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ARCHITECTURAL POTENTIALITY OF FREE-FORM STRUCTURES

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Contemporary architecture has witnessed a new innovative trend in design characterized by the creation of interesting free-flowing structures that reflect expressiveness of form and design, as well as the uniqueness of structure and approaches of construction. These fascinating structures are often perceived as landmarks that blend harmoniously into their surroundings. In the last two decades, parametric design and advanced computational tools, with prefabrication and construction techniques, enabled architects and engineers to explore new materials and methods to create such impressive structures, breaking the obsolete ways of thinking. Several examples of free-form structures lack obviously to explore architectural potentialities, that enrich the intention of architect, are still unformulated. The main objective of the present paper includes a conceptual proposal exploring the architectural potentiality of the free-form structures, focusing on form-finding possibilities through optimizing both the geometry and the mass of the structure, to generate configurations that ensure self-supported forms with stable force equilibrium. The paper introduces two simplified analytical methods to achieve the efficiency of the free-form architectural structures: the first depends on using extra materials to strengthen surfaces (such as grid shell system), and the second includes changing the geometry to achieve high "strength-to-weight" ratio (such as folding or conical self supports). By applying these methods, it is possible to explore various form-finding possibilities that contribute to the generation of characteristic landmarks with impressive structures.

Keywords: Free-flowing structure, Landmarks, Form-finding, Optimization, Shell system, Space system.

1 INTRODUCTION

This paper attempts to discover and highlight generation methods of efficient free-form architecture which have seen a rise in recent years. The efficiency of these structures depends on their geometries with the flow of forces and form-finding. Many architects tried to explore the potentiality of free-flowing structures which includes meanings of power, capacity, and the ability to determine object qualities that distinguish it from others.

Free-flowing structures have the ability to create eye-catching forms as landmarks, that follow the concept 'form follows forces' and depend on several types of simulation models summarized by physical models and computational models.

Physical models follow a trial-and-error manner, based on experiences and intuition with the point of material minimization and stiffness maximization. Computational models produce free-forms, forwarded towards topological differentiation with directly controlled parameters to find an optimal geometry with minimized material, or maximized stiffness of structure.

This paper attempts to achieve an adequate efficiency of optimal free-form structures by reliance on two basic methods: using extra materials or changing the geometry. Using extra materials can be presented by creating space frame structures with complex geometries, which are elegantly efficient huge masses with low densities. A wide domain in architectural potentiality can be defined by including the location of the joints as well as the strength of individual beams in triangular assemblage, depending on forces redirection. Changing the geometry is the second method that tries to achieve a stiff structure made from a very thin surface to carry the load by folding the surface. Potentiality of geometrical change can be achieved by depending on the position of the surface related to the direction of acting forces. This way enables all structural systems to be interpreted with surface-active structure systems and emerge new forms of forces. Finally, it is possible to enlarge potentiality domain by the combination of the two methods.

2 POTENTIALITY OF FREE-FORM STRUCTURES

According to Aristotle's metaphysics, potentiality is what a thing is capable of doing if the conditions are right and it is not prevented by something else (Wikipedia 2019). Architectural potentiality, which can be innate or learned, is another order of creativity that keeps the totality in mind, going from the whole to the parts and back to the whole (Wikipedia 2019). Potentiality includes the meanings of power, capacity, intensity, and energy, as well as the ability to determine the truth of the thing that gives it the qualities which distinguish it from others (Merriam-Webster 2019).

In order to present the domain of potentiality of free-form structures, it is necessary to present the possible types of *elements* and *structures* which free-forms can deal with (Adriaenssens *et al.* 2014):

- Straight-line elements (beams, columns).
- Curved-line elements (arches, curved cables).
- Plates (flat surface structures such as slabs, walls).
- Tension structures (curved surface structures such as nets and fabric structures).
- Shell structures (curved surface structures typically of timber, concrete, metal or masonry).
- Fully three-dimensional masses of material.

3 FORM-FINDING OF FREE-FLOWING STRUCTURES

Free-flowing structures will always have a role in architecture because of the ability to create eye-catching forms as landmarks, providing freedom for design exploration, ranging from initial conception to final fabrication, and dealing with applied geometry, computational design, and practice of case studies (Adriaenssens *et al.* 2014). Free-flowing structures follow the concept 'form follows forces' as Louis Sullivan's famous statement 'form follows function' (Goldsmith and Ap 2014, ThoughtCo 2019). The task of such structures is to convert the form of acting forces through material substance into a new 'form' of forces with equal overall potency *through reinforcement of the form substance*, or *through the additive structure*.

Form-finding of free-flowing structures, is a process of designing ideal free-form geometries with stable force equilibrium and aesthetical reasons, inspired from nature, innovated from precedent structures, or explored from various possibilities with multiple paths for all expected loads, using physical or computational models (Adriaenssens *et al.* 2014).

Physical models are essentially an optimization process, followed by a *trial-and-error* manner, based on experiences and intuition. Examples of this process are Gaudi's pioneering works (1852-1926) presented by vaults of the Sagrada Familia Church using catenary curve models (weighted hanging chain, wire, and rope) and freely-formed solutions, developed by Otto, such as Mannheim Multihalle with the point of material minimization and stiffness maximization, Figure 1 (Adriaenssens *et al.* 2014).

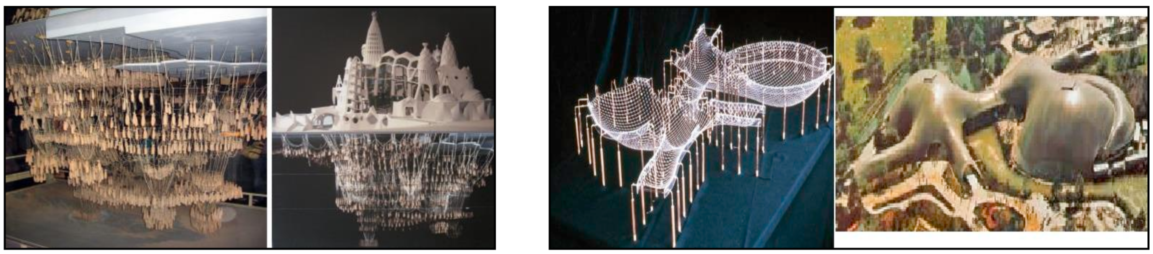

Figure 1. Sagrada Familia Church (left) and Gridshell of Mannheim Multihalle (right).

Computational models produce free-forms, shifting from 'form-making' to 'form-finding' (Agkathidis 2015), by exceeding the limitations of Euclidean geometry, forwarded towards topological differentiation with directly controlled parameters to find an optimal geometry of a static equilibrium structure (Winslow *et al.* 2009). Computational models have been employed in the work of Mutsuro Sasaki, Figure 2 (Adriaenssens *et al.* 2014).

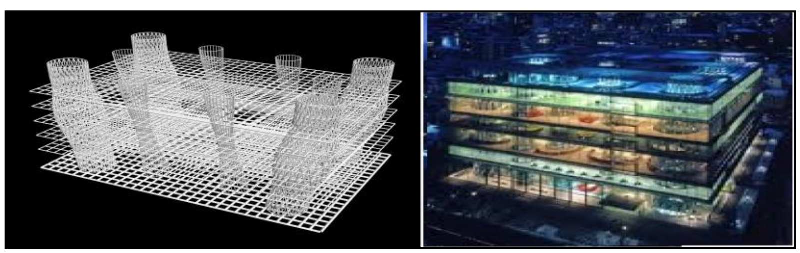

Figure 2. Digital generation of Mutsuro Sasaki's works.

The 'optimal' shape is subject to a set of given requirements and is defined with respect to one or several objectives, such as minimize material, minimize deformations, or maximize the stiffness of structure (Adriaenssens *et al.* 2014).

4 EFFICIENCY METHODS OF THE FREE-FORM ARCHITECTURAL STRUCTURES

This paper attempts to achieve an adequate efficiency of free-form structures by two basic methods: using extra materials or changing the geometry.

4.1 The First Method/ (Using Extra Materials)

Using extra materials can be presented by *creating space frame structures* with complex geometries, which represent a special trend in contemporary architecture. The space frame structure is a *vector-active structure system*, elegantly efficient through huge masses with low densities, derives utility from its simple construction of three-dimensional segments: rod elements which exert only axial forces, connected with joints which may change location during optimization. A wide domain in architectural potentiality can be defined by including the location of the joints as well as the strength of individual beams.

Structural components of the space frame *vectors,* represent magnitude and direction of the force, transmit normal (tension/compression) in direction of their length by triangular assemblage, which receives loads and transfers them to the ends by *forces redirection*. Forces redirection can be accomplished in curved planes or three-dimensional directions. Also, forces redirection can be applied to other structures, such as arches, frames, or shells, which can be designed as space trusses.

With the development of accentuated joints and simple member sections, space frame structures will aesthetically play the form-determining role which design potential and structural quality deserve. So, the potentiality of space frames depends on exploring different forms by repetition and verification to optimize the connectivity, node positions, and cross-sections of the beams, Figure 3. Optimal space frame can be achieved by using a finite number of beams, which starts from an over-complete structure and removes excessive beams to minimize total volume.

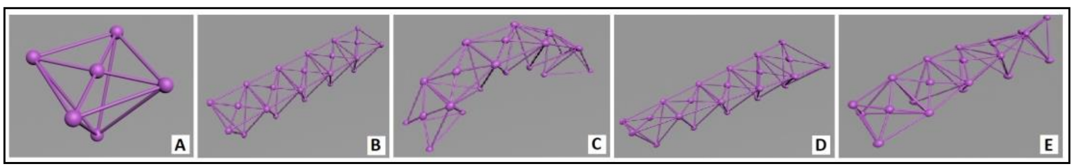

Figure 3. Possible potentialities of stiffening surfaces by using extra materials, (A) triangular modul consists of finite number of beams and finite number of nodes, (B) repeated moduls on one direction, (C) bending shape by changing the dimensions of beams, (D) tapered shape by changing the dimensions of beams and (E) twisted shape by changing the dimensions of beams.

4.2 The Second Method/ (Changing The Geometry)

Changing the geometry can be explained by an illustrative example. The task is to achieve a stiff structure made from a very thin paper as a bridge-carrying load. Because the flat paper is able to only act in bending, stiffeners have to be introduced by folding the paper. This exists in an infinite number of potentialities, all of which create stiff solutions, Figure 4.

Figure 4. Possible potentialities of stiffening surfaces by changing shape.

Surfaces, as *surface-active structure systems*, are the most effective geometrical means of defining form according to their nature of load-bearing. Their potentiality to redirect forces depends on the position of surface related to the direction of acting forces. Inclined surfaces toward the direction of acting forces by means of folding or curving enable all structural systems to be interpreted with surface-active structure systems. Forces redirection is very preconditioned, as the main principle for steering the flow of forces in the form, will emerge new forms of forces.

Changing geometry of surfaces enables a very thin surface to carry heavy loads at large spans. Their potentialities achieved by exceptionally load-carrying behavior due to their curvatures with a pure membrane state, which is maybe single curvature (cylindrical and conical), synclastic (dome-like), anticlastic (saddle-like) or free (experimental).

It is possible to enlarge the potentiality domain by integration between the two methods: space frame and surfaces, producing a *space-framed surface.* Different ways of combining are possible, for example, space-framed surface which is produced by triangles mesh, varies in shape and size, according to free-form geometry. Then, the mesh is stiffened by increasing geometrical moment of inertia through enlarging the cross-section, Figure 5. Table 1 summarizes the comparison between the two methods: using extra materials and changing the geometry.

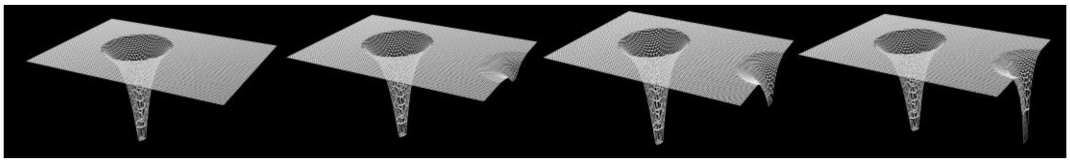

Figure 5. Space-framed surfaces as a combination of the two methods.

Table 1. Comparison between using extra materials and changing the geometry.

Method	Structure	Prototype	Origination	Action
Using extra materials	- Space frames - Vector-active structure systems - Triangulation	- Triangular truss, trussed beam.	- Components of the integral object genesis - Autogenously performance. - One process route subdivided into general operational stages	- Compression or/and tension - Forces redirection is subjected by the direction of structural components (vectors). - Control of flow forces completed by segmental components down to discharge.
Changing the geometry	- Surfaces - Surface-active structure systems - Surface shape	- Plate, folded slab, cylindrical shell	- Separate process subjected to the design of functional form. - Autogenously, performance. - One process route subdivided into specific operational stages	- Membrane stresses - Forces redirection subjected to principles of mechanical physics. - Control of flow forces completed in monolithic object down to discharge.

5 CASE STUDY: BMW WORLD AND MUSEUM, MUNICH, GERMANY 2016

According to analytical descriptive methodology, this project has been chosen for architectural potentiality achieved by the integration of both methods. Spectacular double twisted cone, which supports 180 m length of free-floating roof in the corner, *presented the method of changing the geometry*. Besides, the double layers of twisted cone, which connected by diagonal single beam and every layer consists of variable quadrilateral mesh, and the floating roof from steel space frame *presented the method of using extra materials* that tends to produce fully three-dimensional mass, Figure 6.

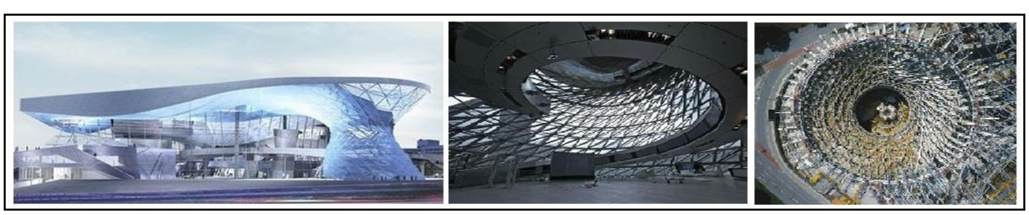

Figure 6. BMW world and museum, Munich, Germany, shows the integration between the two methods.

Table 2 illustrates the integration between the two methods that are used in BMW world and museum, Munich, Germany 2016, depending on analytical descriptive methodology. So, we can conclude from Table 2 that architectural potentialities can be expanded by using space framed -modified- surfaces (twisted, folded, etc.) with cooperation of vector with surface through the principle of triangular segmentations.

Table 2. The integration between the two methods that are used in the project of BMW world and museum, Munich, Germany 2016.

Method	Structure	Prototype	Origination	Action
Integration between using extra materials and changing the geometry	- Space-framed surfaces - Specific vector-active structure systems generates Surface-active structure systems - (fixed numbers and location of nodes with variable beams length)	- Triangular truss, trussed beam. - Free-form segmented plates according to trusses	- Components of the integral object genesis - Autogenously performance. - Several process route collected into general operational stages	- Double twisted cone supports 180 m length of free-floating roof at the corner. - Membrane stresses converted to compression and tension. - Forces redirection is subjected by the direction of structural components (vectors). - Control of flow forces completed by segmental components down to discharge.

6 CONCLUSION

This paper is an attempt to discover and highlight the architectural potentiality of free-form structures through form-finding possibilities to have the sculptural eye-catching. It depends on using extra materials, changing the geometry, or integration between them. This can be achieved by meshed layer and changed geometrical layer which consists of grid-shell with pyramidal, quadrilateral, pentagonal or more units to result in fully three-dimensional masses of architecture.

Mechanisms of redirecting forces, with their possibilities, represent the basic requisite for developing new 'form' of forces, and they are the basis for systematics in architectural structures.

References

Adriaenssens, S., Block P., Veenendaal, D., and Williams, C., *Shell Structures for Architecture, Form-Finding and Optimization*, Routledge Press, London and New York, 2014.

Agkathidis, A., *Generative Design*, Laurence King Publishing Ltd, London, United Kingdom, 2015.

Goldsmith, N. S., and Ap, F. L., *Shape Finding or Form Finding?,* Symposium Shells, Membranes and Spatial Structures: Footprints, IASS-SLTE, Brasilia, Brazil Reyolando M.L.R.F. BRASIL and Ruy M.O. Pauletti (eds.). September 15-19, 2014.

Merriam-Webster Dictionary, *Merriam-Webster, Incorporated*, Merriam-Webster since 1828. Retrieved from https://www.merriam-webster.com/dictionary/potential on August 3, 2019.

ThoughtCo, *The Meaning of 'Form Follows Function', The Famous Architectural Phrase Said Design Should Reflect Activities,* Visiual Arts/ Architecture. Retrieved from https://www.thoughtco.com/form-follows-function-177237 on July 5, 2019.

Wikipedia, *Potentiality and Actuality*, wikipedia.org, Retrieved from https://en.wikipedia.org/wiki/Potentiality_and_actuality on June 28, 2019.

Winslow, P., Pellegrino, S., and Sharma, S. B, *Multi-Objective Optimization of Free-Form Grid Structures*, Structural and Multidisciplinary Optimization, Springer-Verlag, February, 2009.