THE PROBLEMATIZING OF STRUCTURAL SYSTEM DESIGN IN DIGITAL ARCHITECTURAL DESIGN PROCESS: "A NEW RELATION BETWEEN FORM AND STRUCTURE"

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ABSTRACT

In contemporary architecture, digital architectural design goes beyond the scope of designing. Design and production converges into a unique process in digital medium. Structural design becomes an architectural design problem in that unique process rather than being an engineering problem.
In digital architectural design, it is possible to define the design process as form based. Computer aided design allows architects to derive and transform wide range of forms. Complex, irregular, indeterminate, limitless forms become the representatives of the contemporary zeitgeist for architects. However, form based approach brings forth problems in relation to constructability. There is exactly a problem of designing and fabricating structural systems of complex and free forms in architectural design processes. Thus, the new approaches are developed for form-structure relationship to overcome the constructability problem.
In this context, the main aim of this paper is to realize the questioning of form-structure relationship and reveal the problematizing of structural design in digital architectural designs processes. Therefore, this study explains the realization (designing, manufacturing, constructing) of "architectural designs/forms" that are produced in digital medium. It presents the new kinds of relationships between design process and construction process through three cases which exemplifies three different approaches. Each case is discussed in the design process -from conceptual thinking to fabrication- focusing on the type of the relationship between form and structure.

Key words : Digital architectural design, Structural design, Form-structure relationship, Constructability

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1. INTRODUCTION: FORM BASED ARCHITECTURAL DESIGN PROCESS

With development of digital technologies, significant differentiations occur in architectural design processes. Design with its all sub-processes take place in digital medium. Computers become the digital design mediums rather than being used as design tools. Design becomes a computational process; therefore, digital knowledge becomes the background for computer aided design which is based on mathematical equations and parametric relations. Software programs such as Alias, Softimage, Maya, Rhino and Mudbox from industries like automotive industry, aircraft industry and movie industry are used "to introduce new formal vocabularies into the discipline of architecture" (Lynn and Gage 2010). In these changes over architectural design process, it is seen that architects go towards and focus on form based design processes. A design approach is in question where main concern is generally form production. Models that architects use as biological models, motion and force based models, performance based models, parametric models and evolution based models provide directly to intervene in the final product. In contemporary architectural discourses, the process of form creation is expressed as "generation of form", "exploration into new forms", "a new approach to form", "finding of form", "derivation of form" and "potential in new forms". In this context, either for defining and controlling the design processes or identifying the new forms, prevalent concepts change. Architects use the concepts of irregularity, deformability, continuity, transformability, emergence, indeterminacy, adaptability, dynamism, interactivity and variation to define a different design process and new forms. Such a form-based interest is clearly expressed in architect Steve Hatzellis's article of "Formal Complexity in Digital Architecture" in 2006. He asserts that; "digital architecture is an area of design that is leading exploration into new forms of non-standard architecture" (Hatzellis 2006).
Researchers Francesco de Luca and Marco Nardini focus on "generation of form" in their researches and see digital architectural design as "a new approach to form" (Luca and Nardini 2002). Form concern in Bernhard Franken's discourse can be read as "form generation" (Franken 2003), whereas "finding of form" is the approach of Branko Kolarevic for a form based design process (Kolarevic 2000).
Usage of the concepts such as complexity, interactivity, emergence, transformability and variability in project descriptions indicate the group of Zaha Hadid Architects' focus on formal concerns (Patrik Schumacher 2012). Greg Lynn's definition of "animate form" also indicates "form generation" (Lynn 1999).

2. CONSTRUCTABILITY OF FORM

As digital architectural design focuses on "form generation", constructability of these digitally computed, designed and represented forms becomes a crucial problem. Bagneris focuses on the constructability problem in his article of "Structural Morphology Issues in Conceptual Design of Double Curved Systems" in 2008. He states that; "the flexible forms are mainly characterized by portions of

double-curved surfaces. But this is only their formal aspect and is only a geometrical characterization. Problems occur when the mechanical behavior, and moreover, technological solutions have to be handled. Engineers have to solve difficult problems, which can end in nightmares" (Bagneris et al. 2008). Constructability problem necessitates examining the place of structural design within architectural design. Therefore, the problematizing of structural design in digitally driven processes is questioned in this paper in order to find out the response of structural design to the changing environment of computational "form generation." In addition, the relationship of architectural design and structural design is questioned from a viewpoint based on structure. The main of aim of this paper is to realize this questioning and reveal the different approaches which define new relationships between form generation processes and structural system solutions.

In this paper, literature review is done over digital architectural design for answering the questions of how structural design turns into a problem in digitally driven processes which start with constitution of design idea and end with construction. The problem is examined over three different main approaches to form-structure relationship. For studying these three different approaches, case study research is done. For every approach one case study is examined. Therefore, three case studies are selected from digitally designed and realized buildings because of the discussed problem of constructability. Every case is investigated over its general view, design phase, structural system and manufacturing. In addition, architects' discourses and projects and the relationship between them are also examined for understanding the design processes. Architects' firsthand statements are taken as primary source for the paper.

2.1. Relation between Form Based Architectural Design Process and Structural Design

Different approaches to form-structure relationship in digital architectural design process can be collected under three main topics. First approach is the composite approach where digital architectural design is seen as the integration of structural design and architectural design. All processes from constitution of design idea to construction such as form generation, structural design, and materiality integrate and converge in a common platform that is the digital medium. In addition to design of the form of the buildings, structural system and materialization decisions are also given using digital design processes. Computer aided design enables to think about form, aesthetic, structure, and material at the same time on the same model during the computational processes. Models, tools and concepts that are valid for architectural design are also applicable to structural design. Different disciplines such as engineering and architecture do not need to use different programs for architectural design and structural design. There is a unique process and it continues by articulation of the processes. Hierarchical nature of design where disciplines are specialized and completed in themselves is demolished. In his article titled "Mimarlıkta Değişmekte Olan Ne? Biçim Bilgisinden Süreç Bilgisine", Uğur Tanyeli gives the example of Walt Disney Concert Hall of Frank O. Gehry in Los Angeles where aeronautical software CATIA was used in every phase of the project as the only design medium. Design process acted as a unique process where all the

project participants worked in their area of responsibility in relation with each other from form design to construction by using the same software (Tanyeli 2012).
The integrated model in digital architectural design is called as Building Information Modeling (BIM). Architect Jon Pittman describes BIM in his article titled "Building Information Modeling: Current Challenges and Future Directions" as; "a model that takes into account performance characteristics, cost and other issues related to the construction and operation of a building, as well as its design" (Pittman 2003). BIM collects all the useful data throughout the entire design, construction and maintenance processes and provides the opportunity to present the necessary information when it is needed. BIM is accessible by all project participants from designers to manufacturers and tradespeople via online databases such as project websites (Pittman 2003). If any participant makes a change on the model, all the other participants are informed with this change with the updates in the program.
The new understanding of architecture, where there is an integrated development of form design, structural design, materiality, fabrication and construction, actually is not a new approach. Computer scientist Fabian Scheurer argues that this integration of knowledge of different processes has always been the lodestar of every good design (Scheurer 2010). However, digital architectural design's difference is the integration of all different kind of knowledge in the computational design process.
For keeping the integration between architectural design and structural design, some specialized techniques are needed. Software programs such as MoSS and GENR8 by Peter Testa and Devyn Weiser from the Emergent Design Group (EDG) incorporate structural design with material qualities and form generation during computational processes. With the availability of entering different parameters such as geometrical definition of the form, dimensions of the structural system and material quality, a complex contemporary design approach can be assisted. The programming languages of MoSS and GENR8 integrate "knowledge and awareness of structural forms and material qualities along with aesthetics and computational processes" (Testa and Weiser 2002). These two programs can be used in conjunction with AliasWavefront Studio and Maya platforms (Testa and Weiser 2002).
Designing a form and then designing a structural system just for supporting the form is meaningless and problems occur when technological systems have to be solved. Form and structural design should be thought together such as using the folds and contours of the form for its constructability_(Balmond 2002). Alejandro Zaera Polo also supports the integration of form and structural design processes, and he argues that construction should be taken into consideration before the construction phase (Zaera Polo 2002).
Architect and civil engineer Wolf Mangelsdorf offers four design strategies, which are form-finding, simple mathematical geometry, free form and hybrid approach, in his article titled "Structuring strategies for complex geometries" in 2010. These strategies provide the integration of structure, architecture and fabrication. Therefore they overcome the challenge of solving the structural system after the design of form (Mangelsdorf 2010).
In second approach to the existence of structural design in digital design processes, structural design becomes the main concern. It controls the whole design process from the beginning of the constitution of the design idea by giving shape to the

overall form. Engineers such as Arup, Buro Happold and Kristina Shea apply this approach, where structural design drives the design of the form, in their studies. Shea also expresses in the article titled "Creating Synthesis Partners" in 2002 that; "rather than creating the form and then considering structural options, structure is now treated explicitly and drives the definition of the exterior and interior form" (Shea 2002). In this reversed process, Shea uses computational techniques like the program of eifForm for generating structural systems (Shea 2002).

Greg Lynn's Port Authority Gateway Competition project is an example to second approach. Design process is just a structural design process. Initially, the site was modeled and some geometrical particles were located. Particles were movable based on the attraction fields in the site. By superimposing the frozen moments of a period of time, curvilinear vectors were created from the particles and these vectors became the tubular beams of the structural system (Lynn, 1999).

In the third and last approach to the existence of structural design in digital architectural design, there is a linear process. Form is designed first, a suitable structural system is designed according to form design, and finally materiality decisions are made. In this approach, structural design, its analyses and optimizations are not allowed to make changes on form. There are two subcategories for this linear approach. In firstly one, there is an integration where structural design takes the shape of the skin like a surface structure. In second one, structural design and architectural design are separated from each other where skin of the building is supported by an independent structure.

It is possible to see form as the main concern in the projects of architects. For example Frank Gehry's Marta Herford Museum in Herford Germany is a product of linear design process. As form was designed firstly, structural engineers had difficulties in case of finding a suitable structural solution for carrying the form. Therefore, rather than taking the shape of skin, structural system was designed independently from the main form (Bagneris et al. 2008).

In the project of Saint Lazare metro station in Paris by Arte Charpentier & Associés, there is also a linear approach. Structural system was designed based on the geometrical logic of the free form of the metro station (Bagneris et al. 2008).

3. CASE STUDIES: UNDERSTANDING DIGITALLY STRUCTURAL SYSTEM DESIGN

3.1. Composite Relationship of Structural Design and Form Design: Kunsthaus Graz

Kunsthaus Graz of Peter Cook and Colin Fournier was first designed for a competition in Graz, Austria. As Graz was named as the European Culture Capital for the year of 2003, Kunsthaus was planned and designed as an art museum for representing the technological developments of the end of the 20st century (Szalapaj 2005). In addition to representing the technological developments, there were other criteria for the design of the main form such as complex geometry of the site, to establish the alien nature of the building and to make the building look cuddly and friendly (Cook and Fournier 2004).

The Kunsthaus Graz is an example for the first approach of integrated process to form-structure relationship. Structural design is allowed to make changes on the shape of the form during architectural design process. Although structural optimization and form generation feed each other and constitute the final shape in Kunsthaus project, main concern is the form generation. According to the architect Colin Fournier, the irregular form has a "blobby" character which is a suitable example for today's contemporary architecture zeitgeist. Starting architectural design with a sphere and deforming it according to site constraints and architect's formal desires give the building the "biomorphic appearance" like a living organism which adapts to its site for living. Structural system of the building also has an irregular and blobby character which comes from its abstraction from form. Therefore, what defines the form also defines the structural system.

During design process of the irregular form of Kunsthaus to competition, architects did not utilized CAD-CAM technologies. Form was not designed in a digital medium by using computational models based on scripting. Physical model of the project was also handmade. After winning the competition, they took advantage of digital technologies for the realization of the building. Rather than scanning the physical model in three-dimension for creating the digital version of it, they computationally created a 3D model from scratch relying on the design decisions. They began with the conceptual phase to form generation process with the collaboration of architects and engineers using Rhinoceros modeling program (Kloft 2006). Non-uniform rational B-splines (NURBS) were used for modeling the surface which are specialized curves with control points, weights and knots on it. By changing the location of control points, weights and knots; various curves, surfaces and finally forms can be created (Kolarevic 2000). Originating from the shape of a sphere, the irregular final shape of the building was created by positioning the location of the control points and therefore, deforming the sphere (Szalapaj 2005).

During design process, architectural design and structural design were integrated with each other. Based on structural design optimization considering "its geometrical stiffness, and to address some of the manufacturing issues," shape of the form was modified (Kloft 2005). For example, roundness of the roof was increased for improving the structural performance of the building (Chaszar, 2012). Civil engineer Harald Kloft as the project leader emphasizes this integration of form and structure in his article as; "the digital design model of the Kunsthaus was shaped in an iterative process to capture the design intent of the original scheme, optimize the form with regard to structural behavior, such as its geometrical stiffness, and to address manufacturing issues" (Kloft 2006).

Branko Kolarevic also emphasizes the role of structural system optimization over form generation in his book of "Architecture in the digital age – design and manufacturing" in 2003. He asserts that; "the original blobby shape of Peter Cook's and Colin Fournier's competition winning entry for the Kunsthaus in Graz, Austria was altered somewhat after the digital structural analysis, by consulting engineers Bollinger + Grohmann from Frankfurt, revealed that its structural performance could be improved with minor adjustments in the overall form" (Kolarevic 2003).

Having the width of 60 meters, structural system of Kunsthaus consists of the main load bearing structure and the surface structure. As the main load bearing structure,

there is a post and beam system with two exhibition levels. Lower exhibition level is made of solid steel framework. In addition there are concrete cores in the building for reinforcement which are also used for access and infrastructure (Szalapaj 2005). The surface of the building behaves as a shell structure which takes the shape of the doubly curved form. Tubular steel members form the surface structure by constituting a triangulated pattern. The surface structure also supports the skin where there are acrylic glass panels as covering materials (Kloft 2006). All the detailed design information is directly transferred from digital model to construction site and therefore produced with the help of computer aided manufacturing technology.

3.2. Structural Design as the Main Concern: Channel Tunnel Railway Terminal

The Channel Tunnel Railway Terminal of Nicholas Grimshaw and Partners in Waterloo, London is a railway station that Nicholas Grimshaw sees as a 21st century airport with all its accoutrement. Site constraints and Grimshaw's desire "to create a sense of wonderment" were taken as design criteria that shaped the building. Asymmetry of the roof structure as the most striking and elegant feature of the building came from the asymmetrical geometry of platforms and the location of one track. As one of the tracks is on the western edge of the site, roof height was needed to be higher at this point for trains to pass. Trains also approach to the terminal from this western side and for providing the passengers "a public showcase" of Westminister and the River Thames, Grimshaw's team decided to make this façade entirely glass. In addition, structure was set outside of the building over the cladding at West façade. East façade is the inverse of the west façade where structure is under the cladding of solid material (Moore and Powell 1993).

The Channel Tunnel Railway Terminal is an example for the second approach to form-structure relationship where main concern is the structural design rather than form generation. Structural system design is the architectural design itself. In Waterloo Terminal, site constraints are the input parameters as the design criteria. "Irregular", "curvilinear" and "asymmetrical" character of the final structure is the result of design inputs. The asymmetrical building structure is designed by parametric model which provides "variation" in width and size over structural system and its components.

Working as a canopy, design of the irregular roof structure of the Waterloo Railway Terminal was the focal point during design process. For designing the structure, digital technologies were used as Rowan Moore asserts; "the complex geometry of the roof structure was mastered using computer-assisted design" (Moore and Powell 1993). Parametric model was the design method for the structural design which was used starting from the constitution of the design idea to the construction phase. The characteristics of the site as the changing width of 35m to 48m, its narrowness and irregularity and the location of tracks were the design parameters. Initially an arch module was created from two bowstring trusses. The reason why arch was chosen was its perception of lightness and non-necessity for interior supports for crossing the span. Trusses in arches worked against the bending moments and compression forces that were the cause of the asymmetric structure of the arch. As the arches were asymmetrical, longer and shorter sides of these arches worked differently from

each other. Inside of the longer side worked for tension while inside of the shorter side worked for compression (Popovic and Tyas 2002).

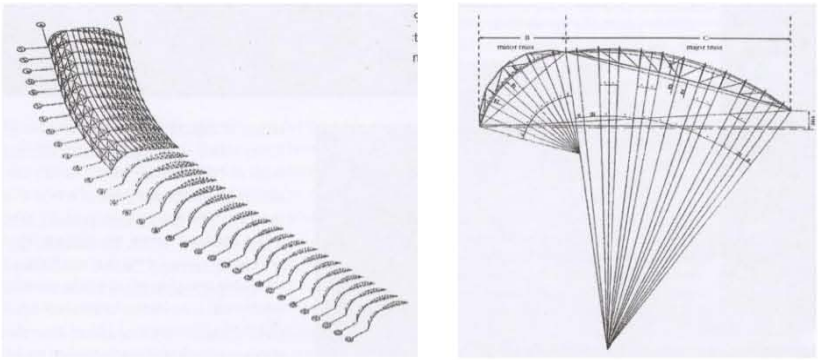

Figure 1a-b. Parametric design process (*Taken from 'Architecture in the Digital Age: design and manufacturing' Edited by Branko Kolarevic 2003)*

There are 36 different arches in the structure with different widths and curvature. Rather than designing every arch separately, a parametric model was created. By changing the value of the design parameters, all the other varieties of arches were created automatically based on the parametric equations. Therefore, different in span, position and curvature yet identical in topology; arches were created in a short time. Generated arches were located through the curvilinear site and constituted the main building. In addition to the configuration of the arches, joints between these arches were also designed with parametric model (Kolarevic 2003).
During design, where the span increased, the arches in the structural system became wider. For an arch to be wider, structural elements that constituted that arch also became longer. Briefly when an input parameter changed such as increase of the span, all the other related parameters such as structural element length were resized based on the parametric equations.
In detail, steel trusses that generate the arches have three pin connections on it. Two of them are for the ground connections of the structure and one of them is for the connection between the major and minor trusses. For these connection details mild-steel pin joints are used (Moore and Powell 1993).

3.3. Linear Design Process from Architectural Design to Structural Design: BMW Exhibition Pavilion Dynaform

The BMW exhibition pavilion Dynaform for the IAA 2001 by Bernhard Franken in association with ABB Architekten in Frankfurt, Germany was designed to host a car exhibition. Communication was an important criteria for the design. Main concern was to create a new spatial experience. Franken and his team developed a design method which included the usage of special-effects software from movie industry. They embraced an approach where "form follows force." Effects of the forces in the design medium reflected to design. Changes in form was realized and calculated by force field application. As Franken asserted that; "admittedly we cannot grasp forces

directly with our senses, but can only infer them through their effects" (Franken 2003), visitors could comprehend the forces that affected the design process by experiencing the space (Franken 2003).
The BMW exhibition pavilion Dynaform is an example for the third approach to form-structure relationship where structural system is designed after form generation process. In this project, main concern is the "digitally generated form" which is designed via motion and force based model. During design process, "virtual forces" in the "dynamic" design field are used for the "deformation" of the form. "Deformed" form, which "bends" and "twists," has an "irregular" character. After determination of the final geometry, structural system takes the shape of the "irregular" form.

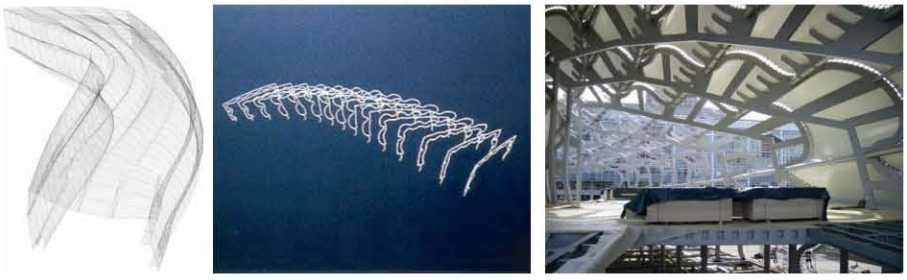

Figure 2a-b-c. Design process of Dynaform (© B+G Ingenieure Grohmann GmbH)

Motion and force based model was the design method for the generation of form. Initially, some basic rectangular structures were handled. During design process, these basic structures were deformed via the field forces by using force field simulations. The field forces were inputted into computational design process as design parameters and therefore, generated the final form. As the forces and the information in the design medium were recorded into the surface of the building, every curve and contour on the surface had a meaning. Final form was not arbitrary. The forces that were used for shaping the form were not only environmental forces such as wind, sun, gravity, pedestrian movement and car traffic. There were also conceptual forces which did not originate within the context itself (Franken 2003). They were created as a result of the acceleration of the space around the vehicles for creating the sensation of driving (Franken \ Architekten 2012). Computational design process continued until an architectural form was found. The found form was called the master geometry which was a single layer surface without any details such as thickness. Franken emphasizes the importance of master geometry by stating that; "the form arising from the force-field simulation process becomes the master geometry, which may not be changed manually in any way; otherwise, the forces of its creation would no longer be perceptible" (Franken 2003). In addition, during design and construction, master geometry was the dimensional reference for the project collaborators including engineers (Kloft 2005).
After generation of form and definition of the master geometry, Franken and his office collaborated with Bollinger + Grohmann Ingenieure for structural system solutions. They used finite element analyses program for analyzing the behavior of

the form as a shell structure, which was abstracted from the master geometry of the building. Structural design was not allowed to make changes on the geometry of the form as Franken asserts in his article titled "Real as Data" in 2003; "since the structural system must not change the form, the load bearing system is continually altered until a suitable system is found for the master geometry" (Franken 2003). After the studies over structural design via the collaboration between architects and engineers, fifteen cross sections were generated from the main form. Structural frames were then inscribed into these cross sections. Outer layer of structural frame was the abstraction of the master geometry which tracked the guidelines of the form. Inner layer was the reverse of the same master geometry. Finally, all planar sections were connected with welded plates for the stability throughout the building. For covering the structural system, pre-tensioned membrane layer was decided to be used as choice of material (Kloft 2005). With the help of CNC plasma cutting, the structural elements manufactured in factory and mounted on site (Franken 2003).

4. CONCLUSION

Form based architectural design process entails the interrogation of constructability problem of buildings. Constructability of digitally designed complex forms is directly related to structural design. Today, structural design gains a digital dimension. Therefore, new kinds of relation between architectural and structural design occur. The approaches that are presented in this paper define different types of relationships between form and structure that are designed in digital medium and constructed with the assistance of computer aided manufacturing.

The three types of relationships that are computationally created are searched by a structural point of view. Constructability of the free forms of the digital era is questioned by emphasizing the existence and place of structural design. By defining the new types of relationships, it is seen that digitally designed forms can be constructible at the same time.

It is possible to say that the second and the third approach do not define totally new approaches to form-structure relationship besides being designed in digital medium. The first approach which is the composite approach defines a new type of relationship considering contemporary approaches where there is a unique process. Hierarchical nature of design where disciplines work separately from each other is demolished. Models, tools and concepts that are used for form generation are also valid for structural design. All disciplines work on the same program in relation with each other (Tanyeli 2012).

Examining contemporary digital architectural production only within the context of "design process" is insufficient. Production process turns into a unique process starting from design to fabrication. So, in case of discussing the constructability of the designs, it is necessary to comprehend the structural design. Therefore, this paper examines the relationship between structural design and architectural design. It presents in which different ways digital structural design becomes a part of digital architectural design.

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