A RESEARCH ON A RECONFIGURABLE HYPAR STRUCTURE FOR ARCHITECTURAL APPLICATIONS

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ABSTRACT

A RESEARCH ON A RECONFIGURABLE HYPAR STRUCTURE FOR ARCHITECTURAL APPLICATIONS

Kinetic design strategy is a way to obtain remarkable applications in architecture. These kinetic designs can offer more advantages compared to conventional ones. Basic knowledge of different disciplines is necessary to generate kinetic designs. In other words, interdisciplinary studies are critical. Therefore, architect's knowledge must be wide-ranging in order to increase novel design approaches and applications.

The resulting rich hybrid products increase the potential of the disciplines individually. Research on kinetic structures shows that the majority of kinetic structures are deployable. However, deployable structures can only be transformed from a closed compact configuration to a predetermined expanded form.

The motivation of the present dissertation is generating a novel 2 DOF 8R reconfigurable structure which can meet different hyperbolic paraboloid surfaces for architectural applications. In order to obtain this novel structure; the integration between the mechanism science and architecture is essential. The term reconfigurable will be used in the present dissertation to describe deployable structures with various configurations. The novel reconfigurable design utilizes the overconstrained Bennett linkage and the production principals of ruled surfaces.

The dissertation begins with a brief summary of deployable structures to show their shortcomings and their lack of form flexibility. Afterward, curved surfaces, basic terms in mechanisms and overconstrained mechanisms were investigated. Finally, a proposed novel mechanism which is inspired from the basic design principles of Bennett linkage and the fundamentals of ruled surfaces are explained with the help of kinematic diagrams and models.

ÖZET

MİMARİ UYGULAMALAR İÇİN HAREKETLİ HİPERBOLİK PARABOLOİT STRÜKTÜRLER ÜZERİNE BİR ARAŞTIRMA

Mimarlar özgün tasarım yaklaşımlarını güçlendirebilmek adına diğer disiplinlerden gelecek bilgilere, yeniliklere açık olmalı bu bilgileri kendi tasarımları ile bütünleştirebilmelidirler. Bunun sonucunda ortaya çıkan hibrit ürünler, daha zengin olup, disiplinlerin ayrı ayrı sahip oldukları potansiyelleri artırmaktadır. Kinetik tasarım, mimaride özgün uygulamalar yaratmanın bir yoludur. Hareketli (kinetik) yapıların günümüz durağan yapılarına göre birçok avantajı vardır. Günümüzde var olan birçok durağan yapı değişen ihtiyaçlara cevap verememekte ve iklimsel değişikliklere adapte olamamaktadır. Hareketli yapı veya yapı bileşenleri mimarlığın değişen ihtiyaçlara adapte olabilme becerisini artırmaktadır. Bu tezin temel amacı; mimariyi bambaşka bir bilim dalı olan mekanik bilimi ile harmanlayarak, günümüz mimarlığının ihtiyaçlarını karşılayan hareketli, özgün bir yapı elemanı tasarlamaktır.

Dört çubuğun dört döner mafsalla bir araya getirilmesinden oluşan üç boyutlu Bennett mekanizması ve çizel yüzeylerin üretim yönteminden yararlanılarak yeni bir mekanizma geliştirilmiştir. Yeni mekanizmanın mafsal imalatı çok basit olup ve hareket kabiliyeti sınırsızdır. Ayrıca, yeni mekanizma istenilen her tür hiperbolit paraboloit biçimini alabilmektedir. Çalışmada; üretilen yeni mekanizmanın, mekanizmaya eklenen ara çubuklara monte edilen kaplama malzemesi ile hareketli üst örtü olarak kullanılabileceği öngörülmüştür. Tezde, konuşlanabilir yapılara, çizel yüzeylere, temel mekanizma bilgisine ve Bennett mekanizmasının özelliklerine kapsamlı bir şekilde yer verilmiştir. Bennett mekanizmasından esinlenerek oluşturulan yeni mekanizma ve bu mekanizma ile oluşturulan mimari üst örtü, yapılan maketler ve kinematik diyagramların yardımı ile anlatılmıştır.

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CHAPTER 1

INTRODUCTION

1.1 Definition Of The Study

The use of the kinetic design strategy in architecture traces back to the first structures of human beings. Kinetic design strategy in architecture is essential in order to obtain adaptable structures. These structures satisfy the needs of various users and programs of the structures, because change always becomes a part of human life. From the nomadic tribes' tents to today's modern examples, the majority of structures in kinetic architecture are deployable. "Deployable structure is a generic name for a broad category of prefabricated structures that can be transformed from a closed compact configuration to a predetermined, expanded form, in which they are stable and can carry loads'' (Gantes, 2001, p.3). Applications in deployable structures range from Nomad shelters to Da Vinci's umbrella. In this work, deployable structures with various configurations are called reconfigurable structures. Reconfigurable structures can be transformed from a closed compact configuration to multiple alternative expanded forms. The present thesis will focus on the possibilities of constructing a reconfigurable hyperbolic paraboloid (hypar) structure. Hypars can be generated as a ruled and translational surface. Moreover, they add strength to the structure with their double curvature. The term hypar first was introduced by the architect Heinrich Engel in his book Structure Systems (Engel, 1967). Hypar surfaces distinguish themselves among other geometrical forms in architecture. Hypars or networks of hypars have been used extensively in architecture. A Spanish architect Félix Candela's slender concrete shells are the best reference for hypars in architecture. After Candela's concrete shells, steel and similar metals have been used to produce hypar surfaces but all these examples are static structures. Generating a reconfigurable hypar surface is just possible with the fusion of architecture and mechanism science. The present study deals with the spatial overconstrained linkage Bennett mechanism, which was discovered in 1903 by Dr. Geoffrey Thomas Bennett.

1.2 Scope And Aim Of Dissertation

The aim of this dissertation is to explore the possibility of constructing reconfigurable hyperbolic structure for architectural applications by doing research on an existing 3D overconstrained linkage mechanism.

In this process, firstly existing deployable structures are reviewed. Especially, the present dissertation attempts to cover rigid bar structures. Then the geometrical properties of ruled surfaces, especially hyperbolic paraboloid are examined. Moreover, the basic terms of mechanisms and the Bennett linkage are investigated. Finally, a novel reconfigurable hyperbolic paraboloid structure derived from the Bennett linkage for architectural applications is investigated and developed.

1.3 Outline Of Dissertation

The present dissertation is composed of six chapters.

Chapter 2 comprises the background of the study with the explanations of kinetic design strategy in art and architecture.

Chapter 3 is concerned with the existing deployable structures and their classifications by different researchers like Gantes, Pellegrino, Hanaor and Korkmaz in order to shed light on the researchers' perspectives about deployable structures.

Chapter 4 presents the geometric principles and the types of curved surfaces in order to comprehend ruled surfaces, especially hyperbolic paraboloids. The curved surfaces are evaluated over Curt Siegel's classification. Plus, the use of curved surfaces in architecture is illustrated.

Chapter 5 is concerned with overconstrained mechanisms and developing a reconfigurable hyperbolic structure. First of all, basic definitions of mechanism and kinetic structure are presented. This is followed by overconstrained mechanisms. Then, the geometric principles, shape limitations and the alternative forms of modified Bennett linkage are presented. Finally, reconfigurable mechanism which is inspired from the basic design principles of Bennett linkage and the fundamentals of ruled surfaces are explained.

The research is summarized in Chapter 6 with the suggestions for future works.

CHAPTER 2

KINETIC DESIGN STRATEGY

2.1 Kinetic Design Strategy in Art and Architecture

Throughout architectural history, timeless monuments of the ancient, classical and medieval world have been lauded as great cultural achievements. These monuments, temples, cathedrals aimed to be the national symbols of excellence. “Unfortunately, the result has been that most current buildings were also designed to be monuments. It has not been considered that any building might at some future time be altered, expanded, contracted, moved or terminated.” (Zuk & Clark, 1970, p. 4). However, expectations from architecture change rapidly to satisfy the needs of a dynamically changing society. As Zuk expressed; “The architecture is simply a physical expression of a continually changing society.” (Zuk & Clark, 1970, p. 4) .

Therefore, a new architecture is needed. Primitive forms and functions of architecture were basically for simple organizations; since architecture had been direct responses to simple, limited needs. This is not true for today’s architecture because the needs are rapidly changing. The typical static forms of architecture that took their places in the past cannot respond to the changing needs of our present, dynamic society. The necessity of adaptability, sustainability and extended capabilities of functional flexibility of structures are enhancing. Furthermore, the place concept is not a static perception; it develops rapidly with time. Today’s architecture seeks buildings that can adapt to functional, spatial and environmental changes. “Architecture stands at the threshold of a new evolution. Charles Darwin has suggested that the problem of survival always depends upon the capability of an object to adapt in a changing environment. This theory holds true for architecture.” (Zuk & Clark, 1970, p. 4).

As it was previously mentioned, architecture has to respond to the needs of a dynamically changing society. Alexander (1966) has suggested that the concept of a need has several flaws, since the concept of “need” does not consist of all factors which influence form and moreover the concept of need is primarily inactive. “Rather than refer to need as a concept that occasions response, a concept of pressure, which implies energy, an action, will be substituted.” (Zuk & Clark, 1970, p. 5). Even in nature, form is a direct response to pressure. There is an established relation between form and pressure, form is a response to pressure. This relation between form and pressure is defined as the set of pressures that acts upon and generates form (Figure 2.1). For that reason, every designer must be able to assess all the pressures for his/her design. (Zuk & Clark, 1970, p. 5).

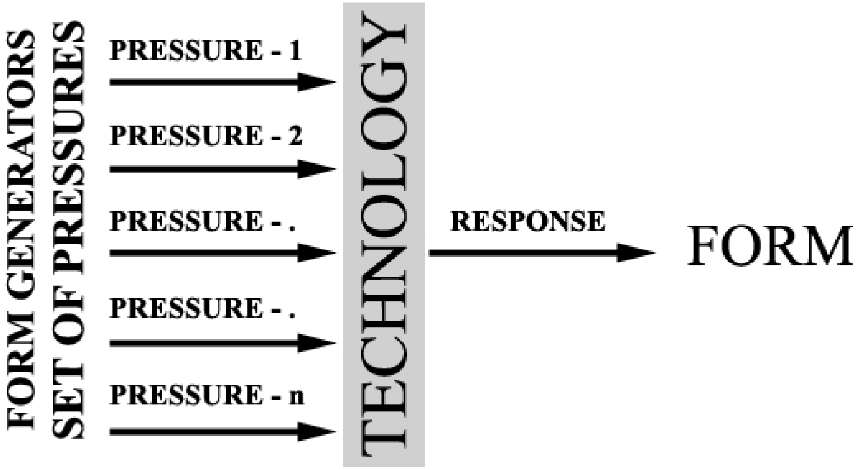


Figure 2. 1. Basic pressure-response diagram showing relationship between the set of pressures and the form (Source: Zuk & Clark, 1970)

Zuk (1970) categorized possible approaches to the problem of change into two with a few exceptions.

The first one is the typical static solution that is found most often in practice today. In this case, the architect thinks about the pressures at a single point in time and while he attempts to forecast the future, the immediate problem generally dictates the solution. The typical program from which the architect works represents only one point in a continuum of change. The buildings designed with this method accommodate the pressures uncomfortably or the physically sound building is remodeled or replaced.

The second approach is best represented by Mies van der Rohe’s principle of universal space. In this case, the architect designs a space that meets any functional demand. The buildings designed with this method are not adjusted to any function. The universal space solution as explored by Mies van der Rohe, attempts to solve all functions but very often satisfies none. It is difficult to accept the concept that all forms fit all tasks.

It is necessary to develop a third conceptual approach, which will adapt to continuous and accelerating change. The architectural form must be inherently displaceable, deformable, expandable, disposable, and in some other manner capable of kinematic movement. This is kinetic architecture, which recognizes the fluidity of the set of pressures to which form must respond. In this case, space is adaptable, thereby encouraging the set of pressures to change (Zuk & Clark, 1970).

The term “kinetic”, in other words “kinetic design strategy”, exists in almost all types of art. It is a unique type of art that either contains moving parts or depends on motion for its effects. Kinetic design, or kinetic art, or kineticism is an international movement that was created between 1920 and 1970. Although it was not recognized as a movement until the 1955 exhibition *Le movement* (*Movement*) at Galerie Denise René in Paris and the ensuing international exhibitions during the 1960s, kinetic art claimed Constructivism and Dada as its historical precedents (“Movement-Kinetic Art”, 2012). Dvizhenie (Movement) was a Soviet Kinetic Art Group which was active in 1960s and 1970s. They were the first art group in the Soviet Union that worked with cybernetics. The group was initiated by Lev Nussberg who gathered young artists from various Moscow institutes and arts schools. The group cooperated with actors, musicians, chemists, engineers in radio-electronic and light-technology, psychologists, architects, physicists, poets and performing dancers. “Their works stressed the necessity of contiguity between art and science” (Tillberg, 2007). Their early works focused on abstraction and autonomous kinetic objects-often animated by simple electrical mechanisms, from the mid-1960s their practice turned towards public space, designing the environment and considering future cities (Kurg, 2012). The exhibition called “Our Metamorphic Futures” comprises some works of Dvizhenie Figure 2.3, Figure 2.5 and Figure 2.7 show kinetic object designs, Figure 2.4 shows sketches for a kinetic fountain. Figure 2.6 shows the drawings of a kinetic sculpture called “Lighthouse” which is designed for an ideologically aesthetic landmark and symbol of dynamic life in contemporary Riga the capital of Latvia. This sculpture also aims to be a visual reference point of the new centre of the city. According to the explanations in the exhibition, the lighthouse in the sculpture symbolizes the Latvian people plus the coast and the pulsation of the sculpture symbolizes life (Kurg, 2012). Today, kinetic art especially kinetic sculpture still enjoys its popularity. There is a kinetic sculpture museum in Ferndale CA, USA and the museum of kinetic art called “Kinetica Art Fair” in London, UK.

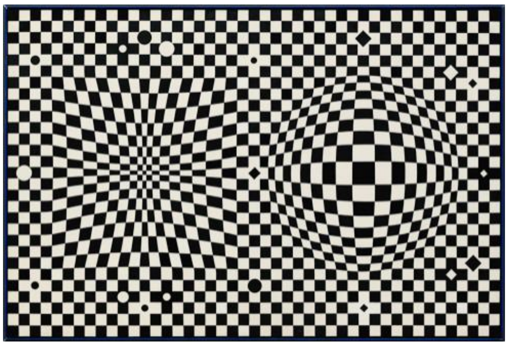


Figure 2. 2. Example of a kinetic painting. *VEGA III*, 1957–59. Oil on canvas (Source: Guggenheim, 2012)

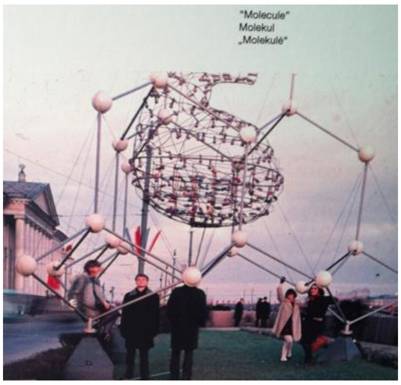


Figure 2.3. Kinetic object called “Molecule” by Dvizhenie (Source: Kurg, 2012)

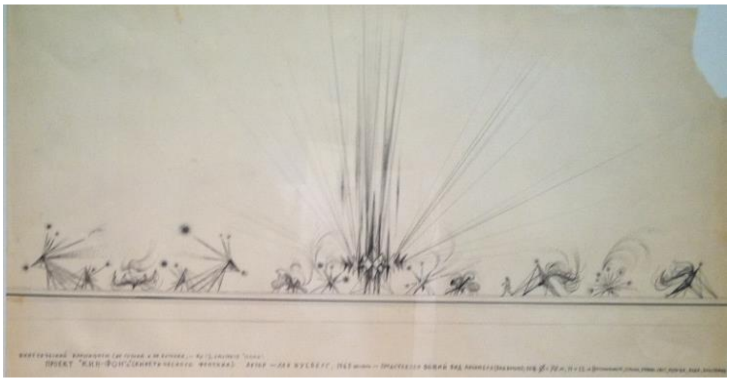


Figure 2.4. Project for a kinetic fountain 1965 by Lev Nussberg (Source: Kurg, 2012)

Figure 2.5. Kinetic light object called “Flame” (Source: Kurg, 2012)

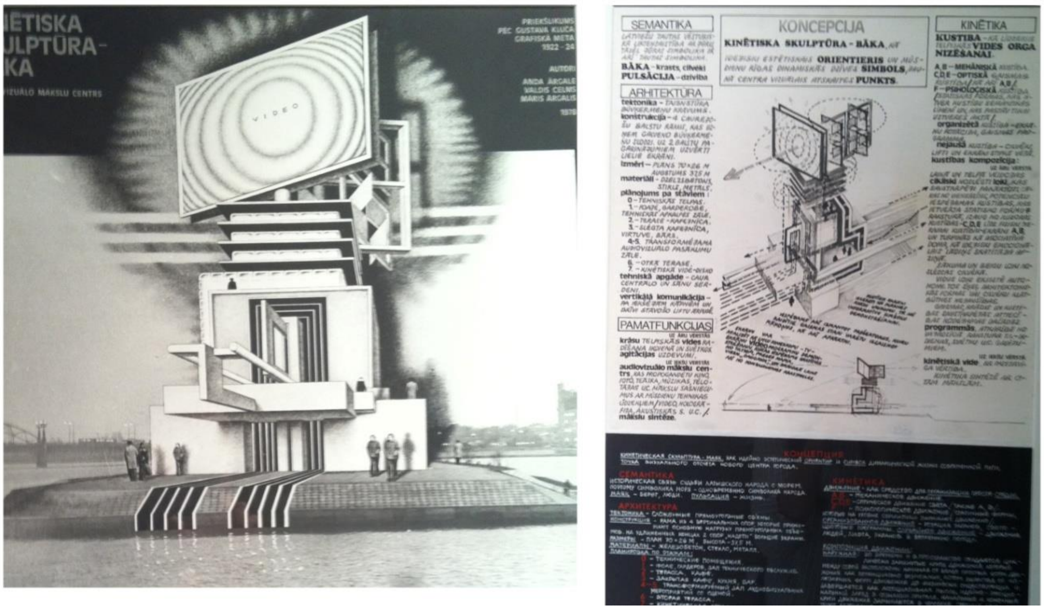


Figure 2.6. Kinetic Sculpture called “Lighthouse” designed for Riga city centre. (Source: Kurg, 2012)

Figure 2.7. Kinetic object inside Tallinn’s post office 1980 by Kaarel Kurismaa.
(Source: Kurg, 2012)

The kinetic art movement has effects on architecture. For instance the Russian artist and architecture Viacheslav Koleichuk from Dvizhenie movement designed a self-building structure in 1967. This structure consists of flat rectangular modular elements that can produce different configurations. Thus changing the shape of the structure, it can be extended or stretched taught by a winch and cables depending on particular needs. For example, it can be a half-opened in hot weather and closed in cold weather (Figure 2.8) (Kurg, 2012).

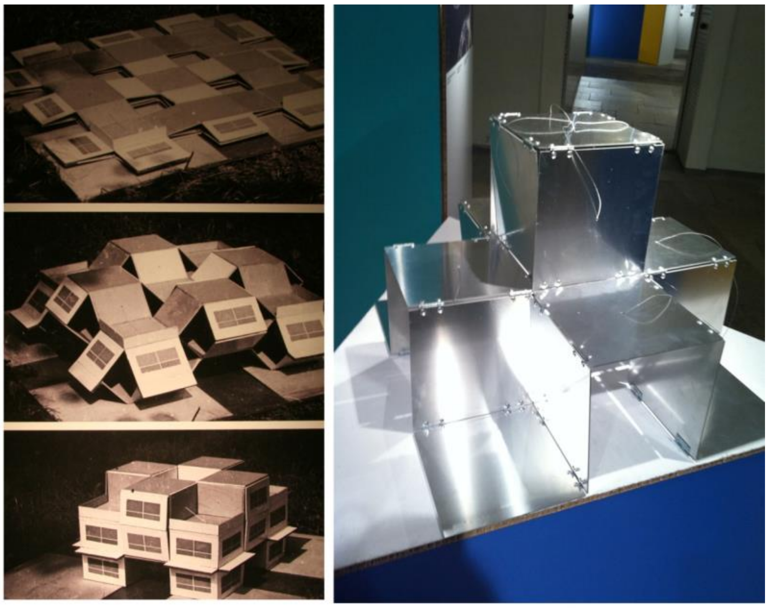


Figure 2.8. Model photo and the model of Self-Building Structure by Viacheslav Koleichuk (Source: Kurg, 2012)

It is possible to claim that ‘kinetic architecture’ has been in use since humankind began to build because change has always been a part of the human condition. In the past, humankind used kinetic structures in order to survive and adapted them to their impermanent nature. The numerous rudimentary forms of deployable structures exist like the Bedouin tents, the North American tipi or drawbridge (Figure 2.9) from the Middle Ages. During the first and second world wars, military field studies on deployable structures formed an important basis for the kinetic architecture. Additionally, natural disasters and wars triggered the development of kinetic architecture

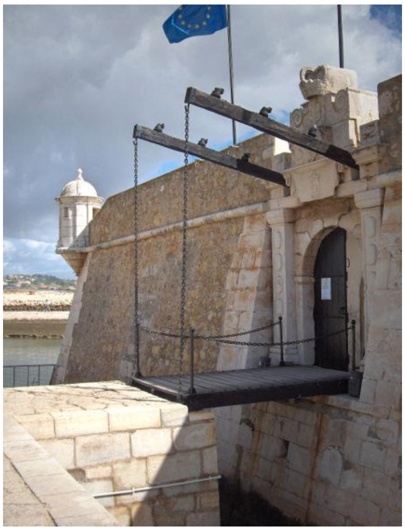


Figure 2.9. Example of a drawbridge from the middle ages (Source: Wikipedia, 2012)

The term "kinetic architecture" is difficult to be defined because it is a wide field that can refer and include many subjects. "Kinetic architecture is defined generally as buildings or building components, with variable location or mobility and/or variable geometry or movement" (as cited in Fox, 2001, p.12) is the most accepted definition for kinetic architecture. It is worthwhile to highlight that; kinetic architecture has lots of advantages to be preferred compared to conventional buildings. Conventional buildings are not adaptable and reusable. Structures that change shape and form to adapt to different functions and weather conditions have an obvious positive impact on the economy of environmental resources. Kinetic structures are ecological structures because they damage the nature less compared to stable structures. Additionally, kinetic architecture provides strategies for designing and constructing moveable building elements that optimize sustainability in architecture. Another considerable reason which makes kinetic structure attractive is their unique and remarkable form compared to static, traditional structures. "When done properly, kinetic architecture can inspire, surprise and even touch the soul." (Razaz, 2010, p. 341) Kinetic design strategy is significant in order to obtain wholly unexplored applications in architecture. It is possible to produce architecture in a peculiar way. So; some architects are searching to find other ways of producing architecture under the rubric of kinetic architecture. The explosion of technology also helps kinetic architecture in order to take its place in the field of architecture with its spectacular implementations. Kinetic architecture requires a totally new architectural vocabulary because new construction techniques, new power systems, new criteria for materials, new transportation systems, new building economics, and a new technology must be established (Zuk & Clark, 1970). Therefore, interdisciplinary studies between mechanism science, structural engineering, and material science are vital to construct kinetic structures because a basic knowledge from different disciplines is necessary to generate kinetic designs. These rich hybrid products increase the potentials of the disciplines separately. For this reason, architects must be receptive in order to integrate the knowledge from other disciplines to increase the novel design approaches and applications of kinetic architecture. The famous Spanish architect Santiago Calatrava has succeeded to integrate mechanisms with architecture. By using simple four bar mechanisms, he designed his famous buildings like Ernsting Warehouse (1983-1985 Germany), Pfalzkeller Emergency Service Center (1996-1999, Switzerland) (Figure 2.10), Alcoy Community Hall (1995, Spain) and the kinetic entrance of Hemispheric in City of Arts and Science in Valencia (2007, Spain) (Figure 2.11). Calatrava succeed to make a difference with his kinetic structures.

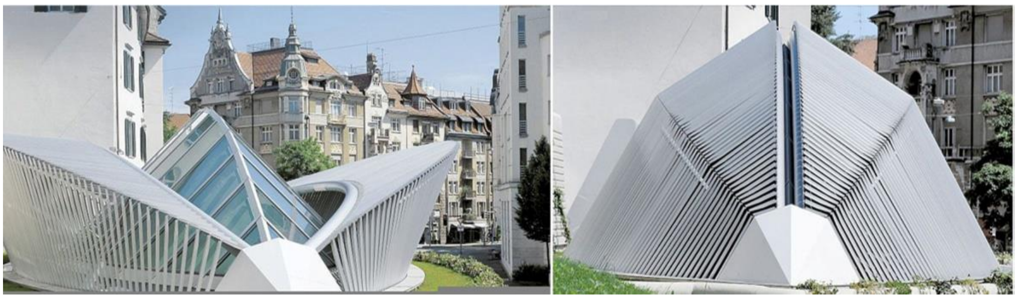


Figure 2.10. Pfalzkeller Emergency Service Center (Source: Miestai, 2012)

Figure 2.11. Hemispheric in City of Arts and Science in Valencia (2007, Spain)

CHAPTER 3

DEPLOYABLE STRUCTURES

3.1 Review Of Previous Works

The connection between machines and architecture traces back to BC. Vitruvius's Book X of his treatise on architecture was a key reference to mechanical engineering of Roman and Greek antiquity. As it was stated in the introduction part of the present thesis, today's architects are searching for the methods of producing remarkable structures. This effort in architecture has not changed since ancient Greek. Heron of Alexandria was a mathematician, physicist and engineer who lived around 10–85 AD. He designed a device that allowed the doors of a temple to open when a fire was lit at the altar (Figure 3.1) (Papadopoulos, 2010). Just like today, designers at the past designed to produce astonishment and wonder with the help of kinetic design strategies (Razaz, 2010).

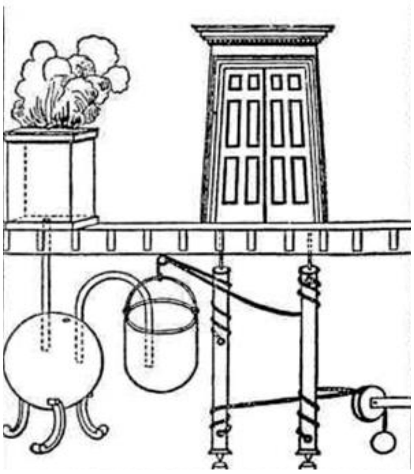


Figure 3.1. The doors of the temple open automatically when a fire is started at the altar (Source: Papadopoulos, 2010)

Major machine Renaissance designers such as Brunelleschi, or Francesco di Giorgio Martini were both architects and mechanical engineers. Francesco de Giorgio Martini is an Italian painter, sculptor, engineer plus an architectural theorist who has proposed machines based on diagonal ties that pull or push to change geometry (Gantes, 2001). Also Gantes (2001) mentions that Italian Renaissance architect Andrea Palladio, Verantius and Primaticio proposed temporary bridge systems. The sketchbooks of Leonardo da Vinci consists of hundreds of geometric shapes side by side with renderings of designs for buildings, dams and machines (Gantes, 2001). This connection between machines and architecture can also be found in the 19th century work of the machine theorist Robert Willis of Cambridge who published books on both kinematics of machines as well as the history of construction of British cathedrals (Moon, 2007). Leonardo da Vinci’s umbrella and a pantographic weightlifting crane designs are both examples for deployable designs (Figure 3.2). The idea of building variably and allowing adaptation to changing weather conditions is an old tradition. Even in ancient times removable tension roof of canvas were used as a protection against the sun and to regulate the climate. Coverings were placed over small courtyards and right up to the Roman custom of roofing large theatres and amphitheatres with removable tension roof of canvas (Frei Otto, 1995) (Figure 3.3). Nomadic tribes also used deployable structures because they are small, light and compact structures.,

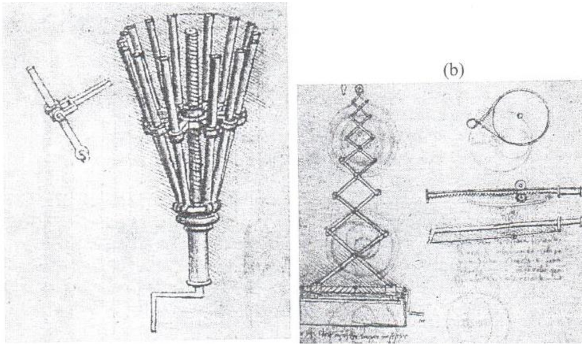


Figure 3.2. Designs of deployable structures by Leonardo da Vinci (Source: Gantes, 2001)

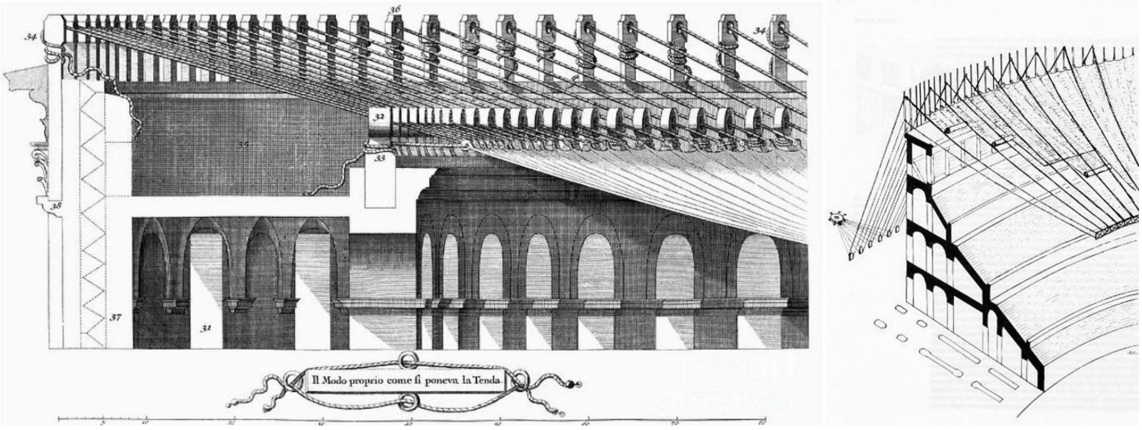


Figure 3.3. The Roman amphitheatres' removable tension roof of canvas (Source: Fineartamerica, 2013)

"Deployable structure is a generic name for a broad category of prefabricated structures that can be transformed from a closed compact configuration to a predetermined, expanded form, in which they are stable and can carry loads'' (Gantes, 2001, p.4). Deployable structures are popular and they can be regarded as an extensive research topic in Japan and Spain, Gantes (2001) mentions that strong origami tradition of these countries causes this popularity.

The most common deployable structures are the scissor-hinge structural mechanisms. They are formed by combining multiple scissors like elements, in other words pantographic elements. Emilio Perez Pinero's movable theater (1960s, Spain) is a milestone for scissor-hinge structural mechanisms because this structure has motivated many architects and engineers to work on scissor-hinge structural mechanisms. Escrig et al (2013) have experimented with lightweight folding spatial grid structures. Calatrava (1981) proposed different deployable mechanisms and spatial grids. Chuck Hoberman is a significant name with his angulated scissor-like element. He designed various deployable spatial scissor-hinge structural mechanisms like Iris Dome or Hoberman Sphere (Figure 3.4).

Figure 3.4. Iris dome by Hoberman (Source: Escrig, 2013)

Further, some researchers have focused on explaining the structural, geometric and kinematic behaviors of spatial scissor-hinge structural mechanisms by various analytical, numerical and geometrical methods. (Pellegrino S., 2003) Escrig (2013), Gantes (2001), Langbecker (2003) explained the main principles, geometric properties and shape limitations of both planar and spatial scissor-hinge structural mechanisms. Pellegrino and his research team in Cambridge University worked on Hoberman's designs. They had a research center called Deployable Structures Laboratory (DSL) and it was the most organized international center of deployable structures. They explained the geometry of structural mechanisms in analytical and numerical ways and proposed several novel concepts. Dr. Pellegrino's student Dr. Zhong You organized a similar laboratory at the University of Oxford. Professor Waclaw Zalewski is another important person for development of deployable structures. Zalewski's students Sivam Krishnapillai, Carlos Henrique Hernandez Merchan, Charis Gantes, Yechiel Rosenfeld also contributed with their works to deployable structures. Scissor-hinged structural mechanisms are essential for aerospace companies. Therefore, there are laboratories of the National Air and Space Agency (NASA). One of the major centers of NASA related university research into deployable structures is the University of Colorado, particularly the group of Professor Peterson (Gantes, 2001).

Usually, deployable structures are temporary and reusable like; emergency shelters after natural disasters, bridges, temporary protective covers for outdoor activities, exhibition structures, warehouses, hangars, greenhouses, and aerospace structures. Deployable structures are characterized by their ability to adapt their shape to the external conditions. Most of the systems in nature are the samples of deployable structures. Insect wings, honeycomb, plant leaves may be shown as an example of foldable /deployable structures in the nature. “One could almost redefine biology as the natural history of deployable structures” (Pellegrino, 2001, p.37). Hachem et al (2004) studied some sampled deployable forms in nature, their morphologies and their potentials to be used in manmade structural systems. Well known examples from our daily lives are umbrellas and tents.

Deployable structures have various advantages. They are transformable, reusable, easy to store and erect. They reduce working time at the site and built under factory conditions. They require minimum skill and equipment for erection and dismantling at the construction site. They increase safety by minimizing or eliminating the need for scaffolding, they can also reduce cost; at times the rental, transportation, assembly, and disassembly of scaffolding are the largest single cost of a structure. However as Gantes (2001) has mentioned, the aim of deployable structures’ designers is to obtain the deployability feature as a ‘bonus’ to their designs without adding weight and decreasing their structure’s load bearing capacity.

3.2 Classification Of Deployable Structures

Deployable structures can be classified into several categories, including the type of use, the type of structural members, the way in which these members are connected, the location and so on. In that sense, this chapter attempts to disclose the most precise classifications for deployable structures.

3.2.1.Gantes Classification

Charis J. Gantes is a structural engineer who had focused on deployable structures during his graduate studies at the Massachusetts Institute of Technology. He has a major classification of deployable structures in his book. First he classified deployable structures into two groups, due to the ones that are built and used on the earth, and the ones that are built on the earth but are deployed in space (Gantes, 2001).

The group called ‘Earth-based deployable structures’ in Gantes’ classification is primarily used for architectural applications. Therefore, deployable structures that were used for architectural applications are the one related to this dissertation. These groups of deployable structures are mainly used for temporary construction or emergency situations. However, other applications are possible with earth-based deployable structures such as exhibition purposes, toys or art pieces (Figure 3.5). Gantes (2001) also took another criterion into account in his classification, such as the type of structural members employed in the structure. He divides the structures into subgroups that consist of 2-D or 3-D building modules and strut structures which have 1-D bars as basic modules (Figure 3.6). Deployable structures based on pantographs consist of 1-D bars. Foldable structures consist of stiff 2-D polygonal panels. Tension structures like either pneumatic or prestressed structures consist of flexible 1-D cables or 2-D membranes or a combination of both. Tensegrity structures are the combination of stiff rods and cables. Because, the last title 'retractable roofs' is a disparate group, Gantes treated retractable roofs as a separate category in his classification.

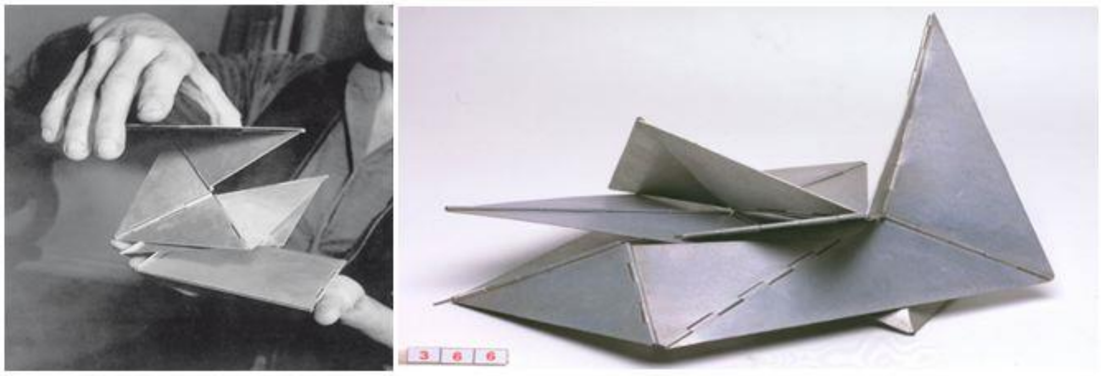


Figure 3.5. Deployable Structure as an art piece, created by Lygia Clark called 'Bichos' (Source: Gaarq, 2013)

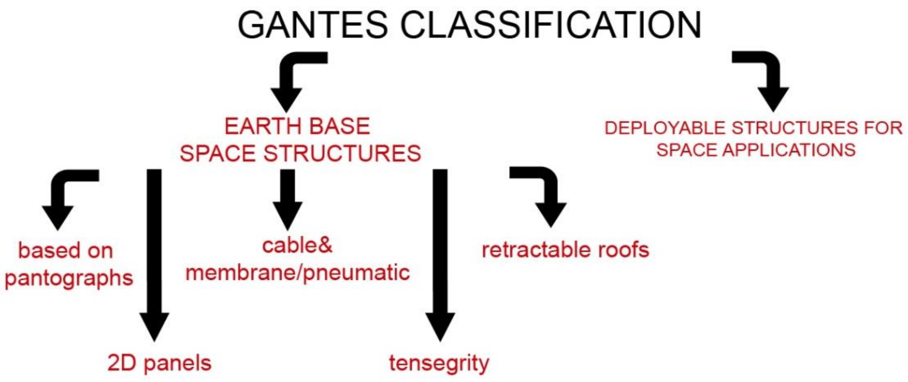


Figure 3.6. Gantes Classification of Deployable Structures (Source: Gantes, 2001)

3.2.1.1 Deployable Structures Based on Pantographs

The majority of deployable structures are composed of pantographs, otherwise called scissor-like elements (SLE's). Different terms are used: pantographs (Pinero, 1961), pivot-hinge structure unit (Gantes, 2001), scissor-like elements (SLE) (Gantes, 2001) in order to describe these units.

Pantographs contain rods that have tree nodes. Two of the nodes take place at the end of the rod and the third node locates at the intermediate point (Figure 3.7). These rods are connected each other with pivotal connections and form the framework of the pantographs. The pivotal connections allow free rotation between two rods about the axis perpendicular to the plane of the pantograph. Many considerable researchers (Pinero, Escrig,Hoberman etc) work on and establish pantographs as viable, exciting form of space structures.

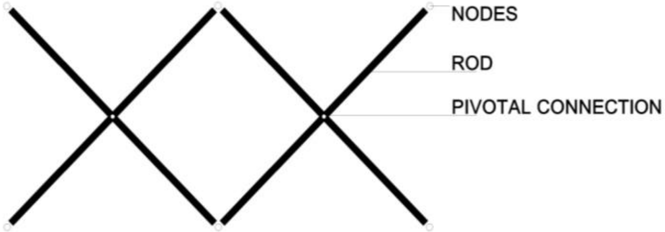


Figure 3. 7. The concept of a pantographs

In 1961, the Spanish architect Emilio Perez Piñero was the first who build a deployable structure in the modern sense; thus, he is known as the pioneer of deployable structures (Gantes, 2001). He designed and constructed a real-size deployable theater. This theater is the first deployable space frame, using the principle of pantograph. He developed a full-size foldable theater, which arrived at the site on a single wheelbarrow and was then unfolded with a scissor mechanism. He used tensile membrane to create shelter (Figure 3.8) (Korkmaz, 2004). Piñero presented his model at the IUA Congress in London in 1961 and received an architectural award for his structure. His design had led to the wide research in deployable scissor structures.

Pinero’s structures are stress-free before, during and after deployment. They always behave like mechanisms. Hence, locking devices such as the additional cables must be used in order to achieve stability in Pinero’s design. External locking devices are acceptable solution for small, simple units or combination of simple units of structures that are deployed one by one and assembled afterwards. Nevertheless for larger and complex structures that are deployed at once, stabilization is the major disadvantage. Thedore Zeigler (1974) has worked to solve this deficiency of Pinero’s structure and improved his own design (Gantes, 2001). Zeigler’s structure also consists of straight bars and has the shape of the partial spherical dome. Also, it is a self-supported structure in the erected form without any additional locking devices. Zeigler chooses to use the limited flexibility of the structural elements in order to ensure self-stabilization.

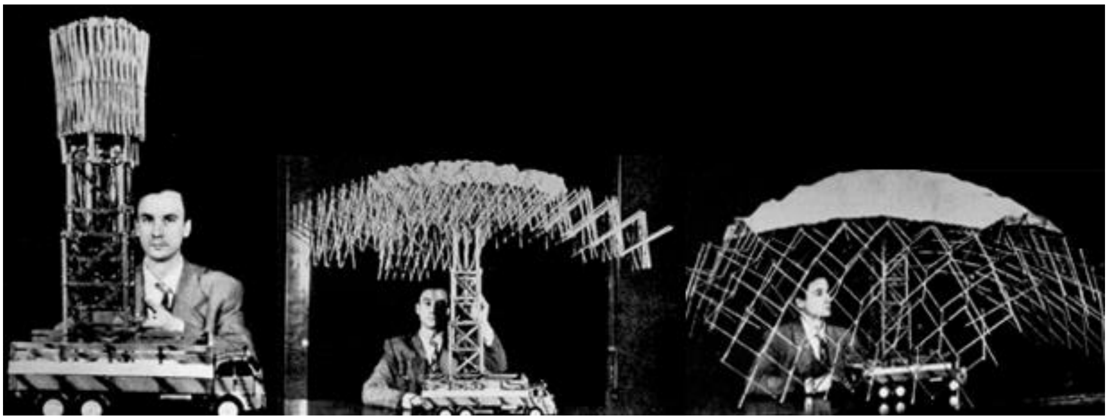


Figure 3.8. Pinero’s deployable structure (Source: Robbin, 1996)

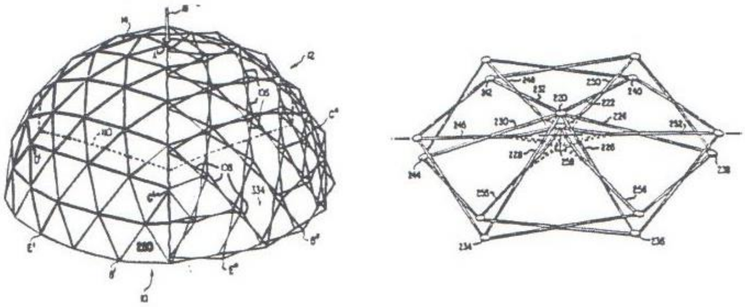


Figure 3.9. Zeigler’s partial spherical dome (Source: Gantes, 2001)

Felix Escrig Pallares is another researcher who was impressed by Pinero's work. Escrig’s works are based on Piñero’s principle. He has worked on cover materials identified that flexible materials are just useful for reduced spans and they don’t contribute to structural strength. He developed deployable vault by incorporating rigid plates which overlaps one another (Figure 3.10). Escrig has also developed several models on pantographs and designed a swimming pool in Seville by utilizing one of his models (spherical lamella grids) on pantographs (Figure 3.10, Figure 3.11).

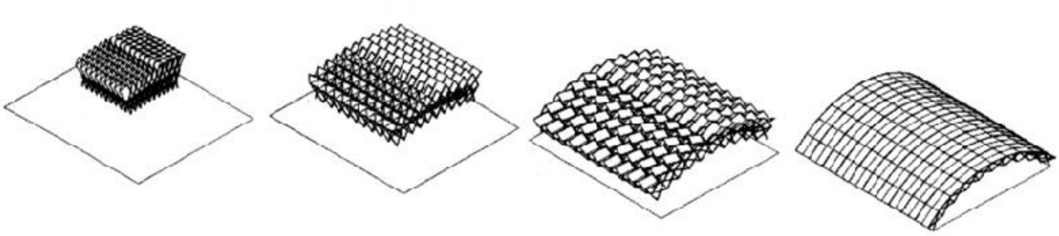


Figure 3.10. Escrig’s deployable vault by incorporating rigid plates. (Source: Gantes, 2001)

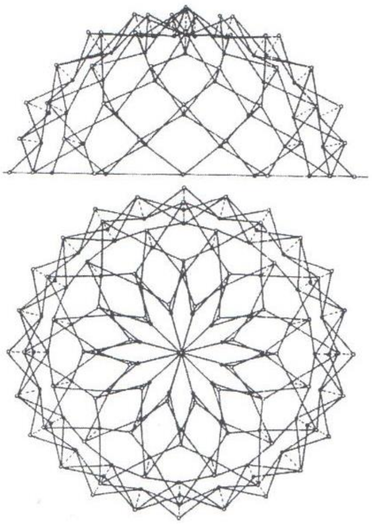


Figure 3.11. Escrig's Spherical Lamella Grids (Source: Gantes, 2001)

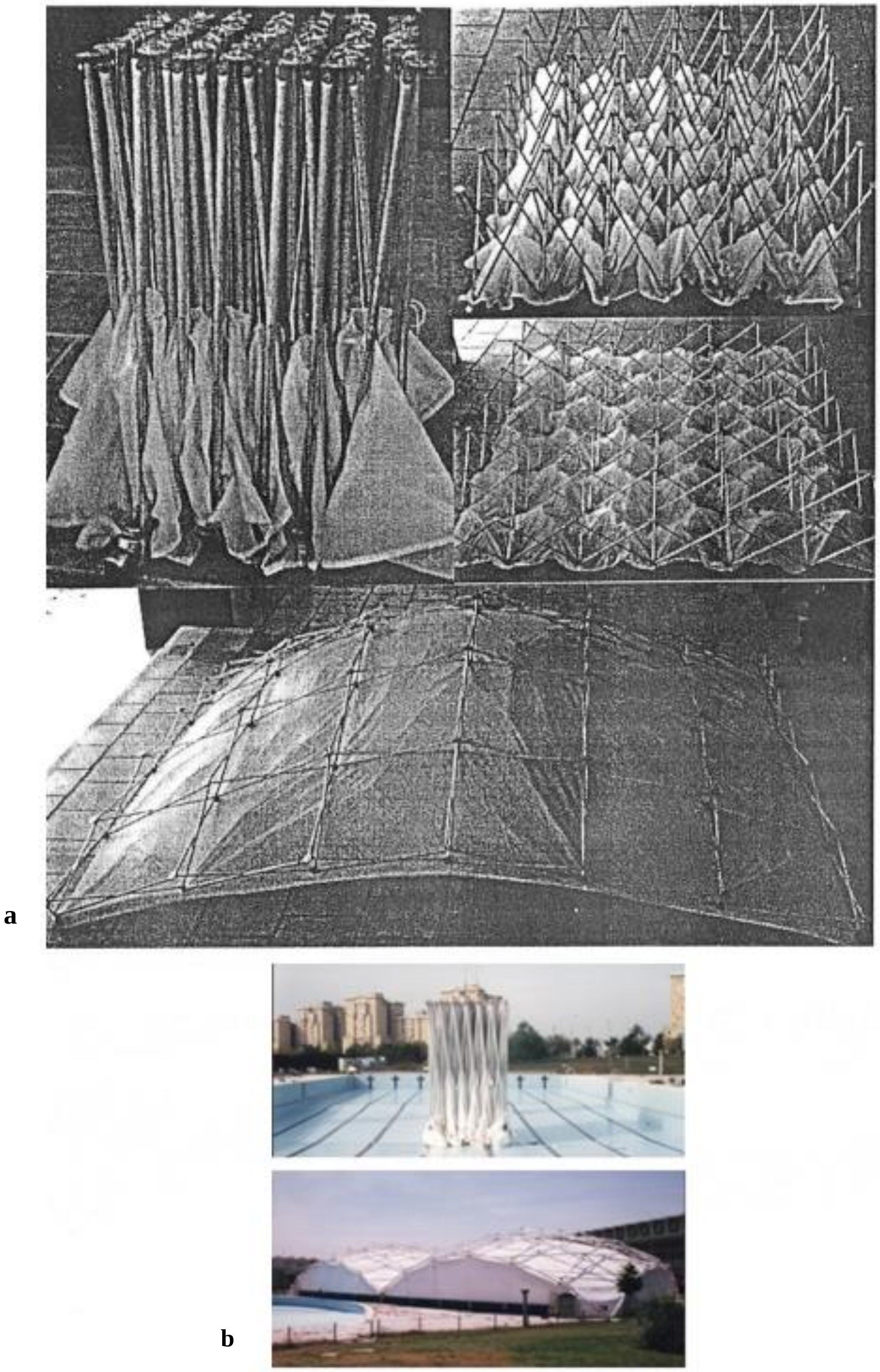


Figure 3.12. a) Model of a Selffolding roof hanging fabric (Source: Escrig et al., 1996)
b) The Photo of the deployable roof for San Pablo Swimming Pool
(Source: Escrig ,2013)

Another notable deployable structure based on pantographs is Chuck Hoberman's installation called 'Expanding Hypar' for the atrium of California Science Center in Los Angeles (Figure 3.13). This five-story-high structure is made of machined aluminum links connected by stainless steel pivots (Gantes, 2001). Hoberman's another significant structure on pantographs is the Iris Dome (Figure 3.4.). It is a retractable roof structure based on a series of angulated elements. These angulated elements have two identical angulated bars connected together by revolute joint (Figure 3.14). As shown in Figure 3.14, α becomes a constant for all θ while elements A, D, B and C are mobile on the lines OP and OR. These pantograph elements support either a membrane cover or partly overlapping, rigid covering elements that can move with respect to one another like the scales of a fish (Pellegrino, 2001). The Iris dome also moves with similar principle with Hoberman's arch. The Iris dome was used as an outdoor installation at the Expo 2000 in Hannover, Germany (Figure 3.15). The dome's perimeter was not constant. It was powered by four computer-controlled hydraulic cylinders, the 6,2 m diameter and 10,2 m high retractable dome smoothly retracts toward its parameter and unfolds (Hoberman, 2013) .

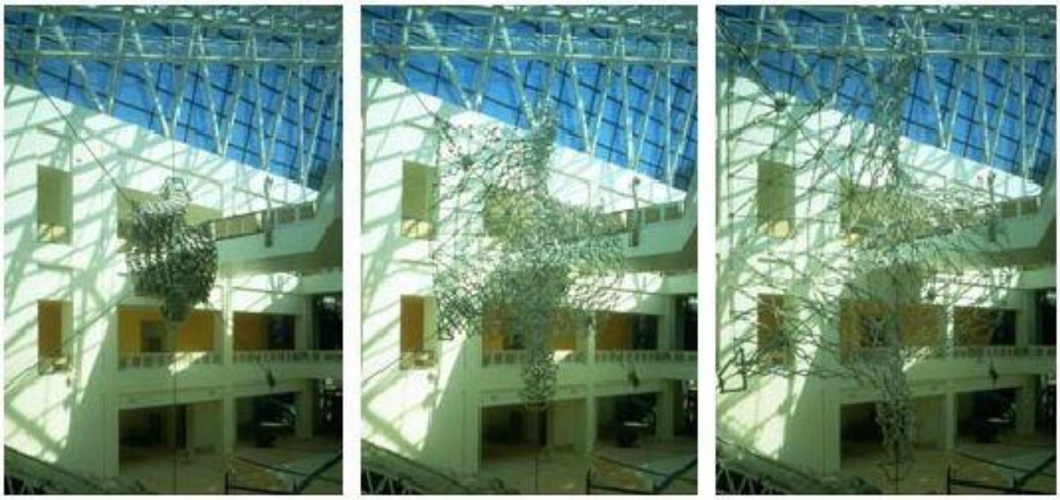


Figure 3.13. Expanding Hypar by Hoberman.1998.California Science Center Installation (Source: Hoberman,2013)

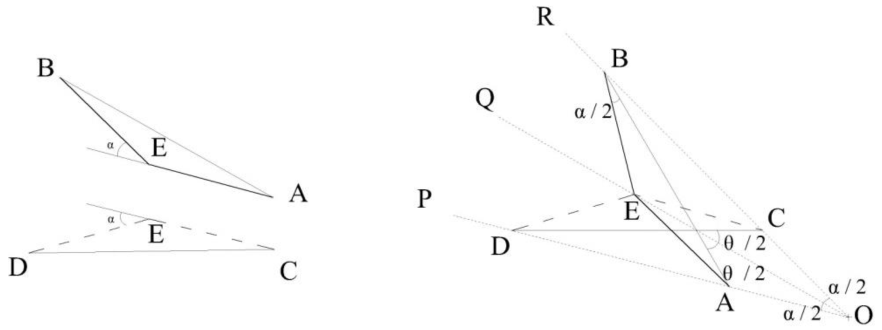


Figure 3.14. Hoberman's element, formed by identical angulated rods (Source: You & Pellegrino, 1997)

Figure 3.15. Iris Dome (Hoberman 1991) 2000's World Fair, Hannover, Germany (Source: Hoberman,2013)

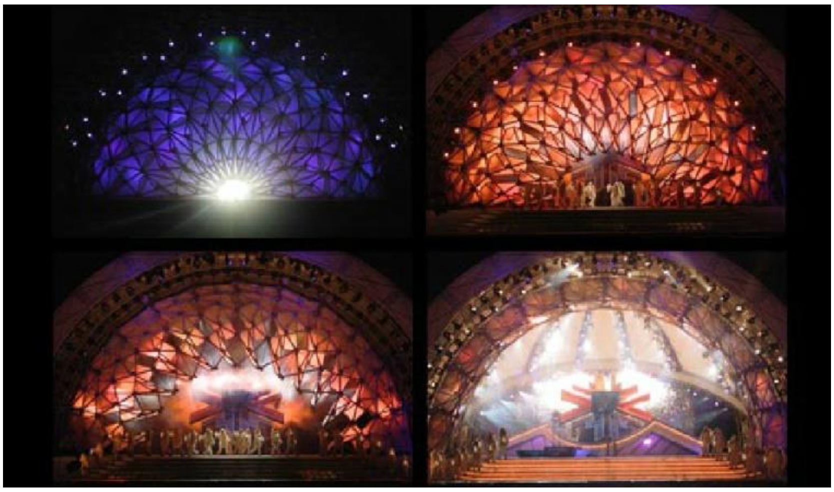


Figure 3.16. Hoberman's Arch (Source: Hoberman,2013)

A group called Deployable Structures Laboratory (DSL) within Cambridge University directed by Dr. Sergio Pellegrino focused on scissor structures in the late 1980's. Hoberman's pioneering idea on angulated element led Pellegrino and Zhong You to investigate the general conditions of pantographic deployable ring structures. They investigated a new, large family of foldable building blocks, which are called generalized angulated elements. These elements maintain a constant angle during folding just like Hoberman's angulated elements, but they afford greater freedom than all other elements previously used. Also, they have discovered that a series of continuous angulated rods can be replaced by a single, multi-angulated rod, reducing the number of components of the structure (Gantes, 2001). Therefore, the structure shown in Figure 3.17 consists of 24 bars, each having four segments with equal link angles: 12 bars are located in a clockwise direction and 12 anti-clockwise. At each crossover point, there is a revolute joint and it has the ability to retract radically towards the perimeter and can be generated for various plan shapes.

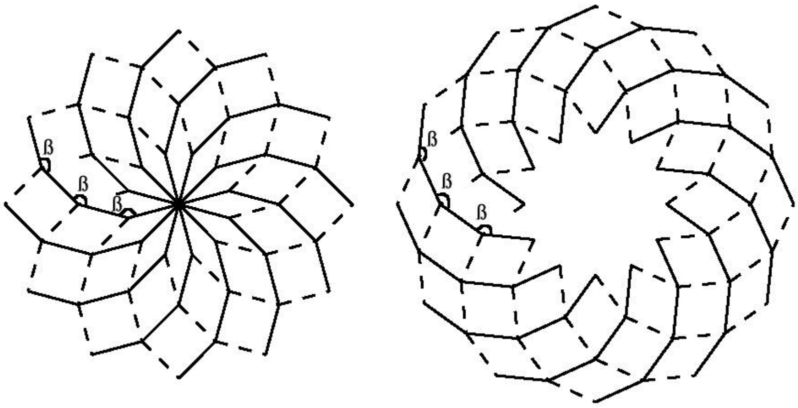


Figure 3.17. Deployable multi-angulated bar by You and Pellegrino (Source: Korkmaz, 2004)

Langbecker is another researcher who improved Hoberman's angulated units and designed synclastic and anticlastic deployable structures with many angulated or polar units (Figure 3.18). In order to increase stiffness and deployability feature, he added numerous rigid units and joints to his design. On the contrary, these numerous rigid units and joints made the structure more complex and expensive to fabricate and the compact volume of the design increased (Langbecker, 2003).

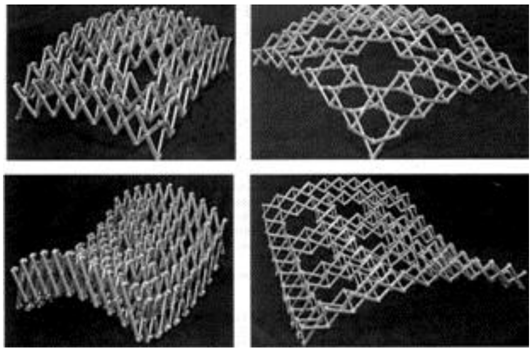


Figure 3.18. Deployable double curvature scissor hinge structures by Travis Langbecker (Source: Langbecker, 2003)

Tom Van Mele's (2008) dissertation is about scissor-hinge structural mechanisms. Mele (2008) worked on several case studies. Figure 3.19 shows his scissor hinged retractable roof over a sports facility. His design requires additional retractable supportive elements like a strut, an arch or a frame. These supportive struts are necessary because in his system, the scissor-arches are cut in half and in the closed configuration these 'halves' are connected at a central hinge. To avoid a permanent structure that remains over the area even when the roof is open, each of the ‘half’ scissor-arches should be supported by a moveable supporting structure .The intermediate configuration of the system is cantilever, so the deployable supportive structures bear the cantilever part of the design (Mele, 2008).

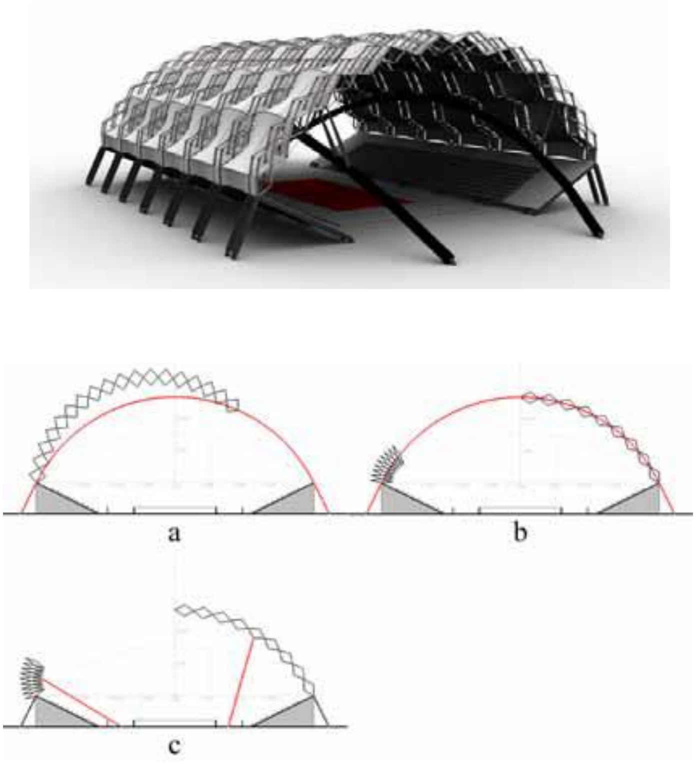


Figure 3.19. Tom Van Mele’s visualization for retractable membrane roof (Source: Mele, 2008)

3.2.1.2 Deployable Structures Based on 2-D Panels

Deployable structures based on 2-D panels are foldable structures. The basic element of foldable structures is triangular panel. Foster & Krishnakumar (1986) presented a family of foldable, portable structures which are based on the Yoshimura buckle pattern for axially compressed cylindrical shells (Figure 3.20) (Gantes, 2001). In this structure; in the basic triangular panel, one angle must be at least 90˚ and all elements in the section must have the same shape and equal apex angles. Each module must be capable of folding to a flat, compact form and these modules are joined with continuous hinges from the parallel sides in order to form the complete structure.

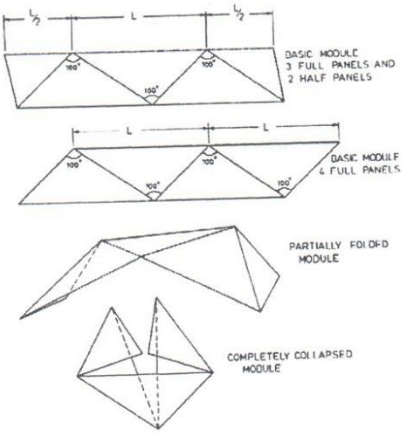


Figure 3.20. Basic Layout of Foster’s module (Source: Gantes 2001)

With appropriate combinations of modules, structures with a large clear span are possible. As the apex angle increases, the clear width and headroom also increase even though the length of the erected module decreases and the number of elements and hinges increase. Another important feature of foldable structures is that, as the number of folds increases, the load bearing capacity of the structure increases too (Gantes, 2001).

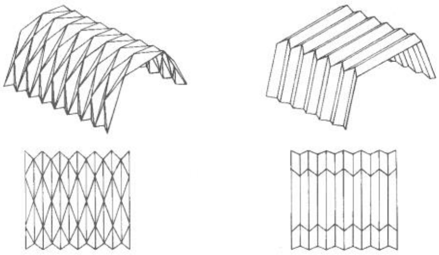


Figure 3.21. Deployable Structures Based on 2-D Panels (Source: Gantes 2001)

Guest (1994) and Pellegrino (1994) have focused on deployable structures and folding principles of triangulated cylinders. They had generated proposals such as triangular foldable cylinders, wrapping fold pattern and solid surface deployable antenna. Foldable cylinders are new way of packaging cylinders. All cylinders made of isosceles triangles fold down to prisms. With this principle, it is possible to obtain various kinds of deployable cylinders (Figure 3.22) (Gantes, 2001).

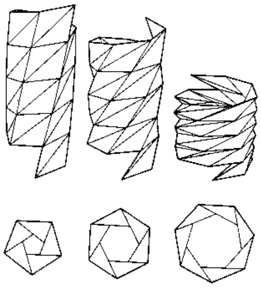


Figure 3.22.Triangulated foldable cylinders by Guest and Pellegrino (Source: Gantes 2001)

The “Kinetic Design Group” in the leadership of Michael A. Fox has developed projects and applications for kinetic designs in MIT (Gantes, 2001). They have applications as kinetic shading wall systems, kinetic partitioning wall systems, architectural accessories and lightning, furniture. They have folding sheet structures that can be an example for deployable structures based on 2-D panels (Figure 3.23). These structures are prototypes which can shed light to various possible configurations of deployable structures like exterior shelter, interior partitions or furniture (Gantes, 2001).

Figure 3.23. Half-shell with 3 Triangulated panels by “Kinetic Design Group” (Source:Fox & Yeh, 1999)

Kinetic origami structures are on the agenda among deployable structures and they can be regarded as deployable structures based on 2-D panels. These structures can be applied to kinetic structures as retractable roofs, openings, temporary shelters and space structures. Transformable polyhedral surfaces with rigid facets, i.e., rigid origami, are useful for designing kinetic and deployable structures. Several designs of rigid-origami structures have been proposed since 1970’s (Tachi, 2010). Tachi (2010) worked on origami structures and he mentions that actual designs of architectural space with origami have been unachieved because there is lack of design ability in the existing methods. Therefore, he works on alternative methods on origami structures and computational design of origami. He claims that dynamic property of origami structures forms continuous surfaces unlike truss structures and scissor structures. And also, this continuity preserves transformation (Tachi, 2010). Tachi (2010) works on plate-and-hinge model of origami, which is called Rigid Origami. In rigid origami each rigid panel is connected to adjacent panel with rotational one axis hinge. Thus, panels do not deform and the system provides watertight cover for a space. In addition, Tachi (2010) mentions that rigid origami is applicable for self deployable structures and large architectural scale objects under gravity by using thick panels. He uses rigid origami by generalizing rigid foldable structures to shapes like cylinders and more. Figure 3.24 and Figure 3.25 show Tachi's design. He has designed a foldable space to connect temporarily the openings of existing two separate buildings having different sizes and orientations.

Figure 3.24. Perspective view of Tachi's design (Source: Architizer, 2012)

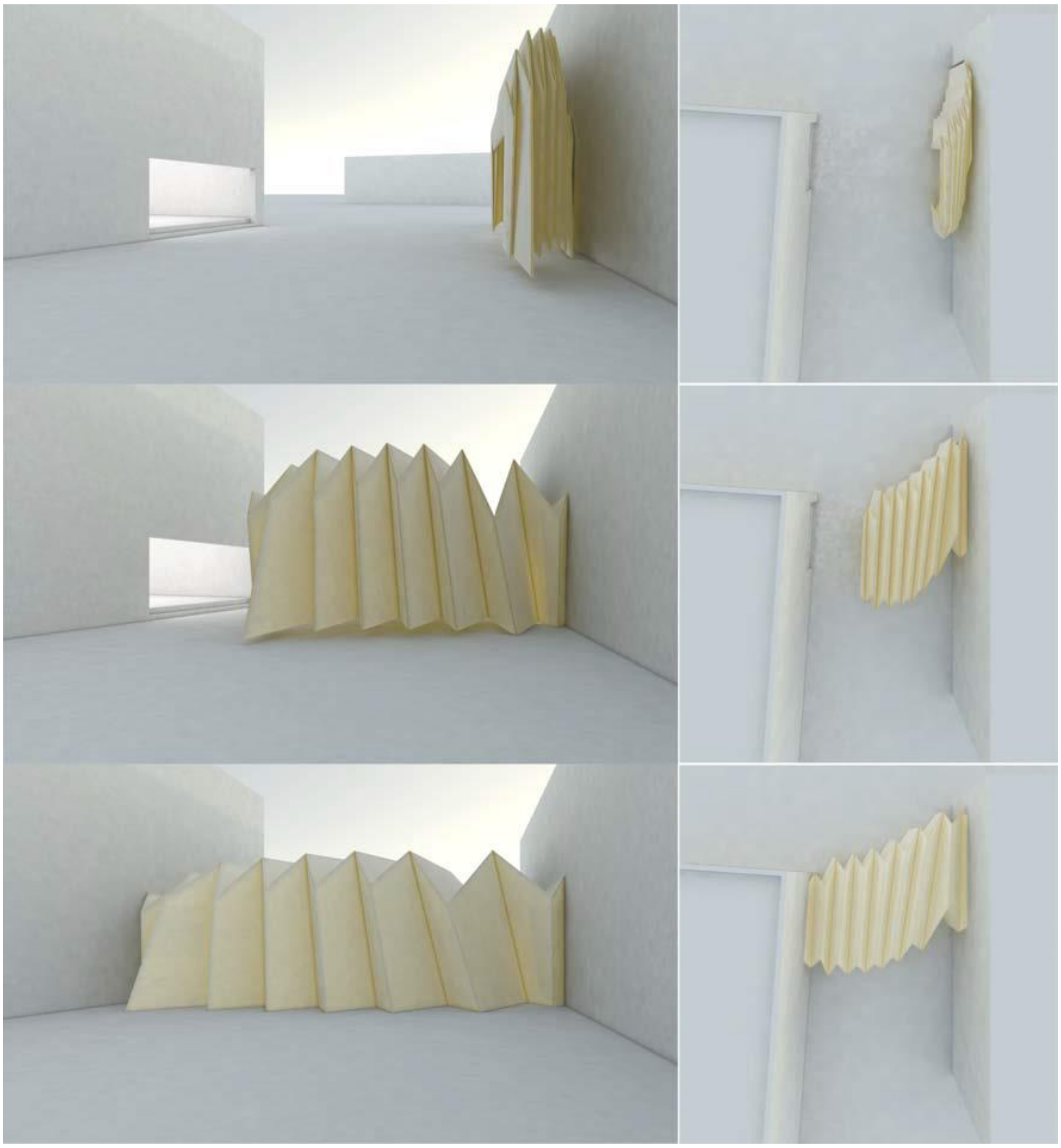


Figure 3.25. Tomohiro Tachi’s design to connect existing buildings (Source: Architizer, 2012)

You (2007) has devised origami structures to make common engineering structures foldable. With the help of origami techniques and geometrical analysis You have successfully developed a few concepts allowing thin-walled cylinders to be shortened to a small package by introducing folding patterns on their surfaces (Figure 3.26) (You, 2012).

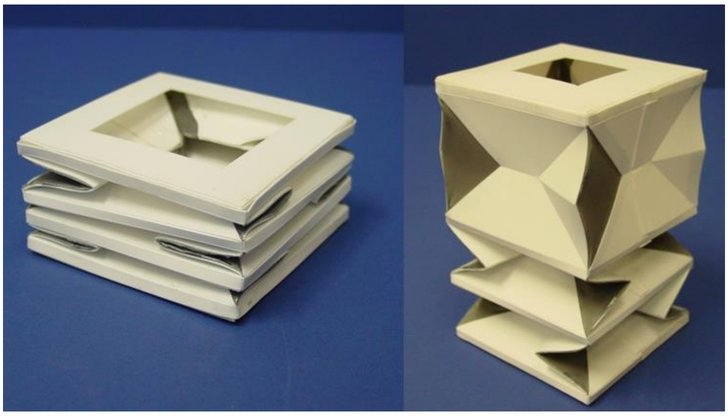


Figure 3.26. Bi stable foldable tubes (Source: You, 2012)

Deployable structures based on 2D panels can be a subject for art pieces as well as architecture. İlhan Koman is a Turkish sculptor and he is renowned with his nonfigurative static and kinetic works that gather art and science. He focuses on geometrical forms. He has worked on polyhedra and discovered a foldable polyhedron that is not rigid, having 10 vertices and 16 equal triangular faces (Figure 3.27). "I considered that light-weight foldable construction elements based on such a polyhedron might have application in engineering structures to be erected in space." (Koman İ. & Ribeyrolles F., 1979, p.1).

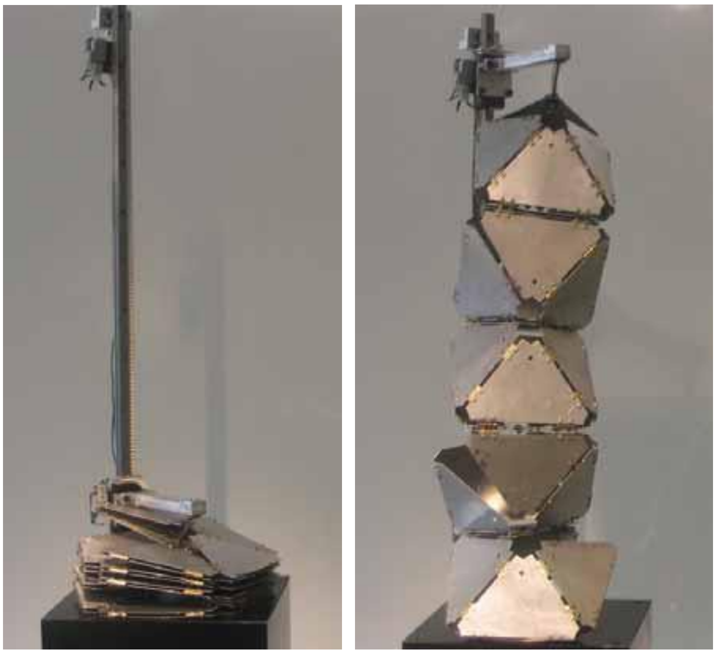


Figure 3.27. Koman's foldable polyhedron (Source: Koman, 2011)

3.2.1.3 Cable-Membrane and Pneumatic Deployable Structures

Cables and membranes are proper materials for deployable structures due to their fundamental characteristics. One of the main characteristics of cable-membrane structures is that they have no stiffness against the perpendicular loads (Figure 3.28). There is a substantial displacement between beam and a cable structure. The large displacements may result in significant change of the geometry. But it is possible to increase the stiffness of the cable-membrane structure like using pre-stressing or they may acquire stiffness via their connection to cables and other, stiffer elements.

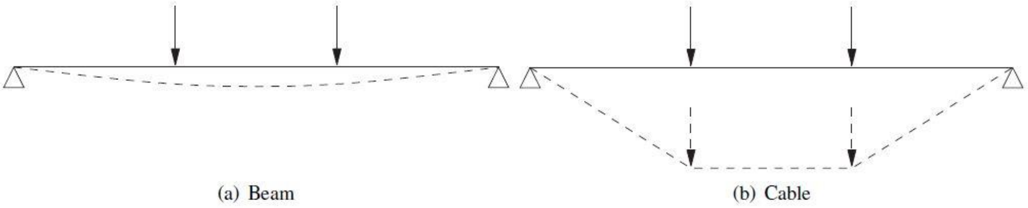


Figure 3.28. Displacement of beams and cable structures

Cable-membrane structures have both advantages and disadvantages. From the historical point of view, the designing process of cable-membrane structures is complex but with the help of technology, designing process of cable-membrane structures is not complex with advanced computer simulation programs. Another difficulty regarding these structures is manufacturing of them because cable-membrane structures are manufactured from industrial textiles which are produced in rolls. Maybe, manufacturing problem increase the labor cost of the structure but it doesn’t make the structure insoluble. On the other hand, cable-membrane structures have vital advantages like they have self-adaptability for earthquakes.

The best-known traditional example for cable-membrane systems are ‘toldos’ (spanish: awning). These traditional cotton awnings are still used to provide shade in the streets of Spanish suburbs. They can be moved from the houses, roofs or street with simple rope mechanisms (Figure 3.29) (Otto & Rasch, 1995).

Figure 3.29. Traditional toldos providing shade in the streets of Cordoba,Spain (Source: Otto & Rasch, 1995)

German architect and research engineer Frei Otto, focused on lightweight tent-like structures (Figure 3.30). He designed a series of retractable fabric coverings controlled by cables. Adaptable architecture is the focal point of Frei Otto's career. He is interested in buildings that can be altered or simply dismantled (Nerdinger, 2005). He supports the necessity of adaptable structures with his following words;

> Static persistence is unnatural. Both dead and living nature change. No one here doubts the validity of so-called static architecture. It is our daily handwork, our usual method of building. We are familiar with historically changeable, adaptable methods of construction (…) adobe buildings, the tents, dry brick, the wagon barricade, military and civilian camps (…) and we have mobile architecture. (…) Then we have convertible architecture, namely the tent roof, tents, shells, lightweight structures. Convertible architecture already has its place among the many architectures of the future. (Nerdinger, 2005, p. 31)

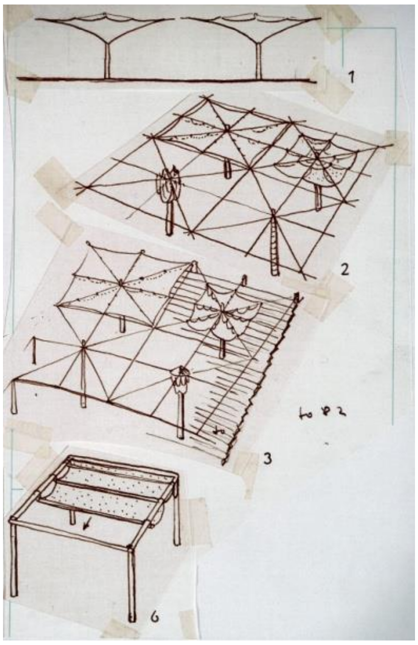


Figure 3.30. Frei Otto’s sketches; umbrellas and blinds as possible additive, convertible canopies (Source:Nerdinger, 2005)

Frei Otto designed a convertible roof for Bad Hersfeld in 1968. The structure has a central mast which stands by the nave of the ruin and it is guyed by two cables at the rear and fourteen guy ropes running like rays over the nave. The roof can be in place within four minutes and covers an area of 1315 square meters (Figure 3.31) (Otto & Rasch, 1995).

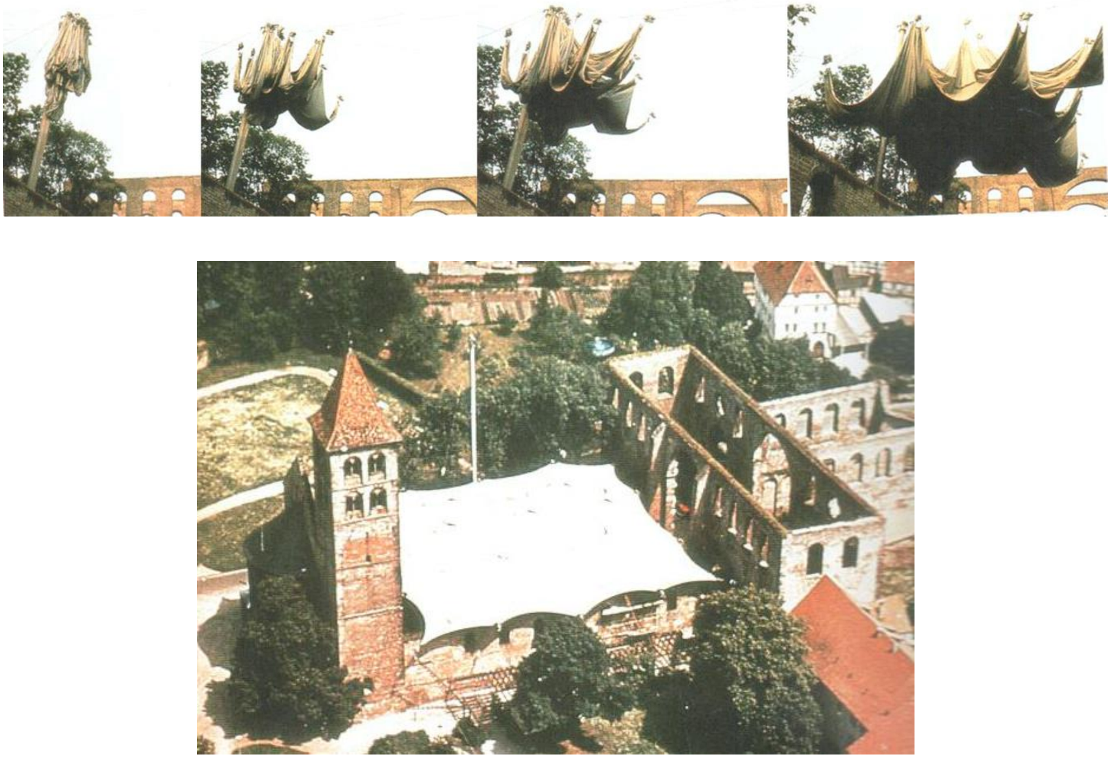


Figure 3.31. Frei Otto's convertible roof design for Bad Hersfeld in 1968 (Source: Otto & Rasch,1995)

Bodo Rasch is a German architect and an engineer, who worked with Frei Otto. Bodo Rasch has a similar cable membrane convertible roof design into the historical castle for the open-air theatre in Wiltz in Luxemburg in 1988. The concept of this design is the minimum intervention to the historical place. The designer aimed to preserve the character of the place. The support structure of the roof runs around the spectators and stage areas. The structure consists of tubular steel supports, guy ropes and a ring rope. Folded membrane is parked in the area behind the spectators so it does not interfere with their views. In bad weather, the roof is moved into place with the help of mechanism and automatically gets its final position. The roof covers an area of 1200 square meters. The whole roof structure can be removed at the end of the theatre season and then rebuilt without difficulty (Figure 3.32) (Otto & Rasch, 1995).

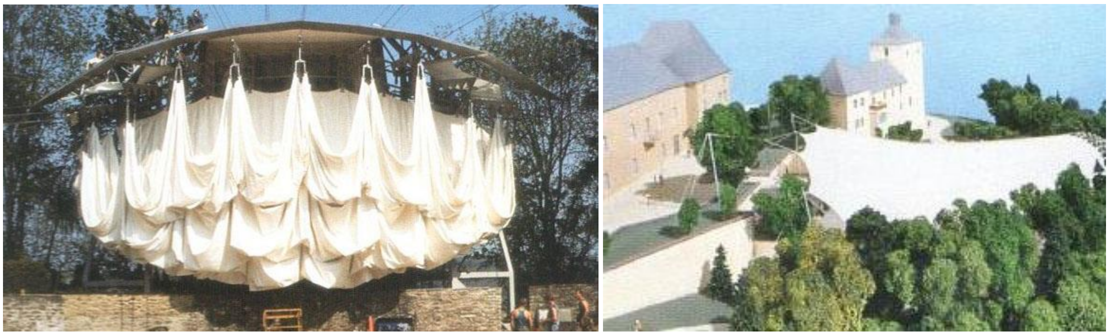


Figure 3.32. Cable membrane roof for the open-air theatre in Wiltz,Luxemburg by Bodo Rasch ,1988 (Source: Otto & Rasch,1995)

Frei Otto founded Institute for Lightweight Structures at Stuttgart in 1964. One of the designs of this institute is adapted to Multimedia Stadium for the Olympic buildings in Munich in 1970 (Figure 3.33), even though there were no plans to put design into practice. 180 meters long mast with 5-6 meters diameter had designed to suspend the membrane which covers the 60,000 m² area and the cables run from the head of the mast to 15 base points around the area.

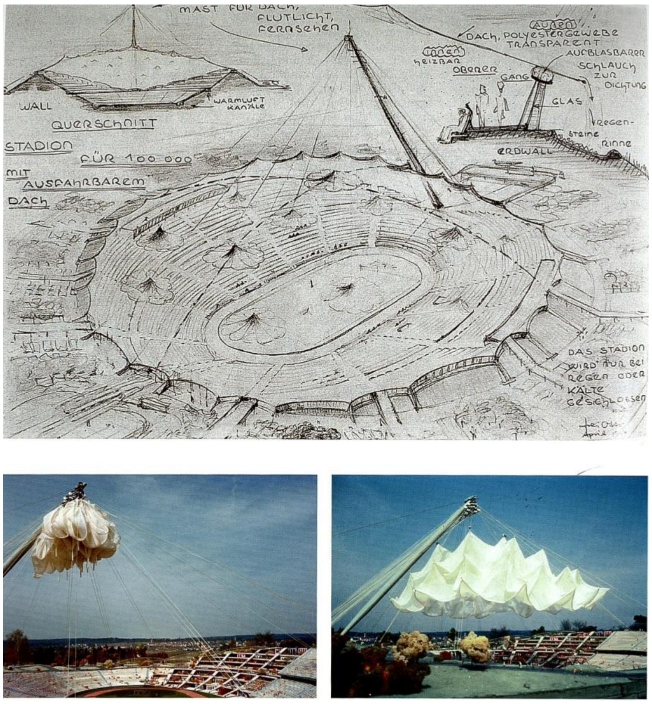


Figure 3.33. Convertible Structure of Multimedia Stadium for the Olympic buildings 1970 (Source: Otto & Rasch, 1995)

Another deployable example for cable-membrane structure is the retractable roof of Olympic complex in Montréal, Canada. The French architect Roger Tailibert designed an Olympic complex for the Olympic Games in 1976. This complex accommodates the ring-shaped stadium, the mast and the spherical vault of the velodrome. The central playground and the race tracking field are covered by 20 000 m² PVC/Kevlar folding membrane roof which is opened and closed by 28 stray cables connected to 175 m inclined tower. This complex has become one of the Montréal's landmarks. Although, the stadium was opened in 1976 but retractable roof was finished in 1988. The retractable roof replaced with a non-retractable spatial steel roof structure in Olympic Stadium of Montréal, Canada (Figure 3.34) because complication occurred in the case of the the stabilization of the membrane in all the possible configurations (folded, during deployment, opened configuration). The membrane damaged due to local failures and weather conditions (Holgate, 1997).

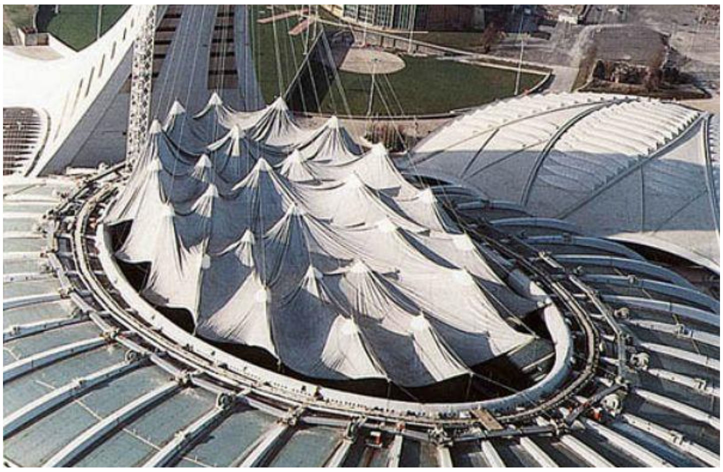


Figure 3.34. Olympic Complex in Montréal, Canada (Source: Taillibert, 2013)

Evidently, a more successful example for deployable membrane structures is the membrane roof of the bullfighting area in Zaragoza, Spain (Figure 3.35). The area is covered with a combination of a fixed and a convertible, central membrane roof. It is designed by the German firm Scleich, Bergman and Partners in 1989. It is a light cable-membrane structure with a fixed exterior ring supported by 32 radial cables. Only the interior part of the roof is retractable. The area of the fixed roof is 4.400 m² and the area of movable part is 1.000 m². The construction does not have any columns over a diameter of 88 meter. The visitors enjoy the stunning spectacle of the unfolding and opening process of the roof because takes only three minutes to unfold. This example is a good one that proofs kinetic structure is an appropriate way to create exceptional structures (Bergermann & Schlaich, 1992).

Figure 3.35. Retractable Roof for bullfighting area in Zaragoza, Spain. (Source: Tensinet, 2012)

As aforementioned in the beginning of the current section (3.2.1.3), cable-membrane structures have low stiffness. Prestressing is a method to increase their stiffness. There is another group of membrane structures, which uses internal pressure to control their stiffness characteristics called pneumatic structures. Probably, the balloon is the most well-known basic pneumatic structure.

Pneumatic structures have natural deployability character due to their property of controlling stiffness through pressure. Pneumatic structures are divided into two; 1) air supported structures and 2) inflated structures (Figure 3.37). Air supported structures consist of a single structural membrane, which is supported by a small air pressure differential. The internal building volume is at a pressure slightly above atmospheric so pressure differential occurs in and out of the building. On the contrary, in air inflated construction, air is contained in a close membrane to form inflated structural elements, such as walls, beams, arches, columns. Air inflated structures composed of small air inflated structures inside and outside of the main structure. In inflated constructions, loss of air pressure is less but periodic air replenishment is needed. The principles of these structures are shown in Figure 3.36.

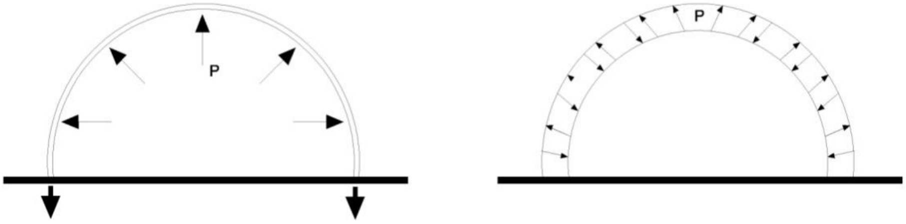


Figure 3.36. Principles of Air Supported and Air Inflated Membrane (Source: Gantes, 2001)

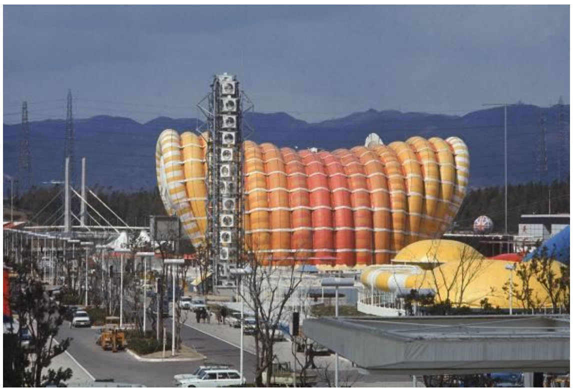


Figure 3.37. Fuji Group Pavilion EXPO ’70 Osaka, Japan; is an example for air inflated membrane (Source: Tumblr, 2013)

Mush-balloon designed by Tanero Oki Architects for EXPO ’70 in Osaka, Japan; is an example for kinetic air supported pneumatic structures (Figure 3.38). It is an inverted shaped balloon, suspended by 45 wire ropes that pass from the top of a pole through the center of the balloon. The balloon is made of an upper and lower fabric. These fabrics are braced by inner ropes. Opening and closing process of the balloon automatically has controlled by air pressure and ventilation system. But the most appropriate control is to blow air in or vent it out, adjusting the pressure continuously, accurately and keeping it within a range that would cause no deformation at all.

Figure 3.38. Mush-balloon designed by Tanero Oki Architects for EXPO ’70 in Osaka. (Source: Tensinet, 2012)

3.2.1.4 Tensegrity Deployable Structures

Tensegrity is a fascinating concept developed by sculptor Kennet Snelson, and later patented and explored by Buckminster Fuller (1962). The architect Fuller pioneered that the method “tensegrity” could be applied to large architectural domes. Fuller describes tensegrity as follows; “A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space.”(as cited inTibert, 2002, p.24). Hanaor and Levy (1980) have a simple tensegrity definition as “In its purest form, a tensegrity structure consists of a network of bars and cables, in which any bar is connected only to cables and to no other bar” (Hanaor & Levy, 2001, p.218). Pugh’s (1976) definition as follows; “A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space” (as cited inTibert, 2002, p.24).

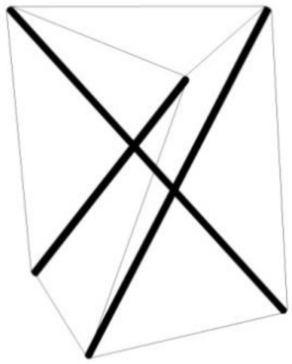


Figure 3.39. Simple Tensegrity Structure with Three Compression Struts

Tensegrity structures have no redundant parts. As a consequence, they are lightweight structures in comparison to other structures with similar resistance. Tensegrity modules can be joined in order to create structural elements as beams, columns. Tensegrity systems are self-anchored, however; they pull against themselves. Such structures are self-stressed in a "closed" system (Robbin, 1996). Self stressing and the load bearing capacity are directly proportional in tensegrity structures. If the self-stressing capacity is higher, its load-bearing capacity is higher too. The flexibility and the stiffness of the structure depend on the material employed and by their method of assembly. To sum up, tensegrity structures have many properties. As a deployable structure, tensegrity structures are practical because a small quantity of energy is needed to change their configuration because its shape changes with the equilibrium of the structure. Consequently, they are used in various kinds of deployable architectural applications like shelter systems, domes, roof structures and towers. Tensegrity structures can be used as installations, sculptures, furniture, toys and leisure applications (Figure 3.40) besides architecture.

Figure 3.40. “Easy-K Installation” Snelson in 1970. Arnhem, (Holland) (Source: Kennethsnelson, 2012)

David George Emmerich, is the the first to have pointed out the possibilities of generating double-layer tensegrity grids (Robbin, 1996). Emmerich’s works motivated researchers about tensegrity systems like René Motro. René Motro is the French engineer and researcher and has studied tensegrity structures and folding tensegrity systems (Figure 3.42). Deployment or folding is very promising application field for tensegrity systems. Tensegrity systems can be folded and unfolded by modification of element lengths. Length changes can be applied to both struts and cables. Many different possibilities can be explored, depending on the designer’s choice (Motro, 2003). Tibert and Pellegrino (2003) also studied on deployable tensegrity masts (Figure 3.41). Hanaor (1980), an Israeli engineer has studied double-layer tensegrity grids and the deployable examples in his research (Robbin, 1996).

Figure 3- 41 Physical model of Pellegrino’s folding mast at different stages of folding process (Source: Tibert & Pellegrino, 2003)

Figure 3- 42 Réne Motro’s prototype of a double-layer, double-curvature tensegrity system, continuous cables join the nodes (Source: Robbin, 1996)

Tensegrity structures had succesfully used as architectural elements in The Prairie House. The Prairie House is a kinetic tensegrity system, designed by Tristan d’estree Sterk who is the founding partner of a group called The Office for Robotic Architectural Media & The Bureau for Responsive Architecture (Orambra) in Northfield, Illinois (Figure 3.43).

Figure 3.43. “The Prairie House” Tristan d’estree Sterk in 2010.Northfield, Illinois (Source: Orambra, 2012)

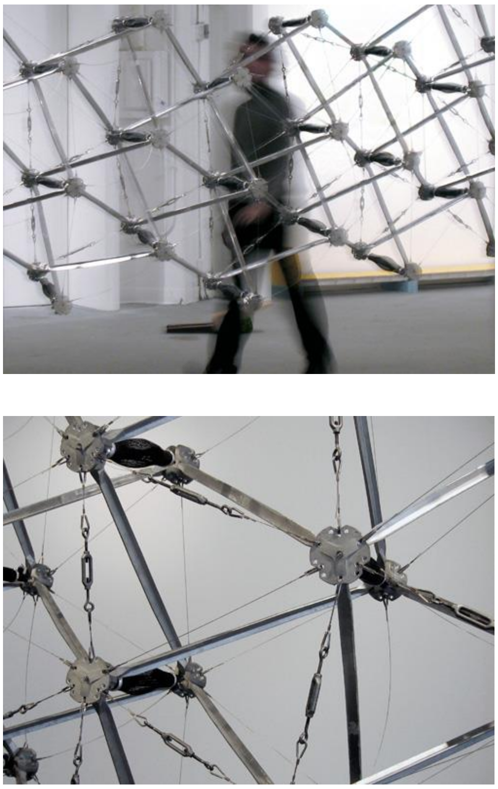


Figure 3.44. Actuated tensegrity prototypes. (Source: Orambra, 2012)

This group focuses on responsive architecture and interests in obtaining the art of construction in a peculiar way by designing structures that can change its shape and volume in order to prevent energy lost within the structure. These systems are parametric structures and surfaces that are actuated with thermal memories. They generate actuated tensegrity prototypes to use them in the projects like Prairie House (Figure 3.44). It is claimed that Prairie house emits less than half of the carbon of a typical house in Illinois because the house can change its shape and volume with its actuated tensegrity structure (Ayres, 2012). In the hot weather, the volume of the house expands to reduce the impact of internal heat loads conversely. In the cold days, it shrinks itself to reduce heating requirements.

3.2.1.5 Retractable Roofs

Retractable roofs are roof structures that can transform from one configuration to another (typically the open and closed roof) to provide variable cover to the space underneath in response to changing conditions and/or functional requirements (Mele, 2008). In their closed configuration, retractable roofs remain rigid and do not fold; this is the main distinguishing feature between retractable roofs and other types of deployable structures. Retractable roofs are usually used for swimming pool enclosures or other sports facilities. These systems have not only found their use in sport venues but also at shipyards, exhibition and recreational spaces, greenhouses, shopping malls, and for public spaces. Moreover, they are mainly used in climates with inclement weather change to allow for playing of traditionally outdoor activities in more favorable conditions. Although small-sized retractable roofs have existed for a long time, since the 1930's, the construction and worldwide spread of large size retractable roof systems is only a recent phenomenon. The first systems were based on well-known crane technology, soon to be followed by folding membranes, inspired by umbrellas and tents, and telescopic systems. (Mele, 2008).

The retractable roof systems can be roughly classified into two according to their coverings. The cladding of the structure should be made of flexible material like membrane to be deployed from retracted or open position into a closed or extended position to cover the area. Either, the cladding can be non-collapsible rigid frames or panels. These panels are covered with rigid or flexile materials such as glass, plastics, membrane materials, and metal plates. Therefore, opening and closing of these roofs involves sliding, rotating, or folding of the panels. As well as, opening and closing should be easy to operate by a few people. The structure should be safe in all three configurations; open, closed and partially open. Horizontally moving systems are popular since they easily fit rectangular swimming pools.

The Pittsburgh Civic Arena, or Mellon Arena, in the United States is known as the earliest example of wide-span retractable roofs that were built according to crane technology in 1958-1961 (Figure 3.45). The arena was designed by Mitchell & Ritchey.

The retractable roof panels rotate and overlap each other, with their central pivot supported by an external cantilevered beam (Mele, 2008).

Figure 3.45. Pittsburgh Civic Arena in the United States in 1958-1961 (Mele, 2008)

The Ocean Dome in Miazaki, Japan is the world’s largest indoor water park with its world’s largest fully retractable roof. The maximum opening of the roof is 100 m by 180m. The structure of the roof contains four sections and each section is 51.5 meter wide and 110 meter long and weighs 700 tons (Figure 3.46). Several projects of this type realized in Japan like Fukuoka stadium by the Takenaka Corporation, with a total floor space of 176.000 m², a retractable roof structure with three spherical steel segments and a parallel lamellar truss system, seven floors above ground (Gantes, 2001). The first successful retractable roof in America was in the Toronto Skydome with its three-panel, steel roof available for use in bad weather. It was designed by Rod Robbie and the retraction time is twenty minutes (Gantes, 2001).

Figure 3.46. Ocean Dome Miazaki City, Japan (Gantes, 2001)

Except horizontal solutions, radial rotational systems are using to enclose circular areas. These radial systems have a circular pillar and the whole system moves around it. Figure 3.47. shows the radial rotating principle of these systems.

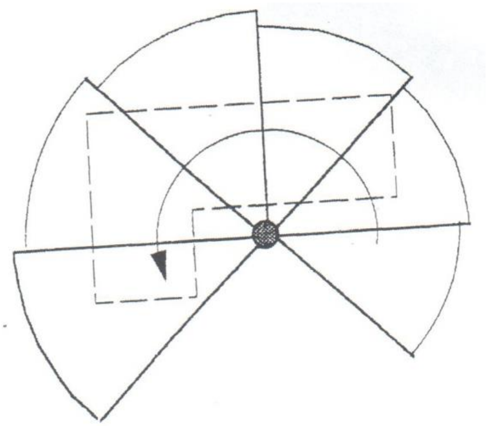


Figure 3.47. Radial rotating principle (Source: Gantes, 2001)

3.2.2 Pellegrino Classification

Prof. Sergio Pellegrino is a specialist in structural mechanics. He founded the deployable structures laboratory in 1990 within University of Cambridge in order to develop novel concepts of deployable and adaptive space structures. He did not propose a clear classification; he grouped deployable structures in the book called “Deployable Structures” which he edited from his courses and lectures.

The majority of the titles in Pellegrino’s book do not contain architectural applications. Consequently, they are not related with the present dissertation. For instance, coiled rods have been extensively used for spacecrafts, to deploy and retract scientific instruments and solar arrays. Flexible shells are also in the same way, they are not related with architecture, and they are for space applications. Pellegrino grouped retractable tension structures, retractable roofs, pre-stressing membranes in the title of “membrane”. This title consists of architectural samples, like retractable tension structures are commonly used for canopies and awnings.

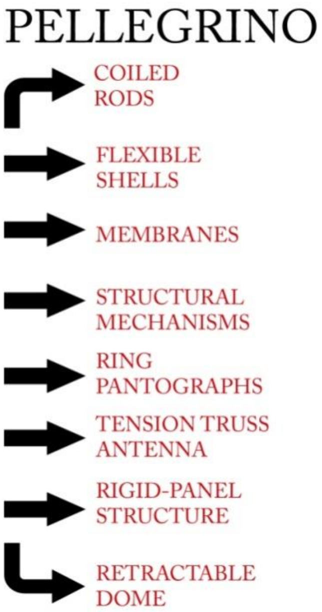


Figure 3.48. Pellegrino’s classification of deployable structures. (Source: Pellegrino,2001)

Structural mechanisms; “deployable structures that belong to the mechanisms category are assemblies of ‘rigid’ parts connected by movable joints, arrange in such a way that the transformation from a packaged configuration to a deployable configuration is possible.” (Pellegrino, 2001, p:16). Structural mechanisms contain pantographs which are mentioned in Gantes’ classification. For structural mechanisms, retractable hardtop of the cars is a good example from automotive industry.

Figure 3.49. Retractable hardtop of the car; is an example for structural mechanisms (Source: Bmw, 2013)

Unlike Gantes, Pellegrino evaluated ring-like pantographs as a special group. These structures are commonly used as deployable antennas. Tension truss antenna and rigid-panel structures are both serving for space applications. Rigid-panel structures are also used for solar arrays to generate electrical power. The last title in Pellegrino's classification is retractable dome. Hoberman's Iris Dome which was discussed in Gantes' classification is the significant one as an example for a retractable dome.

3.2.3 Hanaor Classification

Ariel Hanaor is a civil engineer who had worked on space trusses in his doctoral research at the University of Melbourne, Australia. He had also focused on space structures, structural analysis, tensegrity systems and concrete technology. Prof. Robert Levy is a researcher in the civil engineering department and he had focused on geometrically nonlinear shell structures, fabric structures, optimal seismic control of buildings, structural optimization.

Hanaor and Levy (2001) have a different approach towards deployable structures in their common paper called "Evaluation of Deployable Structures for Space Enclosures". This paper contains a comprehensive classification of deployable structures. According to their view, in deployable structures morphological aspects and kinematic properties are significant and they build the context of deployable structures. They composed a classification chart (Figure 3.50) for deployable structures and in their chart the columns represent the morphological aspects of the structures such as the structure is lattice or skeletal and continuous or stressed-skin structures. In skeletal structures, the primary load-bearing structure consists of discrete members; whereas in continuous structures the covering itself performs the load-bearing function. The rows in the chart represent the kinematic properties. They mentioned that the kinematic property of deployable structures is related to deployment technology. Kinematic properties are divided into two subcategories; the ones with rigid links such as bars, plates and the ones with deformable components. The deployable structures with deformable components lack of flexible stiffness such as cables or fabric.

Lattice bar structures comprise three major parts, double layer grids, single layer grids and spine. Structures based on scissors or pantographic grids are the most widely investigated configurations in the literature. They also divide into subtitles as peripheral scissors, radial scissors, angulated scissors and so on. Except scissors and pantographs, lattice bar structures contains bar structures as ruled surfaces, articulated joints and reciprocal grids. Reciprocal grids are essentially domical surfaces consisting of mutually supported beams. Strut-cable systems are deployable structures with deformable components. It can be claimed that strut-cable systems as tensegrity systems that were mentioned in Gantes' classification. The other deformable group in Hanaor's classification is tension membrane systems. This group possesses two sub-groups; fabric structures which require a surface of negative Gaussian curvature (saddle shape) and pneumatic structures which use air pressure to prestress the membrane in order to obtain stiffness.

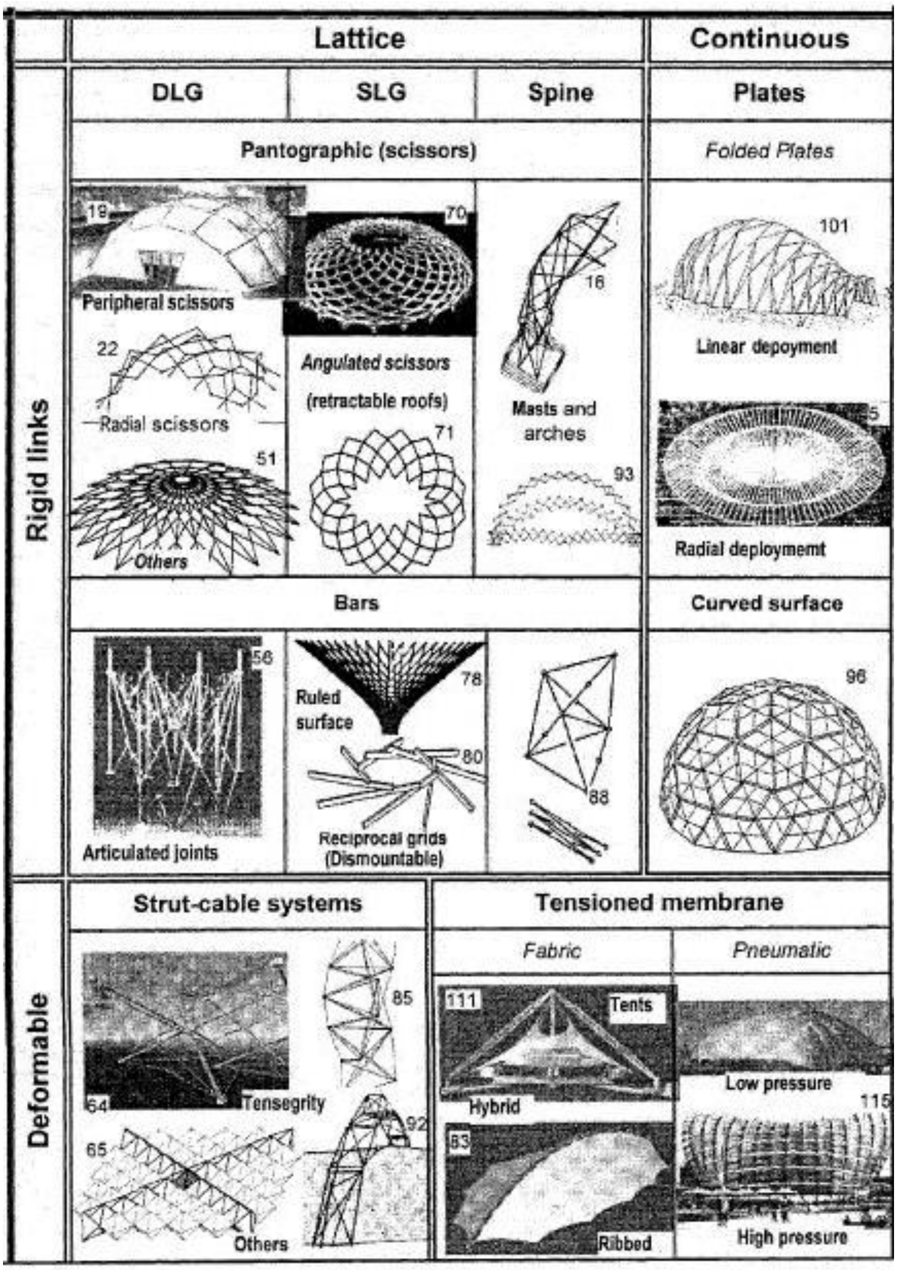


Figure 3.50. Deployable Structure classification chart by A.Hanaor and R.Levy (Source: Hanaor & Levy, 2001)

3.2.4 Korkmaz Classification

Koray Korkmaz is an associate professor who works on kinetic structures and their potentials within the Department of Architecture in Izmir Institute of Technology, Turkey. Korkmaz had constituted a classification chart in his PhD thesis called "An Analytical Study of the Design Potentials in Kinetic Architecture" according to Kronenburg's kinetic architecture definition**.** "Kinetic architecture is defined generally as buildings, or building components with variable location or mobility and/or variable geometry or movement" (as cited in Fox, 200, p:12).

According to Kronenburg's definition he divides kinetic architecture into groups in terms of 'time'. In that sense, Korkmaz grouped the structures into two. In the first group named "Buildings with variable Location or mobility" action takes place before using the structure. This primary action is necessary in order to obtain initial form of the structure. Portable, relocatable and demountable structures belong to this group. In the second group called "Buildings with variable geometry and movement" the action takes place after the initial architectural form of the structure is obtained. In other words, structure contains a continuous movement.

Then Korkmaz created sub-divisions according to structures' materials. (Figure 3.51) For instance, buildings with variable geometry and movement consist of soft formed and rigid formed structures. Soft forms of structures are created with flexible space-enclosing materials such as membranes that are transformed by shoving, twisting, pushing or pulling. Rigid forms of building are those that are converted by sliding, folding or rotating structural elements. Rigid forms of structures still group into two as bar structures and surface structures. Additionally, linkage mechanisms differ from each other with their cover materials; the ones with flexible cover materials and the others with rigid cover materials.

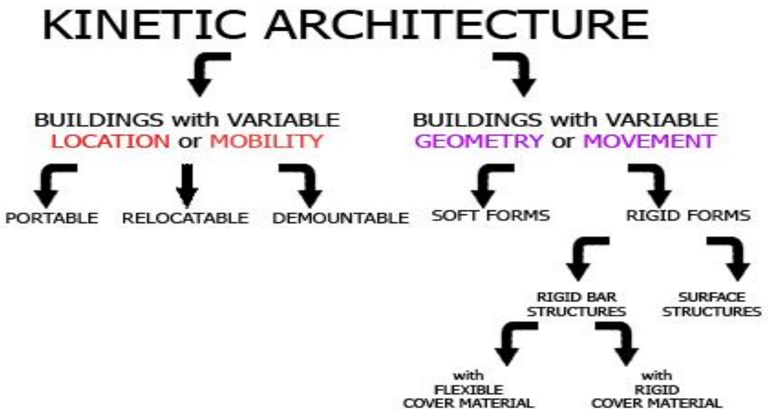


Figure 3.51. Major Classification of Kinetic Architecture (Source: Koray Korkmaz, 2004)

From Gantes' classification cable-membrane structures like Frei Otto's convertible roof structures (Figure 3.30, Figure 2.31) are placed into the subtitle called soft forms of structures in Korkmaz's classification. Rigid forms of structures are bar structures like pantographs in Gantes' classification.

Frei Otto's adaptable weather-protection umbrellas for Pink Floyd's USA concert tour in 1977 (Figure 3.52) is an example for rigid bar structures with flexible cover materials. Frei Otto developed ten umbrellas that can be folded up and retracted into the stage floor. The umbrellas are 4.5 meters in diameter, their height varies between 2.5 and 4.4 meters, and total area covered is 128 m². The umbrellas were so aesthetically attractive, the musicians decided to integrate them into their stage show, so their appearance became a fixed element of the event (Nerdinger, 2005). The other considerable example for rigid bar structures with flexible cover materials is the largest convertible umbrellas that have been built so far for the two courtyard of the Prophet's Holy Mosque in Madinah, Kingdom of Saudi Arabia by Bodo Rasch and Frei Otto in 1995. Each courtyard has six umbrellas. These umbrellas are spanning 17 meters to 18 meters with a height of 14 meters in the open position. The umbrellas are open during the day and close through the night so they contribute to the regulation of the climate in the building (Figure 3.53, Figure 3.54).

Hoberman's arches in Figure 3.15. or Hoberman's Iris Dome covered with rigid panels are examples for rigid bar structures with rigid materials. Chuch Hoberman's Iris Dome has enclosure created by covering angulated elements with rigid plates, which are allowed to overlap in the retracted position (Figure 3.55) (Korkmaz, 2004).

Figure 3.52. Adaptable weather-protection umbrellas for Pink Floyd’s USA concert tour in 1977 (Source: Nerdinger, 2005)

Figure 3- 53 Umbrellas in Madinad during opening process (Source: Otto & Rasch, 1995)

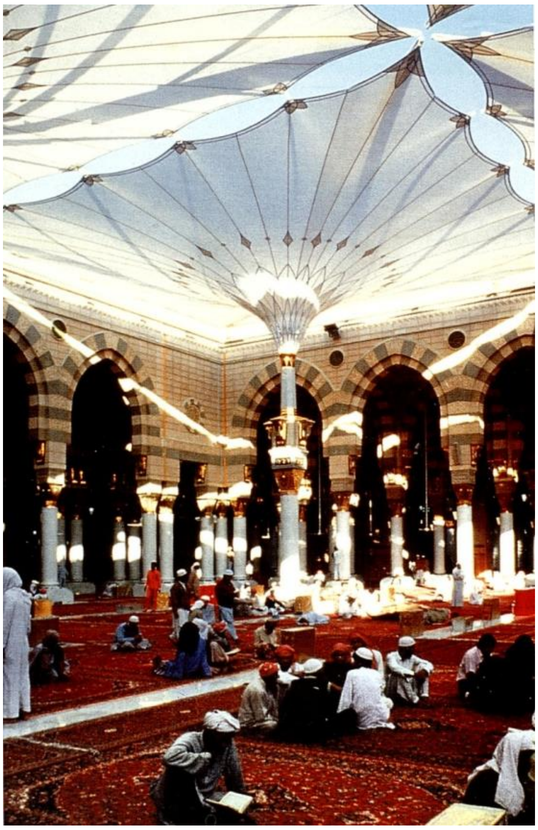


Figure 3- 54 Umbrellas in Madinad (Source:Otto & Rasch, 1995)

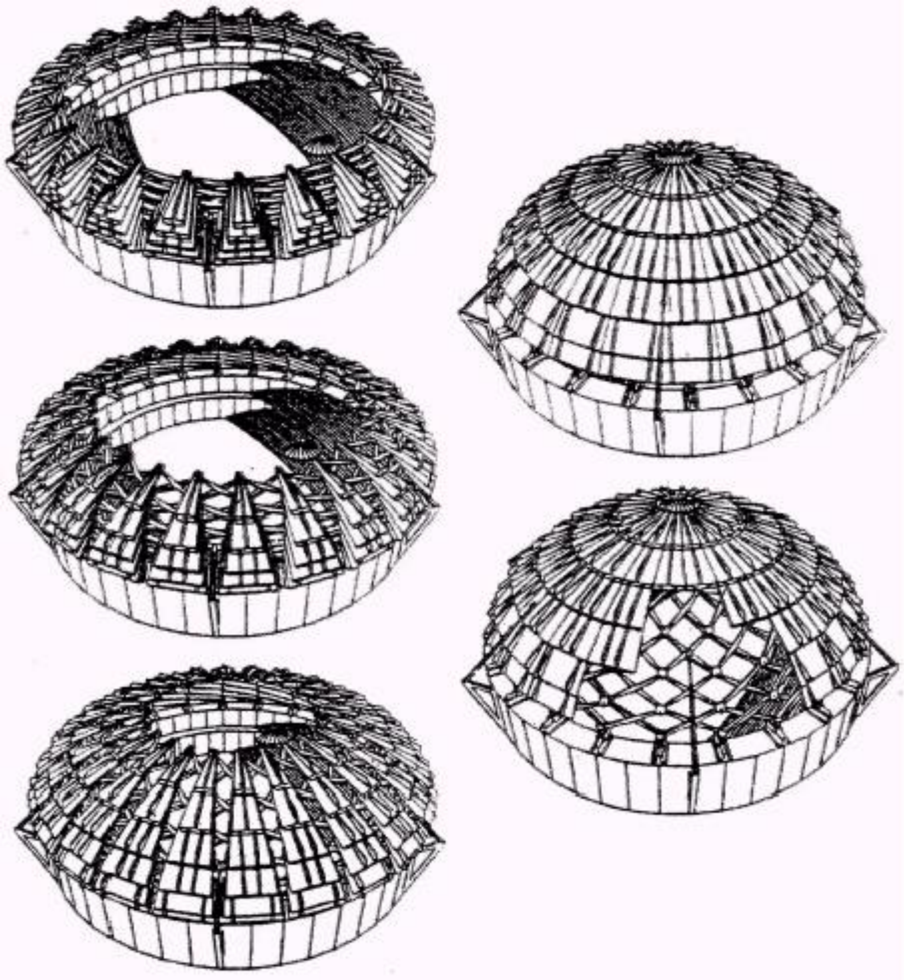


Figure 3.55. Iris dome covered with rigid panels (Source:Korkmaz, 2004)

3.3 Reconfigurable Structures

Mechanisms with multi-degree of freedom are called reconfigurable mechanisms and these structures can offer wide range of form flexibility compared to deployable structures. Reconfigurable structures are prefabricated structures that can be transformed as structural mechanisms from a closed compact configuration to multiple alternative expanded forms, in which they need external stabilization in order to become stable and be able to carry loads.

Since 1990’s, reconfigurable mechanisms and robots are popular between kinematicians and roboticians. So, architects and civil engineers must meet with reconfigurable structures in the present century in order to get rid of deployable structures’ limits. Reconfigurable structures can be designed to respond kinetically to future changes and they ensure re-purpose functionality to the structures. Plus, they enhance the resilience through alteration and just like deployable structures, they hasten the construction process.

Kokawa's (1995) expandable cable scissors arch (CSA) can be an example for reconfigurable structures because of its continuously changing configuration (Figure 3-57). This structure can change its geometry without changing the span length. It is a new type of expandable structure with three hinged arch scissors and zigzag flexible cables through pulleys with them. The changing form of the structure is controlled only by winding up or winding back by a winch. The basic idea of Kokawa's Cable Scissors Arch (CSA) is shown in Figure 3.56.

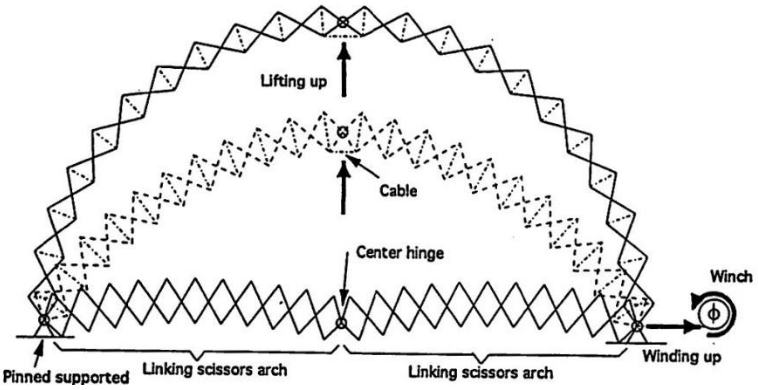


Figure 3.56. Basic Idea of Kokawa's expandable scissors (Source: Kokawa, 95)

Figure 3.57. Prototype of CSA (Source: Kokawa, 2012)

Inoue (2008) designed a movable arch. This arch structure comprises several variable geometry trusses (VGT). These trusses have extendable members, fixed members and hinges, as shown in Figure 3.58.

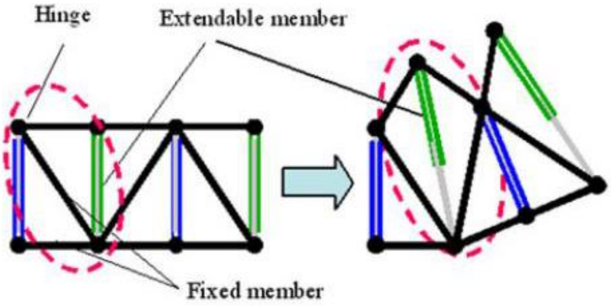


Figure 3.58. Basic Mechanism of VGT (Source: Inoue, 2008)

Inove (2008) explains VGT's working principles as follows;

> "When extendable members are extended simultaneously, the truss beam was changed like a spring stretching from (a) to (b). When the extendable members are extended alternately, the truss beam was changed to a circular shape (c). Moreover, when they are extended optionally and their lengths are controlled, the truss beam can be changed into any intended shape (d). Based on the shape change of such a basic beam, the feasibility of shape change in an actual building was examined. This has been applied to architectural design and construction."(Inoue, 2008 p: 172) (Figure 3.60).

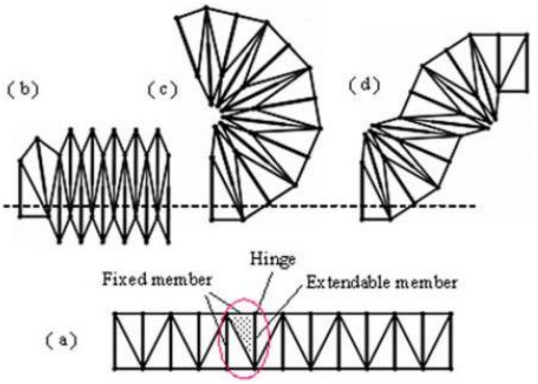


Figure 3.59. Transformation of beam shape using VGT (Source: Inoue, 2008)

Inoue and his colleagues have applied VGT to a spatial truss structure and designed an attractive, unique monument for EXPO 2005 in Japan. Its shape could be changed variably and irregularly (Figure 3.60). The shape of the monument changes according to the performance patterns. On the other hand, Variable Geometry Truss is not feasible as a building component because numerous actuators are needed to realize the movement.

Figure 3.60. Movable Monument at EXPO 2005 designed by Inoue and his colleagues (Source: Inoue 2008)

Akgün (2010) criticized the previous scissor hinge structures in his doctoral dissertation and proposed a novel transformation model for deployable scissor hinge structures in order to overcome the shortcomings of previous examples.

He aimed to achieve remarkable shape transformations with minimum numbers of actuators and increase the feasibility of scissor-like elements. In his dissertation, he noticed that Kokawa’s structure can’t transform to asymmetrical shape. Therefore, he modified scissor-like element by attaching additional revolute joints on the bars. This is called M-SLE. In this way, he enhanced the transformation ability of the structure. Transformation ability depends on the number of M-SLEs, the number of SLEs and M-SLEs and support points. So, he increased the possibilities of potential configurations. His structure fixed from the both sides to the ground or to the appropriate surfaces of a building and its span length is constant, just like Kokawa’s expandable cable scissors. The proposed structure can be both spatial and planar. Akgün first found M-SLE for the planar version. The planar version of the structure can constitute various curvilinear geometries (Akgün, 2010) (Figure 3.61). Then he designed spatial module shown in figure 3.62.

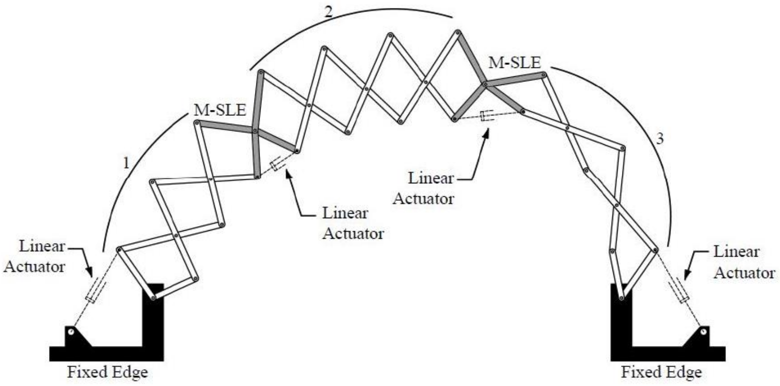


Figure 3.61. Akgün's Proposed planar scissor-hinge and its elements (Source: Akgün 2010)

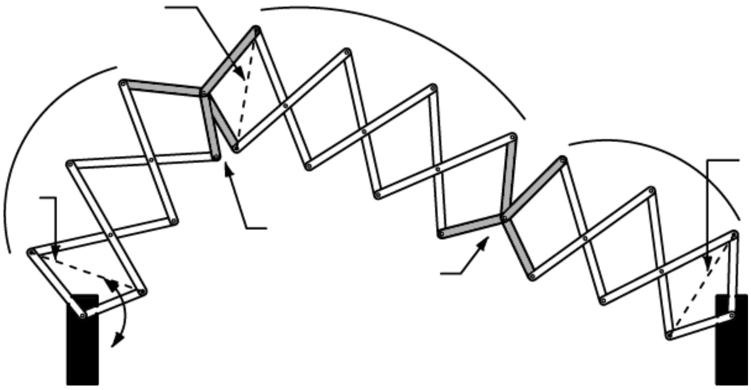


Figure 3.62. Akgün's Proposed planar scissor-hinge and its elements (Source: Akgün, 2010)

Akgün had proposed a roof structure which can offer both flat and curvilinear forms without changing the span length. He ensured the curvilinear form with the help of his proposed modified scissor like elements. Then he designed spatial module shown in Figure 3.63.

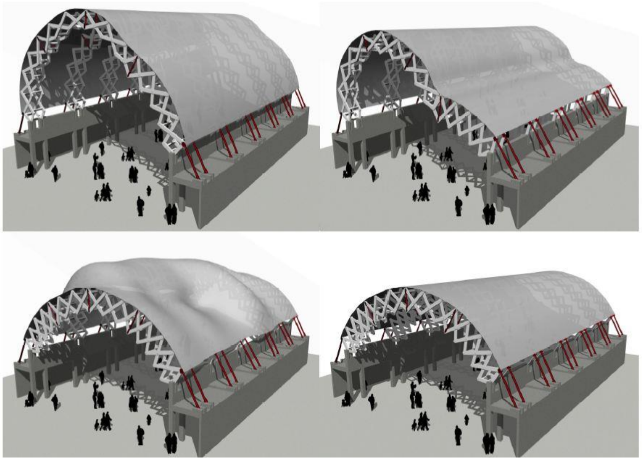


Figure 3.63. Proposed planar scissor-hinge structure as an adaptive roof (Source: Akgün, 2010)

CHAPTER 4

CURVED SURFACES

The surfaces derived from curves commonly arise in architecture because curved surfaces are more resistant than planar structures. Furthermore they are aesthetically well-structured; the best example of this is Félix Candela’s thin shell structures.

There are lots of classifications for the geometry of curved surfaces. Türkçü gives place to a classification of Curt Siegel in his book (Türkçü, 2009) (Figure 4.1). In this classification, the shape of the profile curve is taken into consideration and curved surfaces are divided into three groups; single curvature structures, double curvature structures and freeform surfaces.

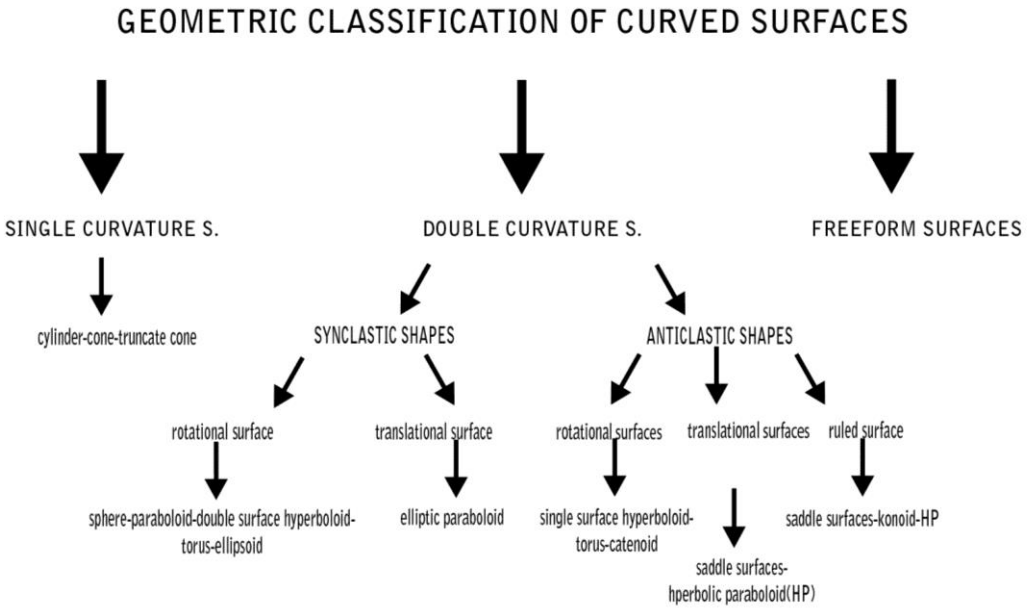


Figure 4.1. Curt Siegel (1972)’s classification (Source: Türkçü, 2009)

In order to describe structures according to their curvatures, some terms must be mentioned. As a matter of fact, in most cases the shape of the profile curve heavily influences the final shape of the emerging surface. The profile curves are called principal curvature and in differential geometry, the Gaussian curvature or Gauss curvature of a point on a surface is the product of the principal curvatures (Wikipedia, 2012). In simplest way, curvatures called k1 and k2 in Figure 4.2. are the “principal curvatures” of the hyperboloid. The product K: k1 x k2 of principal curvatures is “Gaussian curvature”.

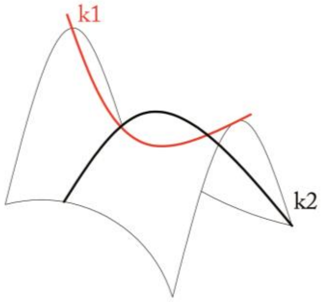


Figure 4.2. Principal Curvatures; k1 and k2

4.1 Single Curvature Surfaces

In single curvature structures Gaussian curvature is always zero because the principal curvature of k1 is a straight line and k2 is a curve. Cylinder, cone, truncate cone are single curvature geometric forms with zero Gaussian curvature (Figure 4.3).

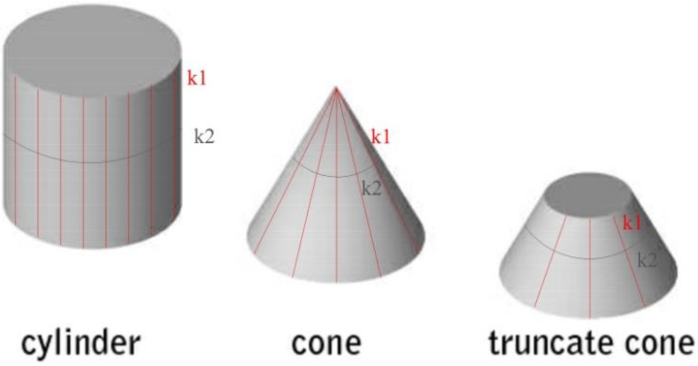


Figure 4.3. Examples of Single Curvature Surfaces.

4.2 Double Curvature Surfaces

Gaussian curvature of all points of double curvature surfaces are different from absolute zero, it varies as minus (-) or plus (+) (Türkçü, 2009). Except cylinder and cone, all rotational surfaces are double curvature surfaces. According Siegel’s classification; double curvature surfaces are divided into two groups as ‘synclatic surfaces’ and ‘anticlastic surfaces’**.**

4.2.1 Synclastic Surfaces

Synclastic surfaces’ Gaussian curvature is positive (+) and according to the generation method they are classified into two groups; they can be generated either by rotation or translation. Tangent planes that are drawn to all synclastic surfaces (both rotational and translational) do not cut off these surfaces. This is not true for anticlastic surfaces. Tangent planes cut the surfaces into several parts in anticlastic surfaces (Türkçü, 2009).

Elliptic paraboloid is a translational synclastic surface (Figure 4.4.). Elliptic paraboloid is generated by translating a parabola along another parabola. Both generating parabolas have to be open to the same side and must have parallel axes. The axis of an elliptic paraboloid is the intersection of the two symmetry planes (Pottmann, 2007).

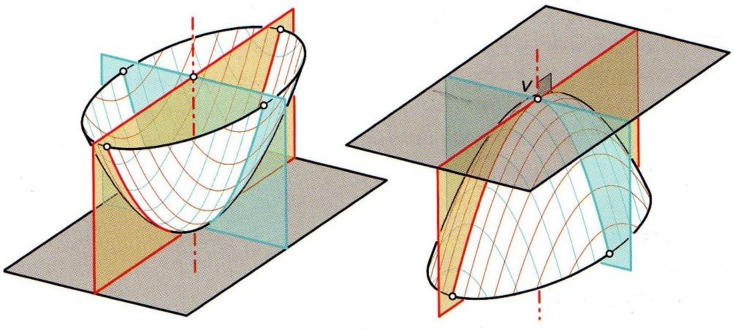


Figure 4.4. Elliptical paraboloid is a translational synclastic surface (Source: Pottmann, 2007)

Sphere, paraboloid, ellipsoid, two-sheet rotational hyperboloid, torus are rotational synclastic surfaces (Figure 4.5.). Rotating a circle about any of its diameters produces a sphere. Rotational synclastic surfaces, especially sphere and spherical pieces are commonly used in architecture. ‘Dome’ which has a great importance in architecture is the architectural term for sphere. A rotational paraboloid arises by rotating a parabola about its axis. Paraboloid is also a suitable form for dome structures. For example, St. Peters Church in Vatican, Florence Catedral of Brunellesci, St. Paul Catedral in London possess parabolic domes (Türkçü, 2009). It is possible to generate two-sheet rotational hyperboloid by rotating a hyperbola about its major axis. And two types of ellipsoids can be generated, first one is oblate rotational ellipsoid generated by rotating the ellipse about its minor axis. The second one called prolate rotational ellipsoid. For the second type of ellipsoid, it is possible to rotate the generating meridian ellipse about its major axis. The Reichstag dome by Norman Foster in Berlin is an example for ellipsoid in architecture; it has the shape of half a rotational ellipsoid (Figure 4.6). Torus can be generated by rotating a circle about an arbitrary line. An industrial building for Walloon Branch of Reproduction Forestry Materials in Marche-en-Famenne by Samyn and Partners features a part of a torus and the shape of the TGV railway station in Avignon was obtained by the intersection of two ring tori (Figure 4.7) (Pottmann, 2007). As a summary, every synclastic surfaces are useful and important basic elements of many architectural design processes.

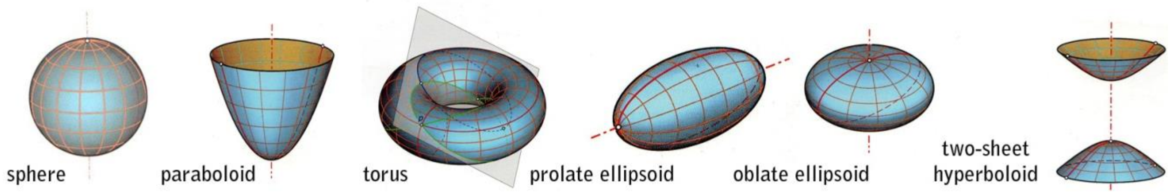


Figure 4.5. Examples of rotational synclastic surfaces (Source: Pottmann, 2007)

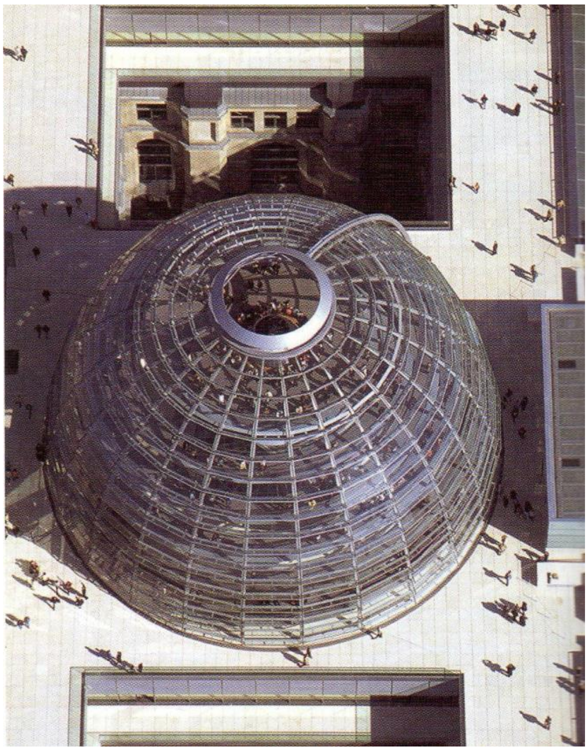


Figure 4.6. The Reichstag Dome in Berlin by Norman Foster (Source: Pottmann, 2007)

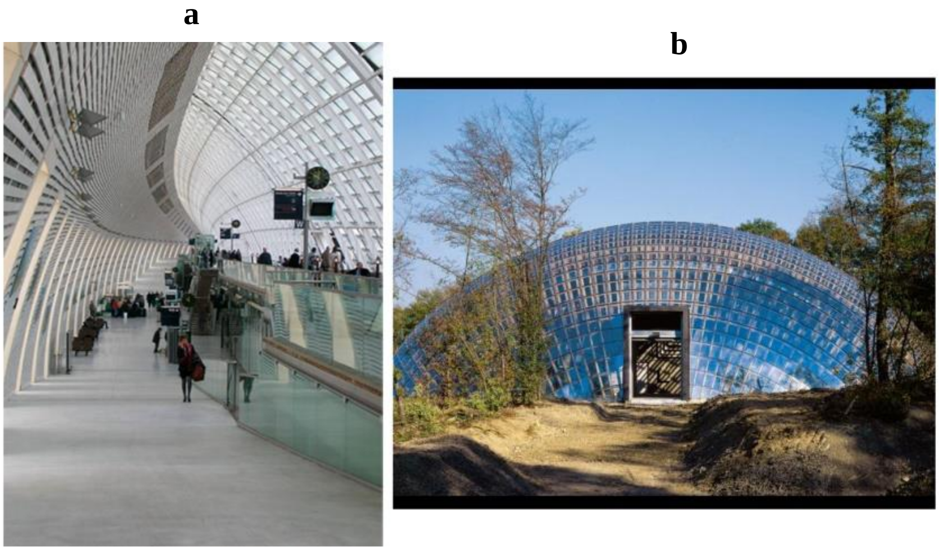


Figure 4.7. a) TGV railway station in Avignon b) An industrial building in Marche-en-Famenne by Samyn and Partners (Source: Pottmann, 2007)

4.2.2 Anticlastic Surfaces

Anticlastic surfaces' Gaussian curvature is negative (-). According to the generation method, they are classified into three groups, rotational surfaces, translational surfaces and ruled surfaces. As shown in Figure 4.8, rotational anticlastic surfaces are one sheet hyperboloid, torus and catenoid.

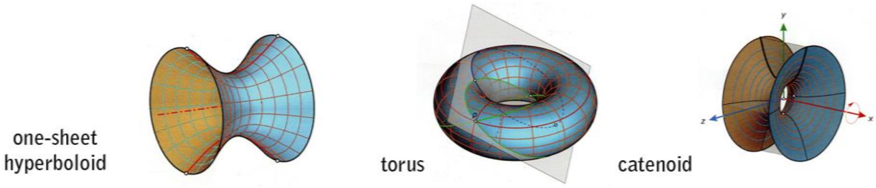


Figure 4.8. Examples of rotational anticlastic surfaces (Source: Pottmann, 2007)

The one-sheet rotational hyperboloid is a rotational surface resulting from a conic section being rotated about one of its axes (Pottmann, 2007). Parts of one-sheet rotational hyperboloids are commonly used in architecture and design. In architecture they can be seen widely as cooling towers and water storages. Metropolitan cathedral designed by Oscar Niemeyer and Joaquim is an example for one-sheet rotational hyperboloid in architecture (Figure 4.9).

Figure 4.9. Metropolitan Cathedral in Brasilia 1959-1970 (Source: Architectureabout, 2013)

Prior to the description of the catenoid, it is good to look at the definition of the term catenary. “It is the equilibrium shape attained by an idealized rope (homogeneous, completely flexible, and not flexible) under the influence of gravity.” (Pottmann, 2007 p.652) (Figure 4.10). A catenoid is a three-dimensional surface made by rotating a catenary curve about its directrix (Wikipedia, 2012) (Figure 4.8).

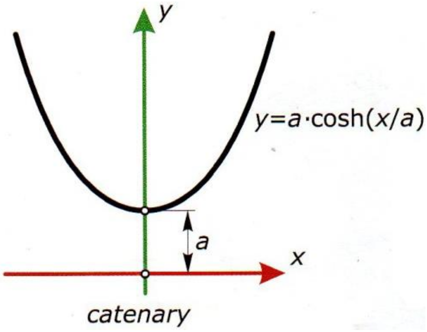


Figure 4.10. The shape of the catenary. (Source: Pottmann, 2007)

Translational anticlastic surfaces are hyperbolic sections (saddle shaped surfaces) and hyperbolic paraboloids. Hyperbolic paraboloids, also called as hypars, can be generated as a ruled and translational surface. For example, in Figure 4.11 there is a hyperbolic paraboloid which is generated by translating a parabola along another parabola. Every cross section of hyperbolic paraboloid surface is a saddle shaped, in other words they are hyperbolic sections. Hyperbolic sections can be generated as ruled and translational surface like hypars (Figure 4.12). These special forms of translational and ruled surfaces are seen widely in architecture and design.

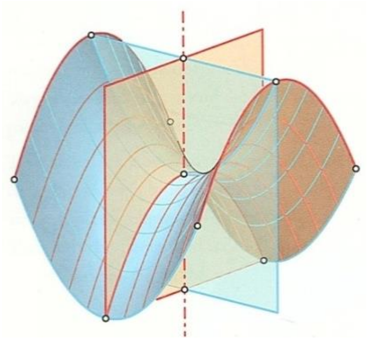


Figure 4.11. A hyperbolic paraboloid which is generated by translating a parabola along another parabola (Source: Pottmann, 2007)

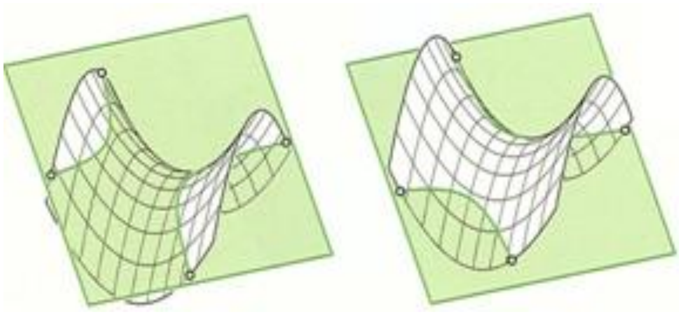


Figure 4.12. Hyperbolic sections (Source: Pottmann, 2007)

4.2.2.1 Anticlastic Ruled Surfaces

One-sheet hyperboloids , hyperbolic paraboloids, conoids are anticlastic ruled surfaces. Ruled surfaces can be generated by moving a generatrix and the most prominent property of ruled surfaces is that their generatrix is always a straight line. In order to generate a ruled surface, one generatrix (straight line) and two directrices are necessary. The directrices position on separate planes. One end of the generatrix is on one of the two directrices and the second end always positions on the other directrice. The generatrix sweeps the directrices by rulings with the same ratio distances, which is the method of generating a ruled surface. The directrices can be a point, a straight line, a circle or a curve. Another property of ruled surfaces is that they always extend to infinity because the generating straight lines extend to infinity. It is possible to create remarkable ruled surfaces with special choices of directrices and their parameterization. The designers have freedom to choose the directrices and the parameterization, this technique leads a wide diversity of possible shape.

Conoids are ruled surfaces which can be generated by moving a straight line segment along a directrix curve and a line. In other words, the first directrix of the conoids is always a straight line and the second directrix is a curve (Figure 4.13). Parts of the conoids are commonly used for design of shells or shed roofs. Allowing only rotations about the directrix, it is possible to generate a special type of conoid (Figure 4.14).

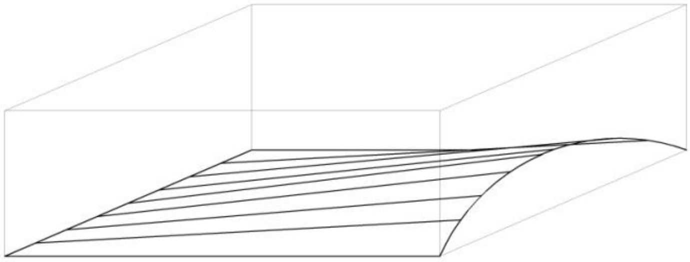


Figure 4.13. Conoid- 1st directirice – straight line, 2nd directrice – curve

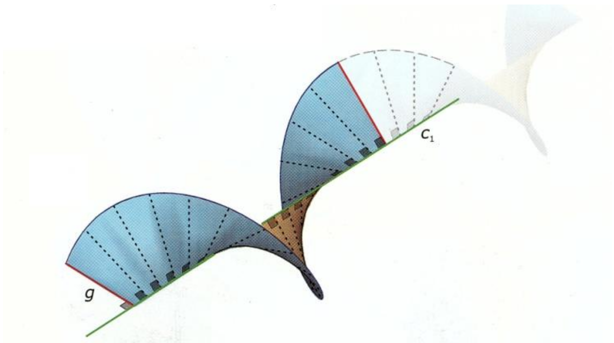


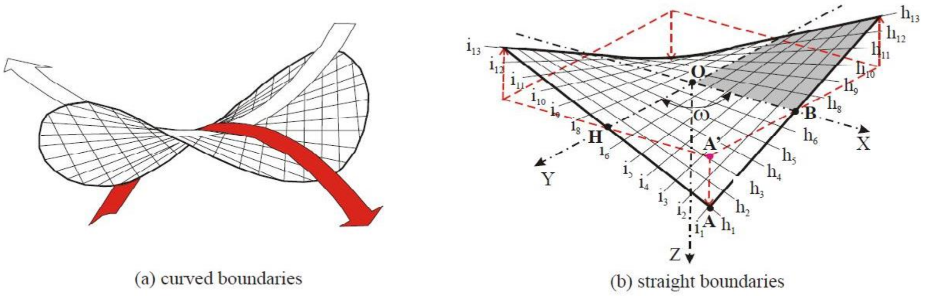
Figure 4.14. Special type of conoid (Source: Pottmann, 2007)

The New State Gallery which is designed by James Stirling has ruled surface facades which are generated by using two arbitrary curves as directrices (Figure 4.15). Furthermore, The Japanese Art and Technology Center's roof consists of ruled surfaces that are generated by arbitrary curves as directrices (Figure 4.16).

Figure 4.15. The New State Gallery (1977-1983) in Stuttgart by James Stirling (Source: Pottmann, 2007)

Figure 4.16. The Japanese Art and Technology Center in Krakow, Poland, by Arata Isozaki (Source: Pottmann, 2007)

Hyperbolic paraboloids are one of the most used ruled surfaces in architecture, especially in the area of shells. They are easy-to-use architectural elements and offer a wide range of design possibilities. Hyperbolic paraboloid is a ruled surface which has convex one way along and the concave along the other. Hyperbolic paraboloid (HP) can be obtained as a ruled surface by sweeping a straight line over a straight path at one end and another non-parallel straight path (Pottmann, 2007). The boundaries, or edges, of the hyperbolic paraboloid can be straight or curved (Figure 4.17.). In Figure 4.18., HP ruled surface is obtained by sweeping the lines *ab* and *dc,* these lines are divided with the same ratio *dist (a,p) /dist (p,b) = dist (d,q)/dist(d,c).*



(a) curved boundaries

(b) straight boundaries

Figure 4.17. The boundaries, or edges, of the hyperbolic paraboloid can be straight or curved (Source: Pottmann, 2007)

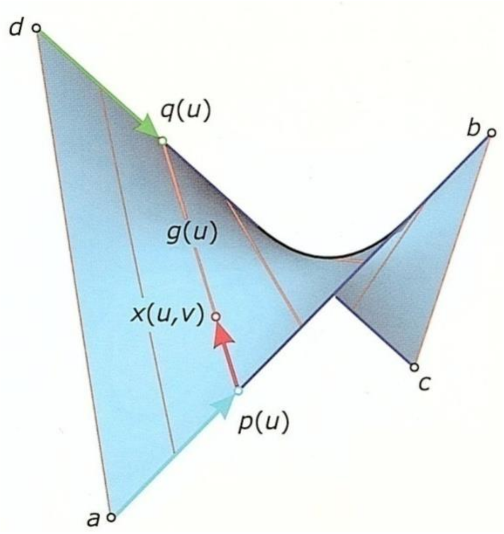


Figure 4.18. A hyperbolic paraboloid which is generated as a ruled surface (Source: Pottmann, 2007)

Hypar surfaces in architecture distinguish themselves both with their aesthetic beauty and with their relative ease of construction. They also add strength to the structure with their double curvature. They are generated with straight lines like all other ruled surfaces. As it was previously stated above, ruled surfaces' generatrix is always a straight line. This leads ease in the formwork of the structure. Thus, the construction of ruled surfaces is more economic compared to the other geometric forms (Figure 4.20).

HP surfaces are well established in the area of shells in architecture. The first concrete roof of this type was built in 1922, spanning 16m with just 3 cm thickness by the famous German shell builder Franz Dischinger. This structure triggered the success story of concrete shells (Figure 4.19) (Sciaich, 2010). There are hundreds of masonry or concrete shells which were built in the period from 1925 to 1975. Most of them come from the following nine engineers or architects: Eduardo Torroja, Félix Candela, Robert Maillart, Heinz Isler, Franz Dischinger, Ulrich Müther, Anton Tedesko and Eladio Dieste. Factories, warehouses, metro stops, grandstands, theatres, cinemas, churches, restaurants, bars and even houses used to be covered by shells (Sciaich, 2010). Félix Candela was a world-renowned structural artist of thin-shell concrete-roof structures in the mid 20th century. His elegant thin shell structures created great excitement in 1950's and 60's. He was trained as an architect and self-educated in the theory and design of thin-shell concrete structures in Mexico. It is possible to claim Candela's structures as structural art. He could build hypars only 4 cm thick. Candela had tried to construct significant, slender, aesthetic structures as well as economical and efficient structures; this approach had made his reputation. As candela explained:

But an efficient and economical structure has not necessarily to be ugly. Beauty has no price tag and there is never one single solution to an engineering problem. Therefore, it is always possible to modify the whole or the parts until the ugliness disappears. This aversion to ugliness is quite the opposite of the task of the professional artist who has to produce beauty as an obligation or of today's star-architect who has to be original at any cost in each project. (cited in, (Garlock & Billington, 2010, p. 131)

The first hypar structure built by Candela was The Cosmic Rays Pavilion, built on the campus of the Universidad Nacional Autónoma de Mexico (UNAM) in 1951 (Figure 4.21). This is only 1.5 centimeters thickness and is one of the thinnest structures ever built. Furthermore, Candela had tried different combinations of hypars. For example, in the design of Bacardi Rum Factory's roof, he used three adjacent hyperbolic paraboloids (Figure 4.22).

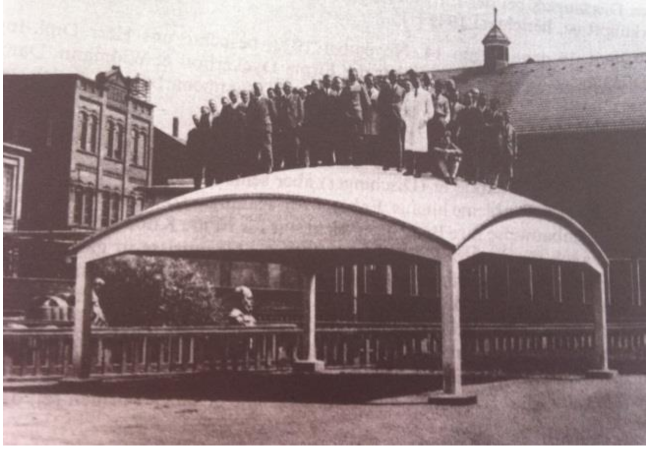


Figure 4.19. The first concrete shell structure designed by Franz Dischinger in 1922. (Source: Cassinello, 2010)

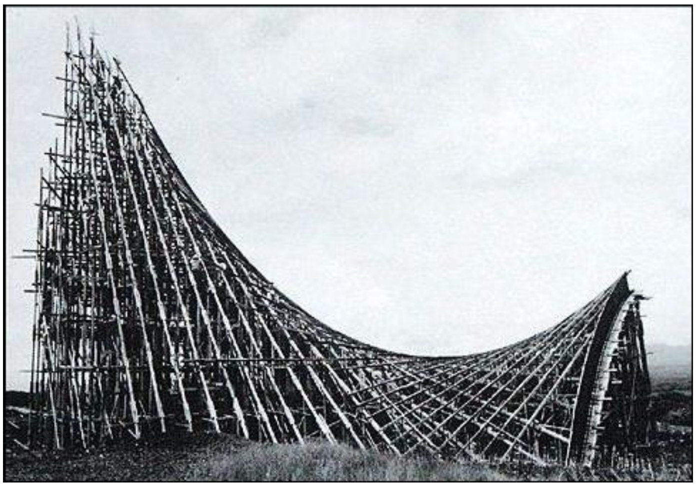


Figure 4.20. Straight formwork of Chapel Lomas de Cuernavaca (1958) (Source: Tectonicablog, 2010)

Figure 4.21. The Cosmic Rays Pavilion in Mexico,1951. Felix Candela's first hypar structure. (Source: Cassinello,2010)

Figure 4.22. Bacardi Rum Factory (1960). (Source: Billington & Garlock, 2010)

Candela aimed to achieve structural equilibrium in shells and in other structures and this nearly always meant symmetry (Margolius, 2002). He did not use computers to analyze or design hypar structures, but instead he used membrane theory in his designs. He used both straight edges and curved edges hypars to create his designs. The church of Our Lady of the Miraculous Medal (1955), Restaurant Los Manantiales (1958), Chapel Lomas de Cuernavaca (1958) (Figure 4.23), Bacardi Rum Factory (1960) are the major works of Félix Candela. Félix Candela had pioneered an era with his elegance and resistant hyperbolic-paraboloid shell structures. Today, almost all his innovative structures are landmark structures.

Figure 4.23. Chapel Lomas de Cuernavaca (1958) (Source: Billington & Garlock, 2010)

On the other hand, Candela's slender concrete shell structures do not belong to today's architecture. First of all, they became out of fashion and difficult to analyze. They are not appropriate for big spans. Candela was convinced that spans of more than 30 meters were not economical (Sciaich, 2010). Moreover, they are dark structures which mean they are opaque and do not permit light to enter the space below. For natural light, openings are required but they make them even more difficult to analyze. In addition, shells are not compatible with modern building physics because the reinforced concrete does not have a good thermal insulation. Also, insulation claddings eliminate shell's slenderness. They provided labor intensive formwork that makes shell structures expensive because especially in the developing countries labor became more and more expensive. As a summary, it is not feasible to construct dark concrete shells today. Constructing hypars as light weight structures are mainly successful for special purpose structures. For instance, Figure 3.24 shows glass hypar roof with plane quadrangular glass panels. It is an elegance transparent light weight structure. Nonetheless, today's architecture needs more to make a difference.

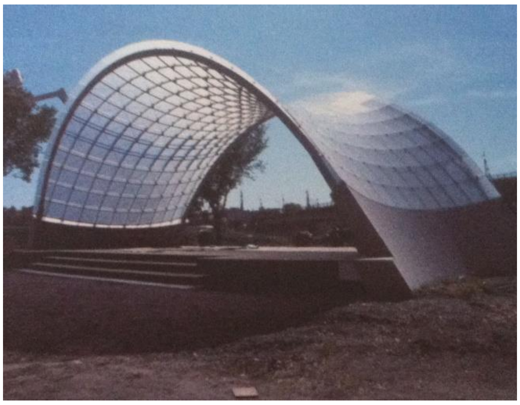


Figure 4.24. Glass Hypar Roof, Schubert Club Band, Minneapolis, 2001. (Source: Sciaich, 2010)

4.3 Freform Curved Surfaces

Freeform surfaces are complex surfaces and it is hard to define these surfaces mathematically, but they offer much more flexibility. In architecture, only in the nineteenth century architects started to use freeform surfaces in their expressions with industrialization and improved building materials such as iron, steel, and reinforced concrete. Antoni Gaudi (1852-1926) successfully used freeform surfaces in his structures. His Sagrada Familia (1882- today) and the Casa Mila (1905-1907) (Figure 4.25) are the most prominent examples.

Figure 4.25. The Casa Mila (1905-1907) (Source: Zoomandgo, 2012)

In today's architecture, designing freeform structures is much more possible with the help of computer-aided geometric design (CAGD) technologies.

Freeform curved surface is hard to be defined mathematically just like freeform surfaces. It is possible to shape freeform surfaces by a small number of control points. It is important to master freeform curves because the solution of curves can trigger the development of freeform surface modeling.

Bézier curves are the most widely used freeform curves. For the design of complex curves, the more powerful B-spline curves which offer local shape control had present. Nonuniform rational B-spline (NURBS) curves are used to draw most complex planar and spatial freeform curves, as well as to draw all types of conic sections (Figure 4.26) (Pottmann, 2007) .

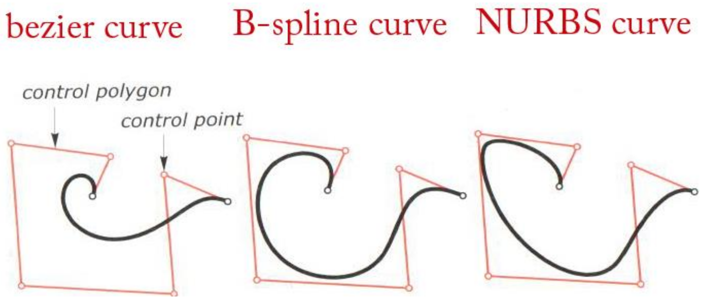


Figure 4.26. Types of freeform curves. (Source: Pottmann, 2007)

CHAPTER 5

MECHANISMS

Structure is made of several parts put together in a particular way so as to resist to do impact of loads imposes on it. Kinetic structure is a collection of mechanisms arrange to transmit forces and motion. Therefore, firstly mechanism should be defined in order to understand kinetic structures.

Mechanism consists of several parts put together in a particular way that has the purpose of transferring motion and force from a source to an output. Basically there are three types of mechanisms. These are linkage mechanisms, gear mechanisms (Figure 5.4) and cam mechanisms (Figure 5.5). A linkage is particular type of mechanism consisting of a number of interconnected rigid components, individually called links. The connection between the links is called joint. The joints of the linkages are spherical joint, planar joint, screw joint, revolute joint and prismatic joint. A linkage modeled as a network of rigid links and ideal joints is called a kinematic chain. Linkages may be constructed from open chains (Figure 5.3), closed chains (Figure 5.1), or a combination of open and closed chains (Figure 5.2). When any link is fixed, the chain becomes mechanism.

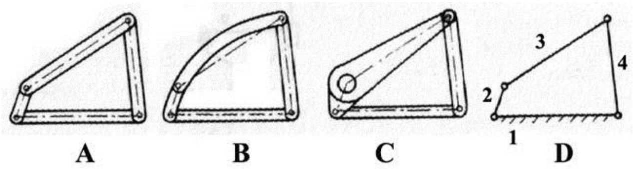


Figure 5.1. Closed loop linkage mechanism A, B, C and their kinematic diagram D.

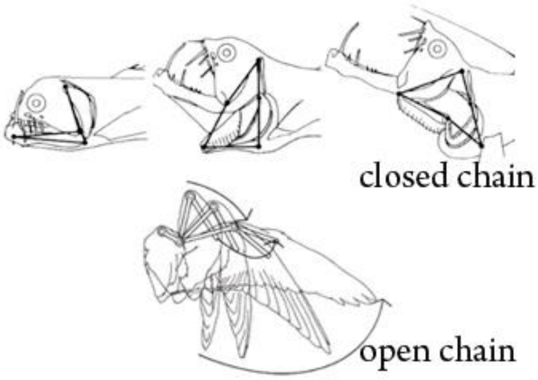


Figure 5.2. Closed and open chain from nature (Source: Pellegrino, 2001)

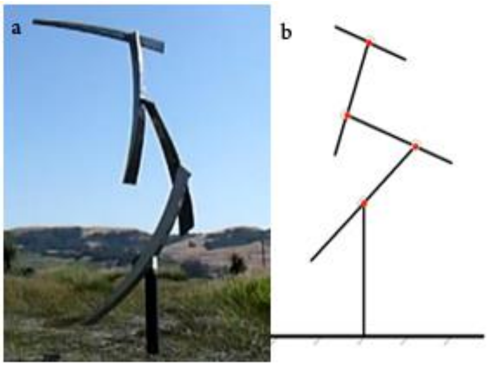


Figure 5.3. a) Open chain-Kinetic Sculpture by Jeffery Laudenslager b) Kinematic diagram of the sculpture (Source: Laudenslagersculpture, 2013)

Gears are links that are used, by means of successively engaging teeth, to provide positive motion from a rotating shaft to another that rotates, or from a rotating shaft to a body that translates. Gears can be classified as spur gears, bevel gears, helical gears, and worm and worm gears (Yan, 1998).

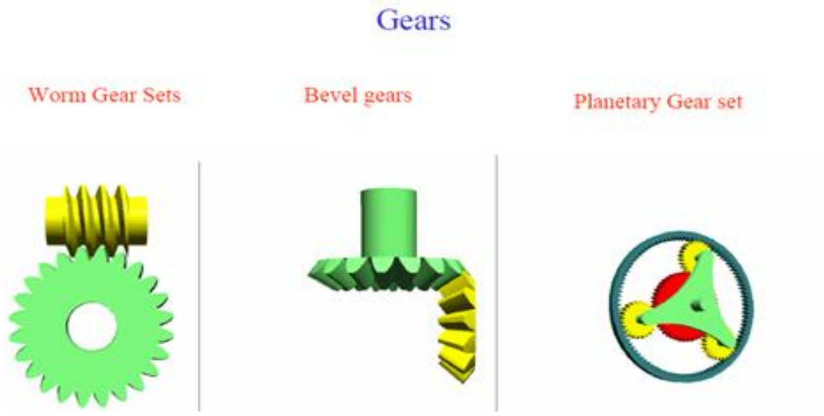


Figure 5.4. Some types of gear sets (Source: Norton, 2004)

A cam is an irregular shaped link that serves as a driving member and imparts a prescribed motion to a driven link called follower. Cams can be classified as wedge cams, disk cams, cylindrical cams, barrel cams, conical cams, spherical cams, roller gear cams, and others (Yan, 1998). The sculpture designed by Laikingland Yatzer in Figure 5-6 is an example for cam mechanisms. In the sculptor, fingers represent the followers so there are four cams and the input is the motor.

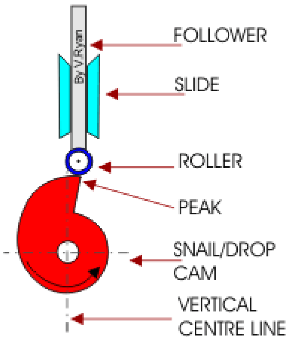


Figure 5.5. Cam mechanism (Source: Dawie-sutton,2012)

Figure 5.6. Cam mechanism- Designed by Laikingland Yatzer (Source: Yatzer, 2012)

5.1 Overconstrained Linkages

Overconstrained linkages are mechanisms which have special geometric conditions among the links and joint's axes. These are linkages that are connected only by revolute joints. From classical mobility analysis, it is known that spatial linkages should have at least seven links to be mobile (Chen, 2003). General mobility criterion for mechanisms was established by Grübler (or Kutzbach) in 1921. According to this criterion, mobility of a spatial linkage can be found with the equation shown below. In the following equation n is the number of links and $\{p_i\}_1^5$ is number of joints having i degree of freedom (DOF) of joints.

$$\begin{aligned} M &= 6(n-1) - \sum_{i=1}^{5} (6-i)\, p_i \\ M &= 6(n-1) - 5p_1 - 4p_2 - 3p_3 - 2p_2 - 1p_5 \end{aligned} \tag{5.1}$$

A closed loop linkage with n-link has same number of revolute joints. Therefore p_1=n. Then according above equation;

$$\begin{aligned} M &= 6(n-1) - 5n \\ M &= n-6 \\ 1 &= n-6 \\ n &= 7 \end{aligned} \tag{5.2}$$

Thus, to obtain a mobility of one, a spatial single loop linkage with only revolute joints must have at least seven links. However, some mechanisms, which have specific geometric condition in the assembly of its parts do not obey Grübler criterion. These are overconstrained mechanisms with four, five or six links. They are exceptional mechanisms that have full range mobility. Thereby, overconstrained mechanisms can be define as distinct form; if a system of links and joints has mobility M=0 or less according to Grübler criterion , yet still moves, then it is called an overconstrained mechanism.

The first published research on over-constrained mechanisms is traced back to 150 years ago when Sarrus (1853) discovered his six-bar mechanisms (Figure 5.7). Since then, various researchers have worked on other overconstrained mechanisms such as Bennett (1903), Delassus (1922), Bricard (1927) (Figure 5.8.), Myard (1931), Goldberg (1943), Waldron (1967, 1968 and 1969) Wohlhart (1987, 1991 and 1993) and Dietmaier (1995). Philips (1984, 1990) summarized all of the known over-constrained mechanisms in his two-volume book. The most detailed studies on over-constrained mechanisms belong to Baker (1980.1984, etc.) (Chen, 2003). 3D single loop over-constrained linkages can have four, five or six links. When these linkages consist of only revolute joints, they are called 4R, 5R or 6R linkages.

Figure 5.7. 6R Sarrus Mechanism (Source: Chen, 2003)

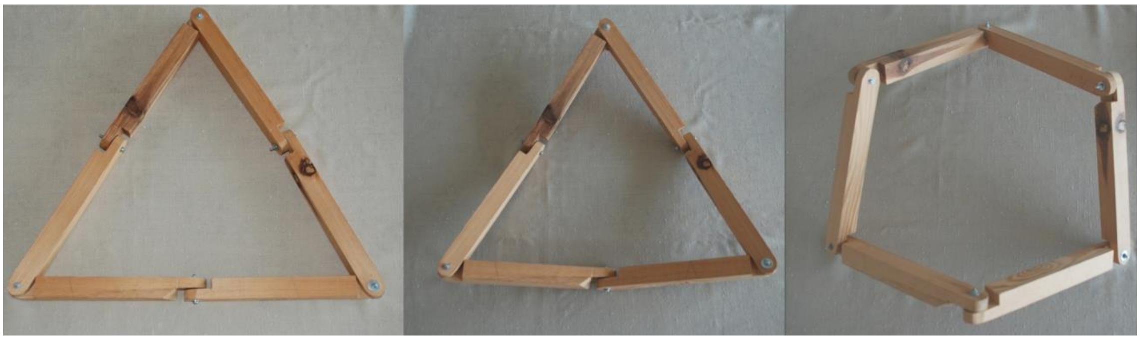


Figure 5.8. 6R Bricard Mechanism

By the rapid development on structural engineering and deployable structures, over-constrained mechanisms have started to be preferred because it provides extra stiffness. When overconstrained mechanisms have only hinged connections, they provide more robust performance than slider or other type of connections. Their spatial kinematic characteristics make them good candidates in modern linkage designs where spatial motion is needed. Another advantage of overconstrained mechanisms is that they are mobile using fewer links and joints than it is expected. Fewer links and joints in a mechanism mean reduction in cost and complexity (Mavroidis & Beddows, 1997).

5.1.1 Geometric and Kinematic Principles of Bennett Linkage

The Bennett mechanism, which was discovered in 1903 by Dr. Geoffrey Thomas Bennett, is 4R spatial overconstrained linkage mechanism (Bennett, 1914). It has four rigid links that are connected by four hinges, commonly known in the mechanical engineering literature as revolutes. Therefore it is also called a mobile 4R linkage. The axes of revolute joints of Bennett linkage are neither parallel as planar nor concurrent as spherical linkages. This appealing characteristic of Bennett linkage has attracted the attention of many researchers. According to the Grübler equation, mobility of Bennett linkage can be calculated as follows.

$$M = 6(4-1) - 5\times 4 = -2 \tag{5.3}$$

As shown above, Bennett linkage does not meet the mobility criterion but it has full-range mobility. Bennett mechanism is an exception like all other overconstrained mechanisms because of their special geometric conditions among the links and joint axes. The dimension of subspace is λ=3 (Korkmaz, Akgün & Maden, 2012). The Grübler formula for subspace λ=3 gives:

$$\begin{aligned} M &= 3(n-1) - 2p_1 \\ M &= 3(4-1) - 2x4 = 1 \end{aligned} \tag{5.4}$$

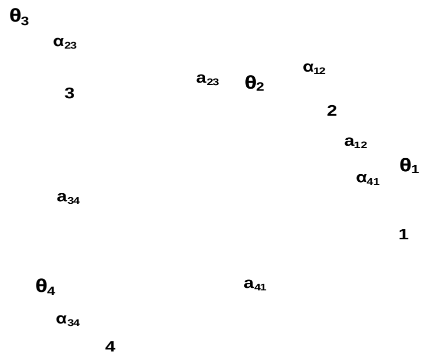


Figure 5.9. Schematic representation of the Bennett Mechanism (Korkmaz, Susam & Akgün, 2013)

The special geometric conditions of Bennett linkage are listed below as:

1) The skewed angles between the axes of two revolute at the ends of the links and the lengths of the bars on opposite sides are equal.

$$\begin{aligned} a_{12} &= a_{34} = a \\ a_{23} &= a_{41} = b \\ \alpha_{12} &= \alpha_{34} = \alpha \\ \alpha_{23} &= \alpha_{41} = \beta \end{aligned} \tag{5.5}$$

2) The twists and the lengths must satisfy the condition of

$$\frac{a}{\sin\alpha} = \frac{b}{\sin\beta} \tag{5.6}$$

3) The skewed angles α and β are restricted to the range (0,π), the displacement closure equations depends on four variable joint angles θi that provide below conditions:

$$\theta_1 + \theta_3 = 2\pi = \theta_2 + \theta_4 \tag{5.7}$$

$$\tan\frac{\theta_1}{2}\tan\frac{\theta_2}{2} = \frac{\sin\frac{1}{2}(\beta+\alpha)}{\sin\frac{1}{2}(\beta-\alpha)} \tag{5.8}$$

These closure equations are only in use when one of the revolute variables θ_i is independent. In addition to above conditions, there is a special case in which a different type of Bennett linkage is generated (5.4). When $\alpha+\beta=\pi$ and $a=b$, an equilateral linkage is obtained. Therefore, Eq. 5.7 becomes as;

$$\tan\frac{\theta_1}{2} \times \tan\frac{\theta_2}{2} = \frac{1}{\cos\alpha} \tag{5.9}$$

5.1.2 Deficiencies and Alternative Works on Bennett Linkage

Bennett linkage is a spatial mechanism which can constitute a deployable hypar. But it has many geometric limitations. For instance, Bennett linkage neither can fully close to a bundle nor can fully deploy to a flat surface. The revolute joints used in the Bennett linkage are mechanically simple but their placement along each link and angle between the pin axes are complicated.

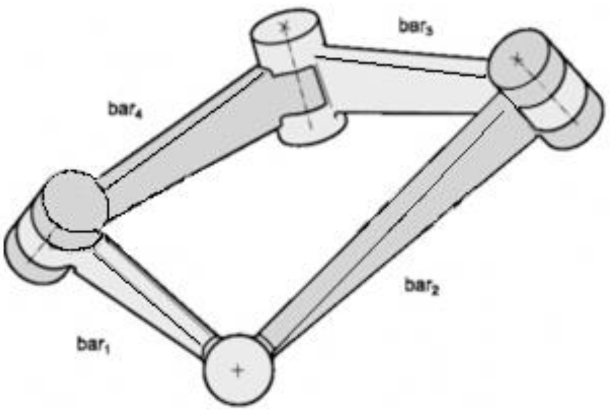


Figure 5.10. Bennett Linkage (Source: Springerimages, 2013)

Notwithstanding, in the last ten decades many researchers studied on Bennett Linkage in different fields. Perez and McCarty focused on the relation between Bennett mechanism and cylindroids (Perez & McCarthy, 2002), Baker has established the relationship between the ruled surface and the corresponding centrode of the Bennett linkage’s planar form (Baker, 2001), Peilin Tian and Yan Chen devised a shelter and the frame of the shelter is an assembly of 5 Bennett linkages (Figure 5.11) (Tian & Chen, 2010). Yan Chen tried different variations of Bennett Linkage in her doctoral thesis. She focused on connectivity and the network of Bennett Linkages (Figure 5.12). (Chen, 2003) Chen and Baker published an article on using Bennett Linkage as a connector between other Bennett loops (Figure 5.12) (Baker & Chen, 2005) (Yu, Luo, & Li, 2007).

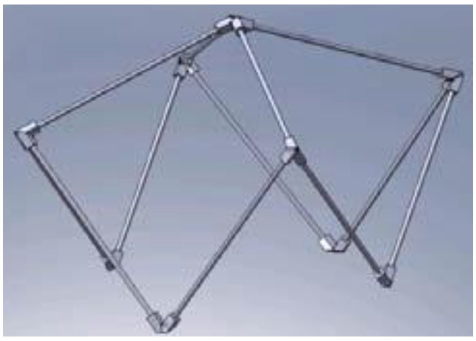


Figure 5.11. A product design of the foldable shelter frame (Source: Chen, 2003)

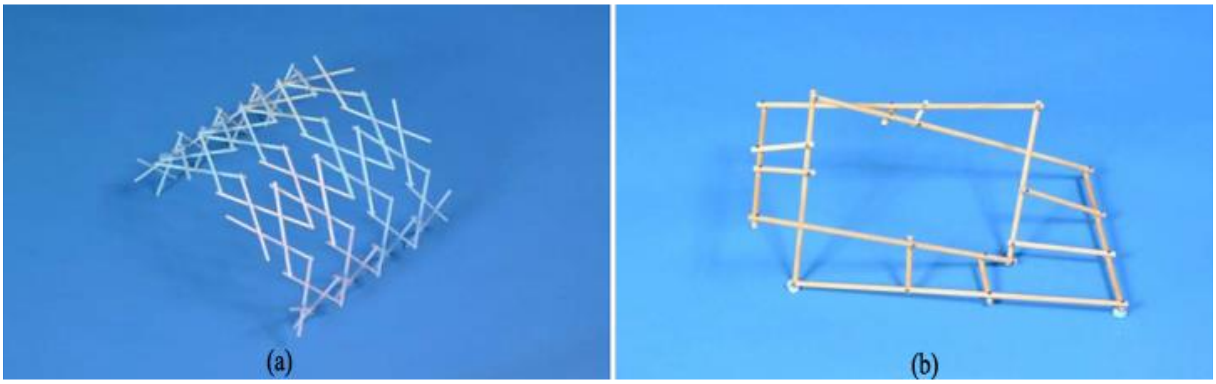


Figure 5.12. (a) deployable arch made of Bennett network (b) Bennett Linkage as a connector between other Bennett loops (Source: Chen, 2003)

Therewithal, Chen improved a novel joint detail in her dissertation for Bennett mechanism. First of all Chen identifies basic element from Bennett linkage with skew square cross-section bars to obtain compact folding and maximum expansion (Figure 5.13). With this particular example Chen shows that the construction of a Bennett linkage with compact folding and maximum expansion is not only mathematically feasible, but also practically possible. Figure 5.14 shows the geometry of the square cross-section bar. As shown in the Figure 5.14 in geometry of the novel joint there are parameters and it is hard to ensure these parameters (the angles that have to be satisfied in Figure 5.14) at the practice. Plus, her design has single degree of freedom and cannot ensure full form flexibility and adaptability like a reconfigurable structure.

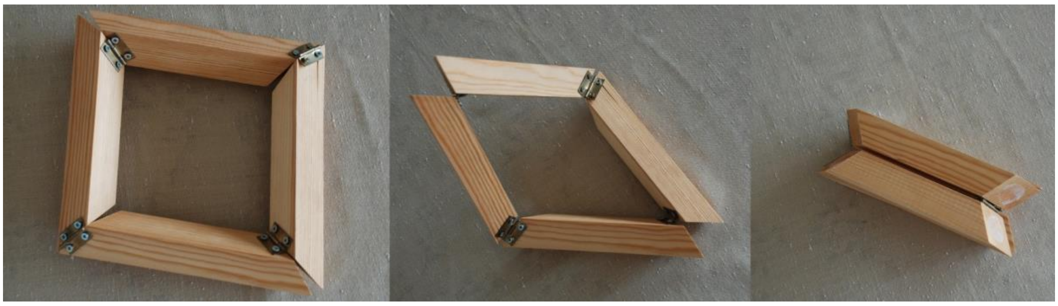


Figure 5.13. Bennett linkage with skew square cross-section bars

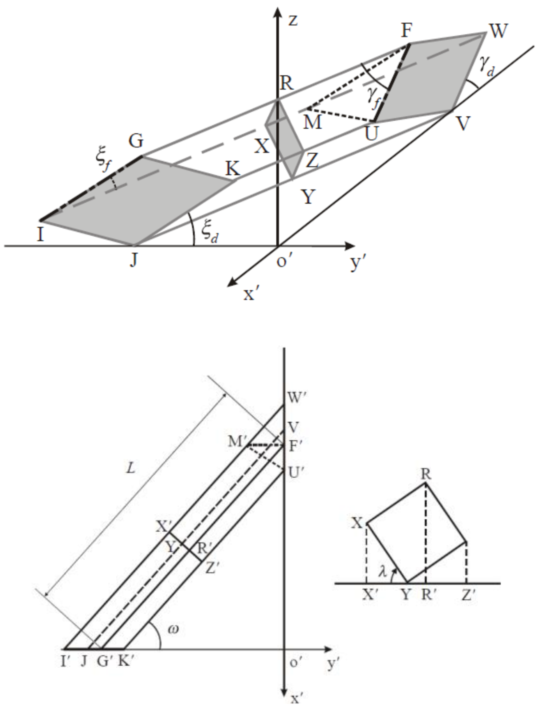


Figure 5.14. The geometry of the square-cross section bar (Source: Chen, 2003)

Figure 5.15 shows a deployable structure with a membrane attached to it. Yang Yu et al (2007) investigated the compatibility between the membrane and Chen’s structure during the process of deployment. In order to identify the behavior of the membrane, they first simplified the membrane with cable net layout with two main directions perpendicular to each other. By this way length variations of the cables are determined. The necessary geometric calculations had done to determine the limitations to ensure the compatibility between the membrane and the linkage (Yu, Luo, & Li, 2007).

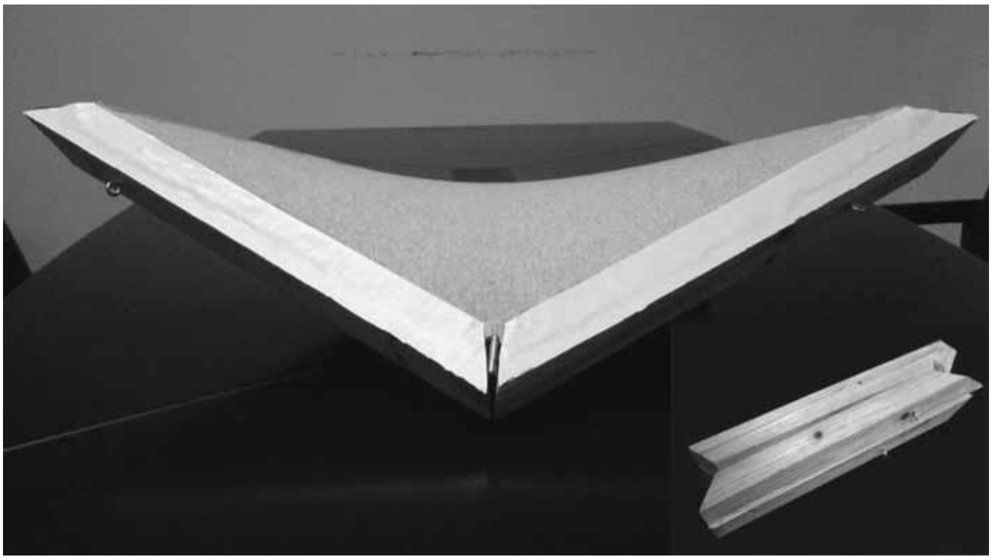


Figure 5.15. A deployable membrane structure in the folded and unfolded configurations (Source: Yu, Luo, & Li, 2007)

5.2 Proposed 8R Reconfigurable Linkage Mechanism

Bennett linkage has limitations to offer flexible solutions. To obtain real flexible solutions, the proposed mechanism must have 2-DOF with distinctive connection details and additional links. The idea of novel mechanism originated from the simple models seen in Figure 5.16. The models made with straws show three equilateral Bennett linkages with same joint angle θ_1. Even though these three linkages have same lengths and same joint angles, their configurations are different. This is because of the different skewed angles α and β for each linkage. Thus any linkage cannot transform to another one. The skewed angles of the novel mechanism must be changeable. To reach this aim, additional links 2, 3and 6,7 are connected with revolute joints as shown in Figure 5.17. Four revolute joints between links 1and 2, 3 and 4, 5 and 6, 7 and 8 let rotations about the links' axes. Now skewed angles $\alpha12$, $\alpha23$, $\alpha34$, $\alpha41$ are changeable and the mechanism can physically move with overlapped circular section links. It is easy to realize the overlapped circular sections compared with Yan Chen's skew square cross-section bars. Furthermore, since M=2 both side of the mechanism can move individually, and the system can transform from planar geometries to various hypars (Korkmaz, Susam & Akgün, 2013).

Figure 5.18 shows shape alternatives of the proposed 8R linkage. Now the new mechanism operates in λ=6. It can also stow and deploy completely. This shape flexibility proves the superiority of the novel mechanism over Bennett Linkage.

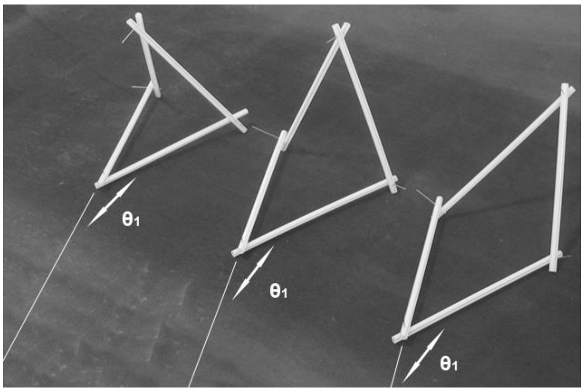


Figure 5.16. Equilateral Bennett linkages with same joint angle θ_1 but different skewed angles α and β (Korkmaz, Susam & Akgün, 2013)

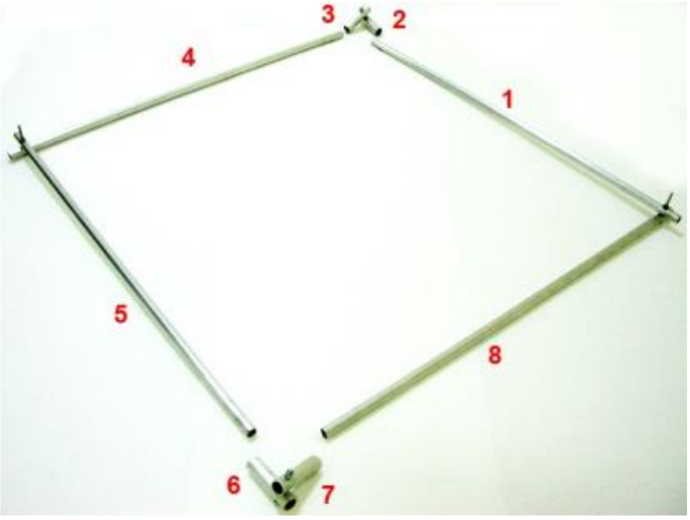


Figure 5.17. The proposed 8R reconfigurable linkage mechanisms (Korkmaz, Susam & Akgün, 2013)

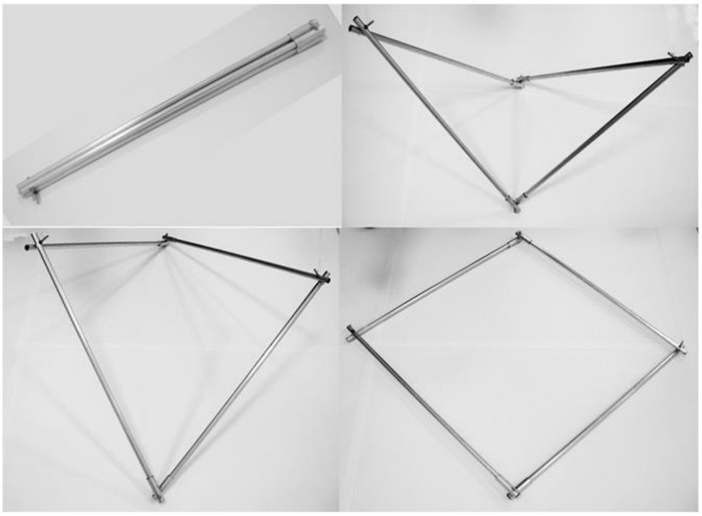


Figure 5.18. Transformation capacity of the proposed novel mechanism (Korkmaz, Susam & Akgün, 2013)

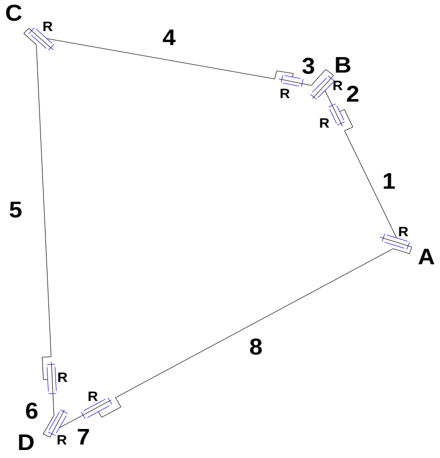


Figure 5.19 Kinematic diagram of the proposed mechanism (Korkmaz, Susam & Akgün, 2013)

Kinematic diagram of the novel mechanism is shown in shown in Figure 5.19. According to Grübler's criterion, the mobility of this novel mechanism is:

$$\begin{aligned} M &= 6(n-1)-5p_1 \\ M &= 6(8-1)-5\times 8=2 \end{aligned} \tag{5.10}$$

This mechanism can be used as an adaptable building component (such as a roof, façade system, or furniture, etc.) which can change its shape according to the expectations of the users. In order to use this system as a roof structure, some intermediate links would be necessary to attach the rigid cover materials for long span architectural applications. But, the connection points of the intermediate links on opposite sides of the linkage come closer during the deployment process. During the deployment process each intermediate link must extend or shorten. Therefore, it is impossible to attach one rigid straight rod to the linkage

Initially, the proposal for the intermediate links consists of two square section links connected with prismatic joints which allow translation. The experimental studies with prototypes have revealed that there is also rotation besides translation between the two bars. Therefore, cylindrical joints that can let both rotation and translation are used instead of prismatic joints between additional circular bars. Figure 5.20 shows the kinematic diagram of the novel mechanism with intermediate links.

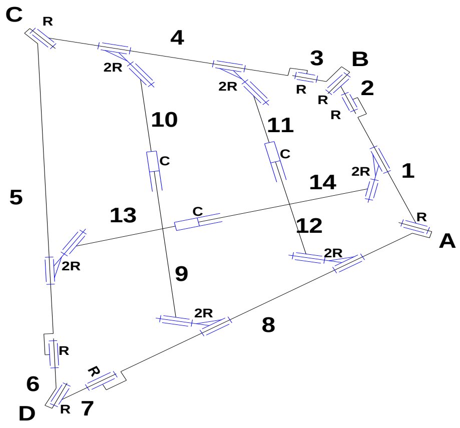


Figure 5.20 Kinematic diagram with intermediate links (Korkmaz, Susam & Akgün, 2013)

With the addition of the intermediate links the mechanism remains 2 DOF because the additional intermediate links are structural groups. Structural groups have zero mobility. Figure 5.21 shows the kinematic diagram of the structural group which consists of two moveable links and three 2DOF joints.

$$\begin{aligned} M &= 6(m) - 4p_2 = 0 \\ M &= 6x2 - 4x3 = 0 \end{aligned} \tag{5.11}$$

In the above equation m is the number of moveable links, p_2 is the number of 2 DOF joints.

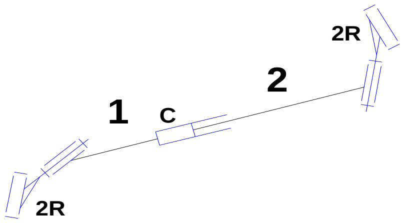


Figure 5.21 Kinematic diagram of the structural group (Korkmaz, Susam & Akgün, 2013)

The whole system remains 2DOF with the additional structural groups. Now it consists of 14 links, eight 1 DOF (R) joints and nine 2DOF (2R and C) joints. The mobility of the new mechanism can be proved with the following Grübler equation.

$$\begin{aligned} M &= 6(n-1) - 5p_1 - 4p_2 \\ M &= 6(14-1) - 5\times 8 - 4\times 9 = 2 \end{aligned} \tag{5.12}$$

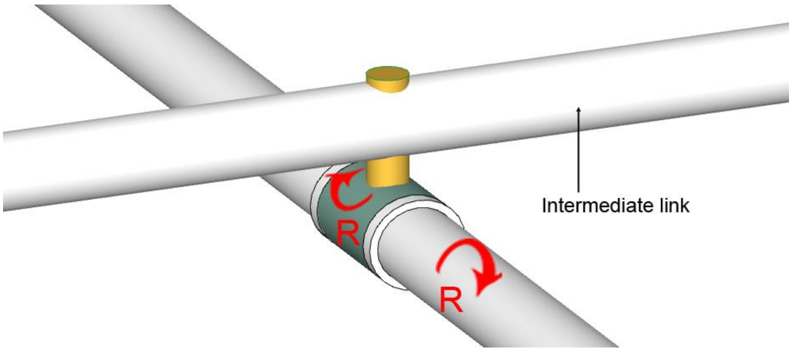


Figure 5.22 Representation of the new 2 DOF joint (Korkmaz, Susam & Akgün, 2013)

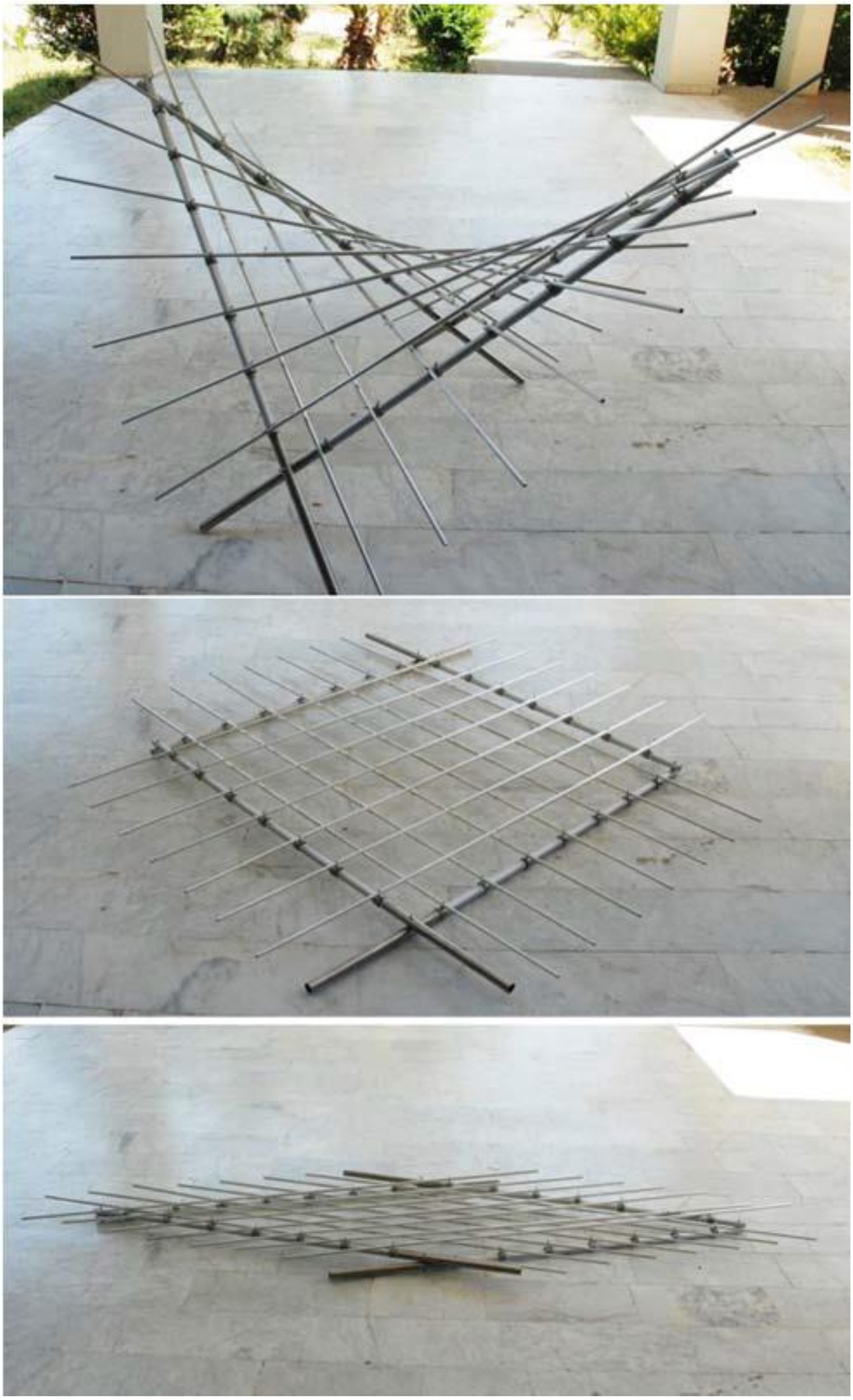


Figure 5.23. The model shows the transformation capacity of the novel mechanism with fourteen intermediate links (Korkmaz, Susam & Akgün, 2013)

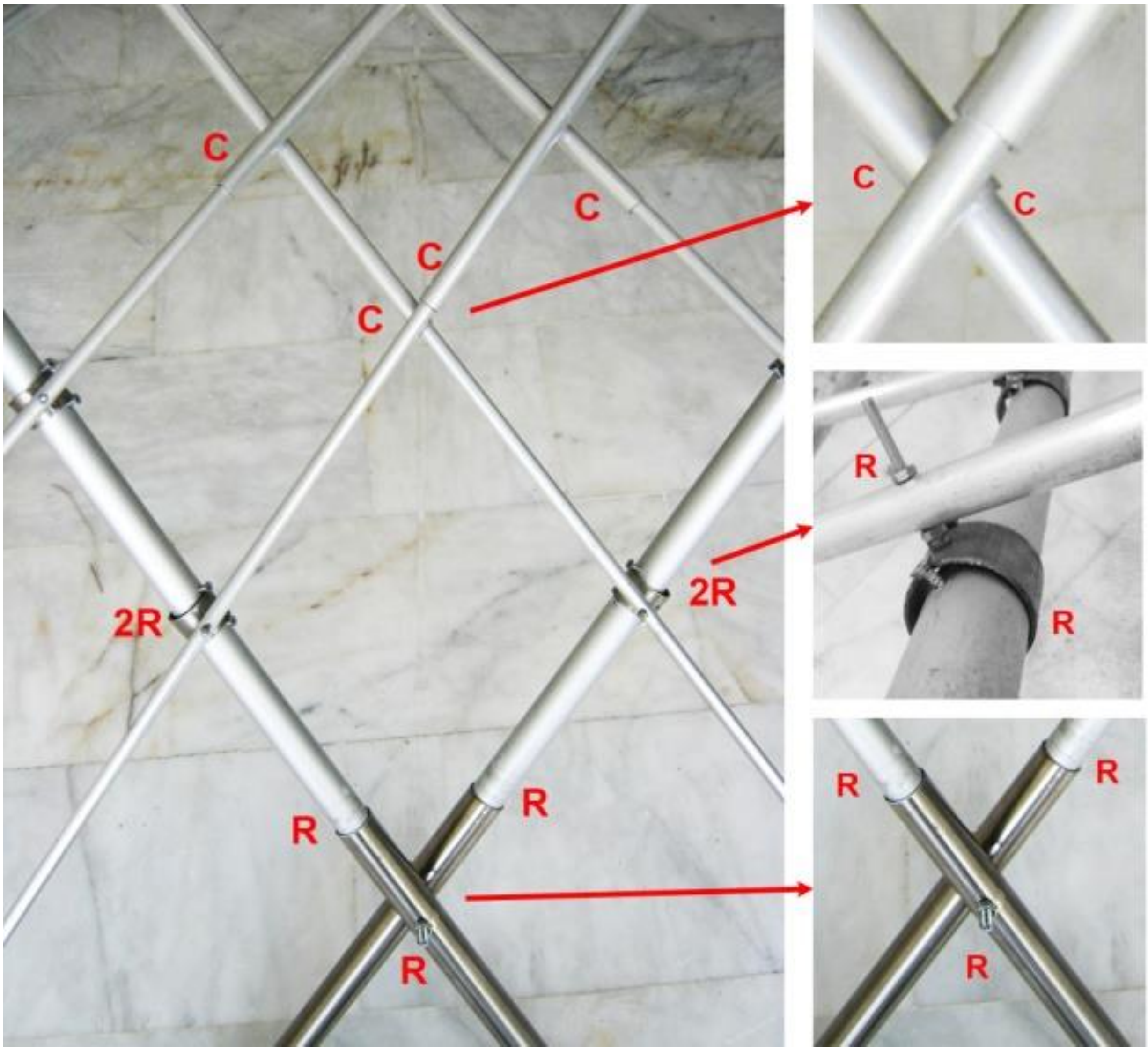


Figure 5.24. 2R and C joints of the model (Korkmaz, Susam & Akgün, 2013)

During the manufacturing process of the cover, it would be complicated to attach any rigid panels to any intermediate link because of translation and rotation between the two links. Connection details of the rigid panels must be solved properly; otherwise panels can block the movement. Besides, bending moment on the intermediate links is another problem. It can cause excessive friction because of the translation between the two links. For that reason, a revision in the intermediate links is essential. In the revised linkage, the cylindrical joint is relocated at the end of the intermediate link. The revised additional link is again a structural group. Figure 5.25 shows the kinematic diagram of the revised structural group which consists of one link, one 2DOF joint and one 4DOF joint. The revised structural group has zero mobility again (5.13).

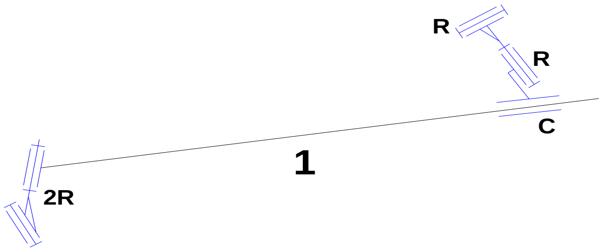


Figure 5. 25 Revised structural group with zero DOF (Korkmaz, Susam & Akgün, 2013)

$$\begin{aligned} M &= 6m - 4p_2 - 2p_4 \\ M &= 6\times 1 - 4\times 1 - 2\times 1 \\ M &= 0 \end{aligned} \tag{5.13}$$

In equation 5.13, *m* is the number of moveable links, p_2 is the number of 2 DOF joints, p_4 is the number of 4 DOF joints.

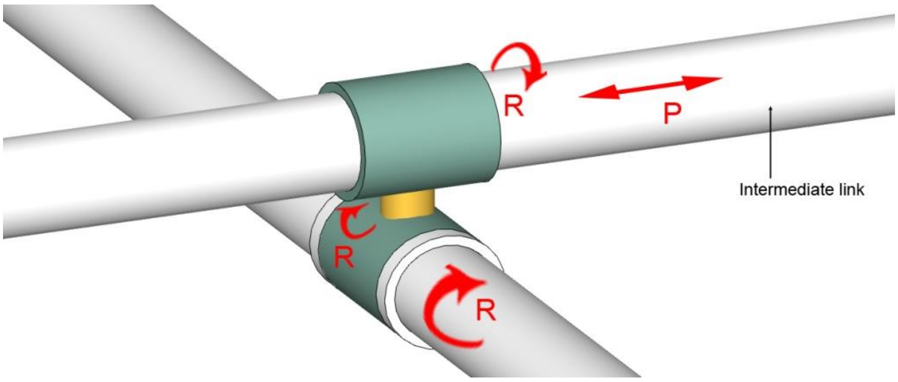


Figure 5.26. Representation of the new 4 DOF joint (Korkmaz, Susam & Akgün, 2013)

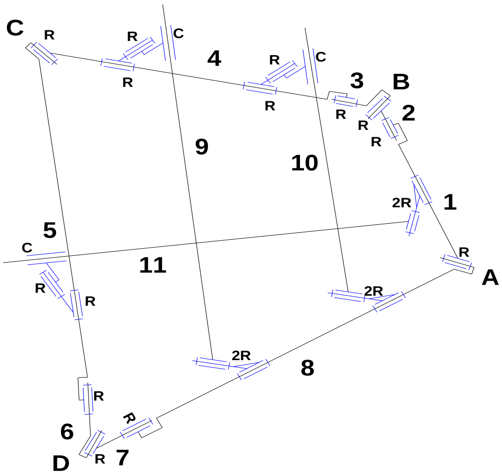


Figure 5.27. Revised kinematic diagram of the proposed mechanism (Korkmaz, Susam & Akgün, 2013)

Figure 5.27. shows the kinematic diagram of the novel mechanism with new intermediate links. With the addition of structural groups, the whole system remains 2DOF again. Now it consists of 11 links, eight 1 DOF (R) joints, three 2DOF (2R) and three 4DOF (2RC) joints. The proof of the revised mechanism with Grübler equation as

$$\begin{aligned} M &= 6(n-1) - 5p_1 - 4p_2 - 2p_4 \\ M &= 6(11-1) - 5\times 8 - 4\times 3 - 2\times 3 = 2 \end{aligned} \tag{5.14}$$

As a result, this thesis has exposed a 2DOF 8R novel linkage mechanism based upon Bennett mechanism. Firstly geometric principles of the 8R linkage mechanism, then superiority over Bennett linkage have been explained. Finally, Bennett mechanism with extra structural groups yields a structural mechanism that takes various forms and provides an adaptable space under it. The specific application considered is a roof structure. It can provide an adaptable space under it. Contrary to single DOF deployable structures, the proposed 2 DOF reconfigurable structure has wider form flexibility.

CHAPTER 6

CONCLUSION

This chapter offers the aforementioned contributions of the dissertation in the development of reconfigurable hyperbolic paraboloid structures and highlights possible future works.

In the context of this dissertation, the review of previous classifications and the types of deployable structures have been thoroughly investigated. This part is requisite because deployable structures form the fundamentals of kinetic structures. Therefore, this investigation is essential in order to expose the deficiencies of the deployable structures that have been created up to now. Deployable structures do not have full form flexibility. This is the main shortcoming of deployable structures. Deployable structures with various configurations are expressed as reconfigurable structures. In this way, the possibilities of constructing a reconfigurable hyperbolic paraboloid structure which is constructed by a novel mechanism built the objective of the present study. The novel reconfigurable mechanism utilizes the overconstrained 4R Bennett linkage and the production principals of ruled surfaces. In this respect, the present study is a pioneer study on reconfigurable structures for architectural applications.

After the investigation of deployable structures, the main properties of curved surfaces especially ruled surfaces are examined. Ruled surfaces particularly hypar surfaces are common forms used in architecture as shell structures. But the existing examples of hypar surfaces are stabile structures. In order to transform these static hyperbolic paraboloid structures into reconfigurable ones, an investigation of mechanisms is necessary. Hence, the present dissertation consists of a chapter on mechanisms. The overconstrained 1 DOF Bennett mechanism is investigated thoroughly. Geometric and kinematic principles of Bennett linkage are examined and their shortcomings with respect to form flexibility are exposed. A novel 2 DOF 8R spatial linkage mechanism has been proposed to overcome these shortcomings. The new mechanism presents remarkable form flexibility from flat to double-curved hypar shapes with new connection details. It can achieve these remarkable shape transformations with two actuators. A reconfigurable deployable hypar structure has been developed by the utilization of this novel mechanism. Furthermore, intermediate links and their connection details are investigated. There are two different proposals for intermediate links and their connections. The structure is analyzed with kinematic diagrams and the models.

6.1 Further Research

In the context of this dissertation, the fusion of architecture and the mechanism science ensured a creative expression for architecture. The proposed mechanism presented in this dissertation can shed light on new future works. The proposed 2 DOF 8R linkage mechanism can open many possibilities of constructing reconfigurable structure and more intensive research could be carried out on this issue.

The proposed mechanism can be used as an adaptable building component. The present study handled the mechanism as a roof structure. More case studies can be done with the proposed linkage. For example, assemblies of the proposed linkage can be a subject for further studies. Networks of the proposed linkage in alternative forms can be developed. It has led to discover many designs like façade systems or furniture designs. Meanwhile, many other deployable linkage mechanisms such as architectural umbrellas can be used as a building component as well. Further studies can concentrate on the other linkage mechanisms and reveal novel transformable structures.

Actuators are the crucial elements of such kind of transformable deployable structures. They provide both the motion and the stability of the whole system. Location, type, and force of the actuators can be changed according to the geometric and material properties of the structure. Thus, future studies should consider the location and type of the actuators. One specific issue that needs more research is the covering of the proposed linkage. The covering is important in order to ensure a real architectural element with the proposed linkage. Therefore, the combination of the proposed linkage with flexible materials, rigid plates which overlap one another or origami type of covering, can be the subject of further research studies. In addition, since the static analyses of the linkage are not within the scope of the present study, static analyses of the linkage for further studies will be highly desira

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