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STRÜKTÜREL MEMBRAN TASARIMINDA GEOMETRİ OPTİMİZASYON İLİŞKİSİ[1]

THE RELATIONSHIP BETWEEN GEOMETRY AND OPTIMIZATION IN STRUCTURAL MEMBRANE DESIGN

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Öz: Günümüz mimarisinde hafif strüktüre sahip ve diğer malzemelere göre ekonomik olan membranın oluşturduğu sistem, tekstil mimarisi, esnek mimari, taşınabilir mimari gibi kavramlarla tanımlanır. Bu kavramlarla birlikte doğada ayrıştıralabilir, dönüştürülebilir ve tekrar kullanılabilir ekolojik malzeme arayışları tasarım süreçlerine kaynak oluşturmaktadır. Bu süreçlerde kullanılan malzeme teknolojilerinde ulaşılan düzey, malzeme performanslarının üst seviyeye taşınması, tekstil kompozitlerinin artması; geniş açıklıklı sistemlerde, strüktürel membranların daha sık kullanılmasını sağlar. Strüktürel menbranlar daha hafif, daha ekonomik, kirlendiğinde değişebilen veya kendini temizleyebilen ve istenilen geometrik formu alabilen bir malzemedir. Taşıyıcı bir malzeme olarak membran; çelik, ahşap gibi taşıyıcı malzemelerin performansını arttırır ve birlikte bir strüktür oluştururlar. Böylece malzeme, tasarımın bir parametresi haline gelir. Membran yapılarda form, sistemin yük etkisi altında dengelenmesi ile bulunur. Bu çalışmada, geometrik modellerden zincir eğrisi (catenary) ve minimal yüzey (minimal surface); optimizasyon yöntemlerinden ise yük yoğunluğu (force density), dinamik rahatlama (dynamic relaxation) arasındaki ilişki değerlendirilecektir.

Anahtar Kelimeler: Strüktürel Tasarım, Membran, Topolojik Geometri, Zincir Eğrisi, Minimal Yüzeyler, Optimizasyon Metodları

Abstract: The system formed in today's architecture by the membrane material which has a light structure and is more affordable compared to other materials, is defined by qualities such as textile architecture, flexible architecture and portable architecture. Nevertheless, as a result of searches for a reusable, recyclable and resolvable material in the nature, new materials and construction systems are being created resources on design process. The achieved level in material technologies, moving material performances to upper levels and the increase in textile composites have enabled structural membranes to be used in long-span systems more frequently in this process. Structural membrane is lighter, more affordable, replaceable or self-cleaning material when it gets dirty, and it can easily take the desired geometrical shape. As a structural material of membrane; increases performances of steel, wood etc. and create whole structure together. Form finding in membrane structures, related with balanced under loads. In this study, relationship between geometric models (catenary, minimal surface) and optimization metods (force density, dynamic relaxation) will evualate.

Key Words: Structural Design, Structural Membrane, Topological Geometry, Catenary, Minimal Surfaces, Optimization Methods

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1. INTRODUCTION

The relationship between material and architecture has been transformed with the developing technology, and today, material has become a tool that is shaped with the designer who assigns its meaning and that gives aesthetics to the structure. As a result of searches for a reusable, recyclable and resolvable material in the nature, new materials and construction systems are being produced. These bring new tendencies to the architectural design, and forms find itself in various concepts such as contemporary, organic, ecological, alive, dynamic, flexible, adaptable, changeable, mobile, portable, smart architecture and digital architecture. These tendencies are driven by development and geometry of nature and the material in the nature, harmony between material and nature and the natural life in generation processes. There are signs of observable changes in the material design in places where borders between the natural and the produced one are being destroyed in consequence of manufacturing of cellular materials developed by self-organized process with reference to the nature.

The system formed by the membrane material which has a light structure and is more affordable compared to other materials, which is portable, flexible and changeable for interior and exterior space applications of today's architecture, is defined by qualities such as textile architecture, flexible architecture and portable architecture. It has become possible to use different mathematical models in design process through the computer-aided design technology which is being used in wider areas of use thanks to the close relationship between mathematics and different disciplines, including architecture, and to the developing technology. With the mathematical models, structural design has brought geometry and material parameters into foreground.

The achieved level in material technologies, moving material performances to upper levels and the increase in textile composites have enabled structural membranes to be used in long-span systems more frequently. Membrane is lighter, more affordable, replaceable or self-cleaning material when it gets dirty, and it can easily take the desired geometrical shape. Thanks to its flexible structure, membrane becomes a parameter of design process. Geometry enables surface mobility to be modeled in a more detailed and extensive way through the development of computer technologies. This ensures performing efficient panneling in wind, snow analyses and manufacturing process more easily according to the technical characteristics of the membrane material in surfaces having complicated geometry. During those analyzes, topological geometry reveals the relationship between equilibrium of forces and form. Topology allows forms to transform instead of their stable structure. Although the topological approach in architecture shows up as a new concept with the inclusion of computer into the design, the existing

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topology concept ensures wider expansions with the developing design understanding.

In relation to the geometry, optimization relies on simulation results. Besides, the problem is defined as the existence of continuous variables and the selection of separate components from catalogs and databases. As a result, the problem is not linear. Optimization is both the evaluation of draft designs and creating new designs. Thus, optimization includes both analyses (evaluation) and synthesis (creating new solutions). Creating new solutions depends on the optimization strategy. Forming those strategies determines the structure of relationship between information and geometry.

2. THE RELATIONSHIP BETWEEN MATERIAL and GEOMETRY

In architecture, material is one of the main components in forming texture and form of design. In terms of engineering, material is the main component in construction of the designed structure practically and economically by resisting against various loads (wind, water, earthquake, etc.). Material is identified with condition differences of the environment it forms and diversification of features in its structure as it incorporates environment at micro or macro scale. This special situation occurred on the material makes it difficult to clearly identify the material. This formation diversity gains a data field that is mysterious, deep and highly energetic and rich options for material architects and designers who want to standardize material characteristics and who want stability in performance. Thus, whether natural or artificial, material takes part in different topologies and each step of design from concepts' forming process to nanoscale with its new conditions that is noticed and with its whole potential (Gezer, 2012).

When we look at historical process, usage of material in structure has developed and diversified thanks to the development of technology. The reason for this is that people are in search of new life styles and new places, materials and systems supporting those life styles by desiring continuously to find the "new". The reason of people's search for the new is that the technological development meets people's request and needs. As a result, this affected people's search intensely together with the industrial revolution.

"Material design is among the areas we may expect to continue to be the subject of researches and designs. This situation will be observed more clearly when it is taken into consideration as parallel to the development of digital manufacturing. Digital manufacturing provides developing a digital sensitivity by recreating the bond that weakened due to information technologies between the physical and the virtual and by researching form, material and structure processes through completely new ways." (Dritsas, 2012, 44)

Developments of tools providing opportunity to follow up and observe today's environmen-

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tal concerns, developments in technology and generation in nature in a better way encouraged interdisciplinary joint studies. In the 21st century, studying relations between form, structure and material jointly and reflecting them to the architectural design enable architects to make more environmentally-friendly and more integrated designs.

2.1. Material of Membrane

For designs requiring long span, new, light membrane materials are used instead of heavy building materials. The first applications of tensioned membrane systems are the tents used by nomadic societies and that were easily set up and dismantled. Frei Otto, who studied on lightweight tensile and membrane structures, established an institution for development of membrane structures at Stuttgart University in the early 1960s. Munich Olympic Stadium was designed at this institution by Frei Otto (Figure 1). Design and analyses of much more complicated structures started to be made with today's technology.

Figure 1. Münich Olympic Stadium, Frei Otto

Source: Self-Organizational Architecture: Design Through Form-Finding Methods, Alison Jean Isaacs, May 2008, pg.14

In membrane systems, tension elements can be manufactured at the thinnest profile possible under the impact of external load, because these elements do not work under pressure and bending. However, if they are tried to be tensioned, they would have a carrying feature. Therefore, membrane structures are lightweight, and long spans can be passed via skeleton systems as there is no bending problem. To pass through long spans, cables are used. As cables are flexible and bendable, it only works for tensioning. The difference between both structures is that cables are linear elements on one direction and the membrane is surface element on two directions (Figure 2).

Figure 2. The Millenium Dome, London, Richard Rogers

Manufacturing membrane cover materials from artificial or mineral fiber, making covers weaved from natural threads more resistant by covering artificial materials, manufacturing stainless cables with high-resistant quality steel, calculating

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and designing as parallel to the development of computer technology and development of technological and theoretical infrastructure in membrane cutting approaches has played an important role in development of membrane structure systems.

2.2. Types of Membrane

After the form is designed on membrane systems, various static analyses are performed according to the load combinations by taking into account the geographical conditions (prestressing -according to the material type-, snow effect, aspiration and pressure effects of wind and according to the wind effects coming from different directions) of the structure on the form. After all analyses are performed, membrane cover type is determined. (There are five types of membrane that are recognized in international community: Type I-800gr/m2, Type II-900 gr/m2, Type III- 1100 gr/m2, Type IV-1300 gr/m2, Type V-1400 gr/m2).

To avoid wrinkles, after completing installation in membrane forms, sheets consisting membrane cover should be removed by taking weft and warp direction of the cover into account and placing it as vertical to these directions. Structural membrane brings together the sheets consisting of upper cover, and "thermal resource" methods made through high frequency resource or special robot machines with speed and heat control are used.

Materials boiled in this way gain the property of acting as a single material and ensure necessary surface static continuity. As membrane materials are used in manufacturing of components limiting places, they should have characteristics that prevent the impacts of rain, snow, wind and ultraviolet beams of sun, that assist heat/sound insulation according to the conditions and that are resistant against fire. Products used as membrane are divided into two groups:

1. Plastic Foils

2. Weaved (woven) Membranes

- Membranes with organic fiber
- Membranes with synthetic fiber
- Mineral-origin membranes

Resistance of membrane materials are determined by testing its 5x30cm part in tensile and tear tests. Tensile and tear strength of plastic foils is lower compared to woven membranes. In terms of woven membranes, membranes produced from artificial threads are stronger. Woven membrane is separated in itself as without upper protection and as covered with materials such as PVC or Teflon. (Türkçü, 2003).

3. GEOMETRIC MODEL

Topology was derived from topos meaning surface and space, and logos meaning science in Ancient Greek, and studies geometrical shapes in maths and objects' characteristics which are not changed by transactions such as stretching and twisting. For example, a circle and an ellipse or a square and a rectangle are the same in

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sense of topology (Figure 3). Topology provides qualitative characteristics of geometrical shapes for us. Specific characteristics of these geometrical shapes change, but they do not lose their topological identities. Topology is the method defining information according to its relativity instead of its precision. Diagrams and drawings used in architecture reveals objects' topological characteristics, either directly or indirectly.

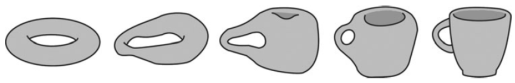

Figure 3. Topological Transformation From Donut To Mug [1]

"In defined geometry, geometrical shape of an object is defined first; on the other hand, in topological geometry, relational structures are defined depending on object's values such as side, corner and point number. In topology-based designs , it is important to make relational reasoning between shapes of stylistic compositions. After reasoning, producing many stylistic alternatives that is open to various transformations based on the same relational system makes a dynamic design possible." (Kolarevic, 2003)

It is the form of membrane surfaces and types of elements carrying the membrane. Membranes should have an anticlastic curve and transfer loads without being exposed to severe deformation of external loads such as snow and wind. As the curve of membrane surfaces increases, their carrying capacities increase as directly proportional. In tensile membrane structures, wind and snow loads are taken by membrane and carried to the carrier system with their nodal points, and from carrier systems, they are carried to floor.

3.1. Catenary

Catenary is a mathematical curve and consists of the shape tensed under its own weight and of which two ends are fixed. If it is reflected according to the X axis, it defines the load showing its own weight on the masonry arch. Parabola is an approach close to catenary. It has a simple formula by finding the points which has equal distance from a point and a line, and it can be built easily. Nicolas Fuss formed the last status of catenary in 1796 (Figure 4), (Burry, 2010).

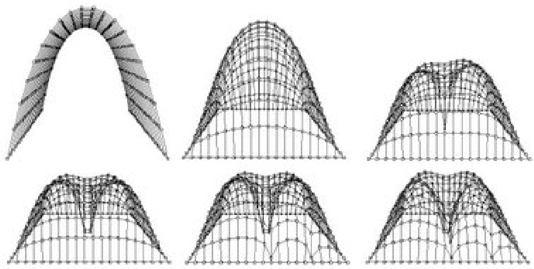

Figure 4. Catenary Models
Source: www. andjelkobt.blogspot. com/2009/02/catenaries.html

The form in calculation method of catenary is created by suspending and releasing the chain from two end points of a homogeneous rope with ideal weight (Figure 5). The bottom point

1 Source: www.rioranchomathcamp.com/Topology. asp

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is the peak point A. The part AP is on balance under the horizontal tension H in A. The tension F is directed through the tangent P and AP's weight is W.

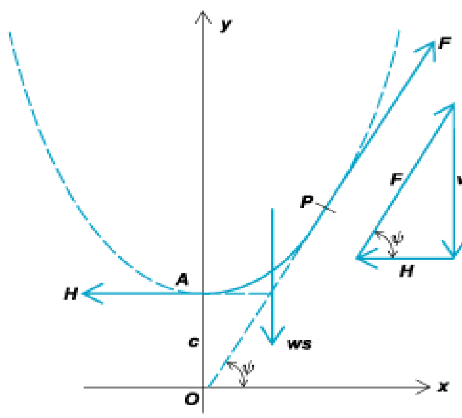

Figure 5. Graphics of Catenary [2]

In catenary model, the free form consists of the chain which is fixed from its two ends creates an independent spring when it is turned down. Free surfaces can be created by using this spring (Figure 6). This spring can be observed in many places such as energy cables and webs.

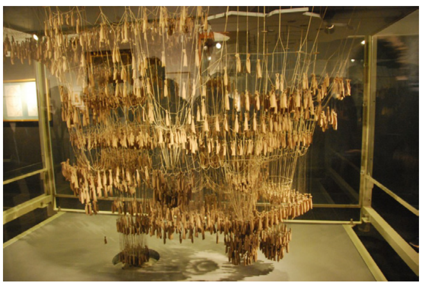

Figure 6. Gaudi, Sagrada Familia Physical Model [3]

In catenary model, it is important that how the structure geometry will be, the rope suspended by its two ends organizes itself by being released on its own weight without external impacts and it contains continuity topologically (Figure 7). If the section of soap bubble formed between two rings is taken, it becomes like this. In other words, if you turn the suspension bridge around the parallel moving axis, there becomes a soap bubble shape. Catenary constitutes the basis of structural models. Even if it is not widely used today, it has inspired the newly developed models (Kavurmacıoğlu, Arıdağ, 2013).

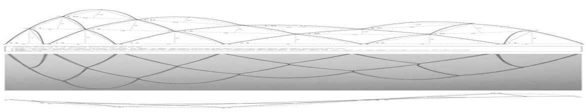

Figure.7. Fixed Chains [4]

According to the catenary research made in Ocean Design Research group, it was observed that mingled chains that were connected to each other were tensed in their environment. A mathematical curve was formed by reversing after the tensed chains gained a form with their own weight and hanging points (Figure 8).

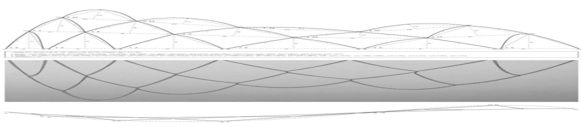

Figure.8. Reversed Fixed Chains [5]

2 Source: http://www.answers.com/topic/catenary
3 Source: www. followtheflammias.com/becoming-spanish-conquistadors-barcelona-spain/
4 Source: www.ocean-designresearch.net/index.php/design-mainmenu-39/architecture-mainmenu-40/nested-catenaries
5 Source: www.ocean-designresearch.net/index.php/

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These mathematical curves constitute the free form of the structure to be designed. The structure designed on the computer environment with this geometry was built at the research center. There is not a static or dynamic load on the structure built by mixing the famous brick and cement, and a structure which carries only its own weight is built (Figure 9).

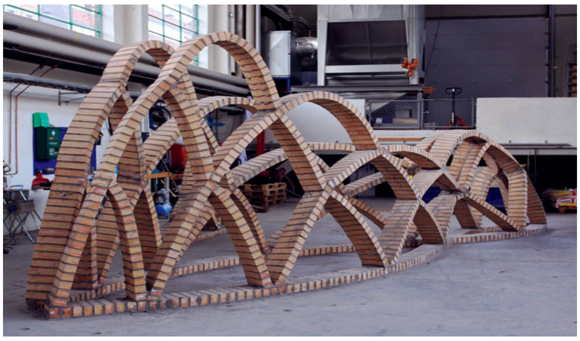

Figure.9. Catenary Model Built with Brick and Cement [6]

3.2. Minimal Surfaces

Technical explanation of minimal levels means bending of zero surface. Minimal surfaces are formed by oscillation of catenary bending around axes that has mutual equal full bending.

Surfaces formed by soap bubbles have a very important characteristic. These surfaces with minimum surface-tension potential energy are minimum in terms of area, too. Thus, the areas consisting of soap bubbles are called "minimal surfaces". Such an area in a closed frame always occupies a smaller place than the other places that may formed (Figure 10), (Polatöz, 2008).

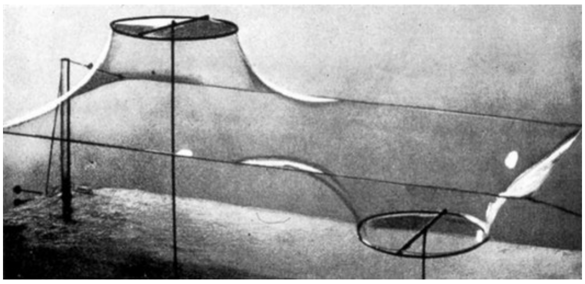

Figure.10. Experiment of Soap Film [7]

Munich Olympic Stadium, one of the first examples of minimal surfaces, is a design of Otto and Behnisch partnership with its ecological approach, visuality, practicality and transport planning (Figure 11). Contrary to traditional structures, tensile membrane structures are softer and lighter. Soft structures are built as tense and with curved geometry due to lack of hardness. The geometry of the surface balancing two counter bending is not Euclidian. The tension induced at space geometry ensures resistance and hardness together with the balance of the form created with pre-tensioning. The surface of tensile membrane structures has three dimensional hyperbolic geometries (Kavurmacıoğlu, Arıdağ, 2013).

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6 Source: http://www.ocean-designresearch.net/index.php/design-mainmenu-39/architecture-mainmenu-40/nested-catenaries

7 Source: www.archdaily.com/610531/frei-otto-and-the-importance-of-experimentation-in-architecture

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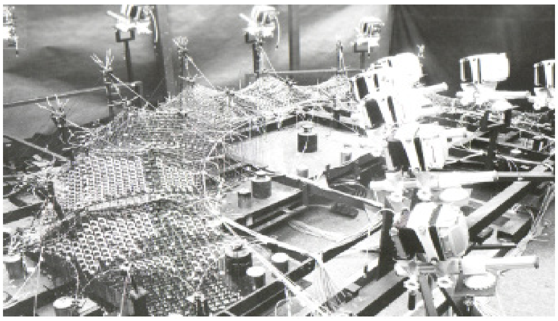

Figure 11. Physical Model of Munich Olympic Stadium [8]

While Frei Otto was studying the optimum shapes of roofs of Munich Olympic Stadium, he tested different wire mesh models by examining how span ranges of soap bubbles occur (Helmut and Raisch, 2012). The first numeric approach was developed while the stadium was being designed. This approach was based on tensile membrane cable systems at tense status that is called as load intensity method (Figure.12.) (Mouton, 2011).

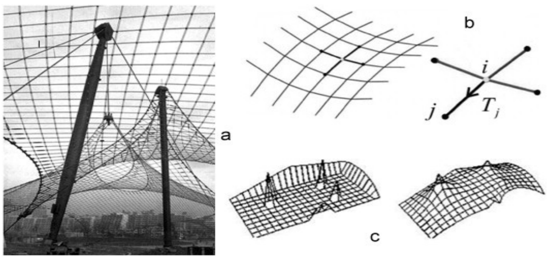

Figure 12. Munich Olympic Stadium Dijital Modelling and Analyze [9]

8 Source: Self-Organizational Architecture: Design Through Form-Finding Methods, Alison Jean Isaacs, May 2008, pg.14

9 Source : www.tensinet.com/database/viewProject/3779

4. OPTIMIZATION METHODS

Optimization means achieving the best, either by decreasing or increasing. Designs are made also by depending on algorithmic processes with computers in addition to traditional design methods. This process continuing on computer environment is defined as "digital process". The basic thought in optimization is to find a solution for a complicated problem by simplifying the problem. Since the main problem was simplified to a simpler problem, an approximate result is achieved rather than a precise result, but it is possible that this result can be improved by making extra effort so that precise result becomes very close. Evaluation is usually made via the target function which includes form of value and determines how well the draft design is. As for each optimization problem, forming the target function is very crucial for the results of optimization.

While tensile membrane structures diversify by the improvement of structural installations, the goal is to pass the biggest span with the lightest material and to form a design containing aesthetic criteria. As the membrane material develops, the system gets lighter with wider spans by taking into consideration the material's characteristic based on tensile strength and by reducing the load to cables.

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4.1. Dynamic Relaxation Method

It is a method of computer modeling for cable and fabric type structure to find their forms. The system oscillates at balanced position under the load impact. If false-dynamic process is simulated in time, repetitive process is obtained. In each repetition, the geometry (node positions) is renewed by using the second law of Newton in which strength is equal to mass and acceleration. Taking its integral twice means creating a relation between speed and geometry. Forces start to move in balance on each individual node. As a result, friction factor touches slightly on the surface by using each structural node through imaginary ropes to gather on the zero point from four neighboring points (Figure.14.), (Burry, 2010).

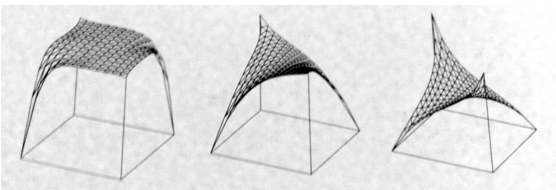

Figure 13. Dynamic Relaxation Process[10]

Dynamic relaxation is the digital net method settled in balance position with repetitive calculations by using membrane's flexibility and material characteristics, its limiting points and usual loads as a basis including finite element analysis.

4.2. Force Density Method

Load density method was developed to facilitate calculations of structures at Munich Olympic complex. The Method relies on assumption that the ratio between tension strength and the length of each rigid cable is based on the transformation of system's non-linear equations into some directly soluble linear equations. This method becomes the balance of cable net structure having different elasticity module under loading.

"Force density methos is one of the simplest algorithms devoloped for form finding. The principle that drives this method to convergence is the nodal force equilibrium. Every node is affected by its neigbour nodes, which subject this node to forces. In the appropriate geometry, the result of these forces equal to zero (Figure 14)" (Kara and Georgoulias,2012, pg:182).

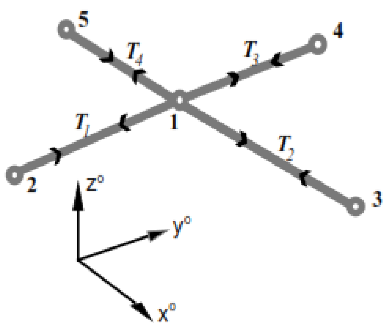

Figure 14. Force Density Method, Node Equilibrium [11]

10 Source: Burry J. (2010). The New Mathematics of Architecture

11 Source: Computational form-finding methods for fabric structures, W.J.Lewis, 2008 pg:11

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Especially the membrane systems, membrane's tension strengths and specially chosen control points under the external impacts applied by limiting membrane while creating form show self-organizing behaviors. Tensile forces are gathered at those points and transferred. As membrane gives shape to a form as a material, it is defined as displacements and pre-stressing forces at some certain limit points. Membrane form is determined with the balances of internal resistances and external forces (Hensel, 2006).

The program Wintess which is used in structural membrane design, analysis and cuttling uses load density method at analysis phase . Moreover, it analyses steel and membrane together, differently from other applications on the market. This method should be preferred for membrane structures more. Optimum profiles cannot be achieved by calculating steel of loads at limit points in another steel analysis program. Thus, Witness draws optimum conclusions from the analysis it made by considering elasticity modules of steel and membrane and maximum displacements.

5. CONCLUSION and SUGGESTIONS

The geometric models and optimization methods examined on this study tries to create physical balance between the forces that ensure structural pattern's remain standing and physical environment parameters such as material, airflow, sunlight, rain, snow. The geometric structure created on computer environment forms a model depending on performance by protecting its characteristic or reaching to a new pattern, in other words by self-organizing. Material selection is important for this performance.

With the discovery of new possibilities with structure basis that may create parameter for architectural design, other than creating ratio or form, mathematical architecture has turned into design processes in which many information can be processed as design parameter through computer simulations and that interdisciplinary information can be understood by engineers and architects together, and into structures such processes refers. Structural design, in other words designing carrying system as an extraordinary structure by carrying an aesthetic value, gives opportunity to the engineer think like an architect and to the architect think like an engineer.

Geometry in structural designs organizes itself and creates a pattern compared to dynamic parameters. The topological continuity of the pattern that arise ensures the structure remain standing. This continuity is achieved by revealing and optimizing time- and movement-based dynamic parameters' structures. Moreover, design thoughts such as sustainability, minimum material use, easy reproducibility and dismantling and installing and development of new materials such as polymer, membrane, etc. supported these new opportunities in structural design.

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Depending on technological progresses and developments in tools used for observing and learning forms in nature, new systems are being developed in architectural discipline to produce optimum solutions by learning from nature. New systems would be able to be developed by using form-structure-material of structures in nature with mathematics, computer technologies and methods as a tool and by increasing relations with other disciplines.

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