ANALYSING STRUCTURE OF CURVILINEAR ARCHITECTURAL FORMS: ZAHA HADID'S ARCHITECTURE

**A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIEDSCIENCES
OF
NEAR EAST UNIVERSITY**

**By
RASHA TARBOUSH**

**In Partial Fulfillment of the Requirements for the Degree of Master of Science
in
Architecture**

NICOSIA, 2019

RASHA TARBOUSH

ANALYSING STRUCTURE OF CURVILINEAR ARCHITECTURAL FORM: ZAHA HADID'S ARCHITECTURE

NEU
2019

ANALYSING STRUCTURE OF CURVILINEAR ARCHITECTURAL FORMS: ZAHA HADID'S ARCHITECTURE

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIEDSCIENCES OF NEAR EAST UNIVERSITY

By
RASHA TARBOUSH

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Architecture

NICOSIA, 2019

Rasha TARBOUSH: ANALYSING STRUCTURE OF CURVILINEAR ARCHITECTURAL FORMS: ZAHA HADID'S ARCHITECTURE

Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Masters of Science in Architecture

Examining Committee in Charge:

Assist. Prof. Dr. Ayten Özsavaş Akçay	Supervisor, Department of Architecture, NEU
Assoc. Prof. Dr. Rifat Reşatoğlu	Department of Civil Engineering, NEU
Dr. Tuğşad Tülbentçi	Department of Architecture, NEU

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name:

Signature:

Date:

ACKNOWLEDGEMENTS

Thankfully for reach this stage of science and progress. I would like to extend my deep thanks and gratitude to my supervisor Assist. Prof. Dr. Ayten Özsavaş AKÇAY for her encouragement and assistance throughout my writing of the thesis, and to her support me with all her positive energy which reflected on my work and gave me a big motivation to complete my thesis with enthusiasm.

I would like to present a special thanks to jury members Assoc. Prof. Dr. Rifat REŞATOĞLU and Dr. Tuğşad TÜLBENTÇİ to their questions and observations that added very important benefits to my thesis.

I would also to say many thanks for the source of my happiness, my strength and my trust in myself and my work for my father and mother, for their constant standing in my side, to their great love, their tenderness and their constant advices, which was the most important reason for my success in my life and my science progress. As well as my sister and my brothers who were and still are my permanent prop in this life.

All thanks to the Faculty of Architecture at Near East University and especially thanks, appreciation and respect to the head of Architecture Department Asst. Assoc. Dr. Kozan UZUNOĞLU and to the vice dean Asst. Assoc. Dr. Sema UZUNOĞLU for their permanent support and to their open doors always when faced with any problem or ask a question.

To my parents...

ABSTRACT

The foundation of the curved architectural design is based on blending the architecture with the surrounding environment. Architects and engineers have inspired the curved forms from nature such as arch; vault and dome, where they have been use it in their designs to create large spans. Curved surfaces have been used either in small curved elements to replace sharp edges, may be completely curved surfaces, or just have a facade curved. After that, the architects developed it by merging the curved forms to create an unique form and to pass larger spans than previous. Then the "curvilinear" term has been launched to describe these forms. But professionals have already faced a challenge in the construction of the curvilinear forms, because of the difficulty of implementing them.

Architects have been used the curvilinear forms by different materials, strategies, styles, and other diversities, which give each architect his/her own features. Zaha Hadid was one of those architects, she designed her projects depending on the properties, history, civilization, traditions, and population movement affiliated to the project site; which helped to form and diversify her projects.

In this research, the history and evolution of the curved forms will be inserted throughout the eras, where the structures and the structural elements have seen important steps in expanding the potential choice in the future, where the aim is to clarified the different types and structural forms which have been used in curvilinear designs and showing the mutual relationship between the form and structure, where the explain will start as generally then concentrate on the curvilinear architecture of Zaha Hadid, the focusing will be on the structural systems of 6 curvilinear buildings which have large spans and fluidity forms.

***Keywords*:** Curved forms; curvilinear forms; curvilinear structures; form-structure relationship; Zaha Hadid designs

ÖZET

Eğri (Kavisli) mimari tasarımın temeli, mimarlığı bulunduğu çevre ile birleştirmeye dayanmaktadır. Mimarlar ve mühendisler eğri formları doğadan ilham almışlardır, kemer, tonoz ve kubbe gibi, büyük açıklıklar oluşturmak için kullanmışlardır. Eğri yüzeyler, keskin kenarları değiştirmek için küçük eğri elemanlar olarak kullanılabileceği gibi, eğri bir cephe veya tamamen eğri yüzeylerden oluşan tüm bina da olabilmektedir. Daha sonramimarlar, eğri formları benzersiz bir form oluşturmak ve daha geniş açıklıklar geçmek için birleştirerek kullanıp geliştirmişlerdir. Bu formları tanımlamak için "eğrisel"kavramı kullanılmaya başlanmıştır. Ancak profesyoneller eğrisel formların inşaatında uygulama zorluğundan kaynaklanan sorunlarla karşılaşabilmektedirler.

Mimarlar, eğrisel formları, her bir mimarın kendi tarzını yansıtacak şekilde farklı malzemeler, stratejiler, stiller ve diğer özellikler olarak kullanmışlardır. Zaha Hadid bu mimarlardan biriydi.Projelerini,yapılacak alanının özelliklerine, tarihine, geleneklerine, kültürüne, nufus hareketlerine göre tasarlamaktaydı. Bu yaklaşım onun projelerini yaratma ve çeşitlendirmesine yardımcı olmaktaydı.

Bu araştırmada, eğri formların tarihçesi ve tarihsel süreçteki gelişimi dönemlere göre incelenmiş, strüktürel sistemler ve strüktürel ögeler gelecekteki potansiyel seçeneklerin artmasında önemli bir adım oluşturmaktadır. Araştırmanın amacı "eğrisel tasarımlarda" kullanılabilecek farklı formları ve yapım sistemleri açıklamak, form ve strüktür arasındaki karşılıklı ilişkiyi incelemektir. Çalışma form-strüktür ilişkisini genel olarak açıkladıktan sonra Mimar Zaha Hadid'in eğrisel mimarisine odaklannıştır. Konu ile ilgili mimarın geniş açıklıklı altı eğrisel formlu tasarımı seçilerek; form özellikleri, strüktürel sistemleri, kullanılan malzemeler analiz edilmiştir.

***Anahtar Kelimeleri*:** Eğri formlar; eğrisel formlar;eğrisel strüktürler; form - strüktür ilişkisi; Zaha Hadid'in tasarımları

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

Curved shapes such as arches, vaults and domes have been used in the construction of the shelter since prehistoric times, as human drew inspiration those shapes from the natural factors and used the materials which existed around them such as tree branches, stones, animal skin. Curved shapes and building materials have evolved throughout history, where the curved forms were used in religious buildings such as churches and mosques, because they provide large areas without interrupted, with using stone, brick or reinforced concrete structures. The evolution of these forms led to changed and advanced the architecture and architectural form greatly over the ages. Building components considered as the important factors that have played a major role in this architectural development that is because the main function of it is the support of loads applicable on the building to ensure the stability and durability of the structure (Butelski, 2000).

In 20th centuries' curved architecture called modern curved architecture, while in 21th century's curved architecture called contemporary curvilinear architecture. The curvilinear forms has been used in design by architects with different methods, where the curvilinear was used in designing of walls, roofs or covering the whole building, where in the late of 20th and 21st century, the curvilinear term was used to describe designs with abstract curved structures, formed by overlapping a set of curves like arches, vaults and domes in a smooth, beautiful form to show a stylish design with a large span and integrated with surrounding environment (Çıngı, 2007).

Contemporary architects have been used the curvilinear lines in their designs, while each one has an own pattern and strategies which gave a various personal architectural character for each one of them. while one of their targets was to showing the interrelationship between forms and structures of the curvilinear shaped buildings and its relation with nature, where this relationship has been clarified as the form determines the place and the boundaries of the structure, while the structure supports the form aesthetically, as well as showing the rigidity and strength of the form. The architect Zaha Hadid was one of those architects, and considered as one of the architects who contributed to the development of curvilinear architecture, and made it an integral part of nature, where the Guardian magazine dubbed Zaha Hadid "Queen of the curve". She had own concepts, strategies, approach, values, and patterns, where here her values were the versatility, complexity, fluidity, and legibility. Zaha Hadid used the infinity free lines and was characterized by abstraction and durability. Reinforced concrete, steel, and aluminum materials have been used in her building structures (The Guardian, 2013).

The focusing will be on the built curvilinear structures of Zaha Hadid architect from 1999 to 2016, with clarifying the structural types and materials which have been used in some of curvilinear building that are popular known, and the relationship between forms with structures.

1.1 Aim and Objective of the Research

Curvilinear structures characterized by its great importance in showing the durability, rigidity and strength of shape. The materials and techniques of construction have evolved throughout the ages, with the advent of high-precision computing programs and efficiency, which helped to create designs in complex forms and large spans and high altitudes while preserving the aesthetic qualities of the project.

There are many curvilinear structural types which have different potentials, and to select and determine the type and material suitable for the appropriate form, must know all the different types and characteristics of each type and the ability to span and rise.

The aim of this research is to clarify the different types and structural forms have been used in the creation of curvilinear designs and showing the mutual relationship between the form and structure and its evolution through the eras, where the explain will start as generally then concentrate on the curvilinear architecture of Zaha Hadid who is "Queen of the Curve" as described by the famous magazine "The Guardian".

At the beginning the research was made for the history of curved forms, the structural systems and materials that were used in their construction and how they evolved throughout history, until the architects began to incorporate these curved forms to create unique designs that inserted under term "Curvilinear". The types of structures used to construct them have been clarified, while the emphasis placed on 6 curvilinear projects of Zaha Hadid, which have fluidity forms and different spans, heights, structures and materials.

1.2 Limitations of the Research

Knowing the history of the curved structures and how they were built and developed throughout history until reach to the contemporary era had an important role in reaching the desired result. The knowledge and determination of the structures and the difference between them, the materials used to construct them, the cladding and ceiling materials were of great importance in clarifying the construction of complex, fluidity and unique curvilinear forms.

This research limited on the different structural systems of curvilinear forms and their importance in creation of large spans, such as truss with space frame structures and shell structures, as well as have been clarified by inserting of curvilinear building examples for each type. The research focusing have been on Zaha Hadid's curvilinear buildings, where 19 curvilinear buildings have been inserted in a table, they goes back for a period between 1999-2016, then 6 buildings have been selected and focused on, which have constructed with different spans, heights, structural systems, materials and curvilinear forms "curvilinear roofs, curvilinear walls or curvilinear cover".

1.3 Research Methodology

In this research, the qualitative method has been used, where many ideas have been collected from different sources then classified and arranged as an exploratory research. The history of the curved structures has been inserted since their first appearance until now, focusing on the structural types and materials used in the curved shape. This phase helped to understand how human began to use the curved shape and its construction with different materials, and the knowledge of basic curves which is the arch, vault and dome, that played a main part in the emergence of complex and abstract shapes by combined them together, then the curved structural types have been added with clarify the characteristics of each one, the illustrations and examples about every type have been inserted to increase understanding the differences between them. The methods of identifying the suitable curvilinear structural systems to the curvilinear forms depending on height and spans of buildings were studied and clarifying.

A table of Zaha Hadid curvilinear buildings from 1999 to 2016 was organized with adding the years of construction, location and the functions included in each one. At the end, the research focused on Zaha Hadid's curvilinear buildings which are popular projects, insert in table with illustrations, structural types, structural materials, shapes, areas, spans and heights, while the structural types and materials which used in each building and the relationship of form with structure will be clarified.

1.4 Literature Review

There are a lot of scholars who gave academic researchers conducted about curvilinear architecture, the architect Zaha Hadid and her upscale art.

The researches which included curvilinear architectural forms have clarified structural system, materials used; relationship between curves shapes and surrounds environment, etc. Here some of those researches:

- “Curvilinear structural envelops in current architecture". Article, by Januszkiewicz, K. (2017.The aim:
  This research presents the spatial structural system used in complex geometry, as well as how to construct curved surfaces using the technique of shotcrete, and will clarify the relationship between geometric shape and the materials used.

- "Complex curvilinear surfaces in composite materials". Master Thesis, by Liao. N. H. (2001).The aim:

  This research presents the method of designing the architectural form used in the continuous and curved surfaces. It also explains and reveals the method of continuous surface involvement with dynamic forces and how they respond to them to provide functional, environmental and other needs.

- "Curvilinear architecture: emotional effect of curvilinear forms in interior design". PHD Thesis, by Nejad. K. M. (2007).The aim:

  This research presented the emotional effects of the curved shape on the interior architectural designs and how to gradually change the shapes from straight to full curved. The reason for the use of curved designs in the built environment and the response of architectural settings for bending was also explained.

The researches which included Zaha Hadid Architect have clarified her design strategies; her styles to put the ideas and linking the interior, exterior spaces in an amazing manner; mentioning the design patterns and techniques that focused on them to show the abstract and fictional work; and here some of those studies:

- "The text of free-form architecture: qualitative study of the discourse of four Architects". Maser Thesis, by Wong. F. J. (2009). The aim:

  In this research, the author Joseph Wong has discussed design strategies of four famous architects, where Zaha Hadid was one of these architects. The main five design factors from their viewpoint also have clarified, such as: context, language, exploration, industry, and inspiration, as well as the sub-factors of each one.

- "The Methodology of Deconstruction in Architectural Education from the viewpoint of Derrida", Article, by Serap Durmus and Sengul Gur (2011).The aim:

  This research have proposes the history of architectural design which depending on Deconstructivist. The focus was on deconstruction philosophy through architecture.

- "Zaha Hadid Form Making Strategies For Design", Master Thesis, by Abdalwahid, A. A. (2013).The aim:

  This research has focus on the architectural forms and theory of Zaha Hadid, and has considered on the Hadid contribution in architecture. It is also clarified how could the architect Zaha Hadid generate such creative forms?

- "Zaha Hadid's Architectural Form Patterns", Master Thesis, by Abdalwahid. A. A, Said. B. I, Ossen. R. D. (2013).The aim:

The aim of this research was to reveal one of Zaha Hadid's mysterious objectives, which she was always keen to present in her architectural projects, characterized by communication, social activity and new landscapes that emerged in her works.

Where the percent of Zaha Hadid design form notion under five patterns: 6% topographic, 7% Organic, 10% parametric, 24% fluid and 53% suprematism.

- "Zaha Hadid's Techniques of Architectural Form-Making", Article, by Abdalwahid. A. A, Said. B. I, Ossen. R. D. (2013).The aim:

  This research provided a systematic analysis of Zaha Hadid's architectural design techniques. This thesis presented a systematic analysis of the architectural design techniques of Zaha Hadid. It also aimed to discover the reasons and techniques behind its distinctive works, as it presented six techniques used by Hadid: play of light; fragmentation and abstraction; Layering; idea of the ground and gravity; fluidity and seamlessness; landscaping project and the surrounding context.

Despite the existence of all these researches related to the works of architect Zaha Hadid, but there is a lack of academic researches on the types of structural system and materials used in Zaha Hadid projects, the reason for their selection and different from one project to another.

CHAPTER 2
THEORETICAL FRAMEWORK

2.1 Curved Forms

The design is a spirited building that must follow or take some of the characteristics of living organisms in nature and derive the most important principles of creation such as innovation, movement, growth, flexibility. So the designers have been inspired the curved forms from nature and living organisms, where one idea gives countless numbers of solutions and forms like the idea of forming a tree, a bird, or a human being, and there are all kinds of trees, birds and humans, which do not resemble two, although they follow the same plan and order. Curved form is the most propagation form in nature. The curved form has held on evolve over the centuries, both structurally and aesthetically, and also aided to obtain ever-larger spaces without interruption with elements of the structural system. Belington termed curved forms as the leading ideals of structural art, efficiency, elegance and economy (Belington, 2000).

These models have been favored by many well-known architects not only for the intent of looking for economic solutions, easiness of construction, but also to seek the aesthetic quality of their designs. Curved forms and structural systems have undergone significant developments throughout history, leading to the expansion of potential options in the future. As human began to seek shelter for protection from external dangers, built a dwelling in various forms including curved forms, using materials available in the place which present in, such as stone, reeds, wood, and palm fronds, with the development of ages and civilizations, the curved forms have been used in religious buildings, such as mosques and churches which need large spaces with unabated spans. The main curved forms are arch, vault and dome. The arch was the first curved form to be used in the construction and then evolved to be a vault which consists of successive arches, after that the dome was formed from the arches twist around the center of the circle which is the base of the dome (Adnan and Yunus, 2009).

2.2 Curvilinear Forms

The curvilinear forms considered as a great progress in architecture, where architects have been contributed to development and progress them over time to create a new and innovative architectural designs. The architects assume that curvilinear forms have positive effects on the human mind, sense of comfort and smooth movement, as well as the creation of large spans without interruption, which led them to integrate the basic curved forms in their designs, while each of architect had an own style and strategy (Nejad, 2007).

In the late of 20th centuries, architects began to incorporate the basic curved forms (arch, vault and dome) to create a new and unique designs with larger spans than previous that combining beauty, elegance and make it an integral part of the surrounding environment, but there was not term describing this kind of forms and designs, while in 20th century the architecture was called by modern architecture. In the 21st century, "curvilinear" term has been launched to describe designs created by merging the curved forms, where the architecture in this century called "contemporary curvilinear architecture". Architects have been used the curvilinear forms for different aims, where curvilinear forms have been used by covering buildings of project to create a large span semi-open areas which make internal relationship between utilities, to create a closed large span area without interruption by using curvilinear roof, or used in design of walls to have a shapely curvilinear facades (Çıngı, 2007).

The architect Zaha Hadid was one of architects who used the curvilinear forms in her designs, and considered as one of the architects who had an important role in contributed to the development of curvilinear forms, and made it an integral part of nature, where the Guardian magazine dubbed Zaha Hadid "Queen of the curve" (The Guardian, 2013).

2.3 Curvilinear Structures

The curvilinear structures of contemporary architecture were characterized by smoothness and abstraction, which combined beauty, elegance, efficiency and economy with the required necessary functions with integration of interior and exterior design and make them an integral part of the surrounding environment. But at first these complex designs faced many criticisms because they were unconventional and out of the ordinary because of the difficulty of their implementation. The engineers and architects began to construct their curvilinear structures at the late of 20th century and 21st century (Mainstone, 2001).

Trusses have been considered as one of the basic systems used to carrying the loads and give the static of structure, so the space frame structures have been used with the trusses to construct static and strong curvilinear structures. After that Shell structures have been used in construction of curvilinear forms. The materials and techniques used to build curved structures have evolved. Architects started to think of larger spans than previous, which needed a light structure to ensure the rigidity of building, so at the first they started to use coffers systems in the structural systems made by reinforced concrete, which give a structure lighter than normal reinforced concrete structures, after that they used metal materials that can give a static structures with larger spans than structures which constructed by reinforced concrete material. At first these complex curvilinear structural forms have been faced many criticisms because they were unconventional and out of the ordinary because of the difficulty of their implementation, while the computer programs and advanced technologies helped to facilitate the design and construction of these types of structures, which led to acceptance the curvilinearity by a lot of people, engineers, and architects (Goldberg, 2006).

2.4 Form-Structure Relationship

The form is a set of points that draw the boundaries of a place and shape (line, curve, surface). The engineering aspects and characteristics associated with the shape are taken into consideration. In some cases, the terms of form and structure can be used in the same place, but when we say the term "form" the whole entity is included, while the term "structure" expresses the strength and durability of the shape, such as the bearing walls, columns and beams used to create the shape. As a result, there is no unique relationship between the terms form and structure when describe the geometrical configuration of the structure, where the structural configuration considered as one aspect from the aspects of the structural form (Gharleson, 2005).

> “Architectural form is the point of contact between mass and space … Architectural forms, textures, materials, modulation of light and shade, color, all combine to inject a quality or spirit that articulates space. The quality of the architecture will be determined by the skill of the designer in using and relating these elements, both in the interior spaces and in the spaces around buildings”. - Edmund N. Bacon.

The structure cannot be imagined without the existence of a shape that determines its size, dimensions, space and location in reality. Figure plays a major role in architecture while it is the most controversial point in architectural designs or constructions (Plan N Design, 2018). There is a strong relationship between the shape, the structure and the internal functions, where the structure forms the inner functions and relationship between them, as well as the structure create the external form of building and the desired design, and the materials are playing an important role in the aesthetics of structure and shape. The structure is the part that resists the loads applied to the building, as it is subjected to static loads and moving loads, for example the loads of snow, wind, rain, passengers and furnishings, as well as carries its own weight. All applied loads affect the shape and durability of the building construction, perhaps the weakness of the structure leads to the distortion of the shape of the building (Macdonald, 2001).

2.5 Zaha Hadid Designs

The architect Zaha Hadid who have brought together fantasy and truth, that her imagination, optimism in architecture future, her will, her faith in her abilities, the power of invention and design have helped her to put her mark around the world. Hadid died in Miami in 2016, aged 65 after a heart attack. Curved shapes have been used by architects by different ways, patterns and strategies, giving each of them special features. Zaha Hadid is distinguished by its genius designs, where achieved a distinguished position in international architecture with its progressive vision of the relationship of architecture with people. She became the first woman in modern history where jumped to the ranks of geniuses of world architecture in the world. She became the world's most famous architect of the world, and the new generations of architects around the world excited about her designs, because she developed architectural values that combine technology-driven faith with social change. The Arab engineer raised the banner of hope in the face of the prevailing perceptions about the death of architecture, and criticized the fear of the speed of modern life and fear of permanent change in the ways of life (Design Boom, 2007).

Zaha Hadid has always worked on creating ideas far from traditional, trying to reflect a new angle that represents the nature of each period and place. The strategy of Hadid can be divided into five stages: Personal Investigation, Form Notion, Form Creation, Circulation Movement and Function, and Interior Design. The first step of Hadid's design starts with rigorous study for site, neighborhoods, environment; function of the project, and any factor could be affected and related to the design of her project, where comprehensive knowledge contributes to the creation of an effective model with environmental conditions, while her ideas were inspired by the movement of people within the city and the information gathered about the site that serves the project in all aspects, linking all these ideas to each other to create a new and unique design, so the different research results from one city to another has helped her to diversify her ideas, designs and projects. As well as the facilities of computing programs played a very important role to achieving the final project form, while this stage is attached to considering distribution of functions in zones (Arch Idialog, 2012).

Before she passed away in the United States, Iraqi architect Zaha Hadid left a distinctive mark in the world of engineering, where she became known as the "Queen of Curves" given the revolutionary nature of her designs and her abandonment of traditional geometric shapes. Zaha Hadid also broke into the fashion world, developed many designs for shoes, and participated in works at the most prestigious fashion forums in Milan, Italy and others. Zaha Hadid started to use the curvilinear architectural forms in her buildings to create unique designs by merging the curved lines with smooth, fluidity style and harmony with surrounding environment, while her curvilinear buildings look like grow thing from the ground. She wanted to achieve total fluidity which changes from the breaks blocks with sharp angles to continuous objects with curved angles and forms (Dezeen, 2018).

CHAPTER 3
CURVILINEAR ARCHITECTURAL FORMS AND STRUCTURES

3.1 Development of Curved forms

Since ancient times, the nature of the place, the weather, the materials and the tools available have defined the shape of the dwelling. These forms and methods have also contributed to the development of architecture as well as structural forms (Borges, 2001).

The curved design is a dynamic building with natural characteristics. The principles and qualities of creativity are derived from movement, flexibility, innovation, growth. Curved form is the most propagation form in nature, have evolved throughout history, where the structures and the structural elements have seen important steps in expanding the potential choice in the future. The arch was the first curved shape to be used in the construction and then evolved to be a vault which consists of successive arches, after that the dome was formed from the arches twist around the center of the circle which is the base of the dome (Adnan and Yunus, 2009). The evolution of these forms led to changed and advanced the architecture and architectural form greatly over the ages. Building components considered as the important factors that have played a major role in this architectural development that is because the main function of it is the support of loads applicable on the building to ensure the stability and durability of the structure (Borges, 2001).

3.1.1 Arch

The stone arch and the brick arch "Masonry Arch" are the first examples in the construction of the arch, and the first using of these arches was appeared as early as the 2nd millennium BC in Mesopotamia. Stone and brick arches have been used to support small structures, while wooden frames have been used to support these structures during construction, and remove it after completion (Figure 3.1), (Figure 3.2), (Figure 3.3) and (Figure 3.4) (Architecture World, 2008).

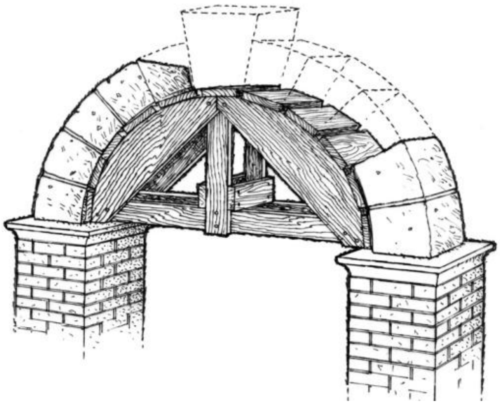


Figure 3.1: Stone arch with wooden frame
(http://blog.stephens.edu/arh101glossary/?glossary=centering)

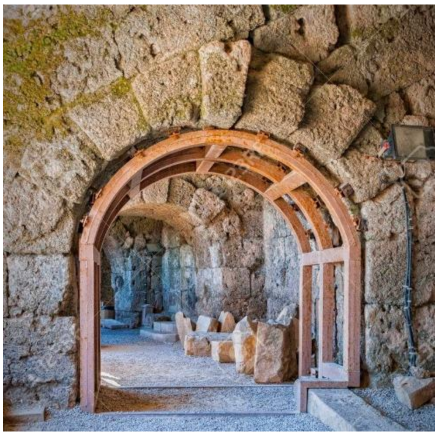


Figure 3.2: A stone archway made with a wooden frame
(https://www.123rf.com/photo_70926566_an-archway-made-safe-with-a-wooden-frame-within-the-ancient-roman-amphitheatre-situated-in-the-turki.html)

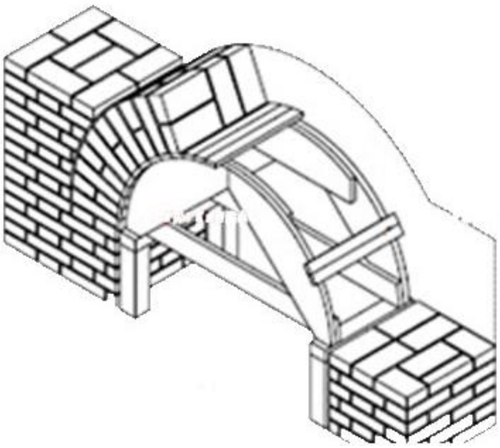


Figure 3.3: Brick arch with wooden frame
(http://the-mind-of-architecture.blogspot.com/2015/08/architecture-basics-arches.html)

Figure 3.4: A brick arch made by wooden frame open window
(https://www.123rf.com/photo_74892460_isolate-background-close-up-picture-wooden-frame-open-window-with-ancient-brick-wall-.html)

In the first century BC, the Romans used stone arch which was not half-circular in bridges and houses, it is called "Segmental Arch" (Figure 3.5) and (Figure 3.6), then used stone arch with circular peaks called the "Round Arch" (Figure 3.7) and (Figure 3.8). After that, the concrete arches have been used in the construction (Figure 3.9) (Technology Student, 2009).

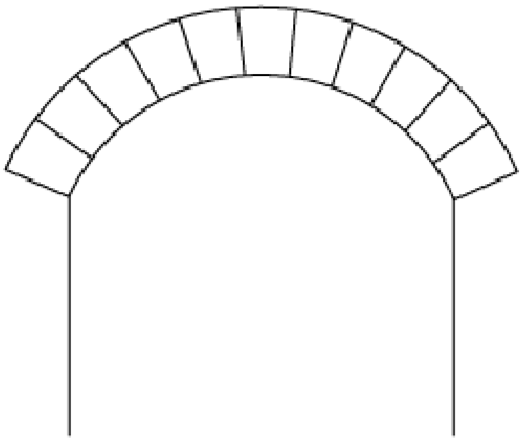


Figure 3.5: Segmental arch
(http://www.architecture-student.com/architecture/types-of-arches-architectural-details/)

Figure 3.6: Stone segmental arch in design of open-door
(http://dlawstonemason.co.uk/portfolio_category/stone-building-work/page/2/)

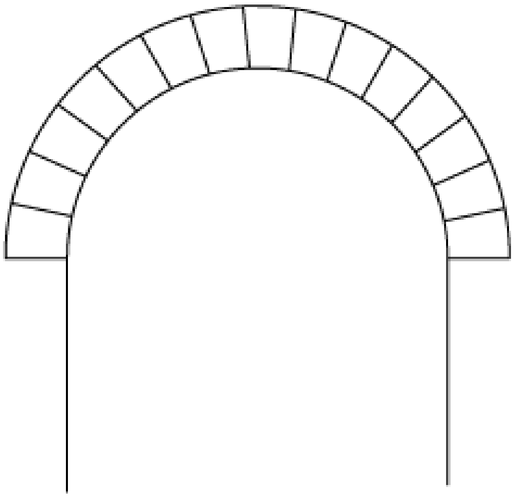


Figure 3.7: Round arch
(http://www.architecture-student.com/architecture/types-of-arches-architectural-details/)

Figure 3.8: Stone round arch in design of Roman aqueducts
(https://www.kidsdiscover.com/quick-reads/roman-aqueducts-dawn-plumbing/)

Figure 3.9: Ancient Roman arches constructed by concrete material (https://sites.google.com/site/furerplox/re/archarchesoftheromanempireandmodernsociety)

In the middle ages, wooden arches have been used, and the first wooden arches have been built by Apollodorus of Damascus in 106 AD was Arch at Benevento. Apollodorus of Damascus was a Syrian-Greek engineer, architect, designer and sculptor from Damascus (Gareth Harney, 2013).

At the beginning of the modern era, arch has been discovered by Voussoir system, and due to the stability and strength of these ancient structures fueled the advancement of masonry arch design well into the 20th century (Figure 3.10) and (Figure 3.11) (Lancaster, 2015).

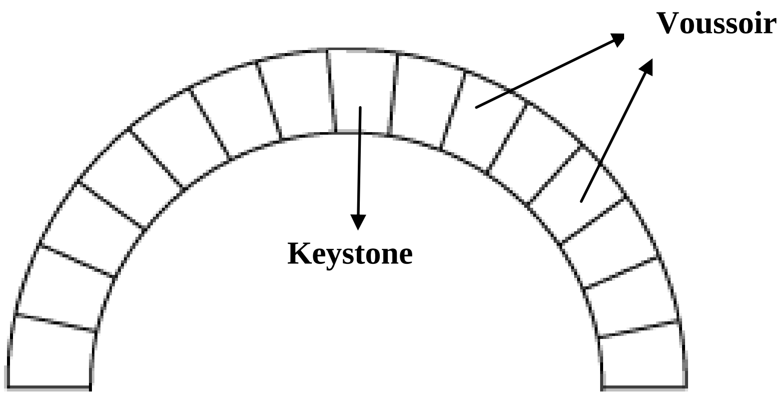


Figure 3.10: Arch by Voussoir system (https://ef.engr.utk.edu/ef158-2006-01/sc/m1/ef158_m1_l9.pdf)

Figure 3.11: Structure of a Roman arch by using Voussoir system (https://www.romeartlover.it/Costroma.html)

3.1.2 Vault

Vault, it is not easy to determine the history of the invention of the cellar, although there are still ancient vaults until now. Where the remains of the Neolithic period vaults are found in 5600 BC in the village of Khirokitia in Seabers, as well as the vaults which is dating from 1500-3000 BC known as Orchomenos and Mycenae, vaults belonging to 2,200 BC were also found (Pozzi, 2014).

The vaults were mainly used by Persians, Assyrians, and Sumerians. And then the Roman vault, where the Romans used the vault not only as a building system but also used it as a morphological element of the archaeological architecture. The irregular stones have been used to construct the arches that used to construction of the vault, and due to the difficulty of cutting stones in a way to proportional to each other, this was not developed directly (The Mind of Architecture, 2008).

At the beginning of the modern era the voussoir form of Arch has been discovered, and used in construction of vaults (Figure 3.12) and (Figure 3.13) (Study, 2018).

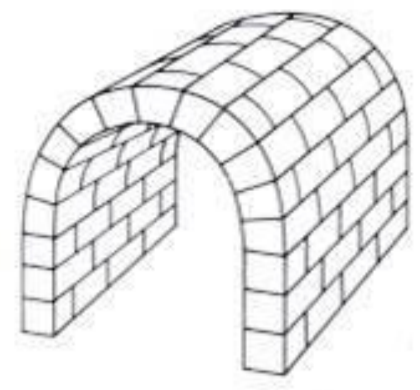


Figure 3.12: Vault by Voussoir system
(http://www.humanitiesresource.com/1020a/lectureImages/test1.htm)

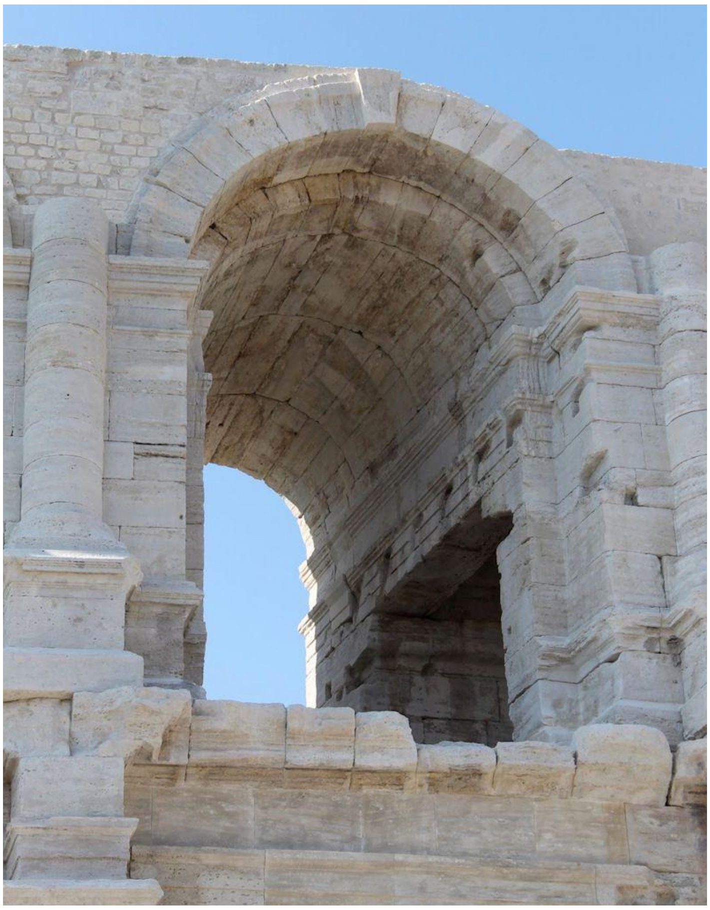


Figure 3.13: Roman arched barrel vault, Arles, France by using Voussoir system (https://www.pinterest.com/pin/505951339360883257/)

3.1.3 Dome

The dome is the last step after the arch and the vault. Since ancient times, humans have been used reed and timber to build simple huts in a dome shape, and then used stone and mud bricks. The first conical dome was made of clay or mud bricks in the fifth or sixth century BC. Stone has been used in the construction of the dome in the middle of the second century BC. Roman builders discovered the dome by rotate the stone arches around a circular center, where it enjoyed great power (Figure 3.14), (Figure 3.15) and (Figure 3.16) (The Vintage News, 2016).

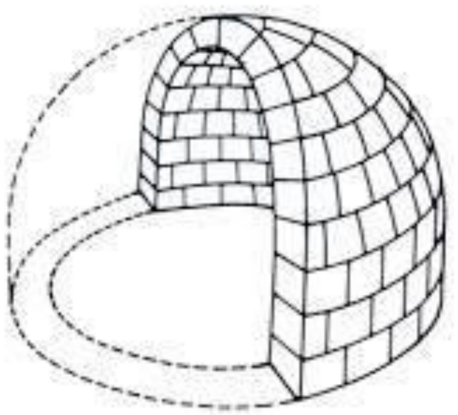


Figure 3.14: The dome by rotate the stone arches around a circular center (http://www.humanitiesresource.com/1020a/lectureImages/test1.htm)

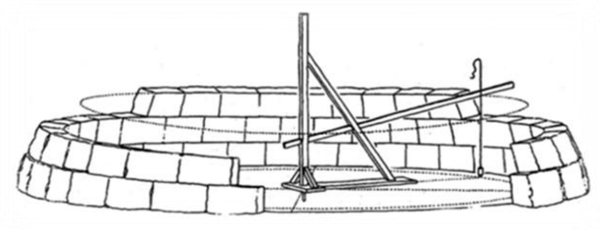


Figure 3.15: Construction of dome by Voussoir system (http://www.mileslewis.net/lectures/04-history-of-building/COB-14-domes-and-vaults.pdf)

Figure 3.16: Stone dome by Voussoir system (https://www.researchgate.net/publication/238181856_Timbrel_Domes_of_Guastavino_Nondestructive_Assessments_On_A_Half-Scale_Model)

Churches and mosques then began to be covered with domes that helped to create large spaces. In 1330 BC large dimensions of the dome were achieved, in the Atreus treasury and the Tomb of Agamemnon in Mycenae, with a diameter of 14.5 m. Later, the domes spread widely in Southern and Western Europe. The stone domes and the supporting columns have suffered from the great weight. Which led to the asylum of engineers at the time to the complex forms, which called “coffers”, along the walls to loosen weights in large buildings, They also they left holes at the peak of the domes called the “Oculus”, which provide daily lighting in the massive structures and Temples (Aliberti et al, 2015).

Later, the light wooden structural domes were used instead of the heavy stone structures, where domes can be built from all soils as well as the soft soil such as clay. At the beginning of the modern era, after the discovery of arch by voussoir system it has been used it in construction of dome (Foti et al, 2016).

The concrete domes have been constructed in the late 2nd and early 1st centuries BC, where its remains have found in Frigidaire or the Stabian cooling-rooms and Forum Baths at Pompeii. Its shape was conical in addition to the open eye at the top, with a diameter of about 6 meters, and these domes were later a model of Roman concrete domes. A hundred years later, they transformed the conical shape into an inner spherical shape, such as the Temple of Mercury in Baia, in addition to the central open eye, with an extension of 21.5 m. The dome have considered as an engineering achievement due to its dimensions and rigidity, as well as its symbolic and religious significance in the Ottoman Empire. This achievement cannot be avoided throughout the history of the Ottomans. Architect Koca Sinan has considered the chief builder of the arched structures and the hanging domes (Melaragno and Michele, 1991).

3.2 Contemporary Curvilinear Forms and Structural Systems

Architects have been used the curved structures in their buildings, by different ways. In the late of 20th century the architects started to think about creating curved forms with larger spans than previous, which needed a light structure to ensure the rigidity of building, so at the first they started to use coffers systems in the structural systems which made by reinforced concrete, while the coffers can give a structure lighter than normal reinforced concrete structures, then they have been used metal materials which can give spans more than reinforced concrete material and can give a static structures. In the late of 20th century, the architects started to merge curved lines to create a new type of architecture, but in this period there was no term describing this kind of designs. The materials and techniques used to build curved structures have evolved, where the reinforced concrete and steel materials have been used to create the curvilinear forms with long spans, while the trusses considered as one of the basic systems used to carrying the loads and give the static of structure, so the space frame structures have been used with the trusses to construct a static and strong curvilinear structures, where the grids of space frame connected by trusses. Space frame structure combined beauty, elegance, efficiency and economy with the required necessary functions with integration of interior and exterior design and make them an integral part of the surrounding environment. After that Shell structures have been used in construction of curvilinear forms. At first these complex curvilinear designs faced many criticisms because they were unconventional and out of the ordinary because of the difficulty of their implementation. However, computer programs and advanced technologies helped to facilitate the design and construction of these types of structures, which led to acceptance the curvilinearity by a lot of people, engineers, architects and critics later on (Goldberg, 2006). In 21st century the curvilinear term has been launched, where curvilinear is a word that describes architecture with free and unfamiliar forms. The architects have been used the curvilinear in their design, such as: Renzo Piano, Mario Botta, Jean Nouvel, Santiago Calatrava, Norman Foster, Frank Gehry, and Zaha Hadid by various pattern and strategies, which gave each one his / her own features.

3.2.1 Trusses

In 20th century, Trusses are the most common structures, where used to create curved designs with achieve long spans, lightweight, support considerable loads and reduced deflection (compared to plain members), and opportunity to support considerable loads (Slide Share, 2013).

The truss is the basic structure that acts as a load device in structural engineering. It consists of long and thin elements by means of concrete, steel or wood. These elements merge together to form triangles by welding or guzzets. These trusses only hold pivotal power, the trusses are either simple, complex. Trusses work under the compression and tension systems, where occur in the joints, where if the forces move toward the joint; called "tension" and when they move away from the joint; called "compression" (Figure 3.17) (Makezine, 2010).

The common types of trusses have been used in curved roof:

- King post truss.
- Pratt truss.
- Fan truss.
- North Light Roof Truss.
- Quadrangular Roof Trusses.
- Warren Truss.

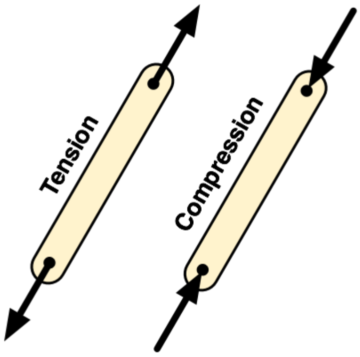


Figure 3.17: Tension and compression in trusses (https://makezine.com/2010/06/10/ask-make-how-do-trusses-work/)

The King post truss: most of the time, particular truss is made out of wood, but also can be manufactured out of wood and a combination of steel.The King Post Truss is considered as perfect type for multiple types of houses, especially the smaller ones of them, because it spans up to 8m. Curved tie-beam can be use with king post truss, while beem can made from timber and steel (Figure 3.18) and (Figure 3.19) (Branco et al, 2009).

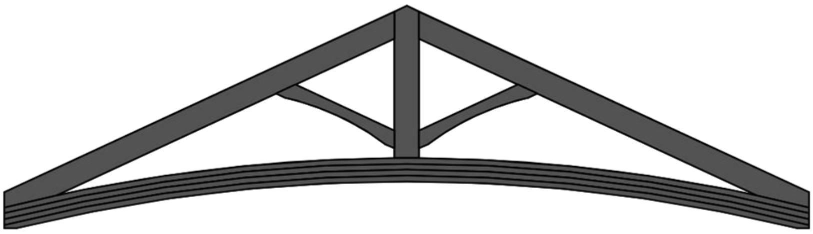


Figure 3.18: King post trusses with curved tie-beam
(http://timberworksnz.com/feature-roof-truss-designs/king-post-curved-tie-beam/)

Figure 3.19: Arched Oak king post trusses
(http://www.oak-beams.co.uk/products/trusses/attachment/view-framed-by-salon-trusses-2/)

In parker truss (pratt truss) type, the vertical members provide tension, while the diagonal ones are bringing in compression, and it can be used for spans which range between 6-10m. This type is quite economical and one of the most popular steel roof truss types (Figure 3.20) and (Figure 3.21) (Sky Civ, 2015).

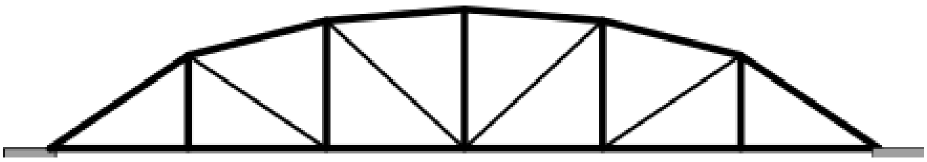


Figure 3.20: The parker trusses of curved roof
(http://www.wikiwand.com/en/Truss_bridge)

Figure 3.21: Prefabricated steel bow string roof trusses built in 1942
(https://en.wikipedia.org/wiki/Truss)

The fan trusses: have a very simple design; it's made out of steel. The fink roof truss formed by the trusses, and the top chords have been split into smaller lengths to get a medium span , around 10-15 m (Figure 3.22) and (Figure 3.23) (Alpha Steel, 2018).

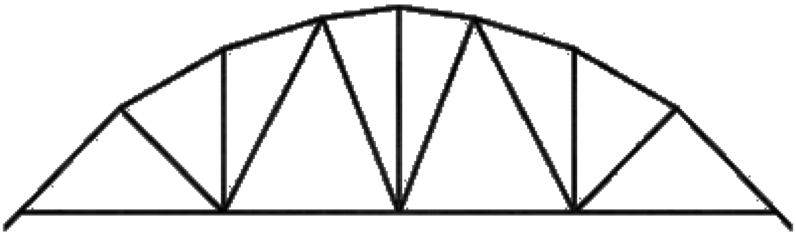


Figure 3.22: The fan trusses of curved roof (http://www.custardkids.com/roofs/trusstypes.asp)

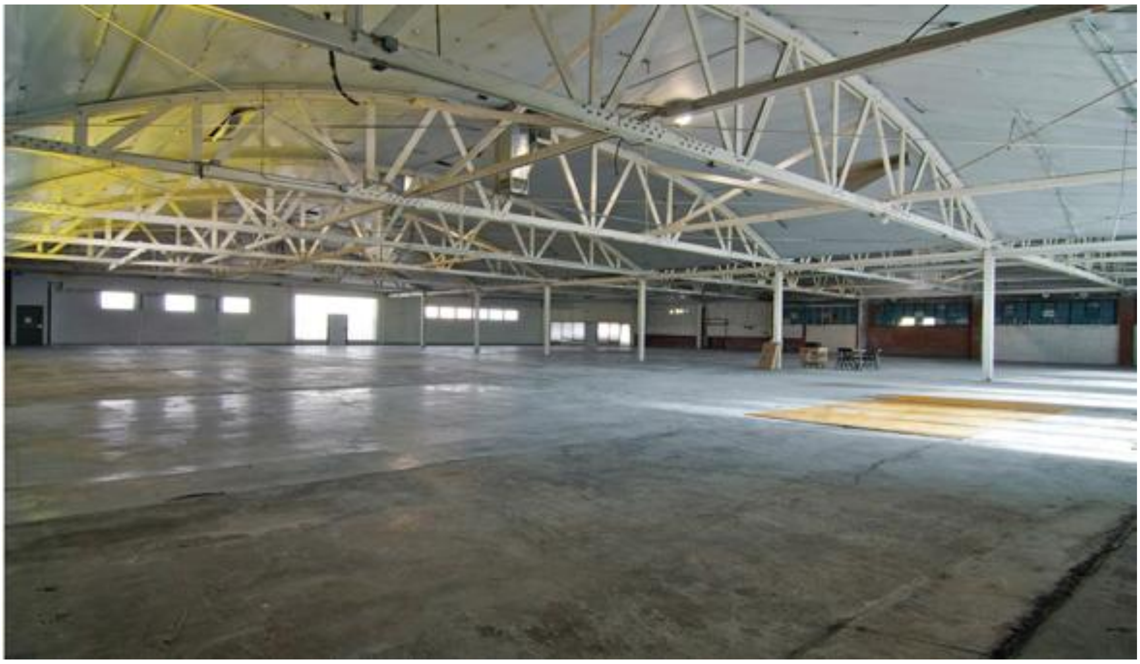


Figure 3.23: Hollywood gallery from Regen projects (https://www.mattconstruction.com/blog/restoration-reuse/regen-projects-a-gallery-goes-to-hollywood/)

The quadrangular roof trusses have been used for steel structures in large spans, like auditoriums or even railway sheds. Its spans reach to 180 m (Figure 3.24) and (Figure 3.25) (Space Frame, 2017).

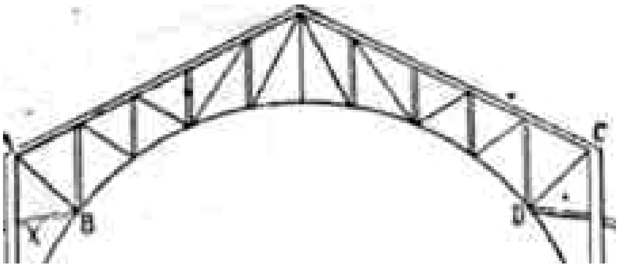


Figure 3.24: The quadrangular trusses of curved roof (https://chestofbooks.com/architecture/Construction-Superintendence/36-The-Quadrangular-Truss.html)

Figure 3.25: Iron and glass roof of Aberdeen station (https://www.123rf.com/photo_47203375_iron-and-glass-roof-of-aberdeen-station.html)

Commonly, Warren Trusses are used for the long span buildings ranging from 20 to 100 m in span. This type is also used for the horizontal truss of gantry/crane girders (Figure 3.26) and (Figure 3.27) (Sky Civ, 2015).

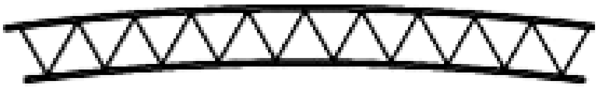


Figure 3.26: The parallel chord trusses of curved roof (https://www.structuremag.org/?p=10300)

Figure 3.27: Space truss structure of train station roof (https://www.alibaba.com/product-detail/Large-span-curved-and-coated-powder_60685407845.html)

3.2.2 Space frame structures

Space frame structure in the architecture and construction in most often consists from steel or timber, and if the height of building was more than 9m should supported by reinforced concrete. The upkeep level of timber material is very high unlike steel and aluminum materials (Space Frame, 2016). Uses of steel and aluminum give the frame light weight, hardness, flexibility and ease of transport and installation, where it is manufactured by factories and transfer to the site. It is characterized by the low cost of construction, and is used to cover large areas and wide with the use of some internal stents. The space frame is a three-dimensional system that is installed and assembled by linear element, it can produce flat or curved frame. This structure has helped to facilitate the engineering of complex shapes due to its ability to distribute loads equally and axially through the system's linear components. The linear elements are connected by knots, which considered as the center of strength and stability of the frame. The size, depth, dimensions, weight, cladding length, cladding size, and the position of the stent are effects on the space engineering. Therefore, precise studies of the various requirements of the structure must be carried out to determine the correct selection about the number of layers, the geometric arrangement of the elements and the grid pattern (Lan, 1999).

The types of space frame:

- Curvature classification: included space plane covers, barrel vaults; and spherical domes.
- Classification by the arrangement of its elements: included Single layer grid, double layer grid; and triple layer grid.

The classification by the arrangement of its elements types uses for long spans and complex structures. Single layer grid (Rectangular) efficient for span up to almost 30 ft, 9 m, Single layer grid (Diagonal) efficient for span up to almost 40 ft, 12 m, double layer grid efficient for up to almost 300 ft span, 91 m; and triple layer grid efficient for more than 300 ft span, 91m (Setareh Arch, 2011).

- **Single layer grids (SLG)**

They are parallel elements that intersect with each other perpendicularly, and all elements meet are in one level. There are three forms of a single-layer grid: two-way grid, three-way grid; and four-way grid, single layer grid used for spans up to 10 m (Figure 3.28) and (Figure 3.29) (Geometrica, 2015).

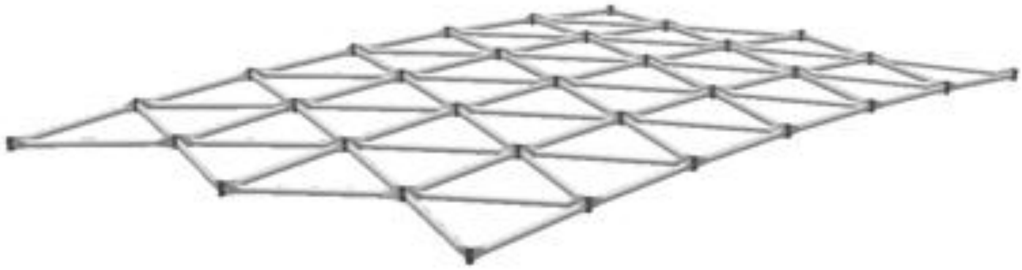


Figure 3.28: Single layer grid
(http://www.geometrica.com/en/domes)

Figure 3.29: Single layer grid of Ujjain dome
(http://www.alcox.in/blog/alcox-space-frame-structure-systems/)

- **Double layer grids (DLG)**

These grids are formed by the extension of single grids systems. It's consisting of two parallel groups connected to each other by tilted angles carried by orthogonal forces at the grid level, uses for flat and curved shapes. The double layer grids have two main types are direct (Truss) Grids and space grid (Setareh Arch, 2011).

Direct (Truss) Grids consists of members of the upper and lower strata, all of which are at the same level, producing a series of planar trusses. Space grid consist from a series of multiple units with triangular, quadrilateral, pentagonal or hexagonal bases with hierarchical multiple surfaces (Linked In, 2016).

There are three types of double layer grids: Double layer grid connected with perpendicular members to the surfaces which use for a huge and centered loads with supporting column, or for considerably long spans (Figure 3.30), double layer grids connected with slant members to the surfaces which are easy to install on the ground then raised into venue (Figure 3.31) and double layer grids by the ribbed geometries which benefit from increased chord density (Figure 3.32), double layer grids used for spans reach to 100 m (Geometrica, 2015).

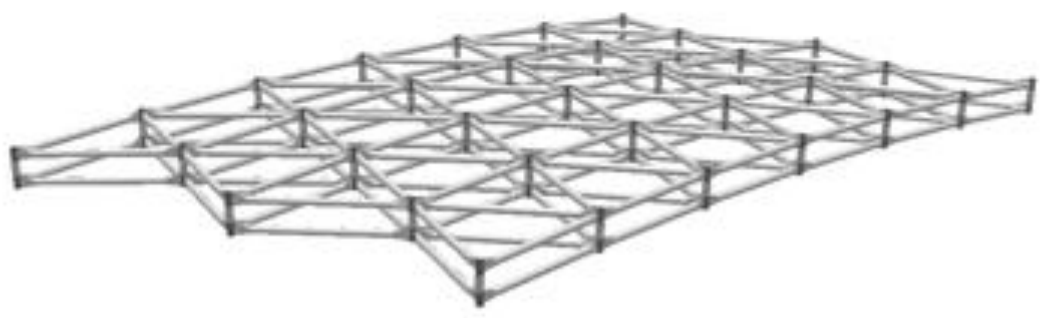


Figure 3.30: DLG connected with perpendicular members to the surfaces (http://www.geometrica.com/en/domes)

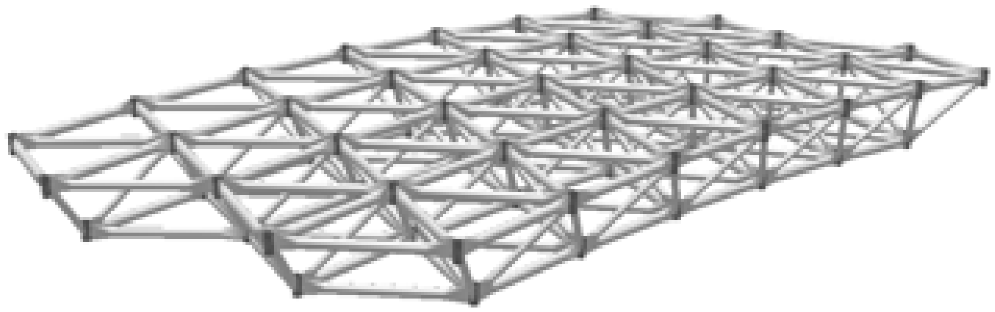


Figure 3.31: Double layer grids connected with slant members to the surfaces (http://www.geometrica.com/en/domes)

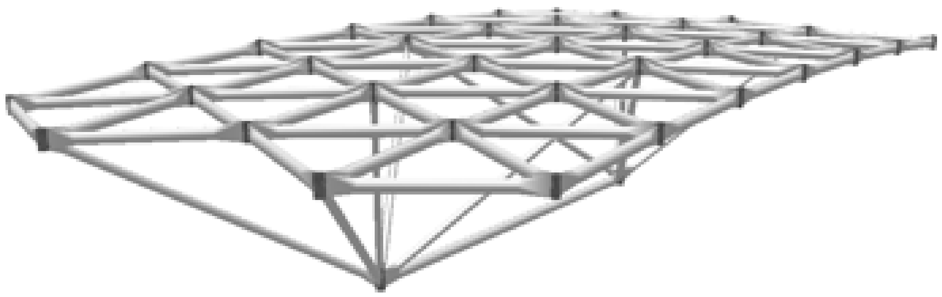


Figure 3.32: Double layer grids by the ribbed geometries (http://www.geometrica.com/en/domes)

o <u>Renzo Piano – Kansai International Airport</u>

Structural system: space frame structure by double layer grids (DLG).
Material of the structure: steel.

It is located on an artificial island in the middle of Osaka Bay in Japan. The construction started in 1987. It's extends over 3000 meters. It is receives about 150 aircraft a day. The roof consists of 900 pillars, each one consists from double-layer grid made of steel, and there are 14.4 meters long between pillars, each pillar extends 92.8 meters. The cladding material made by stainless steel (Figure 3.33). The steel trusses are exposed in interior ceiling design (Figure 3.34) (Archi Travel, 2013).

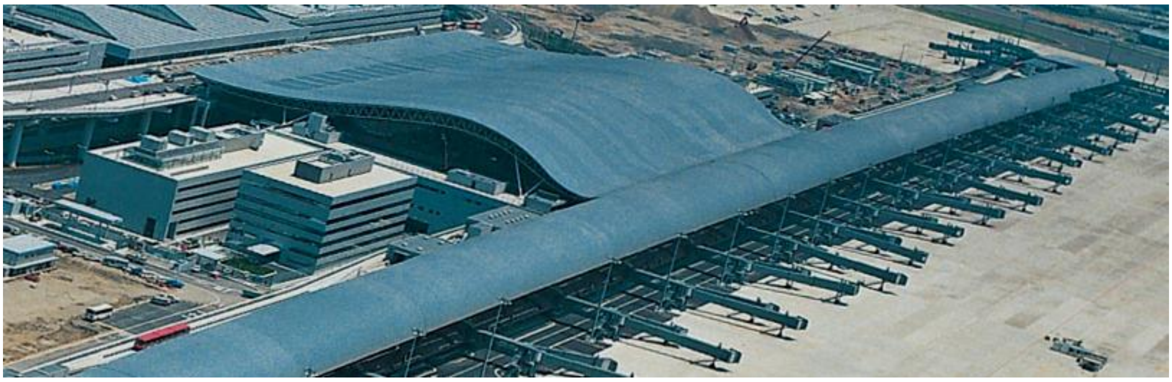


Figure 3.33: Kansai international airport
(https://en.focchi.it/progetti/33-kansai-international-airport)

Figure 3.34: The exposed steel trusses in ceiling design
(http://faculty.arch.tamu.edu/media/cms_page_media/4433/kansai.pdf)

- Frank Gehry - Weatherhead School of Management Peter B. Lewis Building

Structural system: space frame structure by double layer grids (DLG).
Material of the structure: steel.

The Weatherhead School of Management Peter B. Lewis Building in Ohio in 2002 was the first random complicate curvilinear design made by Frank Gehry (Figure 3.35). The area is 14,000 m^2. The concept consists from merging the curved lines (Figure 3.36) (Cleveland, 2012).

Figure 3.35: the Weatherhead School of management (https://www.azahner.com/works/weatherhead)

Figure 3.36: Sketch of the Weatherhead School of management (https://www.pinterest.com/pin/293015519498913119/?lp=true)

The building consists from two structure one of them made of concrete material and other one made of steel material, where concrete flat slabs has been used to support primary floor elements and curved concrete beams for 8-ft deep, while steel material ha been used in roof structure (Figure 3.37), (Figure 3.38) and (Figure 3.39) (Desimone, 2017).

Figure 3.37: Structural systems of the Weatherhead School of management (https://www.de-simone.com/projects/project/peter-b-lewis-building-case-western-university/)

Figure 3.38: Construction of the Weatherhead School of management (https://www.de-simone.com/projects/project/peter-b-lewis-building-case-western-university/)

Figure 3.39: Construction of the Weatherhead School (https://www.donleyinc.com/portfolio/peter-b-lewis-building/)

The cladding materials that used in the Weatherhead School of Management are glass, limestone and titanium while the color of titanium plates' change according to the light and weather conditions (Figure 3.40), the ceiling materials that are glass and wood (Figure 3.41) (Traveler, 2015).

Figure 3.40: Cladding materials of the Weatherhead School of management (https://www.cntraveler.com/galleries/2015-09-17/frank-gehry-architectecture-road-trip)

Figure 3.41: Ceiling materials of Weatherhead School of management (https://www.bluffton.edu/homepages/facstaff/sullivanm/ohio/cleveland/gehry/lewis5.html)

The curved forms which shaped by using the boxes of truss grid, where located parallel and in same heights, such as Robin Hood Airport Roof (Figure 3.42) and (Figure 3.43).

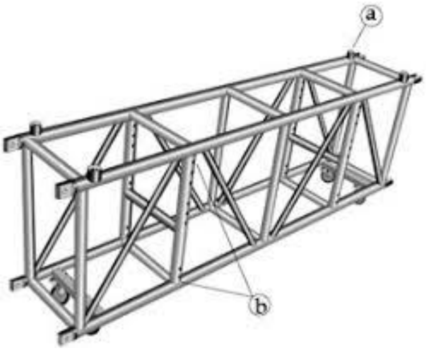


Figure 3.42: Box of truss grids
(http://www.sgps.net/touring-production.html)

Figure 3.43: The mall with temporary space frame
(https://adib.typepad.com/blog/2008/01/temporary-space.html)

- **Triple layer grid (TLG)/ Multiple Layers**

This type of space frames almost use for flat frame, included both of single and double layer grids, which create three layers in parallel, the purpose of its use is to diminution length of the diagonal members and to increase the durability, stiffness and cohesion of the long span structures, where the span of these types uses to more than 100 m (Figure 3.44) (Linked In, 2015).

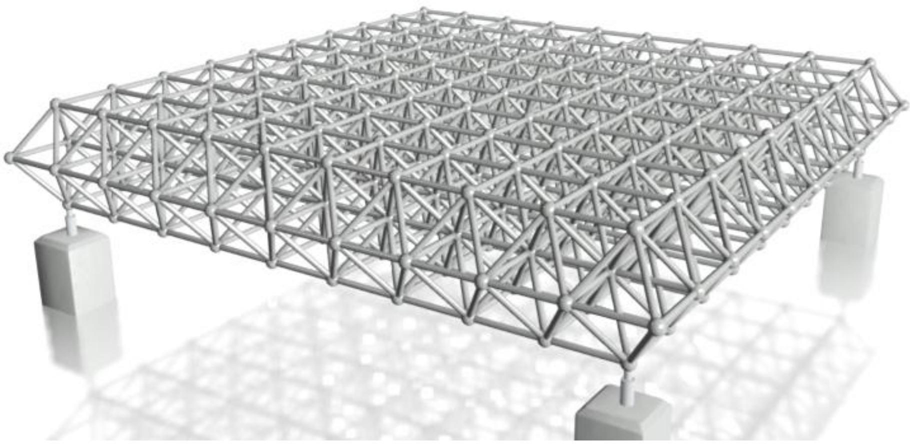


Figure 3.44: Triple layer grids
(https://www.setareh.arch.vt.edu/safas/009_introduction_02_FMLG.html)

- Jean Nouvel – Louvre Museum

Structural system: space frame structure by triple layer grids (TLG).
Material of the structure: steel.

Louvre Museum located on the Saadiyat Island Cultural District - Abu Dhabi - United Arab Emirates, construction started in 2007. The museum houses internal exhibitions used for temporary exhibitions and permanent museums, 23 exhibitions, a children's museum, the Louvre, 270-seat banquet halls, a restaurant, a café and a shop. The area of permanent collection is 6000 m2, and the temporary exhibitions area is 2000 m2. The building has a dome constructed with 10 layers: a double layer grids made of steel material and 8 layers of cladding (Figure 3.47), the diameter of dome is 180 meters. The dome have been created a semi-open space used for special and permanent displays, while the structure type of dome is double layer grids made by steel material, while cladding and ceiling materials is stainless steel (Figure 3.45) and (Figure 3.46) (Arch Daily, 2017).

Figure 3.45: Louvre museum
(https://www.worldarchitecturenews.com/article/1518069/louvre-comes-abu-dhabi)

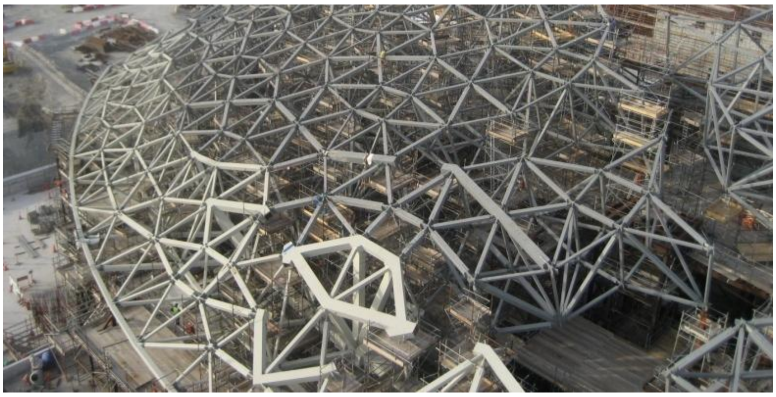


Figure 3.46: Roof structural system of the dome of Louvre museum (http://dnec.com/?portfolio=fairmont-hotel-abu-dhabi-uae)

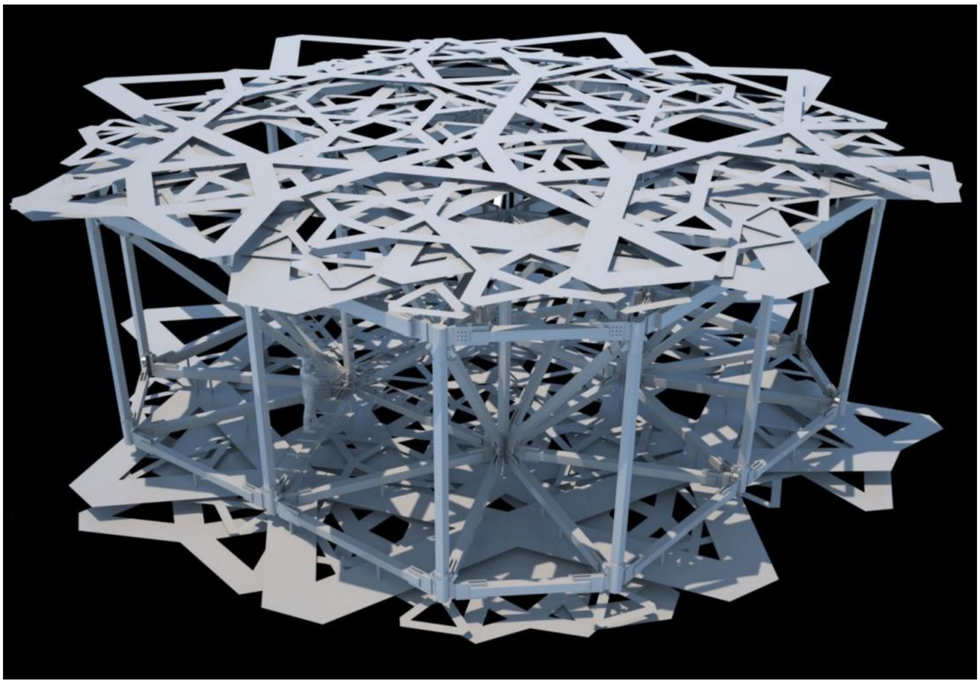


Figure 3.47: The 10 layers of the Louvre museum dome (https://www.archdaily.com/886180/the-engineering-behind-the-louvre-abu-dhabis-striking-geometric-dome/5a44e552b22e38785d000077-the-engineering-behind-the-louvre-abu-dhabis-striking-geometric-dome-photo)

- Frank Gehry - Guggenheim Museum Bilbao

Structural system: space frame structure by triple layer grids (TLG).
Material of the structure: steel.

Guggenheim Museum Bilbao located in Bilbao, Spain, opened in 1997. The museum offers sculptures of free form (Figure 3.48). It contains spaces for presentations and other large spaces for large works and also includes galleries dedicated to the encyclopedic wealth of modern art. The area of Guggenheim museum Bilbao is 32,500 m^2. It consists of a reinforced concrete beams with a steel frame structure. The concept has been appeared by merging curved lines to create a random design (Figure 3.49) (Blog Ferrovial, 2017).

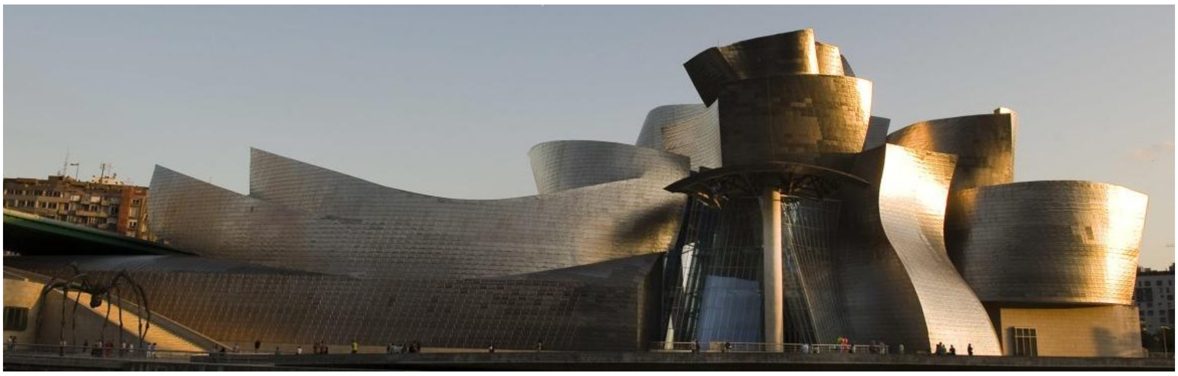


Figure 3.48: Guggenheim museum Bilbao
(https://www.guggenheim.org/about-us)

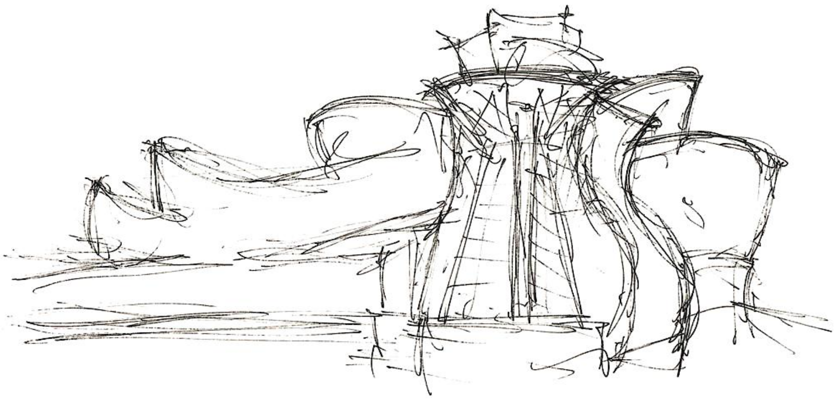


Figure 3.49: Sketch of the museum shown the integration of curved lines
(https://www.cityofsound.com/blog/2004/04/sketches_of_geh.html)

Two structural systems have been used in construction of the museum, the firs structure made of reinforced concrete in construction of internal utilities' walls and foundations, while the curvilinear cover has been constructed by space frame structure with three layer grids made of steel material (Figure 3.50) and (Figure 3.51), as well as The section in (Figure 3.52) had shown the structural system of museum (Arch Daily, 2013).

Figure 3.50: Structures of Guggenheim museum Bilbao (https://www.pinterest.com/pin/514817801135581133/)

Figure 3.51: Space frame structure of Guggenheim museum Bilbao
(http://archikey.com/building/read/2747/Guggenheim-Museum-Bilbao/511/)

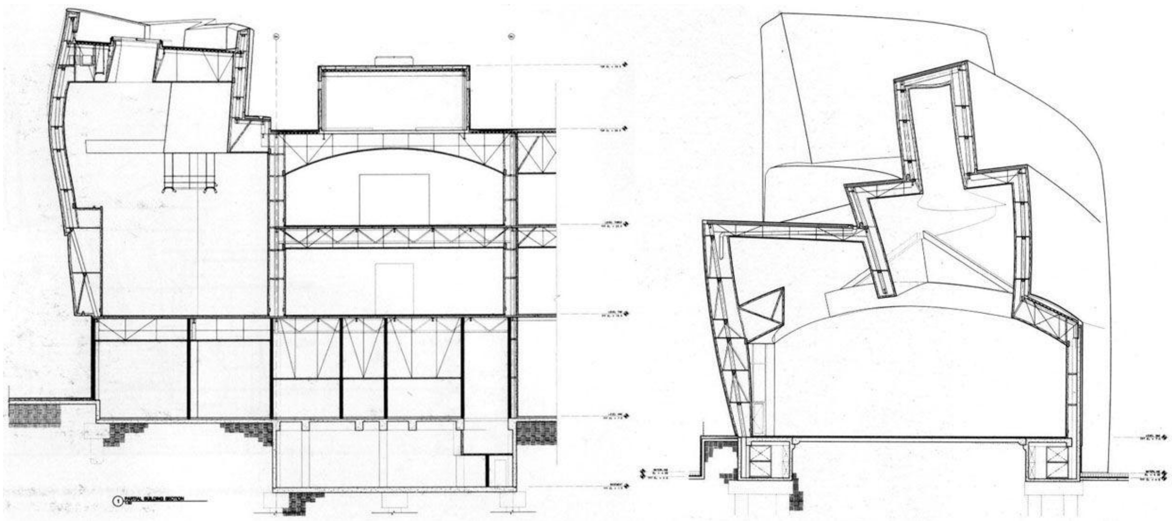


Figure 3.52: Sections of Guggenheim museum Bilbao
(https://www.pinterest.com/pin/381820874629846939/)

The cladding materials that used in the Guggenheim Museum Bilbao are glass, titanium, and limestone, where 33,000 titanium plates have been used, while the color of the plates change according to the light and weather conditions (Figure 3.53). The ceiling materials that used in the Guggenheim Museum Bilbao are glass and wood (Figure 3.54) and (Figure 3.55) (Blog Ferrovial, 2017).

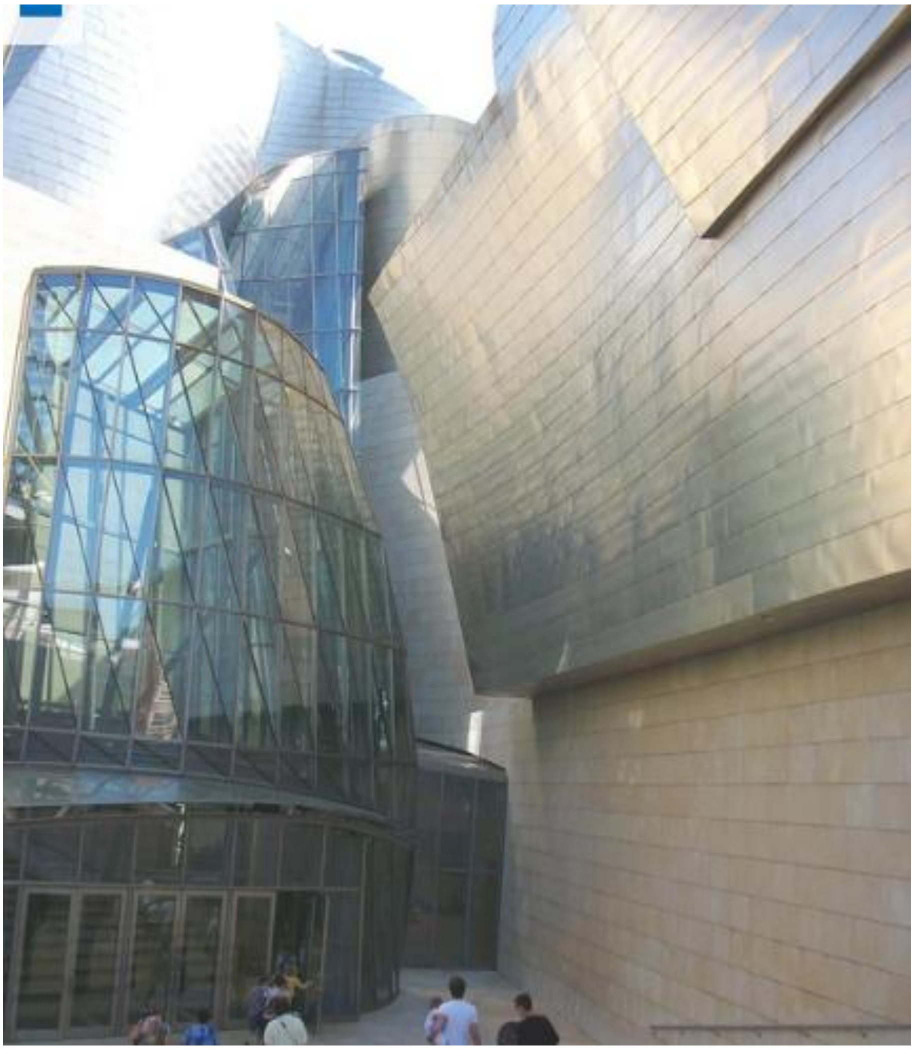


Figure 3.53: Cladding materials of Guggenheim museum Bilbao (https://www.archdaily.com/422470/ad-classics-the-guggenheim-museum-bilbao-frank-gehry)

Figure 3.54: Ceiling materials of Guggenheim museum Bilbao (https://news.artnet.com/art-world/the-bilbao-effect-20th-anniversary-1111583)

Figure 3.55: Interior design and ceiling materials of Guggenheim museum (https://de.phaidon.com/agenda/architecture/articles/2012/november/23/buildings-that-changed-the-world-the-guggenheim-museum-bilbao/)

3.2.3 Shell structures

Structural shapes are classified according to their forms, geometry, functions and constituents (Adriaenssens et al., 2014). The shell forms are derived from sea shells and other sea crusts as well as bird eggs. The bending direction varies between these shapes, where some of them bend around one axis such as the cylinder and the other around two axes such as the dome (Block, 2009).

The elements of shell structures are considered lighter than the elements of space frame structures and are usually used to create curvilinear structures with large spans and include three typical layers: boat hulls, aircraft fuselages; and roofs of large buildings. These thin structures are used to send forces applied to them such as pressure and tensile strength and these structures are usually constructed with timber or steel (Prezi, 2015).There are two types of curvature shells:

- Single curvature shells.
- Double curvature shells.

○ **Single curvature shells (SCS)**

Is a cylindrical or conical shape that is curved on one linear axis, and consists of two types: long barrel shell "Rampant Vault"; where in this type the length is longer than width, and short barrel shell "Conical Vault" (Figure 3.86) and (Figure 3.58), single curvature shells have one axis (Figure 3.87) (SCRIBD, 2013).

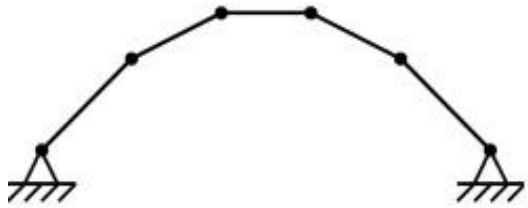


Figure 3.56: Single curvature shell (https://www.sciencedirect.com/science/article/pii/S0141029613000813)

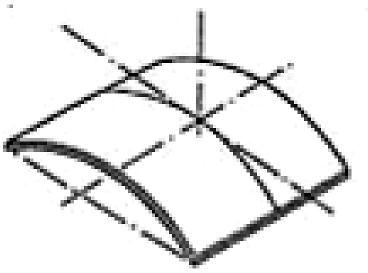


Figure 3.57: Single curvature shells (one axis)
(http://holtz3.cee.carleton.ca/recordings/3204/2016/2016-09-13/Lecture-2016-09-13.pdf)

Figure 3.58: Example of single curvature shell has one axis
(https://www.slideshare.net/alshimaak/buildings-structure-system)

- <u>Zaha Hadid – JS Bach Chamber Music Hall</u>

Structural system: shell structure by single curvature shell (SCS).
Material of the structure: steel.

The JS Bach Chamber Music Hall in Manchester in 2009 was the first smooth and abstract design made by Zaha Hadid. A music hall designed for unique musical performances by Johann Sebastian Bach music with area 425 m2 (17 * 25 m). The hall consists of a huge bar that wraps around each other to form a flexible, coherent and intimate liquid space to form the required functions and places (Figure 3.59). The fluidity concept consists from merging the curved lines (Figure 3.60) (Dezeen, 2009).

Figure 3.59: The JS Bach Chamber music hall
(https://www10.aeccafe.com/blogs/arch-showcase/2012/02/18/js-bach-chamber-music-hall-in-manchester-uk-by-zaha-hadid-architects/)

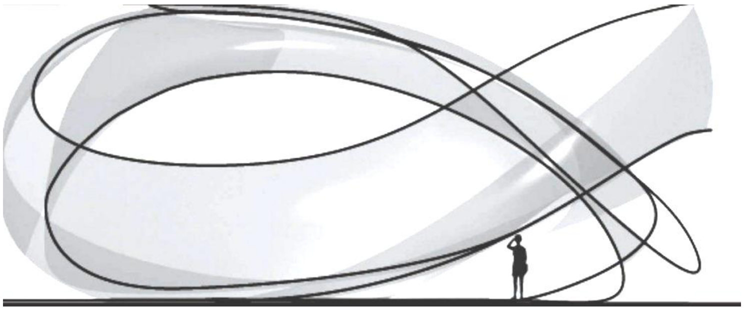


Figure 3.60: Sketch of the JS Bach Chamber music hall
(https://www.pinterest.com/pin/190206784238311317/?lp=true)

The design creates multiple layers at different levels, and the different functions are provided by the spaces formed by the tape by itself, where the interrelated relationship between the layers is discovered and understood when crossing in it (Figure 3.61) (Design boom, 2009).

Figure 3.61: Relationship between the layers of the hall (https://www.pinterest.com/kwaconstruction/steel-structures/)

The shell structure (Single curvature shell**)** has been covered by transparent fabric shell for exterior and interior cladding. The acoustic panels are made of acrylic material to be transparent and invisible, it have been suspended above the wooden stage inside the membrane (Figure 3.62). The tape is composed of a transparent membrane supported by a steel structure suspended which hanging in the ceiling of room (Figure 3.63) (Dezeen, 2009).

Figure 3.62: The hall steel structure with covering of fabric (https://www.youtube.com/watch?v=YQ-fstECTbM)

Figure 3.63: Suspende shell structure to the ceiling of the main room (https://archello.com/project/js-bach-music-hall)

- **Double curvature shells (DCS)**

This type of shells is a Dome, Hyperbolic, or Revolution shapes; and curved these forms on two axes orthogonal lines; and it's consists of two types: hyperbolic paraboloid, and rotational shell like dome and hyperboloid (Figure 3.64), (Figure 3.663) and (Figure 3.94), double curvature shells two axes (Figure 3.65) (SCRIBD, 2013).

Figure 3.64: Double curvature shell
(https://www.sciencedirect.com/science/article/pii/S0141029613000813)

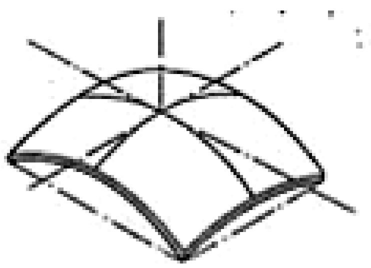


Figure 3.65: Double curvature shells (two axes)
(http://holtz3.cee.carleton.ca/recordings/3204/2016/2016-09-13/Lecture-2016-09-13.pdf)

Figure 3.66: Schubert Club band shell
(https://carpenterlowings.com/portfolio_page/schubert-club-band-shell/)

- Mario Botta - The Museum of Contemporary Art of Trento and Rovereto (MART)

Structural system: shell structure by double curvature shell (DCS).
Material of the structure: steel.

The museum is located in the city of Rovereto, close to the city of Trento, in northeastern Italy, construction began in 1987. The museum contains large areas some of them especially for exhibitions and others for the children's activities and creations, it also contains conference halls, a large open office, a documentation center, a shop of gifts and books and a café-restaurant. This building contains a large dome with an open eye and a missing slide. This dome covers the courtyard of the museum by shell structure (Figure 3.67). It was built of steel and glass and is 40 meters in diameter, while the structure of the building is constructed of yellow stone (Figure 3.68) (In Exhibit, 2018).

Figure 3.67: The museum of contemporary art of Trento and Rovereto (https://www.pinterest.com/pin/575053446146345667/?lp=true)

Figure 3.68: The dome structural system of courtyard in the MART (https://www.inexhibit.com/mymuseum/mart-museum-modern-art-trento-rovereto/)

- Santiago Calatrava – Tenerife Concert Hall

Structural system: shell structure by double curvature shell (DCS).
Material of the structure: reinforced concrete.

Tenerife Concert Hall located in Santa Cruz De Tenerife, Spain, construction began in 1997 (Figure 3.69). The area of Tenerife Concert Hall is 350 m^2 with height 58 m. The Concert Hall included a large hall has a seating area for 1800 spectators, and other hall which has a seating area for 400 spectators. The structure material is white reinforced concrete, and the structure of each arch spans to 50 m from each sides. The concept of concert hall consists from integration of curved lines (Figure 3.70) (Arc Space, 2012).

Figure 3.69: Tenerife concert hall
(https://www.flickr.com/photos/jmhdezhdez/sets/72157630511922146/)

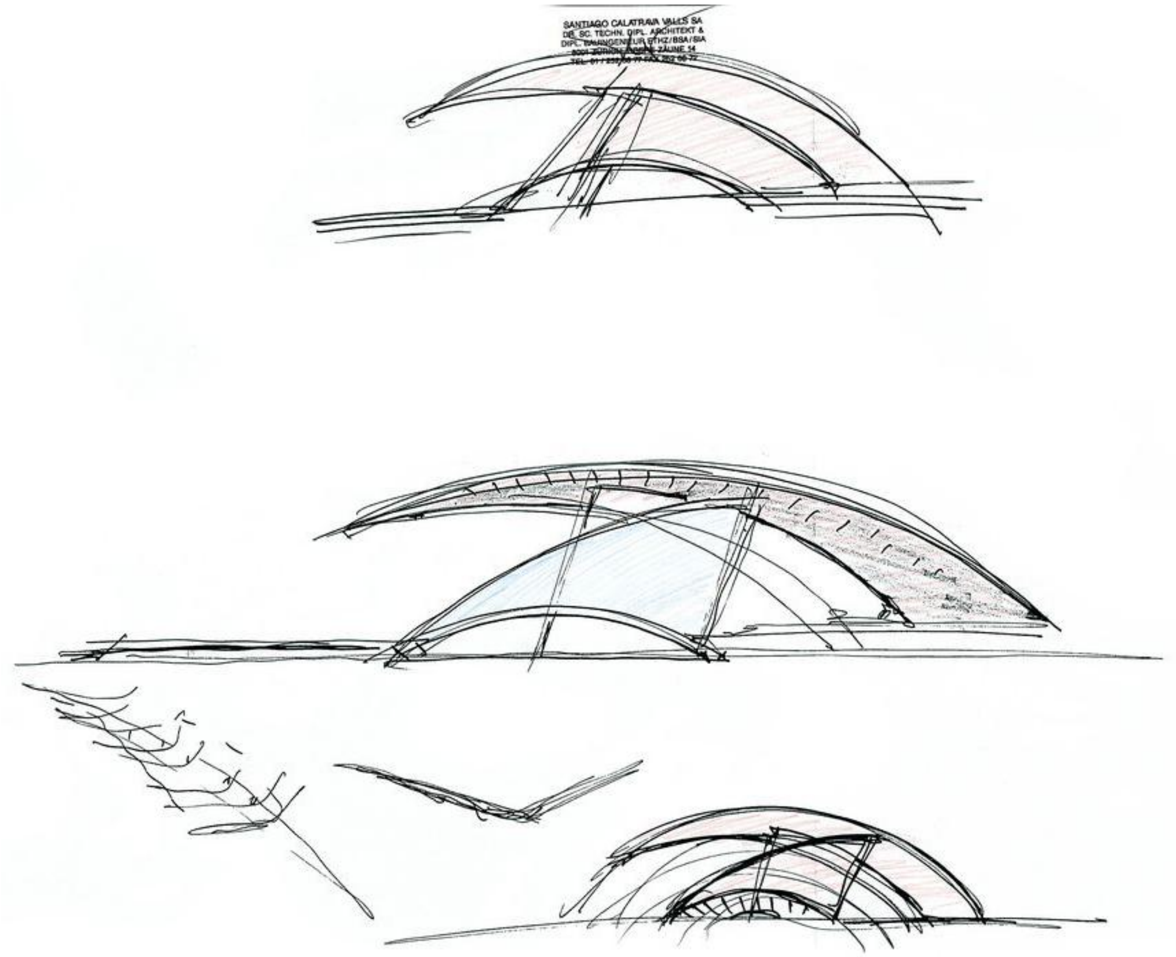


Figure 3.70: Sketches of the hall shown the integration of curved lines (https://www.pinterest.com/pin/484911084855377341/)

TRIO panel formwork have been used for the foundations of concert hall, curved concrete sail-like walls have been constructed by using climbing framework made of metal material, as well as supported the walls by trusses of metal material which helping with carrying the loads of concrete walls (Figure 3.71), (Figure 3.72), (Figure 3.73) and (Figure 3.74) (PERI, 2018).

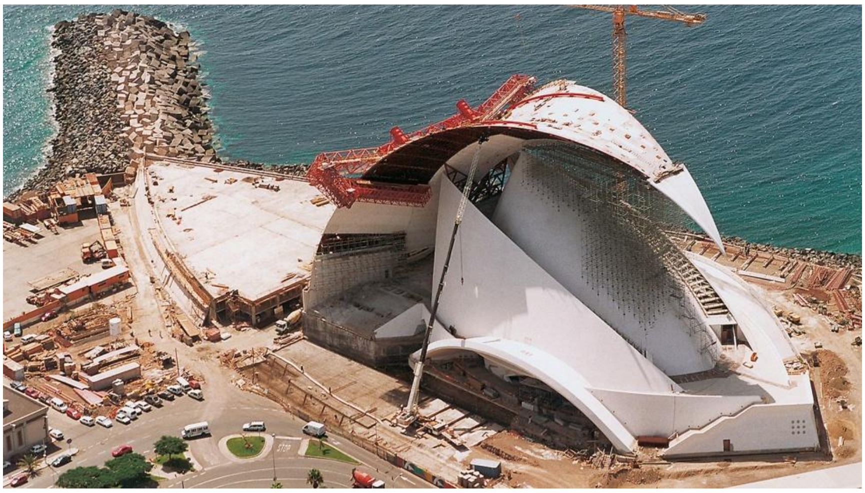


Figure 3.71: Structural system of Tenerife concert hall (https://www.peri.com/en/projects/cultural-buildings/auditorio-de-tenerife.html#&gid=1&pid=1)

Figure 3.72: Supporting the walls of Tenerife concert hall by Trusses (https://www.peri.com/en/projects/cultural-buildings/auditorio-de-tenerife.html#&gid0=1&pid=1)

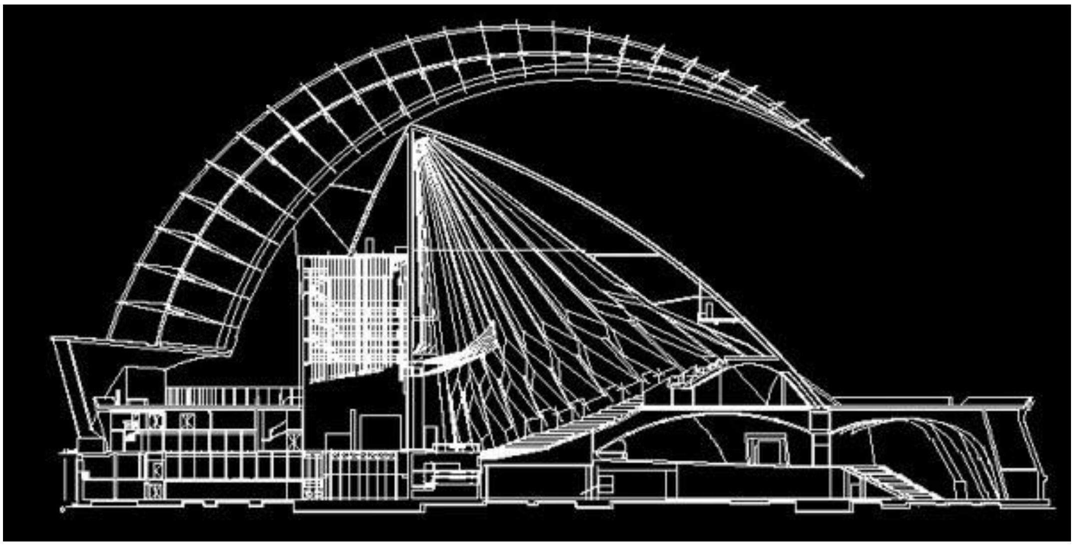


Figure 3.73: Structure the walls of Tenerife concert hall
(https://archidose.blogspot.com/2003/09/tenerife-opera-house.html)

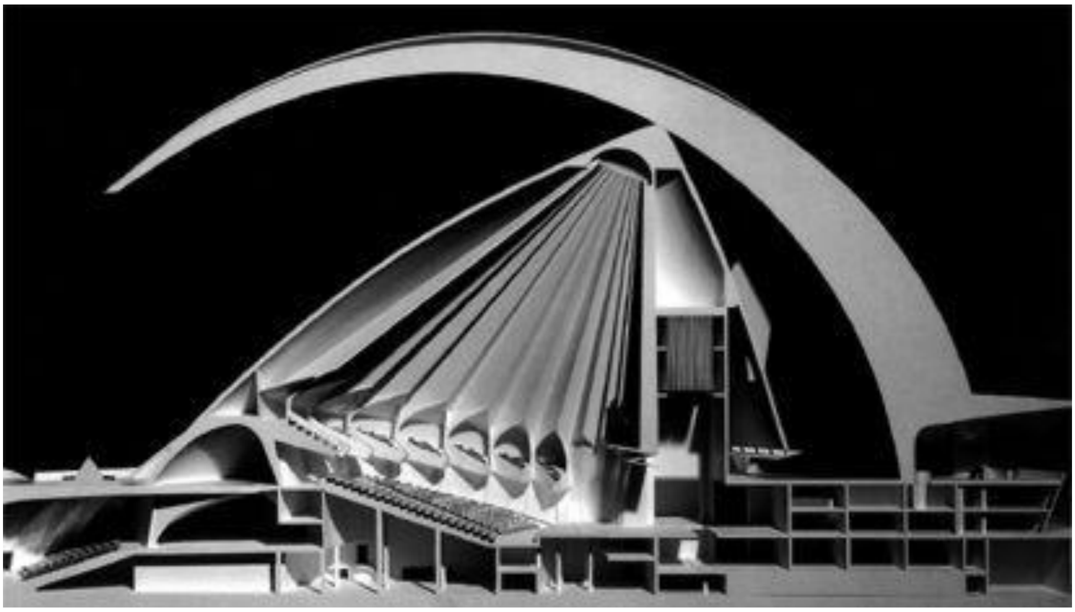


Figure 3.74: Structure the walls of Tenerife concert hall
(https://worldarchitecture.org/architecture-projects/nfc/tenerife-exhibition-center-project-pages.html)

- <u>Norman Foster – The Sage Gateshead Auditorium</u>

Structural system: shell structure by double curvature shell (DCS).
Material of the structure: steel.

The Sage Gateshead Auditorium located in St Mary's square, Gateshead Quays, Gateshead, UK, construction started in 1990_S. It is contains on two rooms, one of them is for The Largest Auditorium which has an seating area for 1650 spectators, and the other one is for Folk Music, Jazz and Chamber music which has an seating area for 400 spectators, as well as it is included a North Rock Foundation Hall, The Barbour Living, Esplanade, Squires Seminar Room and Entertainment Boxes. The roof span consist from 5 arches which supported the roof with span is 80 m (Figure 3.75), while the concept consists from merging the curved lines (Figure 3.76). The Sage Gateshead Auditorium covered by steel frame of shell structure with three separate reinforced concrete buildings (Figure 3.77), (Figure 3.78), (Figure 3.79) and (Figure 3.80) (Wikiarquitectura, 2004).

Figure 3.75: The Sage Gateshead auditorium
(https://en.wikiarquitectura.com/building/the-sage-gateshead-auditorium/)

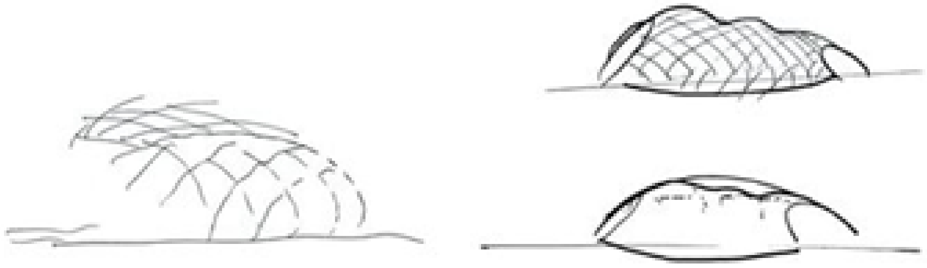


Figure 3.76: Sketches of the auditorium shown the integration of curved lines
(https://www.pinterest.com/tim_jacoby/norman-foster-sage-music-center-gateshead-1997-200/)

Figure 3.77: Concrete buildings with steel frame of shell structure (https://www.chroniclelive.co.uk/lifestyle/gallery/sage-gateshead-ten-your-photos-8265782)

Figure 3.78: Shell structure in the Sage Gateshead auditorium (https://en.wikiarquitectura.com/building/the-sage-gateshead-auditorium/)

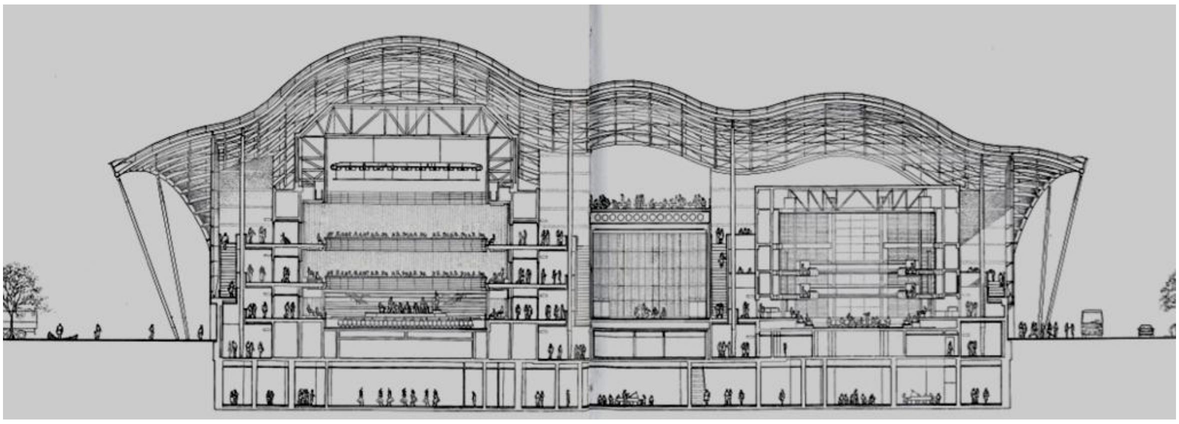


Figure 3.79: North section of the Sage Gateshead auditorium (https://be1380walmsley12007183.wordpress.com/2013/12/13/the-design-process-the-stages-and-implications-of-design-choice/)

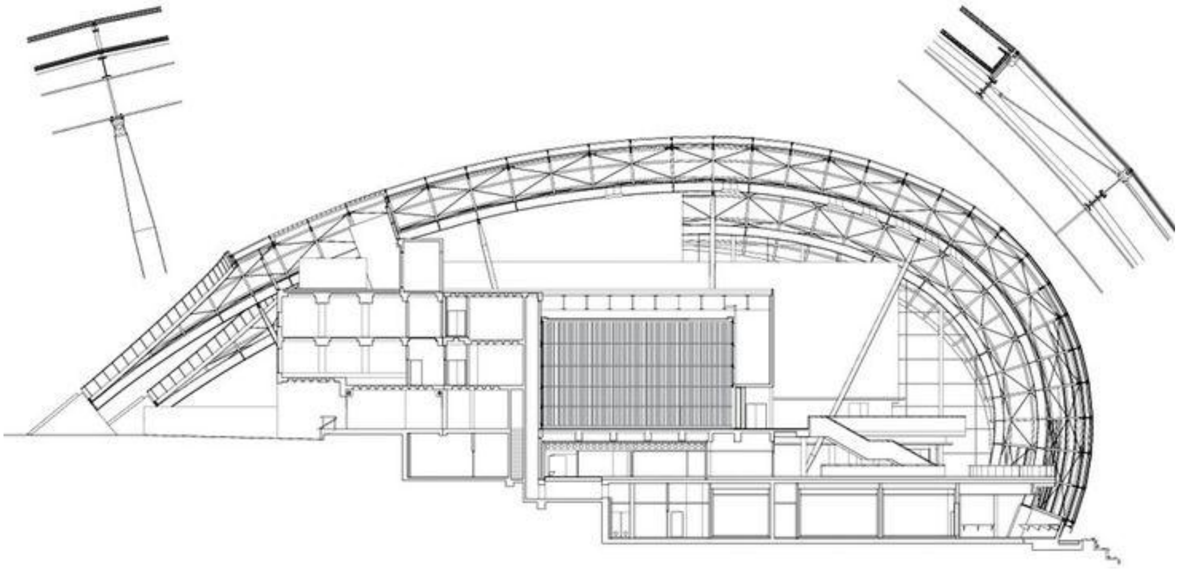


Figure 3.80: East section of the Sage Gateshead auditorium (https://www.pinterest.com/pin/548102217123573399/)

Trapezoidal glass panels have been used for cladding with 3,043 stainless steel panels (Figure 3.81), and the ceiling material is glass moving panels (Figure 3.82) (Designing buildings, 2017).

Figure 3.81: Cladding material of the Sage Gateshead auditorium (http://www.tonyjollyimages.com/sage-gateshead.shtml)

Figure 3.82: Glass moving panels in the Sage Gateshead auditorium (http://www.thejournal.co.uk/culture/arts-culture-news/happy-10th-birthday-sage-gateshead-8306064)

o J. Arquitectos Mayer – Metropol Parasol

Structural system: shell structure by double curvature shell (DCS).
Material of the structure: wood.

Metropol Parasol in Spain in 2011, it is a rectangular area with 15,000 m^2 with height 28 m, width 75 m, length 150 m and orthogonal grid of 1.5 by 1.5 m, located in the old town heart of the city. The design has four levels: Antiquarium Museum, Market, Elevated plaza and Parasols. The structure system is shell structure (DCS) constructed by wood, steel and concrete materials, where the steel and concrete materials have been used the lower levels which supported the wooden shell (Figure 3.83) and (Figure 3.84) (Spain-Holiday, 2018).

Figure 3.83: Metropol Parasol
(https://www.spain-holiday.com/Seville-city/articles/a-visit-to-the-metropol-parasol-in-seville-spain)

Figure 3.84: construction of Metropol Parasol (https://en.wikiarquitectura.com/building/metropol-parasol/)

As was observed, there are two types of curved structures that have been used mostly by architects by using different materials, space frame structure with trusses and shell structure. The table below summering the curvilinear structural systems, types of each one and materials that used in construction of the structures (Table 3.1).

Table 3.1: Curvilinear structural systems and materials

Curvilinear Structural Systems	Types	Materials
Space Frame Structure with Trusses	Single Layer Grid	• Steel • Wood
	Double Layer Grids	
	Triple Layer Grids	
Shell Structure	Single Curvature Shell	• Steel • Reinforced Concrete
	Double Curvature Shell	

CHAPTER 4
EVALUATION OF ZAHA HADID'S CURVILINEAR ARCHITECTURE

4.1 A Brief Overview of Zaha Hadid's Architectural Life

Zaha Muhammad Hadid was born in Baghdad, Iraq in 1950. At a time when Iraq was enjoying intellectual freedom, she studied in Baghdad until the end of her high school and earned her bachelor's degree in mathematics from the American University of Beirut in 1971 (Pritzker Prize., 2018).

She graduated in 1977, at the Architectural Society of London, after she presented a distinguished graduation project "a hotel on the bridge of Hungerford" where she was classified within the framework of the architects of the Deconstructivist, while, used the purely geometric forms and the hotel was about to take off or escape the gravitational attraction, that suggesting her affected by the works of the Russian-Soviet artist and the artistic theorist Kazimir Malevich, where his works had a great influence on the development of abstract art during the 20th century. The late Iraqi architect Zaha Hadid gives her smooth work and does not recognize angles or borders. Her mad designs helped her to put her mark in all countries of the world. She was also named "Queen of the Curve". The architect Zaha Hadid has been inspired her curved lines from nature and added to it her distinctive charming touches, which gave it the title of "architectural genius". Her name in architecture was the story of creativity moved among the most important capitals. Her long career was challenging. Her aim was to break the rules and stereotypes and to create designs that inspired the world freely. She was influenced by abstract geometry, Smoother of Arabic calligraphy and interaction between mathematical logic and architecture. Architect Zaha Hadid belonged to the "Architectural Deconstruction School". Zaha Hadid has followed the structural system that made by steel material in most of her architectural designs, such as "Heydar Aliyev Center", "Aquatic Center", and "Harbin Opera Center", etc **(**The Guardian, 2013**).**

Her designs were characterized by scientific imagination, which led many to say that her initial works are just paper designs and cannot be implemented, until that the Hong Kong company was designed to the construction of the summit resort, but the construction was stopped after the client losing the site, that was the first shock to iron, and after 10 years The Albert building was designed in Cardiff, where Hadid faced the second shock after stopping the implementation as well. From each failure was facing her she tried to create a new dream bigger and stronger than the previous and the will and ambition of Zaha Hadid pushed her to creativity again and that was a reason for her success. Zaha Hadid has always worked on creating ideas far from traditional, trying to reflect a new angle that represents the nature of each period and place. Her adventure and insistence on editing the architectural line and not following the usual has helped her to put a different fingerprint all over the world, giving it the nickname of the best woman architect in the world (Abdullah et al., 2015).

Zaha Hadid have been won in the competition in 2005 of redesign of Eleftheria square in Nicosia, Cyprus, while the aim of this square is to reconnect the moat and Venetian walls of town with the town's modern part. The strategy of Hadid can be divided into five stages: Personal Investigation, Form Notion, Form Creation, Circulation, Movement, Function, and Interior Design. Hadid considers that the conducting the search is the basic and first step of any project, where prior to the design, she was conducting research on the city and the site in terms of the social and political events that make up the history, culture and traditions of the place, and also was holding meetings with residents of the region to know their aspirations for the city future to take them into account, where comprehensive knowledge contributes to the creation of an effective model with environmental conditions. The different research results from one city to another has helped her to diversify her ideas, designs and projects, because her ideas were inspired by the movement of people within the city and the information gathered about the site that serves the project in all aspects, linking all these ideas to each other to create a new and unique design (Arch Idialog, 2012).

Her ideas were confined to five areas: nature, location, architecture, art, and computing programs. The climate, the direction of the wind, the location, the landscape, the terrain and the topography of each place produce different and effective ideas to make design an integral part of the surrounding environment, Hadid's Meditation in that factors had a great role in devising her special ideas and methods (Design Boom, 2007). In her projects, Zaha Hadid refers to organic forms and aesthetics inspired by nature such as waves of the sea, mountains and valleys. Her works were characterized by abstract art that was not easily understood. Early until the mid-1990s, her work was influenced by the works of the artist Kazimir Malevich; she created new forms from abstract thought, where her free ideas led to breaking the usual and established rules. As an Arab Muslim woman, she had inspired the curved shape from the Arabic calligraphy and the floral decoration of Islamic art, which gave her the character of excellence and smoothness and made her a special architectural impression (Abdalwahid, 2013). Throughout Zaha Hadid's traveling around the world, she learned a lot of different cultures and philosophies, which played a major role in promoting and expanding her imagination. For example, she was influenced by Chinese art after her trip to China, where she learned traditional painting that imparts a sense of infinite freedom and overlap engineering in surrounding gardens, and that gave her a role in the development of her landscape design skills. Zaha Hadid announced that architects Frank Lloyd Wright, Oscar Niemeyer and Mies Van Der Rohe had a role in the development of their work, where she learned from them how to edit the fonts (Archidialog, 2012). The development of the computing sector has facilitated the conception and design of complex forms and their implementation. Hadid's company used the Digital Architecture Design (Parametric design system) system which contributed to the creation of different, imaginative and unique designs, while the main ones are:

- Rhino/ Grasshopper 3D.
- AutoCAD.
- Maya 3D.
- Revit.
- Digital project.
- 3D Max but pretty rarely.

These programs have been used by many architects because it gives freedom to create strange and flexible designs, as well as its ability to show the aesthetic sense (Abdullah et al., 2015).

After the stage of personal investigation and the form notion, the project has been taken a special approach and a sophisticated method, and the focus begins on the functional phase. Hadid was drawing at least 100 sketches to reach the appropriate model and then begins to think about the project's functions according to the zones, sun direction, wind and others so that the internal elements of the building are distributed in the best form. Zaha Hadid considered that is the most important stage of design steps and progress of the project (Hadid, 2008).

Zaha Hadid challenged the gravity in her designs by manipulating the block of the project, such as raising the mass on the bevel columns or creating a design with an unusually large cantilever and manipulating the lighting used. It also introduced natural lighting in a way to create harmony between the inside and the outside, while the elements of the lightings and shadows sing the project from the use of decorative elements and colors. Zaha's manipulation in the architectural line and the creation of different and creative levels a major had a role in making it one of the shareholder and the founders of the gravity's challenge. After that, begins with the distribution of tasks, where this stage determines the success of the project according to the format of the design with the surrounding environment to show a wonderful scene that is by introducing gardening to the open spaces of the project. Zaha has given the functions stage a great deal of attention because she does not consider this to be just a shelter, but a place to relax, rest and calm with elements of excitement and creativity (Design Boom, 2007).

Zaha was studying the rotational movement of the project as if she were walking around in it personally. She was trying to explain the movement through the liquid spaces and connected to each other horizontally and vertically through the technique of layers that provide the proper space for the functions. It is considered that this stage is a key factor in design because it provides comfort and ease in the movement of users and visitors inside and outside the building. Zaha Engineers work to show consistency in interior design and design of furniture in a way that suits interior and exterior design. Furniture design plays a major role in the smooth and flow of all parts of the project. Zaha Hadid drew her inspiration from the artistic and sculptural works of Naum Gabo, the design of furniture and the flow from painter László Moholy-Nagy. Finally, the types and forms of lighting that contribute to the perception of the structure are chosen in an integrated manner (Dezeen, 2018). The projects of Zaha Hadid have been created in three basic stages:

- Freeing the lines to produce a free-form.
- Abstract and unique and making the design an integral part.
- Interiority.

Deconstructivism is an architectural style and movement that encourages intriguing and ambiguous design. It deals with complex forms rather than traditional ideas and functional concerns (Built Survey, 2015).

The first appear of the movement of the Deconstructivism was in 1917, featured in works of some architects such as: Coop Himmelblau, Peter Eisenman, Frank Gehry and others. The second appearance was in 1988, where an exhibition was held in The Museum of Modern Art (MOMA), New York, was the first exhibition under the name of Deconstructivism architecture, supervised by Mark Wigley and Philip Johnson. Seven most contemporary architects were invited to the exhibition, who their works were characterized by ideas of instability and multiple acute angles, such as: Frank Gehry, Zaha Hadid, Coop Himmelblau, Thom Mayne, Peter Eisenman, Bernard Tschumi, and Daniel Libeskind (Straeten, 1997), where Zaha Hadid was one of Deconstructivism pioneers.

As a result, the seven architects who participating in the exhibition divided into two groups: The first group included three architects; Zaha Hadid, Frank Gehry and Rem Koolhaas, because they used various resources to inspire their ideas, such as: Zaha Hadid from Suprematism, Frank Gehry from Natural Organic and Rem Koolhaas from Constructivism. The second group included the architects who they inspired their ideas from Derridean styles, because they deconstruct everything in philosophically way then

reflect it in their works, and they called Derridean Architects. While the first one described as more realistic and logical than the second group (Hoteit, 2015).
The Russian art movement which called Suprematism, established by the artist Kazimir Malevich in Russia began around 1915, when Russia was trying to rebuild and make progress in science, arts and other sectors after the First World War (Penn Design, 2006), which led to the emergence of new trend architecture called: Suprematism "Russian". This trend influenced many architects. The main members of Russian artistic movement Vladimir Tatlin and Yakov Chernikhov have been able to apply it in their architectural works, which made it shown in a new, different way and have been described as abstract works (Domus, 2012).

Zaha Hadid presented a project in the exhibition of MOMA, affected by Suprematism, and she managed to show her wide imagination and abstract idea. Parametricism is a new style in architecture, launched by Patrick Schumacher who is one of Zaha Hadid architects. Parametricism is mature style that qualifies it to be the historical style of the 21st century after modernity. It offers innovative and diverse design, and also it has the ability to connect the internal and external areas of project in wonderful and imaginative way to portray them as a single system (Leach, 2009).

Zaha Hadid started to use the curvilinear architectural forms in her buildings to create unique designs by merging the curved lines with smooth, fluidity style and harmony with surrounding environment, while her curvilinear buildings look like grow thing from the ground. She wanted to achieve total fluidity which changes from the breaks blocks with sharp angles to continuous objects with curved angles and forms. So this research will focus on Zaha Hadid’s curvilinear architecture who is "Queen of the Curve" as described by "The Guardian Magazine" the famous magazine, where the structural systems of 6 from her curvilinear buildings will clarify, because they have a large amount of the curved lines integration, as well as have a different height and large spans.

4.2 Curvilinear Buildings of Zaha Hadid

The first designs of Zaha Hadid remained in their theoretical framework, where the most of her projects won in architectural competitions and then began implementing a number of them. Zaha Hadid began designing abstract shapes with acute angles such as the Vitra station in Germany (1994) and was one of its first designs which have been built. After several years, she began to introduce curved shapes in her designs. She designed several projects and Bergisel Ski Jump in Austria (1999-2002) was one of the first projects which have been built.

In the 21st century, Zaha Hadid continued to introduce curved shapes in her design and in different ways. It was used in either angles, facades, in the design of roofs, or in the integration of the roof with the façades to form a smooth and curvilinear cover that surrounds internal functions and creates a reciprocal relationship between building and the surrounding environment (Abdullah et al., 2015).

Some of the curved and curvilinear buildings that designed by the architect Zaha Hadid will be clarified in the order according to the year of construction. These projects achieved large spans with smoothly forms, as well as their aesthetic and intimate relationship to the surrounding environment, where collected from different trusted sources.

Nineteen curved and curvilinear buildings designed by the architect Zaha Hadid from 1999 to 2016 are presenting in the Table 4.1, where have been enrolled in the order according to the years of construction, while that 10 of them have been inserted under term "curvilinear buildings": Hungerburgbahn Station in Innsbruck, Austria, Vilnius Guggenheim Hermitage Museum in Lithuania, JS Bach Chamber Music Hall in UK, London Aquatics Center in UK, Riverside Museum in UK, Heydar Aliyev Cultural Center in Azerbaijan, Serpentine Sackler Gallery in UK, Dongdaemun Design Plaza & Park in South Korea, Investcorp Building in England and Harbin Opera House in China. This table included the names of projects, images, locations, construction years, as well as the internal functions of each one.

Table 4.1: Zaha Hadid Curved and Curvilinear Buildings between 1999 – 2016

No	Name of the Project	Image	Years	Location	Functions
1	**Bergisel Ski Jump**		1999-2002	Innsbruck, Austria	Olympic Ski Jumping
2	**Ordrupgaard Museum Extension**		2001-2005	Copenhagen, Denmark	State-owned art museum
3	**Tondonia Winery Pavilion**		2001-2006	Hero, Spain	Wine store
4	**Hungerburgbahn Station**		2004-2007	Innsbruck, Austria	Railway station
5	**Vilnius Guggenheim Hermitage Museum**		2007-2008	Vilnius, Lithuania	Center for international art
6	**Bridge Pavilion**		2005-2008	Zaragoza, Spain	Pedestrian bridge

Table 4.1: Continued

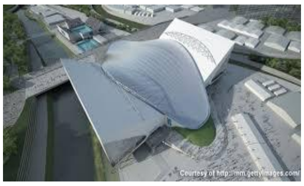
No	Name of the Project	Image	Years	Location	Functions
7	**JS Bach Chamber Music Hall**		2009-2009	Manchester, UK	Mobile music hall
8	**Guangzhou Opera House**		2005-2010	Guangzhou, China	Opera house
9	**Evelyn Grace Academy**		2006-2010	Brixton, London, UK	Secondary school
10	**London Aquatics Center**		2008-2011	London, UK	Olympic center
11	**London Aquatics Center**		2011-2014	London, UK	Olympic center
12	**Riverside Museum**		2007-2012	Glasgow Scotland, UK	Transport museum

Table 4.1: Continued

No	Name of the Project	Image	Years	Location	Functions
13	**Heydar Aliyev Cultural Center**		2007-2012	Baku, Azerbaijan	Culture center
14	**Serpentine Sackler Gallery**		2009-2013	London, UK	Gallery and café
15	**Dongdaemun Design Plaza & Park**		2009-2014	Dongdaemun, Seoul, South Korea	Plaza and park
16	**Wangjing SOHO**		2009-2014	Beijing, China	A mixed-use project
17	**Sky SOHO**		2010-2014	Shanghai, China	Showroom
18	**Investcorp Building**		2013-2015	Oxford, England	Extension to the Saint Antony's College
19	**Harbin Opera House**		2013-2015	Harbin, China	Opera house

4.3 Clarification of Curvilinear Structural Buildings designed by Zaha Hadid

Zaha Hadid has been used curvilinear structure in her buildings by difference types of structures and various materials. She tried every time to create new things, various shapes and harmonious with the surrounding environment, which far from tradition and have been not customary to humanity. Hadid used the curvilinear façade, curvilinear roof, and in some buildings the roof was incorporated with the facades to forming a cover frame. Zaha Hadid has been used in her buildings different structural materials, and that difference depending on the structure system used, the area of building, the spans and the height of building. Zaha Hadid has been merge the curves forms to create unusual and unfamiliar show with took the surrounding environment into consideration to make the building an inseparable part of nature (Numéro, 2018).

Six of Hadid’s curvilinear buildings have been selected to clarify their structural systems and the materials used in construction of structures. These buildings provided large spans with different heights, while that the concept of these buildings included a large amount of mixing of curved lines which resulted in a lot of smooth, fluidity and complex forms, where all of them set under curvilinear term. The 6 chosen curvilinear buildings are:

- London Aquatics Center in UK (2008-2011).
- Riverside Museum in UK (2007-2012).
- Heydar Aliyev Culture Center in Azerbaijan (2007-2012).
- Serpentine Sackler Gallery in UK (2009-2013).
- Dongdaemun Design Plaza & Park in South Korea (2009-2014).
- Harbin Opera House in China (2011-2015).

The information was collected starting from the name of project, location, internal functions, the highest point of building, length, area, the type of structure system and materials used in construction, as well as an explanation about the cladding and ceiling materials with costing and the methods of cleaning. After that, the 6th buildings collected in a table.

4.3.1 London Aquatics center in UK (2008-2011)

Structural system: space frame structure by double layer grids (DLG).
Material of the structure: steel.

London Aquatics Center located in Olympic Park, London (Figure 4.1). It is consist from basement, ground floor and first floor. The center include Olympic pools each one has 50 m length, dry diving zone; diving pool has 25 m length with boards and platforms up to 10 m made of reinforced concrete material (RC) (Figure 4.2), a state of the art gym with 50 station, café and restaurant. The concept has been inspired from the fluid geometries of water waves, and appeared by merging two curved lines in different directions (Figure 4.3). The center's area is 15,400 m^2, span 160 m and height 45 m (Arch Daily, 2011).

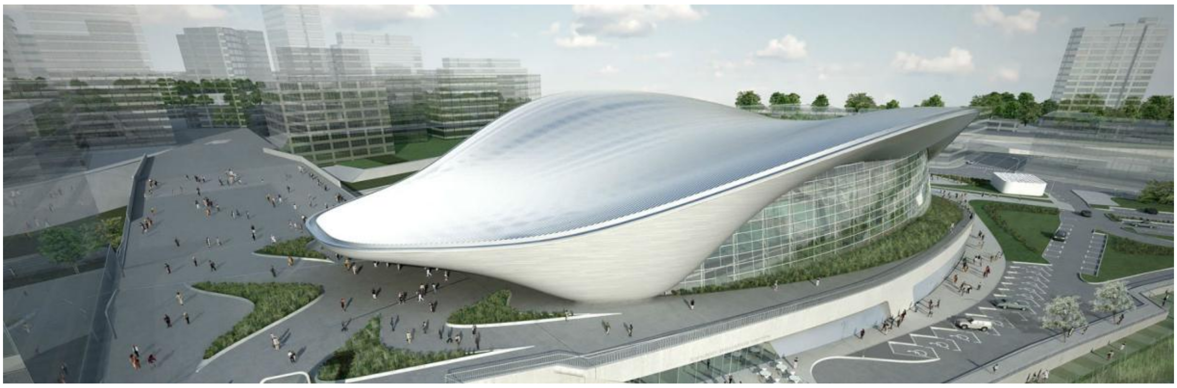


Figure 4.1: London Aquatics center
(https://www.arch2o.com/london-aquatics-centre-zaha-hadid-architects/)

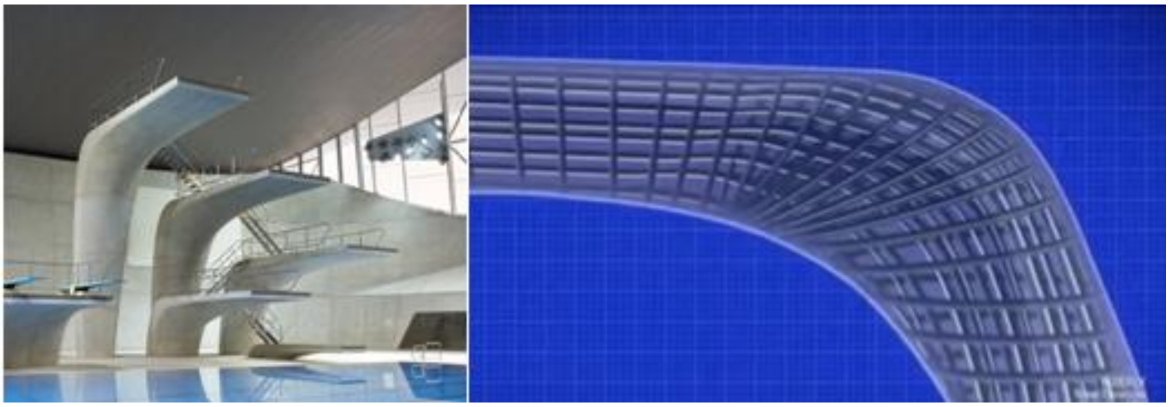


Figure 4.2: Boards and platforms made of RC material
(https://www.youtube.com/watch?v=UKOMi_GwvFk&list=WL&index=57&t=833s)

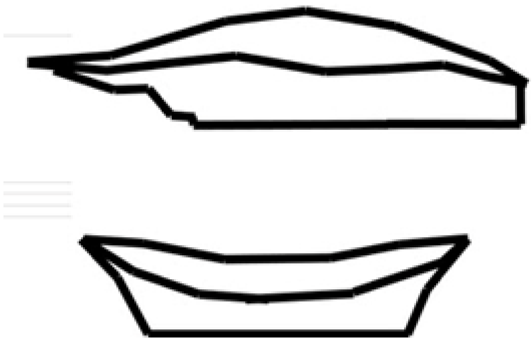


Figure 4.3: The curved lines of concept in different directions (http://hmawyin.blogspot.com/2011/09/london-aquatic-centre.html)

The structural systems have been used in London Aquatics Center is space frame structural system (DLG) made of steel material, while the space frame supported from the southern elevation by reinforced concrete wall and from the northern elevation by two columns made of reinforced concrete (Figure 4.4) and (Figure 4.5). The ceiling material is timber (Figure 4.6) (Buildipedia, 2011). Timber material can clean by using a pressure washer that can remove all dirt without damaging the ceiling material. The average cost of Timber ceiling material is 49.54 £/m2 (Build It, 2018).

Figure 4.4: RC wall with RC columns supporting the space frame structure (https://www.arch2o.com/london-aquatics-centre-zaha-hadid-architects/)

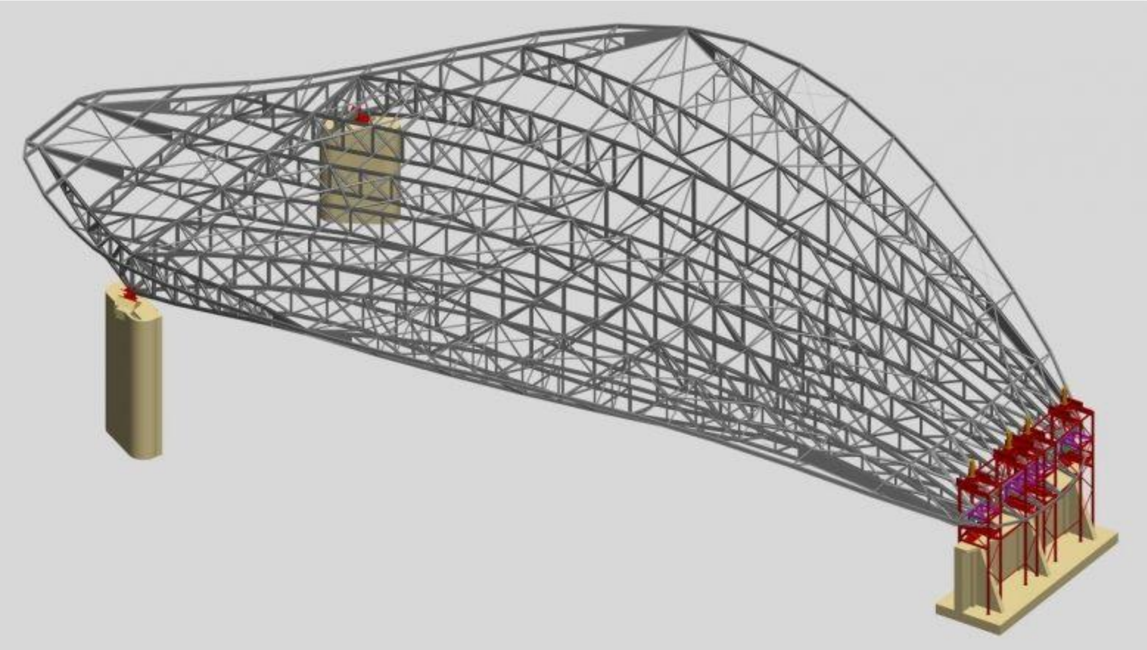


Figure 4.5: Illustration of London Aquatics center's DLG structural system (https://www.pinterest.com/pin/314407617721851768/)

Figure 4.6: Timber ceiling material of London Aquatics center (https://www.e-architect.co.uk/london/london-aquatics-centre-interior)

Due to the highly corrosive environment, the surfaces were coated with zinc silicate then the steel structure was cladding with aluminum panels (Figure 4.7). It can be cleaning with a soft brush by using dish soap and clean water. The cleaner should be tried in a small and unclear place before starting to be sure from the quality of the soap, can be easily processed by pressing. The aluminum cladding material (ACM) is corrosion-resistant and is strong and solid. It is protected by a thin layer of non-magnetic aluminum oxide which plays a major role in giving strength and rigidity. The cost of manufactured ACM ranges from 15 to 35 $ depending of the panel weight (Lakesmere, 2017).

Figure 4.7: Aluminum cladding material of London Aquatics center (https://www.steelconstruction.org/design-awards/2010/award/legacy-roof-london-aquatice-centre/)

The loads transfer from the steel trusses to the concrete point then to the foundation on the ground, while the structure work in tension and compression forces (Figure 4.8) (ISSUU, 2007).

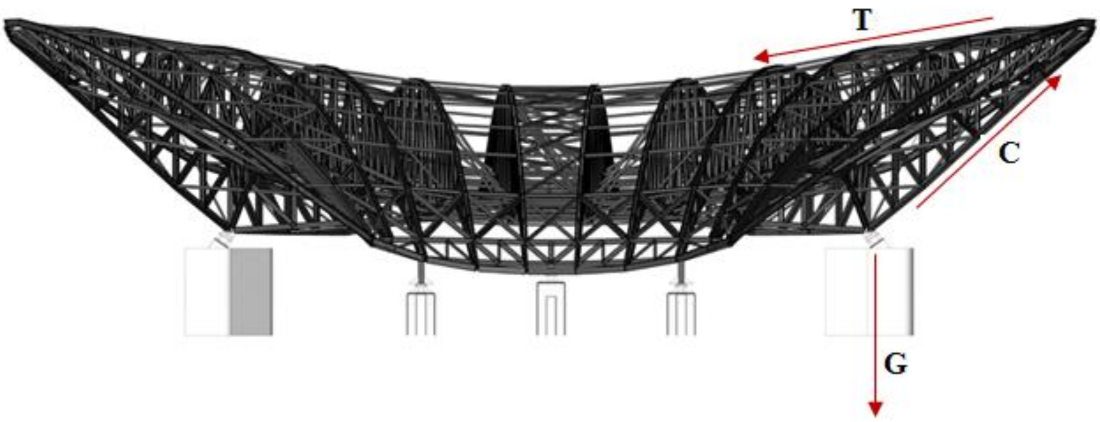


Figure 4.8: Structure stability of London Aquatics center (https://www.youtube.com/watch?v=pfsbzEN113c)

4.3.2 Riverside museum in UK (2007-2012)

Structural system: space frame structure by double layer grids (DLG).
Material of the structure: steel.

Riverside museum located in Glasgow Scotland (Figure 4.9), it consists from ground floor and first floor. The museum includes a large exhibition hall, where there are more than 3000 exhibits, such as: trams, bikes, buses, trains, unique collection of model ships and cars. The concept consists by merging curved lines (Figure 4.10). It has curvilinear facades and a zigzag roof. The museum area is 11,000 m^2, height 20 m and span 150 m (Buildings library, 2010).

Figure 4.9: Riverside museum
(https://www.archdaily.com/161343/over-500000-visitors-to-the-riverside-museum-in-its-first-weeks/501557d028ba0d02f0000e69-over-500000-visitors-to-the-riverside-museum-in-its-first-weeks-photo)

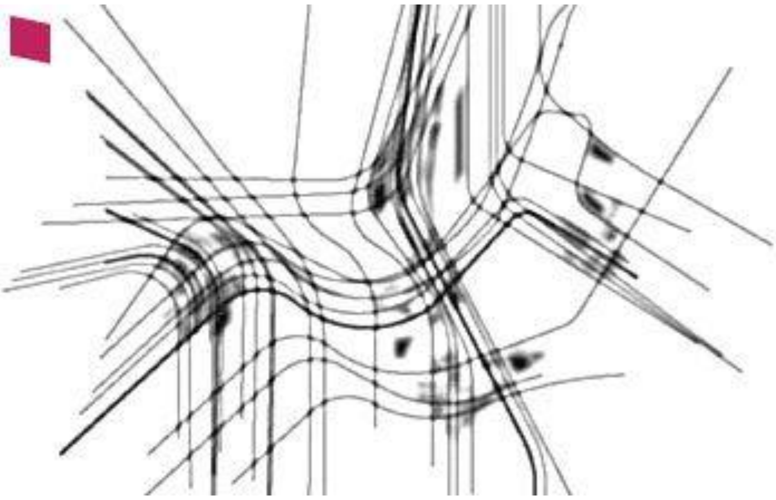


Figure 4.10: Concept of Riverside museum
(https://www.pinterest.com/pin/555350197779732902/)

The structure system is space frame structure (DLG), it has been used as primary structure in Riverside museum and its made by steel material (Figure 4.11) and (Figure 4.12) (Dezeen, 2011).

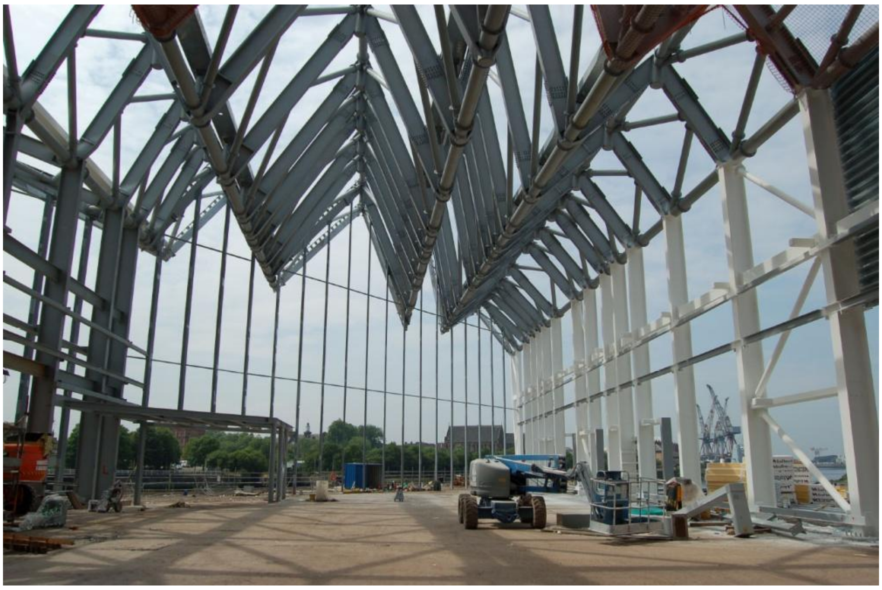


Figure 4.11: Space frame structure of Riverside museum from inside the building
(http://buildipedia.com/aec-pros/engineering-news/case-study-zaha-hadid-architects-riverside-museum-of-transport-and-travel-part-5)

Figure 4.12: Space frame structure of Riverside museum from outside the building (http://buildipedia.com/aec-pros/featured-architecture/case-study-zaha-hadid-architects-riverside-museum-of-transport-and-travel-part-2)

The cladding material used is Rheinzink, where Rheinzink characterized as a self-healing material, if scratched, it can self-repairing after the process of moisturizing and drying (Figure 4.13). Rheinzink cladding can be cleaned with a soft cotton cloth and placed with a small amount of Sika® Remover-208 or Citronex, then should be rubbed gently and lightly, and in the end the solution can be removed with a new cloth, as well as avoid spraying any material directly on the cladding. The average cost of Rheinzink cladding material is between 15 $ and 25 $ pre square feet installed (Rheinzink, 2015). The ceiling material used is glass fiber reinforced gypsum (GFRG), where used with new constructions, lightweight, easy to install and can be retrofit construction and re-installed across unlimited applications (Figure 3.14) (Dezeen, 2011).

Figure 4.13: Rheinzink cladding material of Riverside museum (https://riversidemuseum.wordpress.com/tag/locomotives/)

Figure 4.14: GFRG ceiling material of Riverside museum (https://www.architectural-review.com/today/riverside-museum-by-zaha-hadid-architects-glasgow-uk/8616624.article)

4.3.3 Heydar Aliyev cultural center in Azerbaijan (2007-2012)

Structural system: space frame structure by double layer grids (DLG).
Material of the structure: steel.

Heydar Aliyev center located in Baku (Figure 4.15), it consists of three buildings: museum, conference hall and library, while the library is the highest building, it has nine floors. The buildings have been connected to each other by spaces created by the outer envelope which suggests that they are one building with a total area of 57,519 m^2, with 3,200 m span and 74 m height (Figure 4.16). The concept of Heydar Aliyev cultural center consists by merging the curved lines (Figure 4.17) (Architect Magazine, 2013).

Figure 4.15: Heydar Aliyev cultural center
(https://www.archdaily.com/448774/heydar-aliyev-center-zaha-hadid-architects)

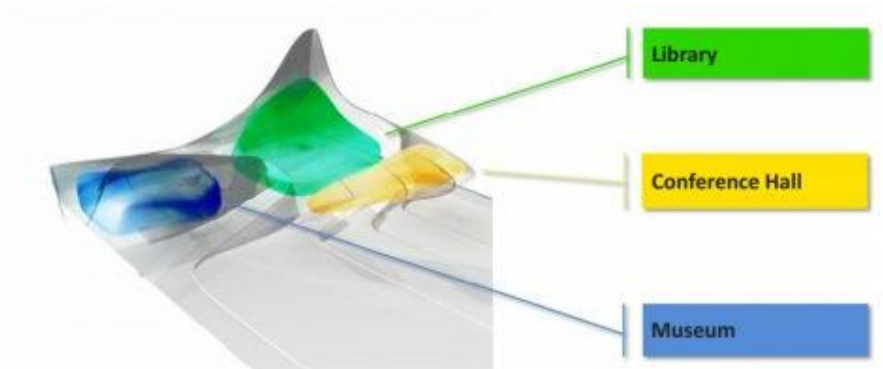


Figure 4.16: The main three buildings of Heydar Aliyev center
(https://en.wikiarquitectura.com/building/heydar-aliyev-cultural-center/)

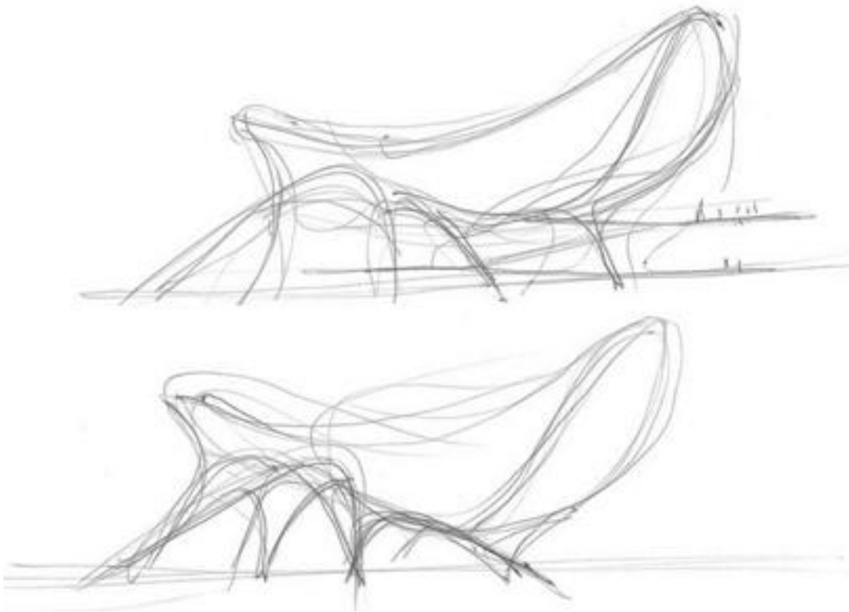


Figure 4.17: Sketch of Heydar Aliyev cultural center
(http://vanim97.wixsite.com/heydar-aliyev-centre/design-concept)

Zaha Hadid designed it by merging a lot of infinite curved lines. Heydar Aliyev center consists mainly of two structural systems that work together: the first one made by reinforced concrete material that forms the boundaries (internal walls) of the three buildings, while the second one is space frame structure (DLG) made of steel material that wraps around the three buildings to cover them completely and creates interior spaces connecting them in a flexible and streamlined way, while the space frame is composite of a special steel tube and nods. The earthquakes are one of the biggest threats to construction in Baku, Azerbaijan, so the building must be reinforced by enormous 150-foot-long concrete piles buried below the earth's measuring up to magnitude (Figure 4.18) and (Figure 4.19) (Arc space, 2014).

Figure 4.18: The space frame structure of Heydar Aliyev center (https://www.adelto.co.uk/construction-of-heydar-aliyev-center-by-zaha-hadid/)

Figure 4.19: Steel and RC materials used in structural system of Heydar Aliyev (https://en.wikiarquitectura.com/building/heydar-aliyev-cultural-center/)

The steel flooring platforms and the intriguing steel boot columns that connected with concrete walls. These columns and beams increase the rigidity of the space frame , the static of glass walls and connecting the concrete structure with the steel structure, creating a steel bridges which connecting the internal utilities in the upper floors of the buildings sporadically (Figure 4.20) (Buildipedia, 2011).

Figure 4.20: Steel columns and beams of Heydar Aliyev center (http://buildipedia.com/aec-pros/from-the-job-site/zaha-hadids-heydar-aliyev-cultural-centre-turning-a-vision-into-reality)

The cladding and Ceiling materials are Glass Fiber Reinforced Concrete (GFRC) which consists from sand, cement, admixtures, fibers and polymer, with Glass Fiber Reinforced Plastic (GFRP), while GFRC and GFRP act together and each beating the deficits of the other (Figure 4.21), (Figure 4.22), (Figure 4.23) and (Figure 4.24). They are used in the facades system and consist of several different layers of white cement concrete with fine grain and supported by glass fiber mats. It is durable and resistant to weather conditions as it is a dirt repellent, easy to clean, lightweight and thin, and is chosen for a long life, high durability and low upkeep efforts. The fingerprints and prints resulting from the movement of users can be cleaned by water, and from time to time should be checked joints that link the panels with the steel frame, and re-caulked if necessary and can be cleaned from the dust by water rinsed sporadically (Buildipedia, 2011). The cost is from 2.50 $ to 3.00 $ per square foot for ¾" thick material, while the cost increases about 3.50 $ to 3.75 $ per square foot when the thickness of its constituent materials increases (Stromberg, 2012).

Figure 4.21: GFRC & GFRP panels of Heydar Aliyev cultural center (https://en.wikiarquitectura.com/building/heydar-aliyev-cultural-center/)

Figure 4.22: Panels with the space frame structure (https://en.wikiarquitectura.com/building/heydar-aliyev-cultural-center/)

Figure 4.23: GFRC & GFRP cladding material of Heydar Aliyev cultural center (https://www.architectural-review.com/buildings/zaha-hadids-heydar-aliyev-centre-in-baku-is-a-shock-to-the-system/8656751.article)

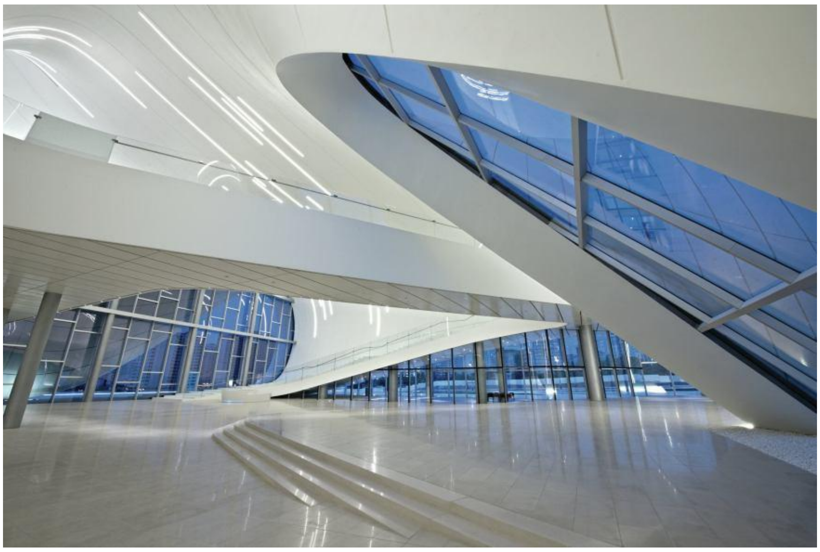


Figure 4.24: GFRC & GFRP ceiling material of Heydar Aliyev cultural center (https://www.architectmagazine.com/design/buildings/heydar-aliyev-cultural-center-designed-by-zaha-hadid-architects_o)

GFRC is concrete made of a low water-cement, polymer and containing non-continuous fibers and distributed randomly in all directions during the concrete mass, while polymer uses with acrylic liquid to prevent the mix water from evaporating. The main reason for the addition of fiber to concrete is to increase Toughness, tensile strength and control plastic shrinkage to protect it from cracking (Figure 4.25), where the fiber is made of steel, plastic, glass, or natural fibers and is available in various shapes, sizes and diameters (Sukumar, 2014).

Figure 4.25: Fiber reinforced concrete (https://theconstructor.org/concrete/fiber-reinforced-concrete/150/)

GFRP is a rebar for concrete structure to give a high strength, corrosion resistant, durability and appropriate for use in a broad range of architectural applications (Figure 4.26) (Research gate, 2015).

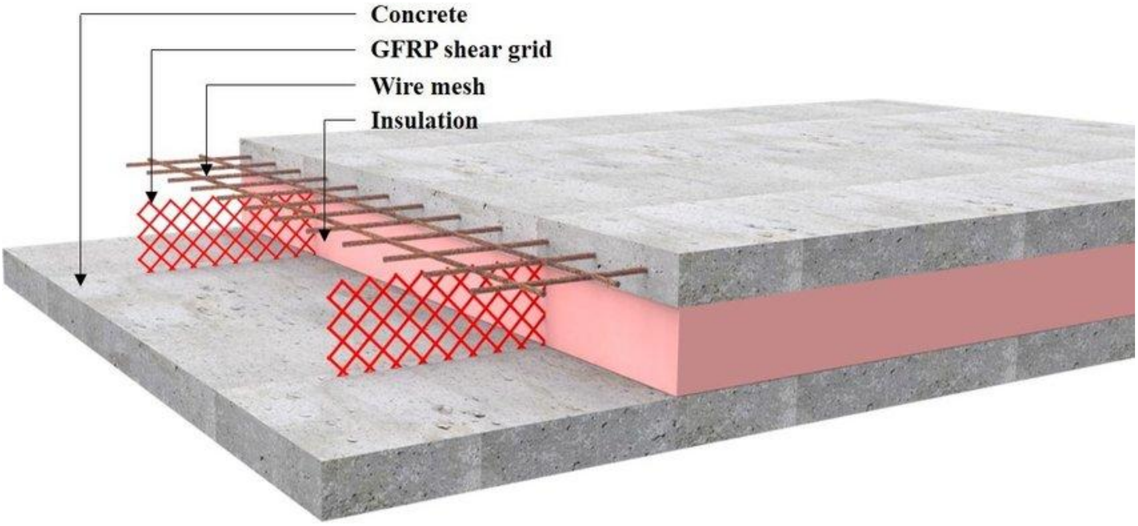


Figure 4.26: GFRC with GFRP
(https://www.researchgate.net/figure/Insulated-concrete-sandwich-wall-panel-reinforced-with-glass-fiber-reinforced-polymer_fig1_276552503)

4.3.4 Serpentine Sackler gallery in UK (2009-2013)

Structural system: shell structure by double curvature shell (DCS).
Material of the structure: steel.

Serpentine Sackler gallery located in London, Zaha Hadid renovated the large old galley brick building, where Zaha's goal was to create additional spaces for gallery, as well as she designed a curvilinear structure extending from one side of the old building to include a café and space for events (Figure 4.27), where the area is 900 m^2, the highest point of curvilinear structure reach up to 6 m and the span is 30 m. The structural system of curvilinear form is shell structure (DCS) by using steel material (Figure 4.28), which supported by five tapered steel columns (Figure 4.29) (Dezeen, 2013).

Figure 4.27: The old gallery brick building with new curvilinear form (https://www.inexhibit.com/case-studies/zaha-hadid-serpentine-sackler-gallery/)

Figure 4.28: Construction of shell structure system (https://arxitektonosis.wordpress.com/category/architecture/)

Figure 4.29: Construction of tapered steel columns (http://www.shstructures.com/projects/serpentine-sackler-gallery/)

The cladding materials have been used is glass reinforced plastic (GRP) which gave the shining to cladding and fiberglass reinforced plastic (FRP) use in ceiling and for columns, while GRP is one type of FRP (Figure 4.30) and (Figure 4.31) (Barbour, 2016). This kind of cladding is cleaned by half a cup of liquid soap with half a cup of warm water with a sponge for the mixture and a soft brush for rubbing (Hunker, 2018). The cost of FRP cladding material is 1,5 $ pre square feet installed (Homewyse, 2018).

Figure 4.30: GRP cladding material of the curvilinear roof (https://www.dezeen.com/2013/09/27/serpentine-sackler-gallery-by-zaha-hadid-photographs-by-luke-hayes/)

Figure 4.31: FRP ceiling material of the curvilinear roof and columns (https://www.dezeen.com/2013/11/01/the-magazine-restaurant-at-the-serpentine-sackler-gallery-extension-by-zaha-hadid/)

4.3.5 Dongdaemun design plaza & park in South Korea (2009-2014).

Structural system: space frame structure by double layer grids (DLG).
Material of the structure: steel.

Dongdaemun Design Plaza & Park located in Dongdaemun Seoul, South Korea (Figure 4.32) and (Figure 4.33), it consists from 3 levels underground and 4 above-ground, including exhibition hall, design museum, seminar room, conference hall, the design lab, media center, the academy hall, Dongdaemun History and Culture Park, the designers lounge, and the design market, as well as has a café, parking areas, a feeding room, a coatroom, dispensaries, and other facilities. The length of main building is 280 m, the width of 188 m, the height of 34 m and the area is 89,574 m2 (Dezeen, 2014).

Figure 4.32: Dongdaemun design plaza & park (https://www.youtube.com/watch?v=1GFNyA_4zMk)

Figure 4.33: Site plan of Dongdaemun design plaza & park (http://news.samsungcnt.com/the-technology-behind-seouls-landmark-dongdaemun-design-plaza/)

Dongdaemun Design Plaza & Park constructed by using mega trusses with space frame structure (DLG) made by steel material, that was minimizing the use of columns to create a large spans, as well as concrete material has been used in internal walls structure of utilities which supported the space frame structure (Figure 4.34) and (Figure 4.35) (Samsung C & T, 2017).

Figure 4.34: The space frame structure (DLG) with concrete columns and walls (http://news.samsungcnt.com/the-technology-behind-seouls-landmark-dongdaemun-design-plaza/)

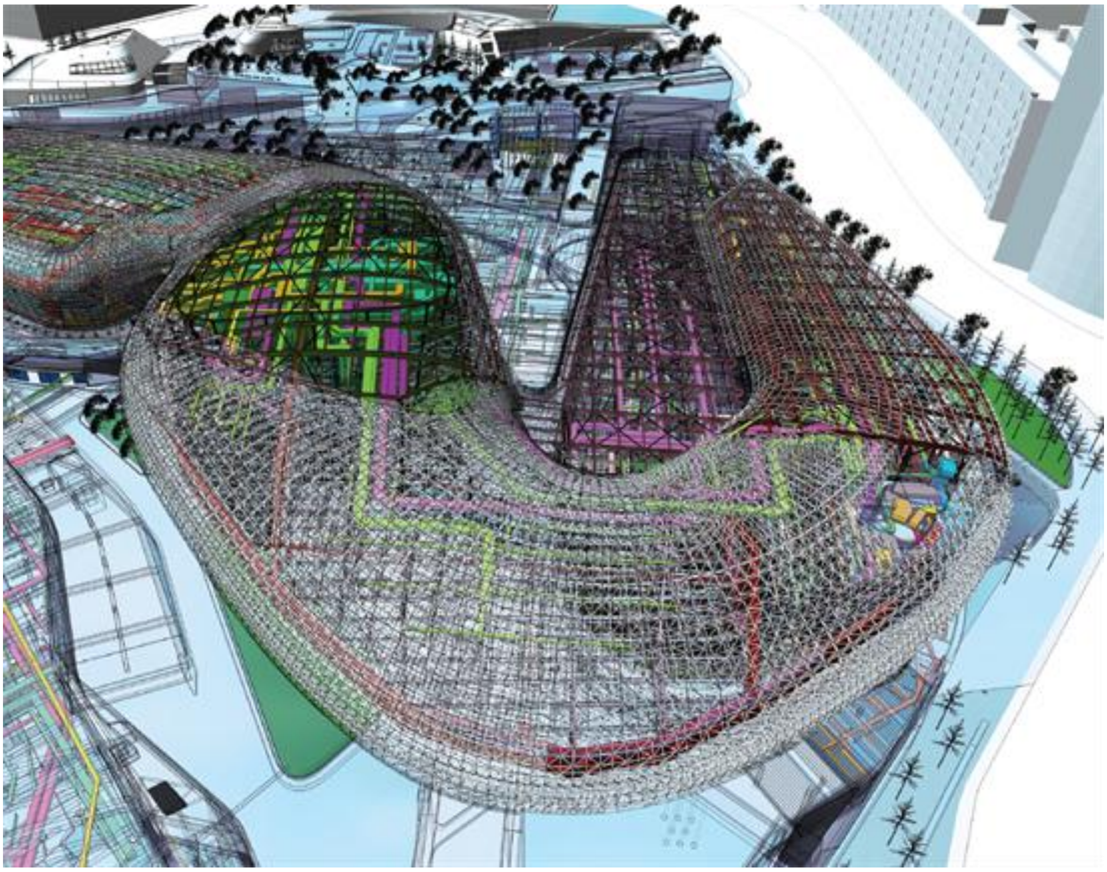


Figure 4.35: Space frame structure of Dongdaemun design plaza & park (https://www.pinterest.com/mamanimamanie/)

The cladding material is aluminum, where the exterior has been covered by 45,000 panels made of aluminum material, where 14,000 flat panels and 31,000 curved panels with different sizes, forms and various curvature degrees. Aluminum material has an important position in provide a degree of thermal insulation, to improve the appearance of buildings and weather resistance (Figure 4.36) (Samsung C & T, 2017). The aluminum material does not rust but suffers from color change due to weather conditions and surrounding pollutants. To protect the aluminum from this change, it is coated with protective materials. It is coated with three famous materials are anodized coating, powder protection layer, stainless steel finishes (Seebrilliance, 2017). The cost is from 15 $ to 35 $ per square foot in majority of situations in coverage area, where this cost return to its unique engineered systems, the various colors, paint finishes, architectural designs, orientation in site and thickness. The cleaning of aluminum facades requires to the specialists with sufficient experience and knowledge on how to deal with this type of façade, because the use of cleaning materials and improper chemicals in surface cleaning may lead to the need to replace the cladding, while this cost more than 12 times from the cost of artisans services (Greenbond, 2018).

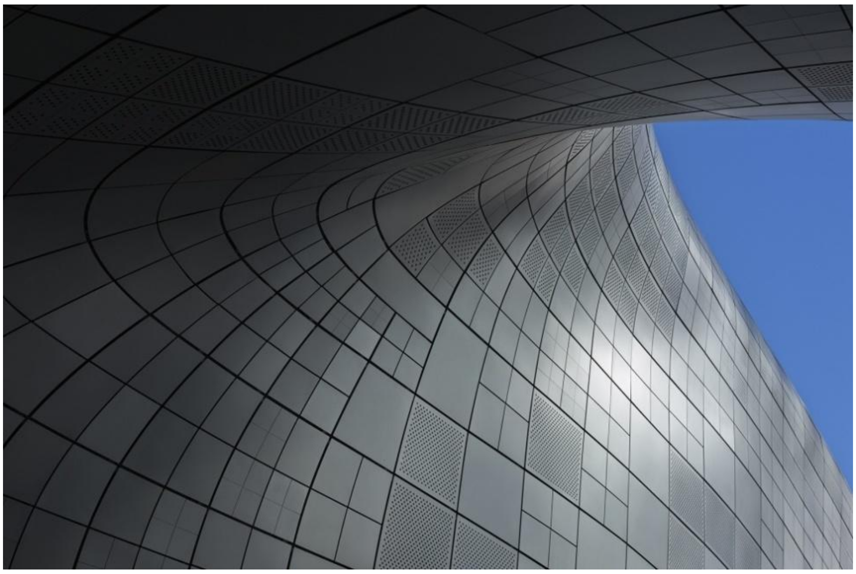


Figure 4.36: Aluminum cladding material of Dongdaemun design plaza & park (https://www.archdaily.com/489604/dongdaemun-design-plaza-zaha-hadid-architects)

The internal cladding material (ceiling material) is glass fiber reinforced gypsum (GFRG) (Figure 4.37); it's a lightweight, strong, and fire retardant material and also protects the material behind it from the fire for two hours. It has been used successfully in cladding panels, column covers, decorative ornamentation, flowerpots and etc. The cleaning of aluminum facades requires to the specialists with sufficient experience and knowledge on how to deal with this type of façade, because the use of cleaning materials and improper chemicals in surface cleaning may lead to the need to replace the cladding, while this cost more than 12 times from the cost of craftsmen services (Indesignlive, 2014).

Figure 4.37: GFRG ceiling material of Dongdaemun design plaza & park (https://www.indesignlive.com/projects/zaha-hadids-fluid-alimunium-cultural-centre)

4.3.6 Harbin Opera house in China (2011-2015)

Structural system: space frame structure by double layer grids (DLG).
Material used of the structure: steel.

The opera house located in Harbin (Figure 4.38), its consists of two large concert halls and a large public square, while the wavy cover wrapping around them similar to an ice sculpture which expresses on the winter carnival in Harbin, covering 97,000 square meters, with 200 m span and height 56 m. The concept consists from merging curved lines (Figure 4.39) (The architectural review, 2015).

Figure 4.38: Harbin Opera house in China
(https://www.dezeen.com/2015/12/16/mad-sinuous-harbin-opera-house-completes-north-east-china/)

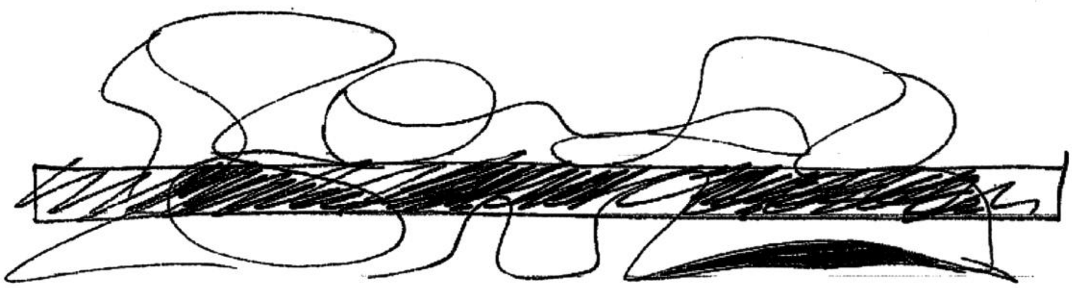


Figure 4.39: Sketch of Harbin Opera house
(https://www.archdaily.com/868315/the-creative-energy-of-zahas-sketches)

The building consists of a space frame structure (DLG) made of steel material, that covered the internal functions which constructed by using reinforced fiber concrete (RFC) with the steel-reinforced glass roofing of the reception areas and lobbies like a glass sunroof which created the patio connected to the outdoor space. This method provides construction by connecting the building to the surrounding environment and providing natural lighting for the project (Figure 4.40) (The State Enterprise of Jahonnamo, 2016).

Figure 4.40: The space frame structure with RFC walls of Harbin Opera house (https://www.pinterest.com/pin/289778557268006621/?lp=true)

The cladding material is smooth white aluminum panels with thickness 5 mm (Figure 4.41) (Inhabit, 2016). Aluminum material has an important position in provide a degree of thermal insulation, to improve the appearance of buildings and weather resistance. The aluminum does not rust but suffers from color change due to weather conditions and surrounding pollutants. To protect the aluminum from this change, it is coated with protective materials. It is coated with three famous materials are anodized coating, powder protection layer, stainless steel finishes (Seebrilliance, 2017).

The cost is from 15 $ to 35 $ per square foot in majority of situations in coverage area, where this cost return to its unique engineered systems, the various colors, paint finishes, architectural designs, orientation in site and thickness. The cleaning of aluminum facades requires to the specialists with sufficient experience and knowledge on how to deal with this type of façade, because the use of cleaning materials and improper chemicals in surface cleaning may lead to the need to replace the cladding, while this cost more than 12 times from the cost of artisans services (Greenbond, 2018).

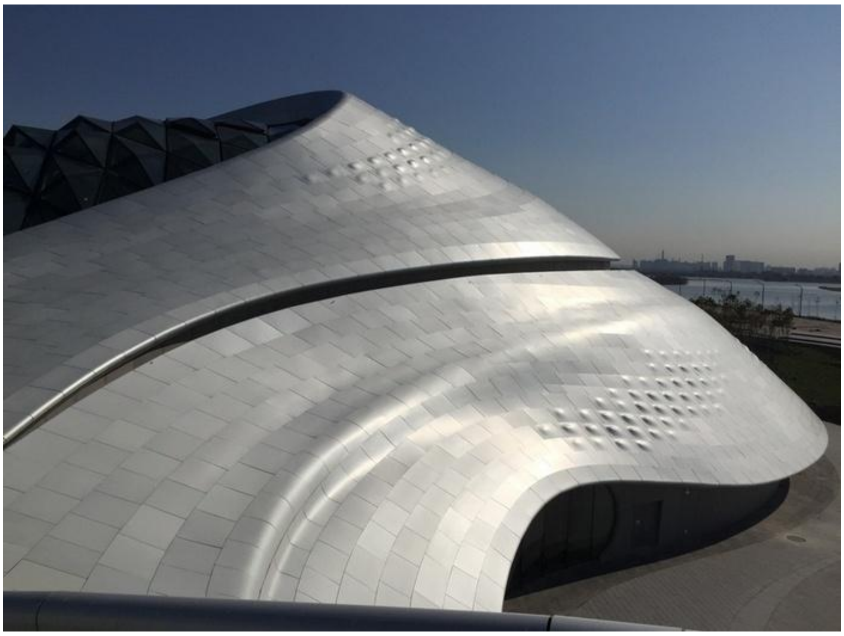


Figure 4.41: Aluminum cladding material of Harbin Opera house (https://inhabitgroup.com/archdaily-2016-building-of-the-year-awards-grand-theatre-opera-house/)

Ceiling materials are white concrete and wooden shell (Figure 4.42). The use of walls with white concrete in the lobby and public areas that create open spaces and wide and full of natural light coming from the glass sunroof, while the walls with wood veneers were used in the main theater areas to give a warm feeling and which indicate to the place of the main theater (Inhabit, 2016).

Figure 4.42: White concrete and wooden shell ceiling materials of Opera house (https://soa.utexas.edu/events/ma-yansong-dialogue-nature)

This chapter included explanation to 6 curvilinear buildings designed by Zaha Hadid where their details have been inserted in the table bellow (Table 4.2). The purpose of this table is to summarize the chapter 4 by collecting the main details of buildings to easy access, where included the name of projects, images, heights, spans, structural systems, material used in construction of curvilinear structures, cladding materials and ceiling materials.

Table 4.2: Six curvilinear buildings designed by Zaha Hadid

Name Of Projects	Images	Height (m)	Span (m)	Structure	Material of Structure	Cladding Material	Ceiling Material
London Aquatics Cultural Center		45	160	Space Frame Structure (DLG)	Steel & RC	Aluminum	Timber
Riverside Museum		20	150	Space Frame Structure (DLG)	Steel	Rheinzink	GFRG
Heydar Aliyev Center		74	3,200	Space Frame Structure (DLG)	Steel & RC	GFRC & GFRP	GFRC & GFRP
Serpentine Sackler Gallery		6	30	Shell Structure (DCS)	Steel	GRP	FRP
Dongdaemun Design Plaza & Park		34	280	Space Frame Structure (DLG)	Steel & RC	Aluminum	GFRG
Harbin Opera House		56	200	Space Frame Structure (DLG)	Steel & RFC	Aluminum	White Concrete & Wood

As shown in the table, the most of those curvilinear buildings have been constructed by using space frame structure (DLG) made of steel material and supported by RC walls and columns, while they have different height and spans.

CHAPTER 5
CONCLUSIONS

No structure can be imagined without existence of a form that determines its size, dimensions, space and location in reality. The form plays a major role in architecture while it is the most controversial point in architectural designs or constructions. The structure is the part that resists the loads applied to the building, as it is subjected to static loads and moving loads, for example the loads of snow, wind, rain, passengers and furnishings, as well as carries its own weight. The loads that applied on a building may affect on the form and durability of it, where the weakness of the structure leads to the distortion of the form of the building, as well as the strength of structure leads to achieve a strong and durable form. Architecture has changed depending on the place and the time.

Construction of the curved structures began from ancient times, where the building materials used have been differed from place to place according to the materials available around human, and developed over time with the development of the world and the human mind until today. The choosing of curvilinear structural system related to the span and height of the building, because these points help to determine the structural system to create a solid and stable curvilinear form. So the choosing of the type and shape of structural systems depend on location, weather, area, height, and span of the building.

The curve has become an integral part of nature and environment surrounding the contribution of many architects, the architect Zaha Hadid was one of the major contributors to the development of curvilinear architecture. Her works were characterized by free and abstract ideas and she always sought to create everything new and strange to the human mind to prove that nothing is impossible. In this research, the curvilinear forms, their structural systems and materials of the structures have been clarified, while the focusing was on Zaha Hadid’s works, who is "Queen of the Curve" as described by the famous magazine "The Guardian", where 6 of her curvilinear buildings have been examined, which have fluidity forms and different spans, heights, structures and materials.

The space frame structure with double layer grids have been used in most of Zaha Hadid’s curvilinear buildings and the material used for the structure of curvilinear forms was steel material and supported by columns and walls made of reinforced concrete, in spite of their differences in the spans, heights and the curvilinear forms from building to other, but she used the same structure system with the same construction materials.

The steel material is used for a height of 8-9 m maximum, but when the structure will be more than that, steel and reinforced concrete are used together to ensure the rigidity and cohesion of the facility and its ability to withstand the loads applied to it. The steel material is described flexible, durability, hardness and lightweight, and can be constructed in special factories and brought ready to the site, where it is easily transportable from the factory to the site and installed. Steel considered as more fire resistant from wood, and also the wood is prone maintenance more than steel with more cost. As well as the external cladding and internal ceiling materials also help to protect the building from external factors, as well as easy to clean walls and facades while ensuring its durability and shortage of maintenance through passage of time.

REFERENCES

Abdalwahid, A. A. (2013). Zaha Hadid form making strategies for design. *(Doctoral dissertation, Universiti Teknologi Malaysia).*

Abdullah, A. R., Said, I. B., & Ossen, D. R. (2015). Zaha Hadid Strategy Of Design. *Sains Humanika, 5(1).*

Adnan, F., & Yunus, R. M. (2012). The Influence of Curvilinear Architectural Forms on Environment-Behaviour. *Procedia - Social and Behavioral Sciences 49* , 341-349.

Adriaenssens, S., Block, P., & Veen, D. (2014). *Shell structures for architecture: form finding and optimization.* Routledge.

Alpha Steel. (2018). *Roof Truss – Definition, Types and Importance*. Retrieved November 11, 2018, from https://www.alphasteel.ph/roof-truss/

Aliberti, L., Canciani, M., & Rodriguéz, M. A. (2015). New contributions on the dome of the pantheon in rome: comparison between the ideal model and the survey model. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40(5)* , 291.

Aranması, K. (2016). 21 st Century Architecture: Search for the Concept. *Megaron, 11(2)* .

Arch Daily. (2010). *AD Classics: Luce Memorial Chapel / I.M. Pei*. Retrieved December 01, 2018, from https://www.archdaily.com/95708/ad-classics-luce-memorial-chapel-i-m-pei

Arch daily. (2011). *London Aquatics Centre for 2012 Summer Olympics / Zaha Hadid Architects*. Retrieved December 01, 2018, from https://www.archdaily.com/161116/london-aquatics-centre-for-2012-summer-olympics-zaha-hadid-architects

Arch Daily. (2013). *AD Classics: The Guggenheim Museum Bilbao / Gehry Partners*. Retrieved October 17, 2018, from https://www.archdaily.com/422470/ad-classics-the-guggenheim-museum-bilbao-frank-gehry

Arch Daily. (2014). *AD Classics: Kresge Auditorium / Eero Saarinen and Associates*. Retrieved December 05, 2018, from https://www.archdaily.com/492176/ad-classics-kresge-auditorium-eero-saarinen-and-associates

Arch Daily. (2016). *Elbphilharmonie Hamburg / Herzog & de Meuron*. Retrieved December 05, 2018, from https://www.archdaily.com/802093/elbphilharmonie-hamburg-herzog-and-de-meuron

Arch Daily. (2017). *The Engineering Behind the Louvre Abu Dhabi's Striking Geometric Dome*. Retrieved December 06, 2018, from https://www.archdaily.com/886180/the-engineering-behind-the-louvre-abu-dhabis-striking-geometric-dome

Arch Idialog. (2012). *Archive for design strategy*. Retrieved December 15, 2018, from https://archidialog.com/tag/design-strategy/

Architect Magazin. (2013). *Heydar Aliyev Cultural Center, Designed by Zaha Hadid Architects*. Retrieved October 20, 2018, from https://www.architectmagazine.com/design/buildings/heydar-aliyev-cultural-center-designed-by-zaha-hadid-architects_o

Architectural Design. (2018). *31 Spectacular Buildings Designed by Frank Gehry*. Retrieved december 10, 2018, from https://www.architecturaldigest.com/gallery/best-of-frank-gehry-slideshow

Architecture World. (2008). *Introduction to history of architecture*. Retrieved May 05, 2018, from http://www.architecturecourses.org/introduction-history-architecture

Archi Travel. (2013). *Kansai International Airport Terminal*. Retrieved December 02, 2018, from https://www.architravel.com/architravel/building/kansai-international-airport-terminal/

Arc Space. (2012). *Tenerife Concert Hall*. Retrieved December 03, 2018, from https://arcspace.com/feature/tenerife-concert-hall/

Arc Space. (2014). *Heydar Aliyev Center*. Retrieved December 19, 2018, from https://arcspace.com/feature/heydar-aliyev-center/

Barbour. (2016). *Organic GRP cladding for Serpentine Sackler Gallery*. Retrieved December 16, 2018, from https://www.barbourproductsearch.info/organic-grp-cladding-for-serpentine-sackler-news041222.html

Billington, D. P. (2000). Bridge Aesthetics — Structural Art. *CRC Press LLC* .

Blog Ferrovial . (2017). *How do you build a Guggenheim museum?* Retrieved December 11, 2018, from https://blog.ferrovial.com/en/2017/10/guggenheim-museum-construction/

Borges, R. F. (2001). Evolution of architectural forms of historic buildings. *Transactions on the Built Environment vol 55* , 601-608.

Branco, J. M., Piazza, M., & Cruz, P. J. (2010). Structural analysis of two King-post timber trusses: Non-destructive evaluation and load-carrying tests. *Construction and Building Materials, 24(3)* , 371-383.

Buildings library. (2010). *Riverside Museum of Transport*. Retrieved December 05, 2018, from https://www.ajbuildingslibrary.co.uk/projects/display/id/3880

Buildipedia. (2011). *London 2012: Aquatics Centre by Zaha Hadid*. Retrieved December 01, 2018, from http://buildipedia.com/aec-pros/featured-architecture/london-2012-aquatics-centre-by-zaha-hadid?print=1&tmpl=component

Buildipedia. (2011). *Zaha Hadid's Heydar Aliyev Cultural Centre: Turning a Vision into Reality*. Retrieved December 21, 2018, from http://buildipedia.com/aec-pros/from-the-job-site/zaha-hadids-heydar-aliyev-cultural-centre-turning-a-vision-into-reality

Build It. (2018). *Timber Cladding: What will it Cost?* Retrieved December 10, 2018, from https://www.self-build.co.uk/timber-cladding-what-will-it-cost/

Built Survey. (2015). *Zaha Hadid's archtecture of form*. Retrieved December 17, 2018, from http://builtsurvey.utm.my/ismail/files/2015/01/Zaha-Hadid-Architecture-of-Form1.pdf

Butelski, K. (2000). The architecture of curved shapes. *Nexus Network Journal , II,* 19-23.

Charleson, A. W. (2005). *Structure as architecture.* Oxford, England: Andrew W. Charleson.

Cleveland. (2012). *Now 10 years old, the Peter B. Lewis Building is quietly transforming business education at CWRU.* Retrieved December 20, 2018, from http://blog.cleveland.com/architecture/2012/11/the_10year_old_peter_b_lewis.html

Çıngı, T. (2007). *An Appraisal of Curvilinear Forms In Architecture With an Emphasis on Structural Behaviour: A Case Study on Channel Tunnel Railway Terminal at Waterloo*. (Doctoral dissertation, Middle East Technical University).

Design Boom. (2007). *interview with zaha hadid*. Retrieved December 16, 2018, from https://www.designboom.com/interviews/designboom-interview-zaha-hadid/

Design Boom. (2009). *Zaha hadid architects: JS bach chamber music hall*. Retrieved December 19, 2018, from https://www.designboom.com/architecture/zaha-hadid-architects-js-bach-chamber-music-hall/

Designing buildings. (2017). *Sage Gateshead*. Retrieved December 11, 2018, from https://www.designingbuildings.co.uk/wiki/Sage_Gateshead

Desimone. (2017). *Peter B. Lewis Building – Case Western University*. Retrieved December 17, 2018, from https://www.de-simone.com/projects/project/peter-b-lewis-building-case-western-university/

Dezeen. (2009). *JS Bach Chamber Music Hall by Zaha Hadid Architects*. Retrieved December 18, 2018, from https://www.dezeen.com/2009/07/07/js-bach-chamber-music-hall-by-zaha-hadid-architects/

Dezeen. (2011). *Riverside Museum by Zaha Hadid Architects*. Retrieved December 10, 2018, from https://www.dezeen.com/2011/06/10/riverside-museum-by-zaha-hadid-architects/

Dezeen. (2013). *Serpentine Sackler Gallery by Zaha Hadid*. Retrieved December 17, 2018, from https://www.dezeen.com/2013/09/25/serpentine-sackler-gallery-by-zaha-hadid/

Dezeen. (2014). *Zaha Hadid's Dongdaemun Design Plaza opens in Seoul*. Retrieved December 22, 2018, from https://www.dezeen.com/2014/03/23/zaha-hadiddongdaemun-design-plaza-seoul/

Dezeen. (2018). *Zaha Hadid Architects*. Retrieved December 17, 2018, from https://www.dezeen.com/tag/zaha-hadid/

Domus. (2012). *Zaha Hadid and Suprematism*. Retrieved December 18, 2018, from https://www.domusweb.it/en/reviews/2012/07/27/zaha-hadid-and-suprematism.html

DSpace. (2009). *Thrust Network Analysis : exploring three-dimensional equilibrium*. Retrieved November 26, 2018, from https://dspace.mit.edu/handle/1721.1/49539

Dwell. (2017). *13 Iconic Buildings Designed by Frank Gehry*. Retrieved October 05, 2018, from https://www.dwell.com/article/frank-gehry-iconic-buildings-1bd2dedc

Foti, P., Fraddosio, A., Lepore, N., & Piccioni, D. M. (2017). On the mechanics of corbelled domes: new analytical and computational approaches. *Research on Engineering Structures and Materials* .

Gareth Harney. (2013). *Roma invicta*. Retrieved May 13, 2018, from https://garethharney.wordpress.com/category/roman/

Geometrica. (2015). *Defining Domes*. Retrieved November 18, 2018, from http://www.geometrica.com/en/domes

Goldberg, S. A. (2006). Computational Design of Parametric Scripts for Digital Fabrication of Curved Structures. *International Journal of Architectural Computing, 4(3)* , 99-117.

Greenbond. (2018). *ACP Panel Manufacturer*. Retrieved December 22, 2018, from http://www.acpsheetprice.com/greenbondproducts.html?jh=xgbbjs3471&gclid=EAIaIQobChMIj_HVg4OP4AIVxzLTCh2YqAGtEAAYAyAAEgI_CPD_BwE

Hadid, Z. (2008). Zaha Hadid. Interview. (V. Belogolovsky, Interviewer).

Hoteit, A. (2015). Deconstructivism: Translation From Philosophy to Architecture. *Canadian Social Science, 11(7)* , 117-129.

Homewyse. (2018). *Cost of FRP Wall Panels*. Retrieved December 11, 2018, from https://www.homewyse.com/costs_1/cost_of_frp_wall_panels.html

Hunker. (2018). *How to Clean an FRP Wall Panel*. Retrieved December 15, 2018, from https://www.hunker.com/13416039/the-best-drill-bits-for-stone

Indesignlive. (2014). *Zaha Hadid's Fluid Alimunium Cultural Centre*. Retrieved December 22, 2018, from https://www.indesignlive.com/projects/zaha-hadids-fluid-alimunium-cultural-centre

In Exhibit. (2018). *MART – Museum of modern and contemporary art of trento & rovereto*. Retrieved December 02, 2018, from https://www.inexhibit.com/mymuseum/mart-museum-modern-art-trento-rovereto/

In Exhibit. (2018). *The architecture of the Zentrum Paul Klee by Renzo Piano*. Retrieved December 19, 2018, from https://www.inexhibit.com/mymuseum/zentrum-paul-klee-bern/

Inhabit. (2016). *ARCHDAILY 2016 BUILDING OF THE YEAR AWARDS: GRAND THEATRE OPERA HOUSE*. Retrieved December 23, 2018, from https://inhabitgroup.com/archdaily-2016-building-of-the-year-awards-grand-theatre-opera-house/

ISSUU. (2007). *London Aquatic Center Case Study* . Retrieved December 02, 2018, from https://issuu.com/bintou_coulibaly/docs/london_20aquatic_20template_20-11.1

Lancaster, L. C. (2015). “Armchair” Voussoir vaults in bath buildings of the western Roman Empire. *In 5th International Congress on Construction History* .

Lan, T. T. (1999). Space Frame Structures. *Boca Raton: CRC Press* , 200, 129.

Leach, N. (2009). Digital Cities. *Architectural Design, 79(4)* , 6-13.

Linked In. (2015). *Space Frames*. Retrieved November 23, 2018, from https://www.slideshare.net/sajidashah14/space-frames-52905493

Linked In. (2016). *Space & diagrid frames- Design*. Retrieved November 20, 2018, from https://www.slideshare.net/Dryoussefhamida/space-diagrid-frames

Macdonald, A. J. (2001). *Structure and Architecture.* Oxford, England: The Reed Elsevier plc group.

Mainstone, R. J. (2001). *Develpments in structural form.* New York, NY: Allen Lane.

Makezine. (2010). *Ask MAKE: How do trusses work?* Retrieved November 04, 2018, from https://makezine.com/2010/06/10/ask-make-how-do-trusses-work/

Melaragno, M. (2012). *An introduction to shell structures: The art and science of vaulting.* Springer Science & Business Media.

Monolithic. (2009). *The History of Thin-Shells and Monolithic Domes*. Retrieved September 03, 2018, from https://www.monolithic.org/blogs/engineering/the-history-of-thin-shells-and-monolithic-domes

Nejad, K. M. (2007, May). Curvilinearity in architecture: emotional effect of curvilinear forms in interior design. *Doctoral dissertation, Texas A&M University* .

Newly Swissed. (2015). *Zentrum Paul Klee in Bern features incredible architecture*. Retrieved December 15, 2018, from https://www.newlyswissed.com/zentrum-paul-klee-bern/

Numéro. (2018). *Zaha Hadid, a vision for eternity*. Retrieved December 19, 2018, from https://www.numero.com/en/architecture/zaha-hadid-vision-architectural-studio-fluidity-lines#_

Penn Design. (2006). *The Modernity of Zaha Hadid*. Retrieved December 18, 2018, from https://repository.upenn.edu/arch_papers/8/

PERI. (2018). *Auditorio de Tenerife, Spain*. Retrieved October 10, 2018, from https://www.peri.com/en/projects/cultural-buildings/auditorio-de-tenerife.html

Plan N Design. (2018). *Importance of form in architecture*. Retrieved October 27, 2018, from https://www.planndesign.com/articles/2758-importance-form-architecture

Pozzi, A. (2014). *Megalithism: Sacred and Pagan Architecture in Prehistory.* Boca Roton, Florida: Universal-Publishers.

Pitzker Prize. (2018). *The pritzker architecture prize*. Retrieved December 11, 2018, from https://www.pritzkerprize.com/biography-zaha-hadid

Prezi. (2014). *Long span structure system*. Retrieved April 27, 2018, from https://prezi.com/69on8ibflxsm/long-span-structure-system/

Prezi. (2015). *Frame and Shell Structure*. Retrieved November 26, 2018, from https://prezi.com/dnfwshrpnzqw/frame-and-shell-structures/

Research gate. (2015). *Composite Behavior of a Novel Insulated Concrete Sandwich Wall Panel Reinforced with GFRP Shear Grids: Effects of Insulation Types*. Retrieved December 15, 2018, from https://www.researchgate.net/figure/Insulated-concrete-sandwich-wall-panel-reinforced-with-glass-fiber-reinforced-polymer_fig1_276552503

Rheinzink. (2015). *Profile Technique for Roofing and Facades*. Retrieved December 10, 2018, from https://www.rheinzink.us/how-to/rheinzink-faqs/

Samsung C & T. (2017). *The Technology Behind Seoul's Landmark*. Retrieved December 22, 2018, from http://news.samsungcnt.com/the-technology-behind-seouls-landmark-dongdaemun-design-plaza/

SCRIBD. (2013). *Shell structure system*. Retrieved November 27, 2018, from https://www.scribd.com/presentation/194481445/SHELL-STRUCTURE-SYSTEM

Seebrilliance. (2017). *Aluminium Cladding Cleaning: DIY Or Hire Specialists?* Retrieved December 22, 2018, from https://www.seebrilliance.com/aluminium-cladding-cleaning.html

Setareh Arch. (2011). *Structure And Form Analysis System*. Retrieved November 16, 2018, from https://www.setareh.arch.vt.edu/safas/009_introduction_03_sl_dl.html

Sky Civ. (2015). *Types of Truss Structures*. Retrieved November 10, 2018, from https://skyciv.com/education/types-of-trusses/

Slide Share. (2013). *Roof trusses*. Retrieved November 03, 2018, from https://www.slideshare.net/AnsherinaDelMundo/roof-trusses-27192104

Slide Share. (2016). *Space frames*. Retrieved November 15, 2018, from https://www.slideshare.net/bnvaditya3/space-frames-57944276

Slide Share. (2017). *Steel trusses*. Retrieved November 13, 2018, from https://www.slideshare.net/roopachikkalgi/steel-trusses

Spaın-Holıday. (2018). *A Visit to the Metropol Parasol in Seville, Spain*. Retrieved November 10, 2018, from https://www.spain-holiday.com/Seville-city/articles/a-visit-to-the-metropol-parasol-in-seville-spain

Study. (2018). *Barrel Vault: Definition, Construction & Architecture*. Retrieved Sebtember 15, 2018, from https://study.com/academy/lesson/barrel-vault-definition-construction-architecture.html

Straeten, B. V. (2003). The uncanny and the architecture of deconstruction. *Image & Narrative, 5* .

Stromberg. (2012). *GFRP - Glass Fiber Reinforced Polymer*. Retrieved December 21, 2018, from https://www.strombergarchitectural.com/materials/gfrc

Sukumar, A., & John, E. (2014). Fiber addition and its effect on concrete strength. *International Journal of Innovative Research in Advanced Engineering (IJIRAE) Volume 1 Issue 8* , 144-149.

Technology Student. (2009). *Typical roman stone arch construction*. Retrieved May 10, 2018, from http://www.technologystudent.com/struct1/roman1.htm

The architectural review. (2015). *Harbin Opera House in China by MAD Architects*. Retrieved December 19, 2018, from https://www.architectural-review.com/today/harbin-opera-house-in-china-by-mad-architects/8691096.article

The Guardian. (2013). *Zaha Hadid: queen of the curve*. Retrieved March 26, 2018, from https://www.theguardian.com/artanddesign/2013/sep/08/zaha-hadid-serpentine-sackler-profile

The mind of architecture. (2008). *Architecture Basics : Vaults*. Retrieved May 18, 2018, from http://the-mind-of-architecture.blogspot.com/2016/03/architecture-basics-vaults.html

The State Enterprise of Jahonnamo. (2016). *Move over Sydney -- the Harbin Opera House is a work of art*. Retrieved October 26, 2018, from http://jahonnamo.tj/en/culture/31831-move-over-sydney-the-harbin-opera-house-is-a-work-of-art.html

The Vintage News. (2016). *The Treasury of Atreus, or Tomb of Agamemnon, is the largest and most impressive of the nine tholos tombs at Mycenae*. Retrieved May 20, 2018, from https://www.thevintagenews.com/2016/10/30/the-treasury-of-atreus-or-tomb-of-agamemnon-is-the-largest-and-most-impressive-of-the-nine-tholos-tombs-at-mycenae/

Traveler. (2015). *Gehry Across America: Chasing the Greatest Living Architect*. Retrieved December 18, 2018, from https://www.cntraveler.com/galleries/2015-09-17/frank-gehry-architectecture-road-trip

UPT. (2017). *LONG SPAN STRUCTURES: PART 1*. Retrieved April 28, 2018, from https://www.ct.upt.ro/suscos/files/20162018/L18_Long%20Span%20Structures.pdf

Wikiarquitectura. (2003). *Walt Disney Concert Hall*. Retrieved October 10, 2018, from https://en.wikiarquitectura.com/building/walt-disney-concert-hall/

Wikiarquitectura. (2004). *The Sage Gateshead Auditorium*. Retrieved December 03, 2018, from https://en.wikiarquitectura.com/building/the-sage-gateshead-auditorium/

Wikiarquitectura. (2007). *Marqués de Riscal Winery*. Retrieved October 12, 2018, from https://en.wikiarquitectura.com/building/marques-de-riscal-winery/

Wikiarquitectura. (2010). Retrieved October 15, 2018, from https://en.wikiarquitectura.com/building/lou-ruvo-center-for-brain-health/