability and constructability. The two approaches are form-finding and material-centric.

2. 2. FORM FINDING

Form-finding is a basic skillset that building designer would inquiry during the study. It falls somewhere in between the theory and practice of architecture. It can be described as the study of emergent properties of complex systems to establish a more intelligent, correct and robust form.[6] Form-finding require not only years of training, also drastic changing in the way designers think about the structures, the stability and their resistance to the external force. It is not metaphor of the arts; it is not a piece of poetry of surrounding, instead, it is rooted from necessity and survival. As pointed out by Julian Vincent, one of the lead thinker of biomimicry: “materials are expensive and shape is cheap” in nature.[7] Professionals in building industry often ask “What is the most economical and efficient way to build?”[8],form-finding is part of an answer to the question. Leaves, waves, shells might not appear to us as architectures, however, nature produce extremely efficient, organic and beautiful forms. At the same time, nature make the most economical use of limited local materials available and the economy is achieved by weaving material properties into the forms. As the global population increase, especially at urban environment, it has become increasingly imperative that we need to find a more efficient way to use the finite materials within limited physical environment.

“The straight line belongs to man, the curved line belongs to God,” – Antonio Gaudi. Antonio Gaudi is one of the great architects and structural engineers who started learning from nature from a performance perspective instead of a merely aesthetic perspective. Gaudi has a famous approach to taking inspiration from natural objects such as trees and flowers, in his structure one can find a clear indication of nature inspiration. Before the term form-finding – which was later practiced by Freit Otto – Gaudi tried to invent his bio-spired structures by conducting experiments, for instance suspending inverted structures using cables and leaving gravity to do its job in determining the resultant organic form. He often applied a form called inverted catenary arches which is mirror image of catenary arches because of the forms ability to be made of minimal materials as well as support tremendous weights. The key is the system active its form and pattern to resist external forces. One can find inverted catenary arches everywhere in the nature, such as a spider web.

In early twenty century, long before the concept of biomimicry being introduced in architectural design filed, numerous architects started explore the innovative approaches using nature as a guiding principle to come up form and structural systems. Frei Otto calls for an architecture of necessity, saying, “Good architecture is more important than beautiful architecture... The ideal is ethical architecture that is also aesthetic.”[9] As a pioneer of light weight construction, Otta focused on finding the most force-resistant efficient building, without his invention of several tensile structures, lots of modern buildings would not be possible. His building are all form-active buildings that utilizing the entire form to resist external forces. Other architects, such as Eero Sarrinene’s dulles airport and Frank Lloyd Wright’s Johnson Wax building have taken the first step to emulate the natural forms, the formers was bird and later was tree.

2.3 MATERAIL-CENTRIC

Materials are defined by their specific composition and structure from which their properties arise.[4] Some material are static while others are more responsive to the natural environment. Researchers have done a range of studies on smart materials, such as shape memory metal alloys, biometals, hydromorphic materials(wood)[10]; those materials have embedded mechanical responsiveness reacting to the changes in a passive way. As a hydromorphic material, wood could vary the dimensions in different directions induced by temperature fluctuation or in ambient humidity change, also different cutting method will have impact on shrinkage and warping of wood. Fluctuating material properties are the indicators to the external stimuli that smart materials will respond to. The response could result to the micro-structure alternation of material or behavior change. Material behavior can be put to task and constitute the potential of material performance.[4]

We often find difficulty to judge between our desire to have high-performance building materials and our responsibility to environment protection while immersed in surge of hyber and synthetic material. And also we often have fixation of advanced material mutation and its related novel effect and capability. Whichever fixation prevails, new materials – from self-cleaning glass, electroluminescent films, photocatalytic, ductile, self-repairing and porous cements, to ultra-insulating foamed aluminum and super-absorbent polymers that can rapidly soak up toxic spills – have launched us into a vortex of “hyper-choice” and infinite material dialogues.[11] One on hand, the invention and focus on nanomaterials bring our attention to novel materials on the molecular level, and on the other hand the upcoming technologies allow new aesthetic and performance become possible, the two trends have put modern materials in an incessant demanding position. But let us don't forget the synthetic and innovative materials could also imbue some unintentional environmental consequences.

The performance of structure depends on the organization and materials, and we shall talk about both structures and materials together; and there is no clear-cut dividing line between a material performance and a structure behavior. Steel is undoubtedly a material and the bridge is undoubtedly a structure, but reinforced concrete, wood and human flesh – all of which have a rather complicated constitution – may be considered either materials or structures.[12]

3. 0. LEVELS OF BIOMIMICRY

The term Biomimcry first appeared in scientific literature in 1962[13] and later has been adopted by material scientist in the 1980s. In 1997 Janine Benyus published a book, Biomimicry Innovation Inspired by Nature reintroduced the term and broad the usage of its application. In her book, biomimicry was introduced as a new discipline that analyzes nature's best ideas and adapts them for human use – such as weaving fibers like a spider or gathering energy like a leaf.[13] According to Benyus, the inspiration from nature could be drawn from three levels. The first level is at organization level which also seen from the biomimetic technologies and techniques, and at this level we could either mimick whole organization or certain parts from the whole. The second level is at behavior level, at this level we could learn from how pine cone could open up due to the shrinkage rate difference and apply to responsive façade design. The third is at system level; this level is considered the most difficult level, as it focuses on a functionally difficult issue to mimic. Five dimensions could be applied to each of those three levels to determine to which extent the mimicry exists. The five dimensions are: in the way it looks (form), what it is made of (material), how it is made (construction), how it works (process) and what its capability is (function).[15] These levels and dimensions are very important and they complete the biomimicry approach, they indeed exist in the structure design context as well.

4.0. BIOMIMICRY APPLICATION IN STRUCTURE DESIGN

Nature could provide us with infinite inspiration and lessons from its 3.8-billion-year evolution. "Biological organism can be seen as embodying technologies that are equivalent to those invented by humans"[16] In nature, embodying technologies could be found everywhere in the optimization of the geometrical form and efficacy of energy and material distribution.

4.1. FORM FINDING - STRUCTURE LESSON

In structure design, there are several structural system utilizing its form to resist external load, both flexural and transversal load, funicular structure and reciprocating structure are two of most obvious examples. A reciprocating structure is a system that overall span is longer than that of its individual pieces, in nature, a bird nest is a reciprocating structure; in construction, truss system is a reciprocating structure.

Imitating shape and form from nature is the most known type of biomimicry in architecture and engineering design. The natural environment in fact inspires a number of structural systems that are considered great man-made achievements, such as Sydney Opera House. Suspension structures, such as long span suspension bridges, share the same structural principles with spider's webs. Membrane structures, such as modern stadium roofs and canopies, behave similarly to cell walls, gaining strength by maintaining constant tension. Someone could argue that the Pantheon of Rome is indeed a biomimetic example, not in terms of its materials but because of its structural behavior, which is similar to that of a sea shell. Like seashells, the roof of the Pantheon gains its strength from its multi-dimensional curvature, which results in a structure that does not require extra reinforcement; hence, it is much lighter than conventional reinforced concrete spanning structures.[17] Most recently, in SOM's competition scheme for the China World Trade Center, the design team took the inspiration from bamboo as a form and structural organization and created a high-rise that could scale up the bamboo's resilience through a deliberate form. Through study, the team discovered the natural formation of bamboo reveals unique structural characteristics. Long, narrow stems provide support for large foliage during its growing life, which also provide strong and predictable support for man-made structures after harvesting.[5]

When encountering tremendous lateral loads such as tsunamis, bamboo structure responds in a very resilient way with minimal materials required, the resilience is rooted from the genius of natural structural organization. When exam the across-section of bamboo, one can recognize the mathematically laid out position of nodes and diaphragms: those elements are not evenly space over the entire height of bamboo, they are closer at the base and top, in the middle the they are further apart. If we construct a buckling diagram of bamboo one can find the diaphragms are located to prevent excess buckling when subjected to transversal and lateral loads. Bamboo consists of several stems that are divided by diaphragm into internodes. From outside, nodes mark the location of diaphragms and provide the location for new growth. The small diameter change happen at node location, typically from large to small from the bottom to the top.This growth pattern is common to all bamboo regardless different subspecies. The wall thicknesses and diameter of the culm are also in the proportion to "meet" the slender ration for bamboo. All equations that define the diaphragm locations, diameter and wall thickness are based on a quadratic formulation.[18] A study conducted by David Taylor and team "....suggest that the morphological features of the node—the internal diaphragm and external thickening of the culm—have evolved as an attempt to avoid failure in the vicinity of the branch...."[19]

Each internodes are hollow, the hollow portion form an inner cavity surrounded by a culm wall. The material within the culm wall is located at the farthest position which is away from the stem's central neutral axis, the distribution and form is following the optimized bending resistance moment and allow the transversal loaded being transferred through the exterior skin of the stem. The fast transferring of load, meanwhile also impede uplift wind force. The combination of hollow structure and material distribution provide the strongest bending resistance with minimal

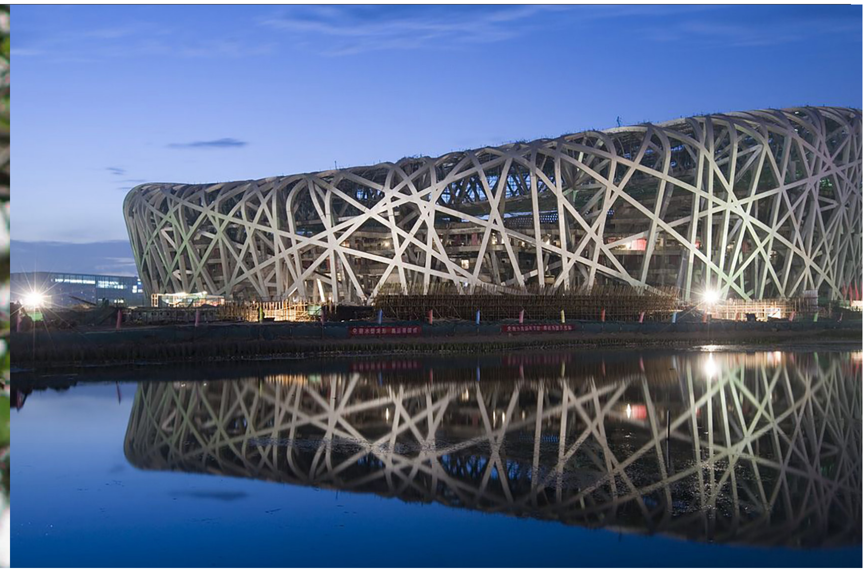


Figure 04: Southern Masked Weaver Nest

Figure 05: Beijing Olympic Stadium

weight. The cellular structure of the bamboo wall reveals tighter cellular density near the outer surface of the wall and less density near the inner wall – once again reinforcing the idea of maximum material efficiency when subjected to bending loads.[18] If we plot the bamboo stem and diaphragm section onto a bending moment diagram, with similar height, diameter and material thickness, one can clear see the shape of bamboo step is the representation of bending and shear force diagram of a cantilever object, the cantilever object could be a beam, also could be a high-rise building, the structural principles is the same for bamboo and other cantilevered objects.

As describe by design team from SOM who worked on China World Trade Center Tower: "The tower is divided into eight segments along its height. The structural demand from the lateral load is highest at the base of the culm (or tower), therefore internode heights are smaller compared to the mid-height. Smaller spacing increases moment capacity and buckling resistance. Beyond the mid-height of the culm (or tower), the heights of the internodes decrease proportionally with the diaphragm diameter. Thus, the form of the culm (tower) responds to structural demands due to lateral loads..."[5] The competition scheme is a large assemblies of bamboo to simulate the way bamboo grow and resistant wind load in an extremely efficient way.

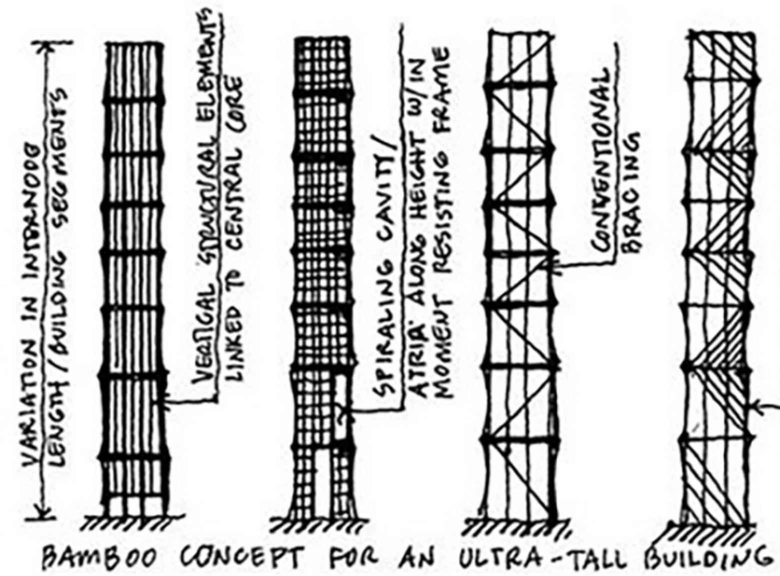
4.2. MATERIALS - MICRO AND MACRO LEVEL

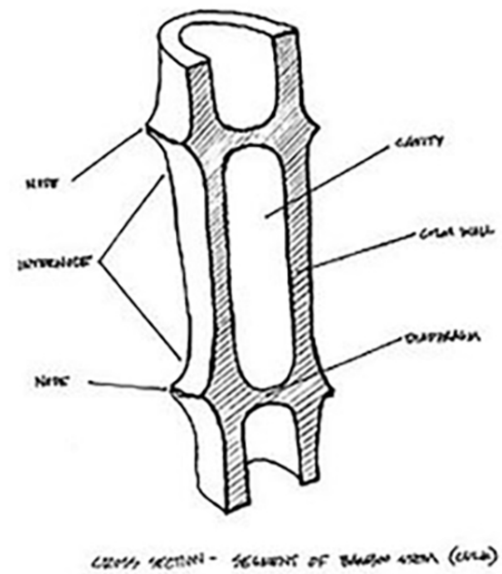
Materiality is not only synonymous with structural and aesthetic categories, but is also aligned with the evolving theoretical position on the perceived or potential role of materials in contemporary culture.[16] The meaning of suitable material is ever-changing, could be sensible, structural, performative, affordable or renewable.

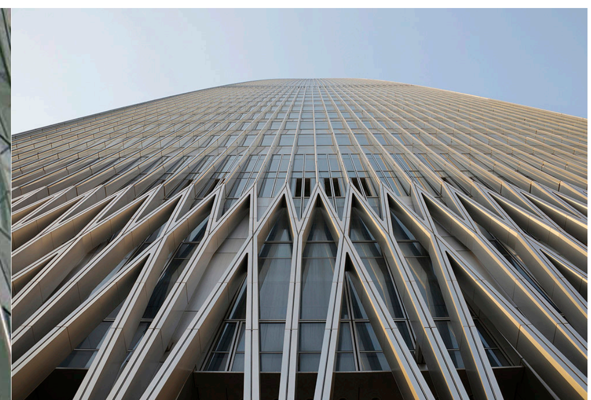
For the last fifty years, the Construction Specifications Institute (CSI) Master Format has prevailed as the standard classification and specification system in the United States. It organizes materials hierarchically, according firstly to function and use group, such as structural, architectural, finish; and secondly, according to generic materials group, such as paint, concrete, steel. The material properties and functions are solely discussed from the perspective of codes and requirements for preconceived applications. A new approach deviated from this isolated categorization of material has merged with the inspiration from nature.

Concepts of biomimicry have applied to product design, such as automobile, shoes, clothing, in the application in architecture does seems to be a growing interest, more designers turn inward to study the sustainable and responsiveness of materials themselves. It is useful to focus one particular material- wood to illustrate the potential application. Due to its nature, wood, has been regarded as one of the hallmarks sustainable building materials. Besides its organic nature, the advantage of wood lies within its responsive behavior to the ambient environment, also its low cost, low eco-footprint and high structural strength in certain direction. The standard approach using wood is timber structure. However, one of the unique and essential characteristic that has not been fully utilized is the different shrinkage and swelling of wood under environmental condition, If one considers, for instance, how wood may be utilized with regards to its hygroscopic behavior, one also needs to take into consideration all properties and characteristics that affect its response to moisture disequilibria, such as its species-specific density anisotropy, porosity and cellular differentiation.[26] There are quite a few architects seeking new ways to use organic wood products or engineered wood products. Shigeru Ban is one of the architects that have been working with a variety of wood products for years. He recently designed a residential tower in Vancouver, and it is said to be the tallest hybrid timber structure in the world.

Another example of the departure from conventional material classification systems is Nanotechnology: the research areas consist a number of disciplines including structure and construction materials. In the case of many building materials – both those cement-based and certain types of polymers or composite materials – the observation of the physical-chemical properties at nanoscale allows such a degree of precision that it is possible to "correct" and optimize the characteristics







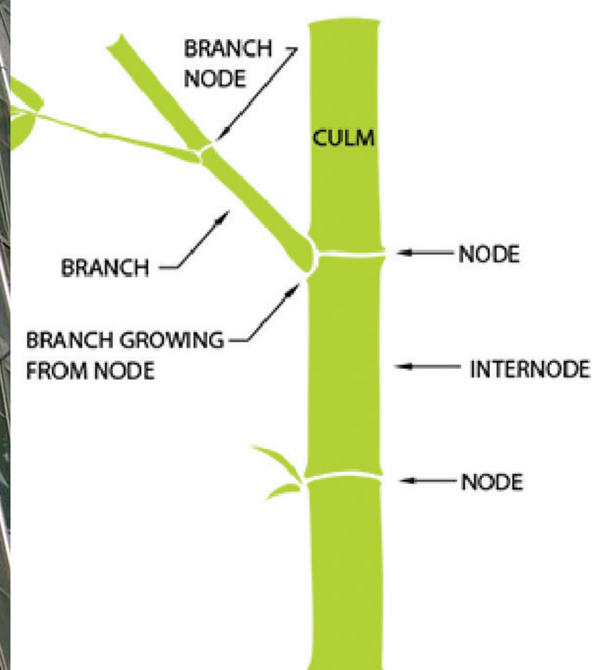


Figure 06: China World Trade Center[18]

Figure 07: Bamboo growth Pattern

Figure 08: China World Trade Center Facade

of a material's nanostructures depending on the final performance expected, even without the addition of nanomaterials.[20 21] The recent bio-inspired concrete and Cementous materials have shown us an alternative approach to conventional thinking about structural materials. Bioinspired means the composition and crystallographic nature of the cement or concrete is seen in biological materials, usually mineralized skeletons.[22] A group of scientists from MIT studied a new version of cement designed to integrate new natural materials, which could last longer and be more sustainable – as well incorporating natural strategies to use material efficiently. The strong material in nature was formed as nanocomposite combing biopolymers with mineral nanoparticles with aims to produce new material stronger and more durable but less weight. The research team chose bone, nacre and sponge, since their high strength and toughness are largely attributed to flaw tolerance at the nanoscale[23] in combination with micro-cracking: crack deflection along interfaces. The microscale structural composition of natural materials could be applied to concrete and cement making, and the products could potentially have enhanced strength, resilience compared to a regular cement or concrete element embedded with conventional steel rebar.[26] These examples emphasize not only the benefits of the selection of additives based on natural design principles in order to achieve more durable cementitious materials[24] but also demonstrate that the inspiration from nature could come from both the micro and macro level, and the microstructure of materials undouble is integral contribution to building structure.

5.0. FUTURE AND OBSTACLES FOR PERFORMANCE-DRIVEN STRUCTURE DESIGN

In the context of information technology – which requires and facilitates new approaches to the conception of architecture and engineering – architects and engineers cannot rely solely on the professional standardized conventions, but rather on innovation in design and the application of new techniques and materials.[25]

While emerging material properties and variable behavior indicate infinite opportunity for performance-based buildings, one cannot ignore a profound obstacle that impede the exploration of biommicry's application in structure design. The obstacle is the increasing strict code and standardization construction methods. Meanwhile the diminished tolerances and stringent liability to building professions make the variable properties and nature of organic material and adaptable structural behavior and associated dimensional change generally deemed as a negative character. Under the pressure of strict code and regulation, architects mainly seek to prevent or neutralize the effects of variable material behavior on the scale of the chosen material, building component or assembly method, to avoid cumulative effects and compliance certainty. Very few practices break away from defined standardized practice and pre-set solutions, most practices cannot afford associated additional cost and lengthy proof of concept process, the materials research timeframe also does not align with the progress of practice. However biological inspirited technologies will continue to be a significant driver of the change in next twenty years, the structural design and architectural practice will need to reposition previous narrowly –defined basic practice-relate research to more advanced interdisciplinary research to variable material behavior and bioinspired structural system.

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