Understanding Architectural Structures Through the Relation of Process To Product: A Critical Comparison of Works by Santiago Calatrava, Pier Luigi Nervi and Frei Otto.

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Abstract: **Structure acts as an ensemble in transferring forces where the components are in a constant congruence with the whole. This paper analyses the implication of 'whole to part' principle from conceptual to constructed design by comparing the works of Santiago Calatrava, Pier Luigi Nervi and Frei Otto. Portraying the dialogue of whole and parts in realizing architectural structures in accordance with the design process and product, exhibits the spatial contribution of structures to the architectural realm. The translation of a space enclosing architecture to a space dominating architecture through exposed structures weaves a common thread in the comparative study. The study concludes by exposing the role of structures in creating places as well as memories of places by influencing space.**

Keywords—Architectural structure;Whole;Part;space;place;Process;Product

I. INTRODUCTION:

A brimful understanding of structure demands knowledge not only about how the structure is designed and constructed but also about it's working and visual experience. Such a comprehensive awareness leads to a pleasurable experience of perceiving structures [1]. A perception of such magnitude includes consideration of both mechanical and spatial concerns about the structure. The Webster meaning of the word structure explains the nature of an edifice which is constituted by the arrangement and relations between parts. According to Daniel Schodek, a Harvard professor, structure is 'a physical entity having a unitary character that can be conceived of as an organization of positioned constituent elements in space in which the character of the whole dominates the interrelationship of the parts' [2]. The description of the principle of parts working together for the realization of whole can be exploited well enough in order to explain the spatial contribution of structures to the realm of architecture. Considering such an approach can also unfold the symbolic application of structures. Thus 'structures influencing and influenced by architectural space' [3] can be well explained and experienced. An approach to explain structure by considering the application potential of Gestalt principle in a situation where the structure is devised to a space enclosing architecture and thus becomes relevant to understanding structures. As the space enclosure in itself is a way of conceiving three dimensional spaces, the wholeness character suits perfectly in relating structure to space. 'Appreciation of structures also requires knowledge of buildings and how they are constructed' [8].The realization from concept to construction thus proves to be vital and requires an in-depth knowledge in proportioning constituent elements to mould a complete structure. The 'detailing' from whole to parts gives individual identity to the structures and expose the creative capability of the designer. Thus the whole to part approach devised by the Nervi, Otto and Calatrava in their respective spectrum of works sheds valuable implication in discovering a common design dialogue among them, which in turn lifts their oeuvre to a different level of understanding.

A. The concept of "whole to part"

The growth stages of embryos (Fig. 1) depict the concept of 'whole to part' approach. Embryo from the first stage portrays completeness but it acquires more clarity through detailing undertaken in subsequent stages. It is possible to trace the original and final product from both ends. In the final product, each part posses its own individual character but depicts complete sense when working as a unified entity. Here 'the character of the whole dominates the interrelationship of the parts' [2].

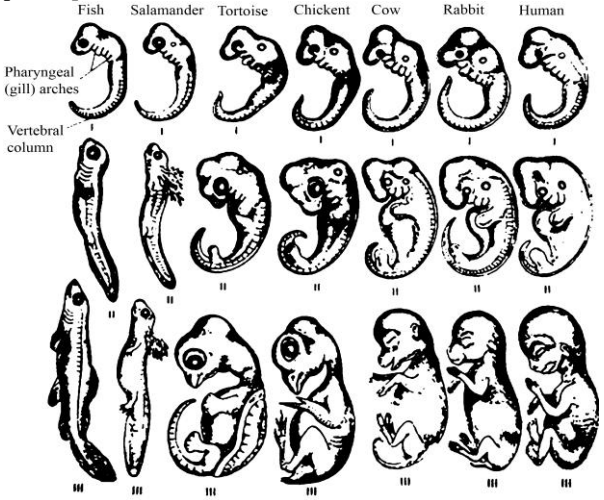


Fig. 1. Ernest Haeckel Embryos, 1870. Haeckel's classic illustration of different vertebrate embryos at comparable stages of development [4].

II. THE DESIGN PROCESS:FROM CONCEPTUAL TO FINALIZATION OF THE DESIGN.

In the course of comparing the work culture of Santiago Calatrava, Pier Luigi Nervi and Frei Otto by investigating the nature of design process they employed, the application of whole to part principle in finalizing their structural form is witnessed. All the three architects used to conceive their designs three dimensionally from the very scratch of the design process. This approach encompassed the entire structural form as an ensemble where the structural components where resolved through structural detailing.

TABLE I. DIAGRAMATIC REPRESENTATION OF THE COMPARISON OF THE DESIGN PROCESS OF THE THREE ARCHITECTS

	Santiago Calatrava	Pier Luigi Nervi	Frei Otto
1	Sketches Sculptural models	Subconcious conception of the entire form	Form-Finding Methods using Physical models
	Conceiving the "whole" by encompassing the space		
2	Physical project models	Small scale and Large scale prototypes	Form study using physical models
3	Computer aided design analysis	Manual calculation and analysis	Computer aided design analysis
	Devising the "whole" by dimensioning the parts		

III. THE DESIGN PRODUCT : IMPLEMENTING DESIGN BY THE FORMULATION OF PARTS FROM THE PRE-CONCEIVED WHOLE

The realization of the surface enclosure which defines and encompasses the space to be confined is deployed using detailing the surface. The surface form dictated by the spatial form is carved into a structural form employing structural detailing. "Etymologically, the word detail consists of two parts: the last –tail in this context means 'to cut something to size' in order to delimit something. This is actually what tailor does.De-tail hence means "to cut off", to separate or isolate from a large piece of work" [5].The best possible way of disintegrating a surface into discrete elements is to subdivide the surface. The subdivided surface needs to be connected to each other. The process of assembly comes to the scene in such a scenario. The subdivided structure can itself undergo further subdivision for the ease of construction, until the practical issues of manufacturing comes to play. This sort of subdivision of surface followed by assembling the discrete elements can be done explicitly by adopting the method of prefabrication. The voyage from a unified surface to subdivided surfaces follow a surface to line approach of realizing the whole from the assembly of parts.

The discrete elements in most cases form structural components or members which are usually made as prefabricated members. In such cases, these members perform as the 'parts' of the entire system. This creates a unified structure assembled by the aggregation of the aforementioned 'parts' (structural members) forming rhythm and unity inviting the context of architectural appreciation. The structural members formed of prefabrication can initially form primary structural units and these units can be also aggregated to achieve the unified whole. The entire structure can thus be traced back from a single structural unit/member or vice-versa. The bond between design and construction is simplified and reinforced by 'implying the inductive connection between parts and whole' [9].

TABLE II. DIAGRAMATIC REPRESENTATION OF THE WHOLE TO PART METHOD BY SUBDIVIDING THE SURFACE

Surface Enclosure	Detailing	Surface Subdivision
Whole	To	Part

TABLE III. DIAGRAMATIC REPRESENTATION OF THE WHOLE TO PART METHOD BY SUBDIVIDING THE SURFACE

Surface Subdivision	Assembly	Prefabrication
Surface to Line Configuration		Aggregation of Structural components/Units

TABLE IV. DIAGRAMATIC REPRESENTATION OF THE PARTS TO WHOLE BY REPEATING STRUCTURAL UNITS/COMPONENTS

Repetition/Aggregation of structural components /units	Prefabricated Precast	Realisation of the edifice as an ensemblage
Part		Whole

IV. CASE STUDY:UNDERSTANDING THE OLYMPIC STADIUM DESIGNS BY SANTIAGO CALATARAVA,PIER LUIGI NERVI AND FREI OTTO IN ACCORDANCE WITH THE RELATION OF PROCESS AND PRODUCT

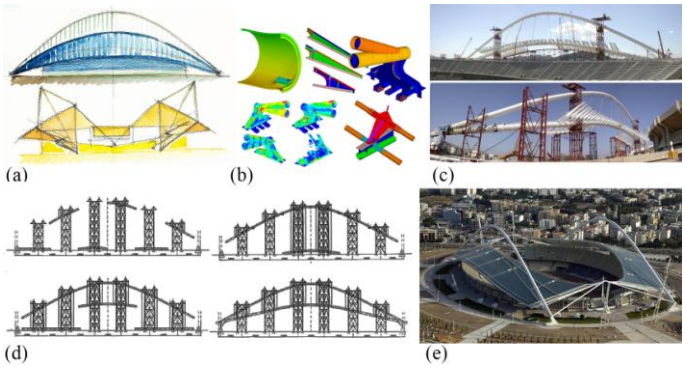


Fig. 2 .Illustrating different stages of Santiago Calatrava's Athens Olympic stadium roof design from conceptual to construction stage.

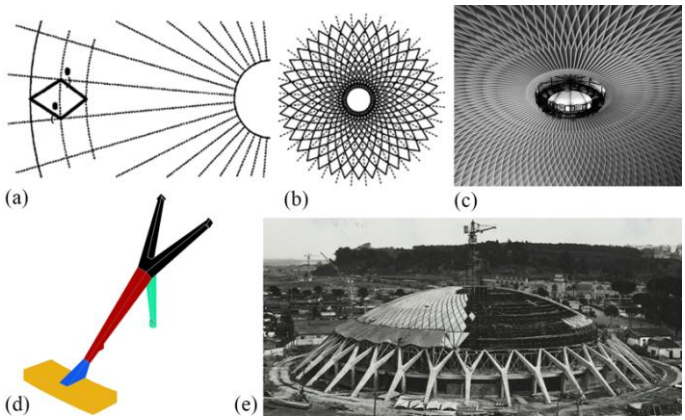


Fig. 3. Illustrating Pier Luigi Nervi's Small sports palace for Rome Olympics in accordance with the relation of process and product

Structures within the same building typology are selected in understanding the relation of process and product in regard of the built works of the three architects. Hence Athens Olympic (2004) stadium roof design, Rome Olympic (1960) stadium design and Munich Olympic (1972) stadium roof design are considered for Santiago Calatrava, Pier Luigi Nervi and Frei Otto respectively.

The Fig. 1 depicts the work culture of Santiago Calatrava in realizing a built work.Fig.1 (a) demonstrates the initial sketches done by Calatrava in conceiving the design.Idealisation of form was done using CAD(computer aided design) where the detailing as per the sketches, matched the construction requirements. Fig. 1 (b) shows detailing done in refining structural components. Most of these structural components especially the array of purlin as shown in fig. 1 (c), is repeated along the surface enclosure as per the finalized design. Demonstration of parts in formulating the 'whole', continuing to the construction stage of a design is visible from the fig. 1 (d).The roof surface was encompassed with polycarbonate sheets of 5meter long and 1 meter wide assembled together forming a single enclosure[fig. 1 (e)].

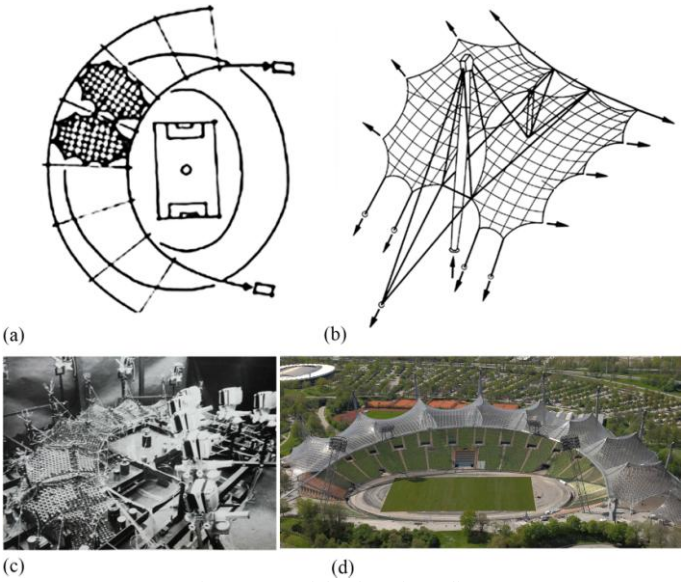


Fig. 4. Illustrating Frei Otto's Munich Olympic stadium design in accordance with the relation of process and product

Pier Luigi Nervi had a tradition of continuing his design ideas from design stage to construction site being a pioneer in precast construction with ferrocement.Palazetto Dello Sport designed for Rome Olympics witnessed his creative implication of realizing a domical structure by providing distinctive design gesture to domical surface as well as the end supports.Fig.2 (a), (b) and (c) portrays the realization of domical surface enclosure of the stadium. Diamond shaped precast ribs [fig. 2 (a)] was repeated about the center based on an inscribed angle and finally a series of spirals were defined on the surface enclosure as shown in fig. 1 (b) and(c).In this case the precast diamond shaped ribs facilitated the role of 'parts' in realizing the 'whole' which is the domical surface itself. In the case of end supports, the design followed the line of thrust of arch from the cross-section of the dome ending in slanting y-shaped supports. The slanting support itself is fabricated from several parts as distinguished by color coding in the fig.2 (d).The Supports thus obtained is repeated along the periphery of the domical surface in completing the edifice as demonstrated in fig. 2 (e).

Frei Otto demonstrated the employment of experimental research in obtaining minimal surface with light weight character in realizing surface enclosures in the Munich Olympic stadium roof design. An initial soap film model was employed to find an ideal form deploying his form finding experiments. It was followed by a demonstration model in tulle as well as a measurement model of wire assigned with weights as shown in fig. 3 (c).The implementation of the design witnessed another approach in which Otto subdivided the surface to be covered into 8 different parts [fig. 3 (a)].A primary structural unit as illustrated in fig.3 (b) was formulated and got repeated as per the subdivided portions. The structural unit itself was an ensemble made of prefabricated units assembled at site. The final entity as shown in fig.3 (d) thus depicts a structure constituted by the arrangement of parts in a specific composition where the character of the whole (stadium roof enclosure) portrays a dominant gesture.

V. CONCLUSION

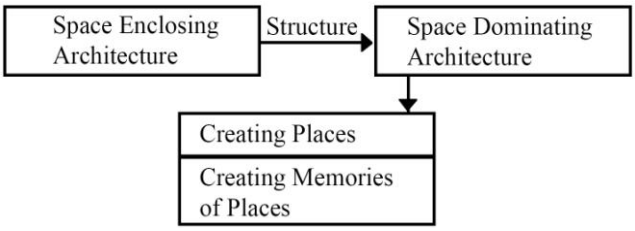
The Process to product transformation as well as procedure, with respect to the three architects, shows explicit connection to the principle of 'Whole to part' process. The techniques like prefabrication and precasting enable the provision for sub-division and the followed assemblage of units or members. The consideration of constructability as a design strategy is a remarkable feature that can be witnessed in understanding the structures designed by these three architects. Such an approach made them pioneers in designing expressive structures while enjoying their own personal freedom and satisfaction.

A. Space to Place through structures

The space covering gives an inherent geometry to the structure and in such cases the structural clarity and geometric purity may cohere. Thus the structure becomes architecture inside out creating 'architectural structures' [7].This can lift the space in and around the structure to a noticeable level where the notions of space becoming a place can be experienced. The relation of space and structure in consideration with the concept of 'whole

to part', witness the structural enclosure getting translated to a level where structure dominates the space. A dominant structure thus creates place by uplifting its surroundings to a vibrant atmosphere. Other than performing the functions of structural stability and space enclosure, structures can be employed with 'meaning, purpose or intention' [6]. Structures which perform space enclosing function are capable to depict a dual function by attaching meaning to a space thereby enriching the enclosure. Structures deploy provisions that can be employed to create not only places but also the memories of places by injecting the representational and symbolic qualities. The outcome of the interrelation of process and product maintaining the 'whole to part' concept in accordance with the enclosed space, figures space both as an identifier of Place as well as a definer of place. The following diagram concludes the relation of space and structure in expressing architectural qualities.

TABLE V. DIAGRAMATIC REPRESENTATION OF STRUCURE CREATING PLACES AS WELL AS MEMORIES OF PLACES.



The representational qualities of Santiago Calatrava's design arouse from his alliance to the zoomorphic and anthropomorphic references through his sketches. The conceptual phase of Athens Olympic stadium went through a series of sketches depicting postures of human movement which Calatrava abstractly portrayed in the surface envelope of the stadium roof. Pier Luigi Nervi believed in structural clarity which illustrated the force flow perceivable to even common man through exposed structures. Such clarity in demonstrating the working of structures through theatrical poses made of structure stimulates visualizing abstract forms for the observer. A remarkable example is the edge supports in Palazetto Dello Sport, Rome where the slanting supports postulate posture of a human pushing or holding the domical surface. Frei Otto was fascinated by nature and its structural makeup and was very keen in studying about the spider web creations. The principle of maximum span with minimum materials emulated spider web like tensile creations with membrane and cable net in the works of Frei Otto. The following diagram concludes the outcome of the critical comparison.

TABLE VI. DIAGRAMATIC REPRESENTATION OF COMPARING THE THREE ARCHITECTS IN RELATION WITH SPACE AND PLACE.

Structure	Santiago Calatrava	Pier Luigi Nervi	Frei Otto
Dominating Quality	Identifying a Place	Identifying a Place	Identifying a Place
Representational Quality	Creating memories of Places	Creating memories of Places	Creating memories of Places

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