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ORIGINAL ARTICLE

Biomimicry as an approach for bio-inspired structure with the aid of computation

Moheb Sabry Aziz *, **Amr Y. El sherif**

Alexandria University, Faculty of Engineering, Architectural Engineering Department, Egypt

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Abstract Biomimicry is the study of emulating and mimicking nature, where it has been used by designers to help in solving human problems. From centuries ago designers and architects looked at nature as a huge source of inspiration. Biomimicry argues that nature is the best, most influencing and the guaranteed source of innovation for the designers as a result of nature's 3.85 billion years of evolution, as it holds a gigantic experience of solving problems of the environment and its inhabitants. The biomimicry emerging field deals with new technologies honed from bio-inspired engineering at the micro and macro scale levels. Architects have been searching for answers from nature to their complex questions about different kinds of structures, and they have mimicked a lot of forms from nature to create better and more efficient structures for different architectural purposes. Without computers these complex ways and forms of structures couldn't been mimicked and thus using computers had risen the way of mimicking and taking inspiration from nature because it is considered a very sophisticated and accurate tool for simulation and computing, as a result designers can imitate different nature's models in spite of its complexity.

1. Introduction

"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. Two facts about the coming century are agreed on by almost everyone. Biology is now bigger than physics, as measured by the size of budgets, by the size of the workforce, or by the output of major discoveries; and biology is likely to remain the biggest part of science through the twenty first century. Biology is also more important than physics, as measured by its economic consequences, by its ethical implication, or by its effects on human welfare" [1]. During history, architects and designers have looked to nature as an inspiration source for different kinds of forms, techniques and function. The philosophers of ancient Greece looked at organisms which offered them perfect models having a very mesmerizing harmony and proportion between their parts, where that was the classical ideal of beauty at that time. The structure, unity and beauty of any design are synonymous with the quality of integration of its forming parts and thus no small part could be removed without deforming and damaging the whole. These thoughts were the main concepts at the age of Aristotle, as it was the essential esthetics and characteristics of

* Corresponding author.

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the best way to have a work of art in the natural history of the Aristotelian age.

It was so trivial at that time the way architects and designers understood nature, they looked to biology as a source of inspiration from the beginning of science. They had a superficial way for imitating and mimicking the forms of plants and animals. But from decades ago architects found other way of understanding nature as methods and analogies of growth and evolution. Those architects had changed the way of design in a very prominent way as it was obvious in their writings, for instance the bold ideas of Le Corbusier and Frank Lloyd Wright. Le Corbusier thought that biology is the greatest word in architecture and planning. But the way they saw nature was still missing where the biological analogy was about superficially artistic picture from nature's wonders and creatures and that was clear in the buildings and products of the industrial age. When we talk about analogies in nature we must think of a deeper way of understanding science and nature not just artistic picture imitation.

2. Biomimicry overview

"The term 'Biomimicry' first appeared in scientific literature in 1962, and grew in usage particularly amongst material scientists in 1980s. Some scientists preferred the term 'Biomimetics' or less frequently 'bionics'. There has been an enormous surge of interest during the last ten years, brought about to a large extent by individuals like biological-sciences writer ***Janine Benyus***, professor of biology ***Steven Vogel*** and professor of Biomimetics ***Julian Vincent***, who have all written extensively in this subject area. Julian Vincent defines it as 'the abstraction of good design from nature', while for Janine Benyus it is 'the conscious emulation of nature's genius'." (Michael [2]). There is no difference between 'Biomimicry' and 'Biomimetics', where Biomimicry is used at developing sustainable design solutions and Biomimetics has been applied to the military technology field.

The biomimicry term appeared in 1982 and it was invented and published by the famous scientist Janine Benyus in her most significant 1997 book (Biomimicry Innovation Inspired by Nature). Biomimicry was manifested in her book as "the new science that studies nature's models and imitating these designs to solve human problems". She also claimed looking to nature as a "Model, Measure, and Mentor" and she also suggested that the main aim of biomimicry is sustainability. Biomimicry is the most brilliant and genius way to look for sustainable solutions to human's problem by mimicking and emulating nature in its analogies, phenomenon and patterns. Biomimicry's main aim is making a great designs by mimicking the different living organisms which have been evolving through 3.8 billion years.

3. Biomimicry theoretical framework

3.1. Biomimicry approaches

Approaches to biomimicry as a design process typically fall into two categories: Defining a human needs or designing problem and looking to the ways other organisms or ecosystems solve this, termed here **Design looking to biology (Top-Down approach)**, or identifying a particular characteristic, behavior or function in an organism or ecosystem and translating that into human designs, referred to as **Biology influencing design (Bottom-Up approach)** (Biomimicry Guild, 2007).

3.1.1. Design looking to biology (Top-Down approach)

Throughout literature review, this approach has different names as "**Design looking to biology**" [3], "**Top-down Approach**" (Jean [4] and "**Problem-Driven Biologically Inspired Design**" [5], "**challenge to biology**" (Biomimicry institute) (Fig. 1). They all have the same meaning and they also point to the way designers look to nature and organisms for solutions, where designers must recognize exactly their design problems and to match their problems with organisms and creatures that have solved similar problems. This king of approach is as a result of the designers knowledge of the aims and triggers of their design.

3.1.2. Biology influencing design (Bottom-Up approach)

Just like the previous approach, this approach has different names and expressions such as "**Biology Influencing Design**", "**Bottom-Up Approach**", "**Solution-Driven Biologically Inspired Design**", and "**Biology to design**". They all refer to the same meaning, where this approach depends on the previous knowledge of biological research and solutions not to search for a solutions in nature, then applying this knowledge on the design problem you already have (Fig. 1).

3.2. Levels of biomimicry

In addition to these two approaches demonstrated previously, there are three levels of biomimicry have to be applied also to design problems. From the biomimetic technologies and techniques, it is obvious and well noticed that there are three levels of mimicry: the organism level, behavior level and ecosystem level. The organism level illustrates the mimicking of certain organism or the mimicry of a part from the whole organism. The second level is the mimicry of behavior of which every organism behaves. The third level is the mimicking of the whole ecosystem and this level is considered the hardest level as it focuses on a functionally very hard issue to mimic. Through each level there are five dimension which determine at which extent the mimicry exists. The design is listed as biomimicry in the way it looks like (form), what it is made of (material), how it is made (construction), how it works (process) and what it's capability (function). The three levels of mimicry are described in Table 1. These levels are very important and they complete the biomimicry approaches.

4. Bio-inspired structures

From the dawn of history architecture inspired its structures from nature and it is manifested at the old temples of the ancient Egyptian civilization, for instance, the columns of the temples which were inspired by the lotus plant, the sacred plant for the Egyptians. Trees and plants generally have been used as a source of inspiration for the ornamented structural columns of the classical order at the Greek and Roman ages respectively. Two of these columns' capitals (the Corinthian and Composite order) were inspired by Acanthus plant, where these columns appeared widely in the Greek and Roman architecture (Fig. 2(a)). Throughout this period of time it

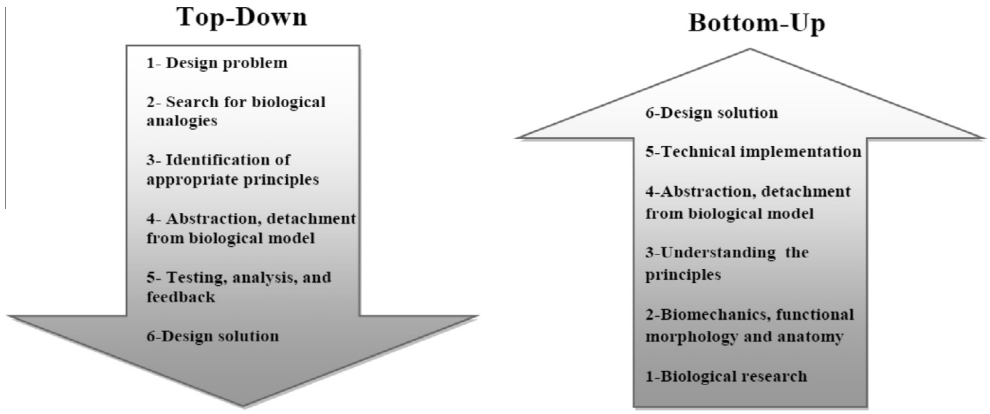

Figure 1 Biomimicry top-down and bottom-up approaches.

Table 1 A framework for the application of biomimicry (adapted from Zari [3]).

Levels of biomimicry	Example: Building that mimics termites	
Organism level (mimicry of a specific organism)	Form	The building looks like a termite
	Material	The building is made from the same material as a termite; a material that mimics termite exoskeleton/skin for example
	Construction	The building is made in the same way as a termite; it goes through various growth cycles for example
	Process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example
	Function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example
Behavior level (mimicry of how an organism behaves or relates to its larger context)	Form	The building looks like it was made by a termite; a replica of a termite mound for example
	Material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example
	Construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example
	Process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or the building mimics how termites work together
	Function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example. It may also function in the same way that a termite mound does in a larger context
Ecosystem level (mimicry of an ecosystem)	Form	The building looks like an ecosystem (a termite would live in)
	Material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example
	Construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example
	Process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example
	Function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles, etc. in a similar way to an ecosystem for example

was obvious that the use of ornaments was inspired by plants and trees very widely used in architectural decoration. At that time design and architecture were very hard profession, as it took a lot of time and also very complex in fabrication, because the ornamental plants and flowers were carved on stones with a very high accuracy and also to be repeated with the same way on the other columns and parts.

After many years, in the beginning of the medieval period in the 12th century, it was the age of the powerful Catholic church, where the cathedrals were the most important buildings at that time. There is an important kind of structure appeared which is the ornamented fan vault as it is inspired from the tree's shape. The fan vault appeared in the Sainte-Chapelle church in Paris which was made at 1248.

Figure 2 Left (a) Acanthus plants; and Corinthian column head in Pantheon, Rome built in 126 AD. Right (b) the gothic flying buttresses. *Source:* Iasef MdRiann et al. [6].

These Gothic style fan vaults are supported by columns and enclosed by stained glass where these vaults are also supported by ribs forming a cross network to carry the vaults. Another kind of character was found at the medieval age, where this structure was the main character for the Gothic style, and it is the flying buttress (Fig. 2(b)). The flying buttress was formed from two parts, first the buttress which is a very huge block made of masonry and second the flyer which is an arch between the buttress and the exterior wall. This structure works by transferring the forces from upper ceiling to the lower buttress to the ground.

At the period of Art Nouveau style from late 19th century to the beginning of the 20th century, a stunning, mesmerizing and very influencing structural forms have been found in the work of the monk of architecture the well known Antonio Gaudi who was famous and familiar of his combination between architectural forms and the structures inspired by nature. He has a famous approach about taking inspiration from plants and trees as structure, and his architecture was really one of a kind. Before the term form finding which was conducted later by Frei Otto, Gaudi tried to understand his bio-inspired structures by making experiments as suspending inverted structural by using cables and leaving gravity to do its job by determining the resulted organic form. The photographs taken to the model could be inverted upside-down to demonstrate the final work. These inverted forms are known as catenary arches, where he used them obviously in many of his projects. The reason of using such forms and techniques is their ability to be made of light materials and also its capability of carrying and supporting great weights (Fig. 3(a)). The Art Nouveau period was really influencing period for structure and architecture as well.

At the beginning of the 20th century, it was really a very peculiar period in the architectural history because the reinforced concrete was invented, where it was the most significant aspect at this century. Many architects used the reinforced concrete to fulfill their design thoughts which was inspired by nature and one of those architects is Felix Candela, the Spanish architect. Candela fascinated by the effect of the geometrical approach on the architectural forms as he studied the shell structures in Germany and he applied his study and thoughts on buildings by using the concrete. Candela used the geometric hyperbolic paraboloid as a source of inspiration for his building, as a builder he could build them. Candela's most famous building is the Los Manatiales restaurant in Xochimilco (Fig. 3(b)), also in Mexico, of 1958. The form is generated from eight separated hyperbolic forms connected to each other along the shared valley joint. It was obvious that the structural forms changed totally at the 20th century.

5. Computation

Through the last thirty years there has been a prosperous theory and thoughts in design and architecture, a theory not looking only to understand and imitate forms from nature, but finding a deeper level of biological analogies, by which architects can take the inspiration. This theory took the credit and the recognition over the last two decades. This activity is the introduction of computers into the architectural, engineering practice and also industrial design. Computer-aided design was just 16 years old in 1979 taking Ivan Sutherland's Sketchpad system of 1963 as year zero. The technology in those days was unwieldy and expensive, the users were mostly government departments and big companies, and the focus in architecture was on prefabricated industrial systems of construction and architectural design.

Kostas Terzidis is one of the Avant-garde architects who has a precise definition for computation and the difference between computation and computerization. "Computation is a term that differs from, but is often confused with, computerization. While computation is the procedure of calculating, i.e. determining something by mathematical or logical methods, computerization is the act of entering, processing, or storing information in a computer or a computer system" [7].

> "Computerization is about automation, mechanization, digitization, and conversion. Generally, it involves the digitization of entities or processes that are preconceived, predetermined, and well defined. In contrast, computation is about the exploration of indeterminate, vague, unclear, and often ill-defined processes; because of its exploratory nature, computation aims at emulating or extending the human intellect. It is about rationalization, reasoning, logic, algorithm, deduction, induction, extrapolation,

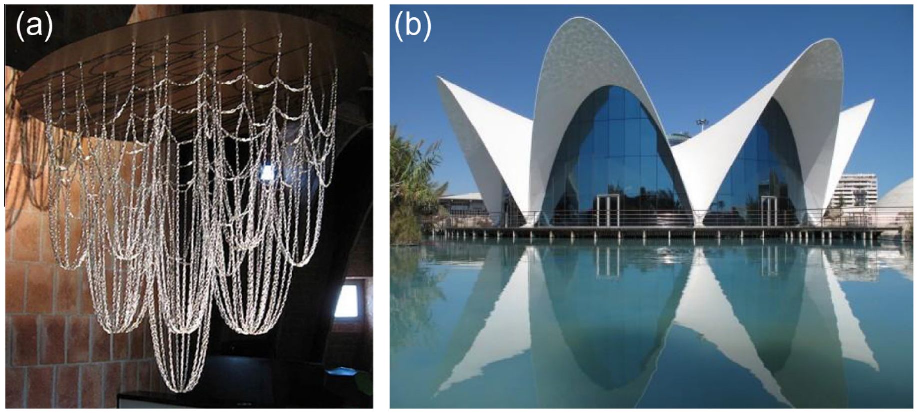

Figure 3 Left (a) Gaudi's catenary arches. Right (b) Felix Candela, Los Manatiales restaurant, Xochimilco, Mexico, 1958. *Source:* http://sean.mcginnis.perso.sfr.fr/SMcQRimages.html.

exploration, and estimation".

[Terzidis [7]]

Everything changed after the computer had arrived since 1980 on every desk, and also when new CAD software of a great graphics and powerful modeling techniques was invented everything changed too. Computer gave the designers a very stunning tool to explore fluidity, curvilinear forms and simulation tools, also merging them into their architectural design. Computer showed designers and engineers a fabulous tools could mimic evolutionary techniques as to help them in their optimization process for the best design. Since 1960 computer scientists started to explore a ways to create genetic algorithms which are capable of imitating evolution and natural selection, to solve design problems and introducing semi-automatic software. In 1990 architects took these algorithms to be introduced into computer software which is responsible for architectural design and also design of artifacts. Nowadays computers are vastly involved in design where their roles vary from drafting and modeling to intelligent knowledge-based processing of architectural information. CAD software is now used at the structural design as it helps at the best and the most efficient structure picking, also conducting simulations on different forms of structure to recognize the effect of the load and the different forces on them. Computer also is very useful in the construction level as the complex forms cannot be constructed by the ordinary ways.

6. Application of biomimicry in structural design

6.1. Minimal surfaces

Many mathematicians were fascinated and mesmerized by the spectacular objects, creatures and forms found in nature. No doubt that soap films are a sort of these forms of nature, where they have been studied intensively by mathematicians as to mimic them and to reveal from them a great geometric forms such as minimal surfaces. Minimal surfaces are named like that because they are the surfaces that tend to minimize their total surface area. These surfaces can be conducted by a very simple way, where to make a physical model of minimal surfaces you have to dip a wire frame into a soap solution and the result will be a soap film which is also a minimal surface. Minimal surfaces also can be self intersect and to be periodically repeated without any constraints and on this occasion they will be called periodic minimal surfaces.

Minimal surfaces have different types and all these types have a wire frame boundary which is dipped into the soap solution. By 1834 the famous mathematician ***Heinrich Scherk*** explored a way to make a no-boundary minimal surface, to be extended through space with no end. He illustrated that the saddle-shaped forms could be repeated identically and joined at their boundaries to form a periodically repeated lattice of these forms. He called it periodic minimal surface, it has also the ability to fill the three-dimensional space and it looks like a labyrinths, where you can't move from one labyrinth to the another without passing through the surface in between. As a result this structure is highly continuous (Fig. 4(a)). Another German, ***Hermann Schwarz***, respectively discovered another continuous periodic minimal surface during the study of plateau's problem which was the shape of the soap film when stretched between tetrahedral frame touching its four corner. ***Schwarz*** found the solution for this question, where the saddle-shaped minimal surface could be pieced together to form periodic minimal surface called P-surface (Fig. 4(b)). The American mathematician ***Alan Schoen*** discovered other two continuous periodic minimal surfaces in 1960, the first one called the D-surface and the other called the G-surface or Gyroid. These different types of minimal surfaces divide space into two parts having equal pressure on each part. Minimal surfaces have the possible minimum total surface area, the reason they have the ability to be the best solution for filling the three-dimensional space.

6.2. Architectural interpretation

A great example for the Architectural interpretation of the minimal surfaces is **Taichung Metropolitan Opera House** designed by the Architect ***Toyo Ito*** (Fig. 5). The dominant structure of the opera house was inspired from ***Schwarz*** P type minimal surface, as it is formed from continuous, seamless and curved walls. This structural form consists of 58 curved wall units, constructed by using steel reinforcement and steel trusses, covered by sprayed concrete. The construction technique used in this project is unique and never been used before at Taiwan or any place else, the reason that the local construction companies

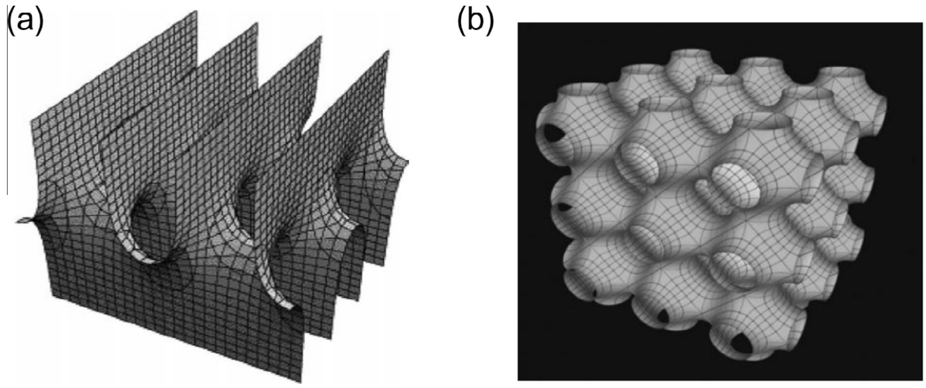

Figure 4 Left (a) Scherk's periodic minimal surface. Right (b) Schwarz's minimal surface. *Source:* Philip ball, nature's pattern, 2009.

Figure 5 (left–middle) The opera house at finishing stage. (right) A model for the opera house. *Source:* http://uk.phaidon.com/agenda/architecture/articles/2014/September.

failed to construct this project and also these companied didn't show any ability and interests in this project.

Taichung Metropolitan Opera House, located in a dense urban area in Taichung city. This opera house was built to be the main landmark for Taichung city, and the design is an open space structure with seamless and continuous curved walls. It was built also to be connected to its surroundings, and to make a big linkage between the high quality art and the popular art, also visitors and artists, that's why the architect called it "the sound cave". The sound cave is a connected space with vertically and horizontally network, and thus it is considered the best and fascinating acoustic three-dimensional space, where the visitors can notice that easily after entering the three theaters, it is a great project because it connects between its different parts and spaces.

The opera house was designed to reveal sustainable concept in three levels. The first level is rain water, where rain water will be collected and filtered and reused for landscape issues, while the gray water will be reused in toilets. This opera house is designed to use recycled materials such as steel and concrete in the case the building needs maintenance or reconstruction. The architect tried to reduce carbon emissions as to save the environment and reduce global warming, while making people aware of the importance of sustainable materials. Working on the sustainability of this project is a main aim for the architect that's why it is going to be a great project.

6.2.1. Geometry and computation

Arup was responsible for the opera house construction, and to achieve such a complex design, Arup's Advanced Geometry Unit formed a group of geometry and structure generation tools. The form has a rectangular boundary within the continuous form was placed. As mentioned before the form of the opera house divided the space into vacuums varies between interior and exterior. The form of the opera house has a smooth surface not only for esthetic purposes but also for getting the most efficient structure, where the shell structure is the best choice because the loads are distributed equally on every part of the structure. A smoothing algorithm was used as the surface subdivided by (Catmull–Clark) subdivision system, where the final surface was an array of polygonal quad facets. Each polygon is divided into other set of smaller polygons and so on, by this way a new set of vertices and polygons are formed by the smoothing algorithm.

The smoothing algorithm was first developed as a prototype for making the concrete shell roof Arnheim Central Station (designed by UN STUDIO). It is an exhausting challenge for the current CAD software tools to perform a complex smooth surface from a set of single NURBS patches and also preserving its curvature and complexity. The smoothing algorithm (Fig. 6) has the ability to form a single complex surface from a single patches. Smoothness is conducted and generated by the neighboring vertices interpolation, where this algorithm is programmed by using Rhinoceros software, as to have a full control over the smoothing process, where this software is a very powerful visualization engine. Other required objects were added to the process to maintain the project's ability and power.

Before the smoothing, all the vertices matching with the boundary box are allowed only to form a 2D smoothing, but after the smoothing is conducted a new geometry is created, where the complexity and topology of every element are showed and a drawing data driven extended model was performed.

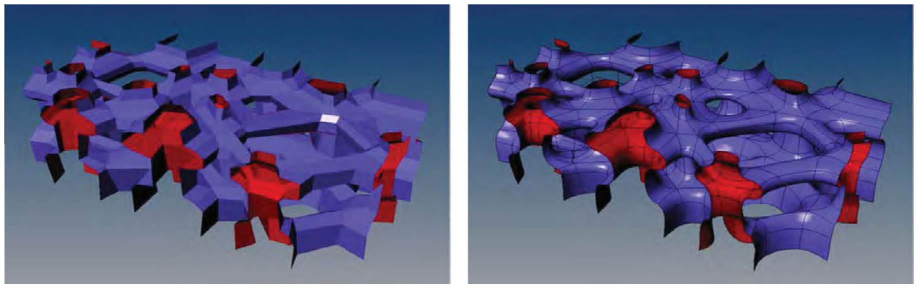

Figure 6 The smoothing algorithm. *Source:* Pottmann [8].

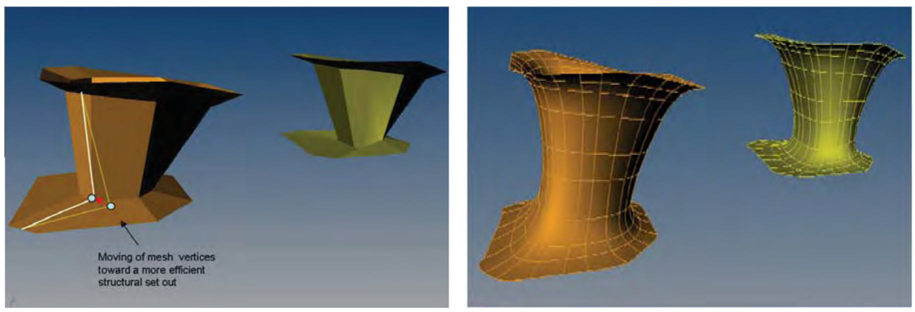

Figure 7 Structural model generation. *Source:* Pottmann [8].

6.2.2. Structure and construction

To recognize the complex freeform geometry, the structural system is performed with the methods of construction. The structure analysis was very hard operation, so the software made for this purpose requires only the edges of the smooth surface to make a meshing algorithm, where this is called the coons patch. The wireframe of edges with their corner points is more than enough to perform and execute the whole structure. The data were provided by the architect are converted to a crude mesh information. The tool developed before is able to choose the most efficient structure and the best architectural design change by the optimization process. Structural optimization of the geometry can be performed many times to reach the best choice. Using computer at this stage is so essential for the opera house construction (Fig. 7).

To recognize such a complex design and also the challenging construction task for the engineering and design teams, a series of studies and experiments have been conducted, after that the engineering team concluded that the Truss Wall System (TWS) which was developed by Asahi Glass Build-wall (AGB) is the best choice for the project. TWS formed 3D surfaces from a set of 2D forms, which can be defined by reinforcement trusses. The 3D surface is divided into different parts of a smooth mesh geometry.

After the structural truss cage was formed, a structural reinforcement was placed over it in order to make it easy fabrication method as much as possible. Over this structure a 3 layers of steel wire mesh are placed, in order to form a double curve structure. The wire mesh is attached to the cage to control the complex geometry and to prevent deformation at the operation of concrete casting. Such a technique allowed the 3D form to be made without tools such as CNC milled Styrofoam. Concrete was casted in the site and rendered manually. A 25 mm thickness concrete was sprayed on the steel structure, and the reason for such a thickness is to absorb any static pressure maybe appeared from the wire mesh structure (Fig. 8).

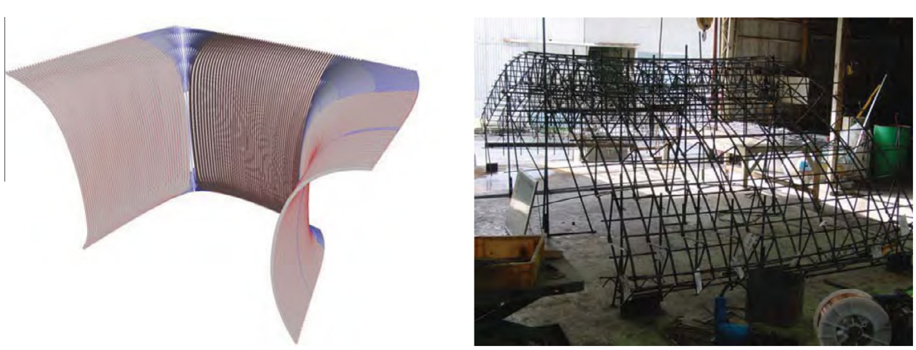

Figure 8 (left) Digital truss wall. (Right) pre assembled truss wall. *Source:* http://www.japantimes.co.jp/culture/2014/11/27/arts/toyo-ito-literally-connects-architecture-people.

7. Conclusion

This paper demonstrates the way Nature has learned how to achieve most efficient multifunctional structures, where designers and architects are trying to learn from nature and to get an optimized solutions from it. Most of the current work focuses on the mimicry of structural forms from nature and using the digital tools as a source of defining and applying simulations on these complex structures. Biomimicry is looking to nature to find a successful solutions from different kinds of organisms that solved their problems from million years ago, as we can then put these design features into use in real-world architecture and structure.

During the last decade, there was a big progress has been achieved in the biological systems understanding and applying this knowledge into the architectural discipline. The latest research conducted in this field allowed a better understanding to the natural forces and structures in addition to the novel ideas brought into the biomimicry field. Nature imitation has become the best approach for architecture and design to be a part of their built environment and to deliver a bold ideas to their surroundings too. At the light of recent natural disasters around the world, especially the geologically as tsunamis and earthquakes, which have proven its destruction power over the current built environment, architects and structural engineers have found in biomimicry an ecological approach in order to improve future building's disaster resilience as to find a good solutions for dealing with such disasters.

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