

## Artículo de investigación

**Evaluation of curvilinear structural systems used by Zaha Hadid's architecture**

Evaluación de sistemas estructurales curvilíneos utilizados por la arquitectura de Zaha Hadid

Avaliação de sistemas estruturais curvilíneos utilizados por arquitetura de Zaha Hadid

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**Abstract**

The fundamental of the curved architectural design is based on blending the architecture with the surrounding environment. Architects and engineers have been inspired the curved forms such as arch; vault and dome from nature, where they have been use it in their designs to create large spans. The architects developed the curved forms by integrated the curved forms to create unique form and to pass larger spans than previous, where 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. This research aims to clarify the different types of curvilinear structures which have been used in Zaha Hadid's buildings, where the research will focus on the curvilinear architectural buildings designed by the architect Zaha Hadid, where six curvilinear buildings with different spans, areas and heights will be studied, while these curvilinear buildings characterized by fluidity and complexity namely 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

**Resumen**

La base del diseño arquitectónico curvo se basa en combinar la arquitectura con el entorno circundante. Los arquitectos e ingenieros se han inspirado en las formas curvas como el arco; bóveda y cúpula de la naturaleza, donde se han utilizado en sus diseños para crear grandes luces. Los arquitectos desarrollaron las formas curvas integrando las formas curvas para crear una forma única y para pasar tramos más grandes que los anteriores, donde se ha lanzado el término "curvilíneo" para describir estas formas. Pero los profesionales ya se han enfrentado a un desafío en la construcción de las formas curvilíneas, debido a la dificultad de implementarlas. Los arquitectos han utilizado las formas curvilíneas por diferentes materiales, estrategias, estilos y otras diversidades, que le dan a cada arquitecto sus propias características. Zaha Hadid fue una de esas arquitectas, diseñó sus proyectos en función de las propiedades, la historia, la civilización, las tradiciones y el movimiento de población afiliado al sitio del proyecto; lo que ayudó a formar y diversificar sus proyectos. Esta investigación tiene como objetivo aclarar los diferentes tipos de estructuras curvilíneas que se han utilizado en los edificios de Zaha Hadid, donde la investigación se centrará en los edificios arquitectónicos curvilíneos diseñados por la arquitecta Zaha Hadid, donde se construirán seis edificios curvilíneos con diferentes tramos, áreas y alturas. estudiaron, mientras que estos edificios curvilíneos se caracterizan por la fluidez y la complejidad, a saber, el London Aquatics Centre en el Reino Unido (2008-2011), el Museo Riverside en el Reino Unido (2007-2012), el

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Plaza & Park in South Korea (2009-2014), Harbin Opera House in China (2011-2015). These curvilinear structures are studied by collecting the main information's of buildings such as site, functions, the height of the building, its length and area, the type of curvilinear structural system used, the structural materials as well as the cladding and ceiling materials.

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

Centro Cultural Heydar Aliyev en Azerbaiyán (2007-2012), la Galería Serpentine Sackler en el Reino Unido (2009-2013), Dongdaemun Design Plaza & Park en Corea del Sur (2009-2014), Harbin Opera House en China (2011-2015). Estas estructuras curvilíneas se estudian mediante la recopilación de la información principal de los edificios, como el sitio, las funciones, la altura del edificio, su longitud y área, el tipo de sistema estructural curvilíneo utilizado, los materiales estructurales, así como los materiales de revestimiento y techo.

**Palabras clave:** Formas curvas; formas curvilíneas; estructuras curvilíneas; relación forma-estructura; Diseños de Zaha Hadid

## Resumo

O fundamental do projeto arquitetônico curvo é baseado na mistura da arquitetura com o ambiente circundante. Arquitetos e engenheiros foram inspirados nas formas curvas, como o arco; abóbada e abóbada da natureza, onde foram usados em seus projetos para criar grandes extensões. Os arquitetos desenvolveram as formas curvas integrando as formas curvas para criar uma forma única e passar por vãos maiores que os anteriores, onde o termo "curvilíneo" foi lançado para descrever essas formas. Mas os profissionais já enfrentaram um desafio na construção das formas curvilíneas, devido à dificuldade de implementá-las. Arquitetos têm sido utilizados as formas curvilíneas por diferentes materiais, estratégias, estilos e outras diversidades, que dão a cada arquiteto suas próprias características. Zaha Hadid era um desses arquitetos, ela projetou seus projetos dependendo das propriedades, história, civilização, tradições e movimento populacional afiliados ao local do projeto; que ajudou a formar e diversificar seus projetos. Esta pesquisa visa esclarecer os diferentes tipos de estruturas curvilíneas que foram utilizadas nos edifícios de Zaha Hadid, onde a pesquisa incidirá sobre os edifícios arquitetônicos curvilíneos projetados pela arquiteta Zaha Hadid, onde seis edifícios curvilíneos com diferentes vãos, áreas e alturas serão estudados, enquanto estes edifícios curvilíneos caracterizaram-se pela fluidez e complexidade, nomeadamente o London Aquatics Centre no Reino Unido (2008-2011), Riverside Museum no Reino Unido (2007-2012), Heydar Aliyev Culture Center no Azerbaijão (2007-2012), Serpentine Sackler Gallery no Reino Unido. (2009-2013), Dongdaemun Design Plaza & Park na Coreia do Sul (2009-2014), Harbin Opera House na China (2011-2015). Estas estruturas curvilíneas são estudadas recolhendo as principais informações dos edifícios, tais como o local, as funções, a altura do edifício, o seu comprimento e área, o tipo de sistema estrutural curvilíneo utilizado, os materiais estruturais, bem como os materiais de revestimento e teto.

**Palavras-Chave:** Formas curvas; formas curvilíneas; estruturas curvilíneas; relação forma-estrutura; Desenhos de Zaha Hadid

## Introduction

In the late of 20th and 21st century, the "curvilinear" term has been launched to describe designs with complex 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. Many architects have contributed to the development of curved architecture and made it an integral part of the surrounding environment, but in different patterns and strategies which gave a various

personal architectural character for each one of them (Çingı, 2007). 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". Zaha Hadid used the infinity free lines and was characterized by abstraction and durability (The Guardian, 2013). This research aim is to clarifying the types of curvilinear

structures have been used in Zaha Hadid's buildings, where the research will focus on the curvilinear architectural buildings of the architect Zaha Hadid, while the research will focus on six curvilinear architectural buildings of the architect Zaha Hadid.

### Methodology

In this research, the qualitative method has been used, where a lot information have been collected about the curvilinear buildings from different sources. The research focused on Zaha Hadid's curvilinear architecture, where six of her curvilinear buildings have been inserted with important details to clarify the structural systems those have been used in her curvilinear buildings. At the end, the buildings have been inserted in

table with name of building, location, illustrations, years, structural system, cladding/ceiling materials, areas, spans and heights.

### London Aquatics Center in UK (2008-2011)

#### General Information

London Aquatics Center located in Olympic Park, London, the building has curvilinear roof. The center's area is 15,400 m<sup>2</sup>, span 160 m and height 45 m. It consists from three floors one of them under ground. The center includes Olympic pools, dry diving zone, diving pool with boards and platforms. A state of the art gym with 50 station, café and restaurant (Fig.1) (Arch Daily, 2011).

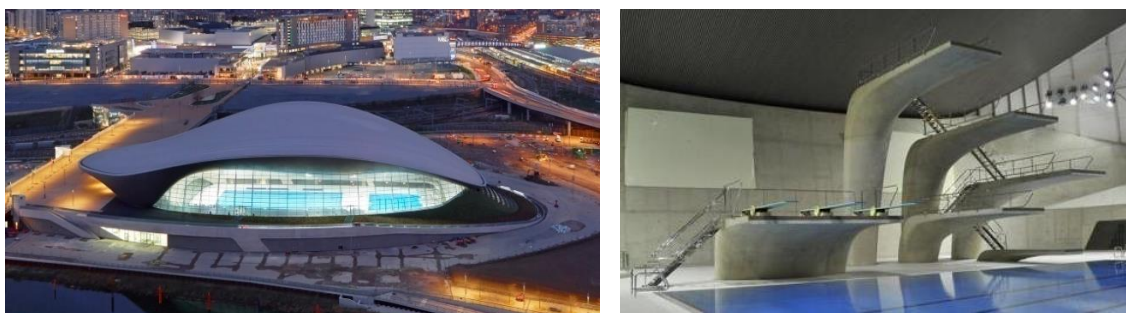


Fig.1. (a) London Aquatics center, (b) Boards and platforms of London Aquatics Center

The concept has been inspired from the fluid geometries of water waves, and appeared by

merging two curved lines in different directions (Fig.2).

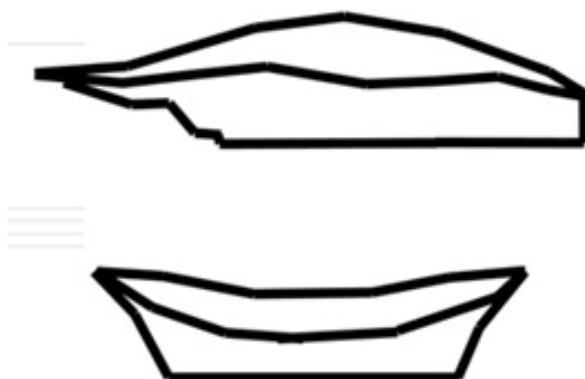


Fig.2. The curved lines of concept in different directions

### Structural System and Materials

The structural systems have been used in London Aquatics Center is space frame structural system with double layer grids (DLG), constructed by

steel material. The space frame supported from the southern elevation by reinforced concrete wall and from the northern elevation by two columns made of reinforced concrete (RC) (Fig.3) (Build It, 2018).



Fig.3. (a) RC wall with RC columns supporting the space frame structure (DLG), (b) Illustration of DLG with RC wall and RC columns

The ceiling material used in London Aquatics center is timber, while the cladding material is zinc silicate that to protect the structure from

corrosion, then the zinc silicate was covered with aluminum panels (Fig..4) (Buildipedia, 2011).

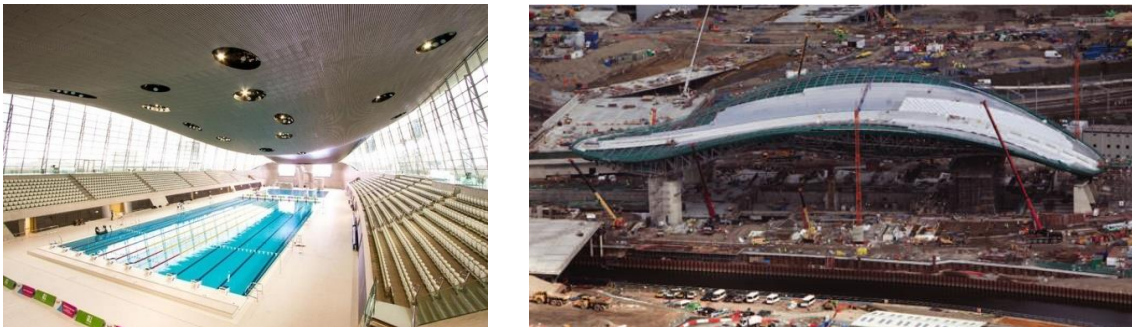


Fig.4. (a) Timber ceiling material of London Aquatics center, (b) Aluminum cladding material of London Aquatics center

The structure of London Aquatics center works in tension and compression forces. The loads transfer from the steel trusses to the concrete

point then to the foundation on the ground (Fig.5) (ISSUU, 2007).

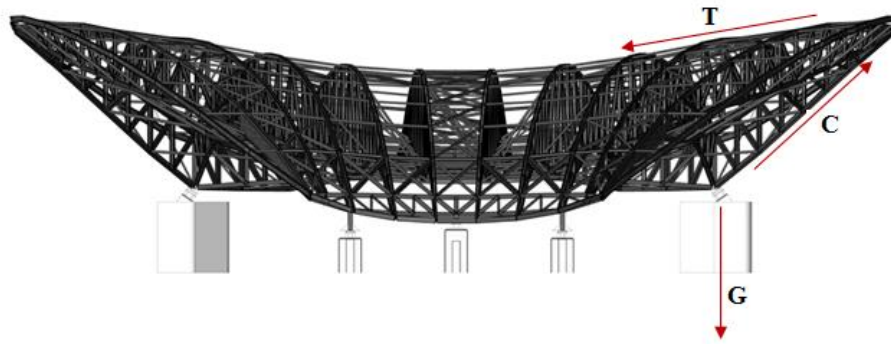


Fig.5. Structure stability of London Aquatics center

### Riverside Museum in UK (2007-2012)

#### General Information

Riverside museum located in Glasgow Scotland, the building has curvilinear facades. The

museum area is 11,000 m<sup>2</sup>, height 20 m and span 150 m. The museum consists from ground floor and first floor, include a large exhibition hall with more than 3000 exhibits, such as trams, bikes, buses, trains, unique collection of model ships and cars (Fig.6) (Buildings library, 2010).

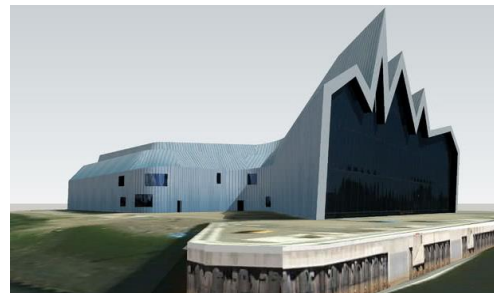


Fig.6. Riverside museum with curvilinear walls

The concept of Riverside Museum consists from merging the curved lines bending by different directions (Fig.7).



Fig.7. The concept of Riverside museum

### Structural System and Materials

The primary structural system used in Riverside museum is space frame structure (DLG), constructed by steel material (F.8).



Fig.8. (a) Space frame structure of Riverside museum from inside the building, (b) Space frame structure of Riverside museum from outside the building

The ceiling material used in Riverside museum is glass fiber reinforced gypsum (GFRG), while the

cladding material used is Rheinzink (Fig.9) (Dezeen, 2011).



Fig.9. (a) GFRG ceiling material of Riverside museum, (b) Rheinzink cladding material of Riverside museum

### Heydar Aliyev Cultural Center in Azerbaijan (2007-2012)

#### General Information

Heydar Aliyev center located in Baku, the building has curvilinear cover that merged the

walls with roofs, where the buildings have been connected to each other by spaces created by the outer wrapper which suggests that they are one building. The total area of building is 57,519 m<sup>2</sup>, with 3,200 m span and 74 m height. The center consists of three buildings: museum, conference hall and library, while the library is the highest building (Fig.10) (Architect Magazine, 2013).

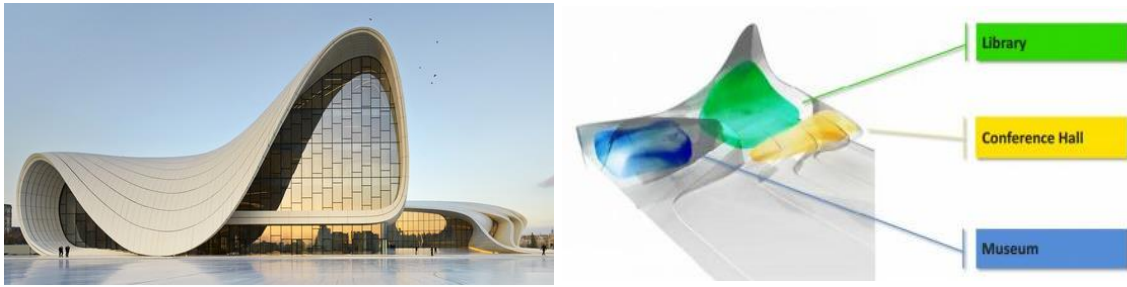


Fig.10. (a) Heydar Aliyev cultural center, (b) The main three buildings of Heydar Aliyev center

The concept of Heydar Aliyev cultural center consists by merging the curved lines (Fig.11).

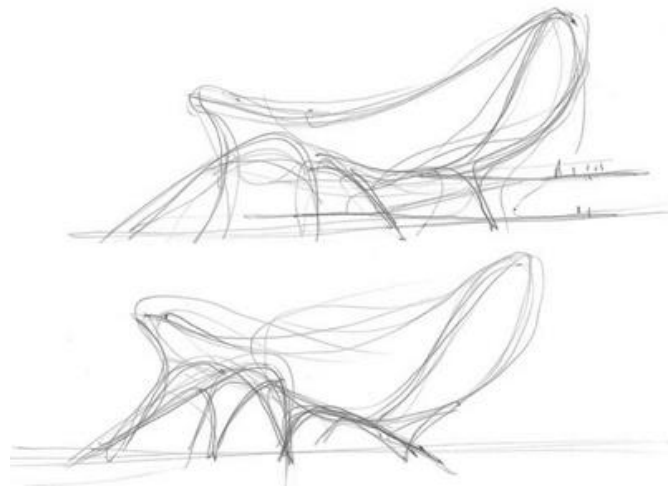


Fig.11. Sketch of Heydar Aliyev cultural center

### Structural System and Materials

Heydar Aliyev center consists mainly of two structural systems that work together: the first one constructed by reinforced concrete material

that forms the boundaries (internal walls) of the three buildings, while the second one is space frame structure (DLG) constructed by steel material (Fig.12).



Fig.12. (a) The space frame structure of Heydar Aliyev center, (b) Steel and RC materials used in structural system of the 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 (Fig.13) (Arc space, 2014).



Fig.13. (a) Steel columns and beams of Heydar Aliyev center, (b) Steel bridge of Heydar Aliyev center

The cladding and Ceiling materials have been used in Heydar Aliyev center are Glass Fiber Reinforced Concrete (GFRC) with Glass Fiber

Reinforced Plastic (GFRP), while GFRC and GFRP act together and each beating the deficits of the other (Fig.14) (Buildipedia, 2011).



Fig.14. (a) GFRC & GFRP cladding material of Heydar Aliyev cultural center, (b) GFRC & GFRP ceiling material of Heydar Aliyev cultural center

### Serpentine Sackler Gallery in UK (2009-2013)

#### General Information

Serpentine Sackler gallery located in London, the building has curvilinear roof (Fig.15). The center

area is 900 m<sup>2</sup>, the highest point reach up to 6 m and the center span is 30 m. Zaha Hadid renovated the large old galley brick building to create additional spaces for gallery and she designed a curvilinear structure extending from one side of the old building included space for events and café (Fig.16).



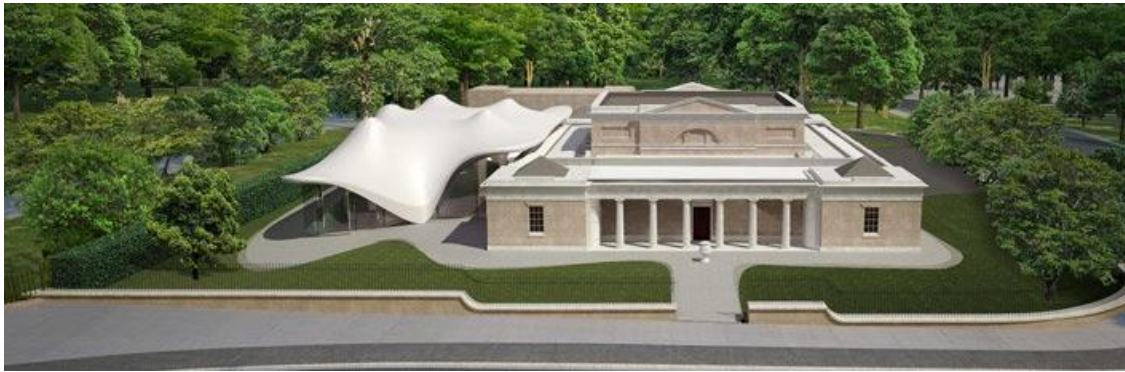


Fig.15. The old gallery brick building with new curvilinear form



Fig.16. (a) The old building included space for events, (b) The old building included café

### Structural System and Materials

The structural system of curvilinear form is shell structure with double curvature shells (DCS)

constructed by steel material, while the curvilinear roof supported by five tapered steel columns (Fig.17) (Dezeen, 2013).



Fig.17. (a) Construction of shell structure system (DCS), (b) Construction of tapered steel columns

The ceiling material used in Serpentine Sackler gallery is fiberglass reinforced plastic (FRP), while the cladding material used is glass

reinforced plastic (GRP) (Fig.18) (Homewyse, 2018).



Fig.18. (a) FRP ceiling material of the curvilinear roof and columns, (b) GRP cladding material of the curvilinear roof

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

#### General Information

Dongdaemun Design Plaza & Park located in Dongdaemun Seoul, South Korea, the building has curvilinear cover that merged the walls with roofs. The area is 89,574 m<sup>2</sup>; the height of 34 m

and the span is 280 m, the width of 188 m. It consists from 3 levels underground and 4 above-ground, included 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 (Fig.19) (Dezeen, 2014).

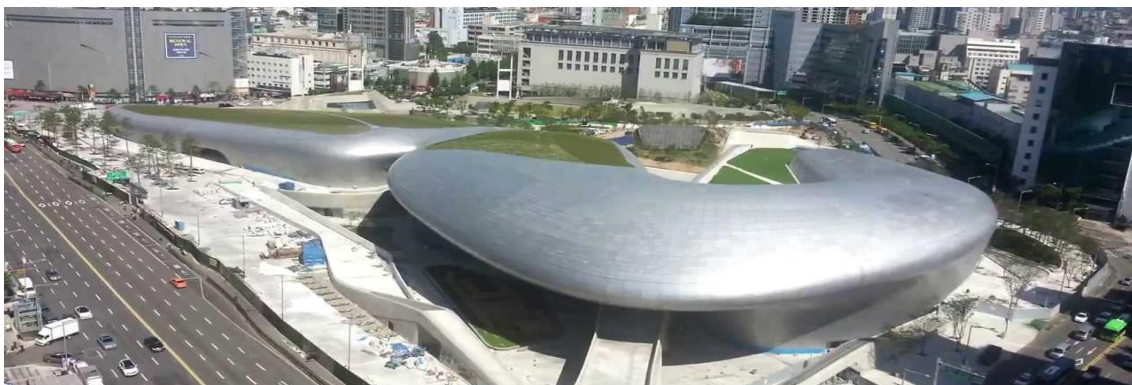


Fig.19. Dongdaemun design plaza & park

#### Structural System and Materials

The structural system of Dongdaemun design plaza & park curvilinear form is space frame

structure (DLG) constructed by steel material, where the space frame structure has been supported by the internal walls structure of utilities which constructed by concrete material (Fig.20) (Samsung C & T, 2017).



Fig.20. (a) The space frame structure (DLG), (b) The space frame structure (DLG) with concrete columns and walls

The ceiling material used in Dongdaemun Design Plaza & Park is glass fiber reinforced

gypsum (GFRG), while the cladding material used is aluminum (Fig.21) (Indesignlive, 2014).

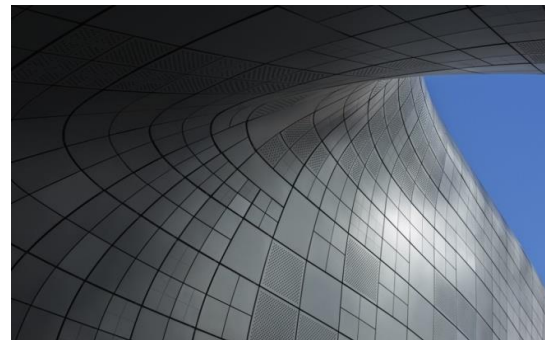


Fig.21. (a) GFRG ceiling material of Dongdaemun design plaza & park, (b) Aluminum cladding material of Dongdaemun design plaza & park

### Harbin Opera house in China (2011-2015)

#### General Information

The opera house located in Harbin, the building has curvilinear cover that merged the walls with roofs. The area is 97,000 m<sup>2</sup>, with height 56 m and span 200 m. It consists of two large concert halls and a large public square (Fig.22).



Fig.22. Harbin Opera house in China

The concept of Harbin opera house consists from merging curved lines (Fig.23) (The architectural review, 2015).

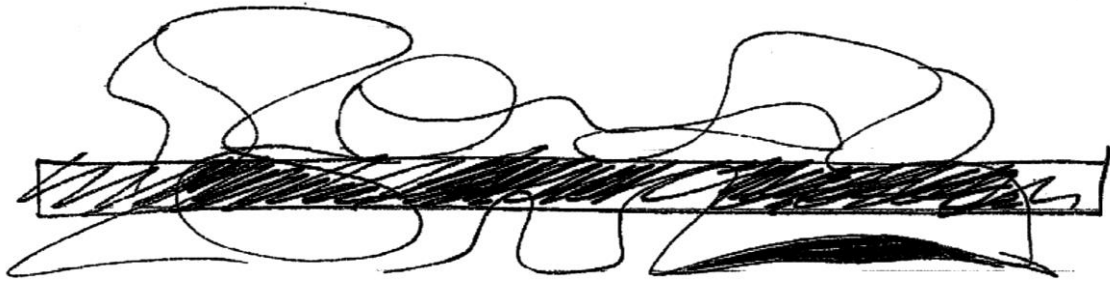


Fig.23. Sketch of Harbin Opera house

The structural system of Harbin opera house is space frame structure (DLG) constructed by steel material, where the space frame structure has

been supported by the internal functions which constructed by reinforced fiber concrete (Fig.24) (The State Enterprise of Jahonnamo, 2016).



Fig.24. The space frame structure with RFC walls of Harbin Opera house

The ceiling material used in Harbin Opera house are white concrete and wooden shell, while the

cladding material used is smooth white aluminum panels (Fig.25) (Inhabit, 2016).

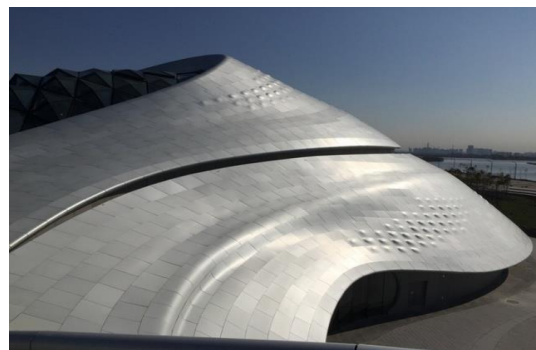


Fig.25. (a) White concrete and wooden shell ceiling materials of Opera house, (b) Aluminum cladding material of Harbin Opera house

This table is included explanation to 6 curvilinear buildings designed by Zaha Hadid where their details have been inserted in the table below (Table 4.1). The purpose of this table is to summarize the research 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 1:** 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

### Conclusion

Zaha Hadid used the same structural system and construction materials, in spite of their differences in the spans, heights and the curvilinear forms from building to other, where the space frame structure with double layer grids (DLG) have been used in most of Zaha Hadid's curvilinear architectural buildings, as well as the material used for the curvilinear forms structure was steel material and supported by columns and walls made of reinforced concrete. The steel material is used for a height of 8-9 m maximum, but when the structure will be more than that,

material and supported by RC walls and columns, while they have different height and spans.

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.

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