Critical Look to the Developments in Architectural Structures

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ABSTRACT

Revolutionary innovations in construction and new materials have enabled architects to design buildings with most unusual shapes. These types of designs started in the 18th century. International style is the idea of making building as a sculpture. Archisculpture is a marketing tool to attract visitors and the example of it is Guggenheim museum in Bilbao, which strategy is known to world as “the Bilbao effect”. There are a number of architects who have followed the footsteps of Guggenheim museum in Bilbao design, such as Santiago calatrava, Rem Koolhaas and Zaha Hadid. Structure is the generator of form and if we look deep and start analyzing these buildings we will find out two important aspects of them. first, sculptural attitude second, structural value, these are the two identical facts about outstanding buildings in the recent past works .these kind of attractive building structures have lots of followers, especially among new architects have not been studied enough and there is a need to study theories and principles behind it.

This study aims to identify and analyze the new architectural structures in order to extract useful principles for application of students as well as the architects. it is also hoped that by such research a body of knowledge will be built up on the architectural structure. architects and designers in the continent need to be aware of these existing new methods in order to be able to develop an appropriate style of building and compete with the method which is fast becoming homogenous in the world today architectural structure building is becoming the global style and architects like Zaha

Hadid have done the projects all over the world which shows the adoptability and sustainability as two important factors has been done in such buildings so far.

Case studies are selected from new outstanding buildings. There are three different structural system approaches that have been used in the systems. Different countries photographs and structural pictures will be available. The samples will be analysed in terms of their architectural structures selection. It will reveal how they work and give comparison between the expressional results of these structures, the way they affect the architectural spaces and the theory behind them. The following questions constitute the focus for the study:

1. What are the new architectural structures? This will be categorized in terms of its distinguishing variations, materials and features there will be three groups' .I. mast structure II. Free form structures III. Innovative structures.

2. How these new architectural structures work?

3. How the architectural structures effect the architectural space?

Hopefully the outcome of this research will be helpful for the designers in their design process. In other word designing the structure is the key to make any desire project. Especially those who seek to create new forms and architectural spaces which will be compatible with world of technology and creation.

The first chapter, the introduction, discusses briefly how the research will be carried out through a classification of structures according to their

system, concept and form. This chapter discusses briefly the qualitative methodology employed in the research based on an extensive literature review and its interpretations. It also includes a theoretical background discussion on architectural structures.

Chapter two is the analyses of selected cases which are the works of outstanding architects. The analysis is from outcomes of the literature review. The last chapter is the conclusion.

Key words: Architectural Structure, Mast Structure, Conceptual Structure, Free- Form Structure, Structural Synthesis.

ÖZET

Yapımda ve yapı malzemelerindeki devrimsel gelişmeler, mimarları alışılmamış formlarda yapılar tasarlamaya götürmüştür. Bu tür tasarımlar 18inci Yüzyılda başlamıştır. Uluslararası stil yapının bir heykel gibi tasarlanması fikridir. *Archisculpture* insanların dikkatini çeken bir pazarlama aracıdır ve en önemli örneği Bilbao'daki Guggenheim Müzesidir. Buradaki yaklaşım "Bilbao Etkisi" olarak da anılır. Santiago Calatrava, Rem Koolhaas ve Zaha Hadid gibi, bu etkiyi izleyen bir dizi mimar vardır, Mimari strüktür, yapı formunun oluşturucusudur. Yapıları analiz ettiğimizde bunu iki önemli olgusu ile karşılaşırız. Birincisi plastik (heykelimsi) yaklaşım, ikincisi plastik (heykelimsi) değer. Bunlar günümüz mimarisinde karşılaştığımız iki benzer oluşumdur. Bunların arkasındaki kuramların, ilkelerin araştırılmasının genç tasarımcılara yol göstereceği düşünülmüştür.

İnsan yaşamını ve aktivitelerini barındıran binalar, fonksiyonel ve biçimsel özeliklerine göre şekillenir. Bu anlamda, cepheleri ve iç mekanları ile bina, madalyonun iki yüzüne benzetilebilir. Hacimsel olarak insan hareketini kolaylaştıran iç mekan, binayı iklimsel etmenlerden koruyan kabuğu aracılığı ile bütünü biçimsel ve fonksiyonel olarak daha iyi algılamamızı sağlar. İç mekanın bir diğer görevi, insanın mahremiyet, güvenlik, dinlence ve eğlence gibi yaşamsal gereksinimlerini sağlamak; dolayısı ile de insanın fizyolojik, psikolojik ve sosyal ihtiyaçlarını karşılamaktır. Kaliteli iç mekanlar tasarlamak için kullanılan ana gereçler duvarlar, tavan yüseklikleri, farklı kat seviyeleri, bölücü elemanlar, farklı malzemeler,

pencereler, aydınlatma, renk, ve bunlara benzer elemanlardır. Ancak, pekçok aktiviteyi ayni anda tek mekanda barındırmak pratik olmadığından iç mekanı bölmek, farklı mekan kaliteleri yaratmak ta önemlidir. Bu bölünmeler fiziksel veya görsel ya da her ikisinden de meydana gelebilir. Ayrıca mekanı bölen elemanlar formal, çizgisel, düzlemsel veya sanal elemanlar olarakda tanımlanabilir.

Bu araştırma seçilmiş örnekerin niceliksel bir analizine dayanır. Bulgular okurun yorumlarına açık olmakla birlikte sonuç kısmı örneklerin üzerine kurgulanmış ve genelleme yapılmamıştır. Çalışma, geniş kaynaklı bir literatür taramasına dayanmakta ve ayrıca akademik grupların görüşlerinden de yararlanmaktadır.

Bu çalışmanın amacı iç mekanı düzlemsel, formal ya da sanal olarak bölen elemanların farklı türlerini araştırmak, bölücü elemanla mekan arasındaki ilişkiyi anlamak ve bazı durumlarda bu elemanların taşıdığı anlamları sorgulamaktır. Sonuç olarak temel olduğu kadar da önemli üç soru ortaya çıkmaktadır. Kulanım açısından bölücü eleman-mekan-strüktür arasındaki ilişki nedir? Anlam açısından bölücü elemanla mekan arasındaki ilişki nasıl açıklanabilir? Mimari strüktürdeki gelişmeler nelerdir? Bu çalışmanın temel hedefi bu sorulara ve benzerlerine yanıt aramaktır.

Bu çalışmanın, genç tasarımcılara yardımcı olması umulmaktadır. Özellikle yeni formlar ve yaratıcılık arayanlar için, mimari tasarımda strüktür, tüm diğer tasarımlar için bir anahtar konumundadır.

Tezin Birinci Bölümü giriş bölümü olup, tezin konusu olan mimari strüktürlerin sınıflandırmasını ve ilgili kavramların tanımını yapmaktadır. Aynı zamanda bu konudaki literature çalışmalarını tanıtmaktadır. İkinci Bölüm araştırmada kullanılan yöntemi, seçilen araştırma örneklerini, araştırma bulgularını vermektedir. Örnekler günümüzün tanınmış mimarlarının son tasarımlarından seçilmiştir. Son Bölüm araştırmanın sonuçlarını vermektedir.

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… Dedicated to my mother Minoo

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INTRODUCTION

1.1 Introduction

Architecture is art of compassion and creation although there is a freedom in this type of work there are some criteria's which have to be considered. The improvement in technology has provided Architects with an opportunity to meet their inspirations in real models .The idea of making a building akin to sculpture had been in the history of architecture since the 18^{th} century. There were also some attempts like Boullee's work, this proposal has been developed in decades and it was with the development of technology. Later, with the developments and inventions of materials and structures the new buildings were made which were attractive for observers and have the sculptural look of a Guggenheim museum in Bilbao. This Revolution in architecture is called Archisculpture and their idea is known as Bilbao Effect.

1.1.1 Purpose of the Study

Globalization has also entered architecture. We have global stars who are designing all over the world and this attractive way of designing as mentioned above "Archisculpture" has lots of followers. The followers are especially among the young designers, still there is a lot of research which needs to be done in order to reveal the formation which is applicable for architects as well as students.

This research aims to point out 1.architectural structural form 2. Structural value, since structure is the generator of form and there are some theories and classifications in this research.

1.1.2 Methodological Approach

Architectural structures are categorized according to their appearance into three different aspects:

- **Mast structures**
- **Conceptual structure**
- **Free Form structure**

Reading structure in each of this classification is different according to their appearance, and also the expression is different according to the observer. As an example for the mast structure the building has a mechanical vision and there is not much detail and the whole form can be easily perceived by the observer. For the conceptual structures the building is a representation of the nature which means the nature is a concept of the form in this type of structures. The structures can be seen clearly in the form.

The third group is free-form structure. The details are very clear and the fragmentation is used in the envelope of the building. Each part of this envelope has its own structure and the interior also takes its form from the exterior. Therefore this research will investigate the forming of these structures and at the same time inspirations which leads to each of them further on the impact of them in architectural space.

> *"Prouvue was very inventive with cladding, in which he was the first to use folded sheet metal for architectural construction. The overall appearance of the building now results from the Qualities of the wall panel themselves. This exterior enclosure –which is hard to all a façade – testifies to its origins in a workshop and development in factory production if this building has an "image", even an "image of," then production is what appears". (Mostafavi, 2001)*

Figure 1: Prouves own house in Nancy, France 1955 (Source:www.designmuseum.org)

Figure 2: Folded sheet metal in the interior of Prouves house (Source:www.designmuseum.org)

With this example from Prouve works it's noticable that despite of masonary structure he started innovative method with folded metal sheets and result is the integration of façade and the building frame.It can be stated that this was the starting point in the developments of Architectural structure .

Architectural structure refers to the type of structure when the building envelop take the whole shape of the building from the inside to the outside.

1.1.3 Scopes and Limitations of this study

The analysis are derived mainly from the literature review and the buildings are selected from recent projects that were very successful. From these explanations we understand the architectural structure and it's value in architectural design production and it's effect in architectural spaces. The various type of architectural structure classification is explained .

Lack of architectural structure in design projects lead to worthless project design for designers so this research will define ways which designer can use technology in architecture and comes up with very innovative design projects.

At the end it hopes that this research will make a significant improvement in the development of Architectural structure forms and it will be widely using within architects as well as designers.

1.2 Review of relevant literature and definitions

The general overview for the three different architectural structures and their subdivisions are discussed in this part and also the related topics, architectural structures and their relationship to the building envelope are explained.

1.3 Mast Structure

“In mast structure buildings ,the roof construction takes the form of a tensile structure based on tall masts from which suspension cables or rods are taken down to provide additional intermediate supports to the roof structure.” (Harris& Pui-K 1996).

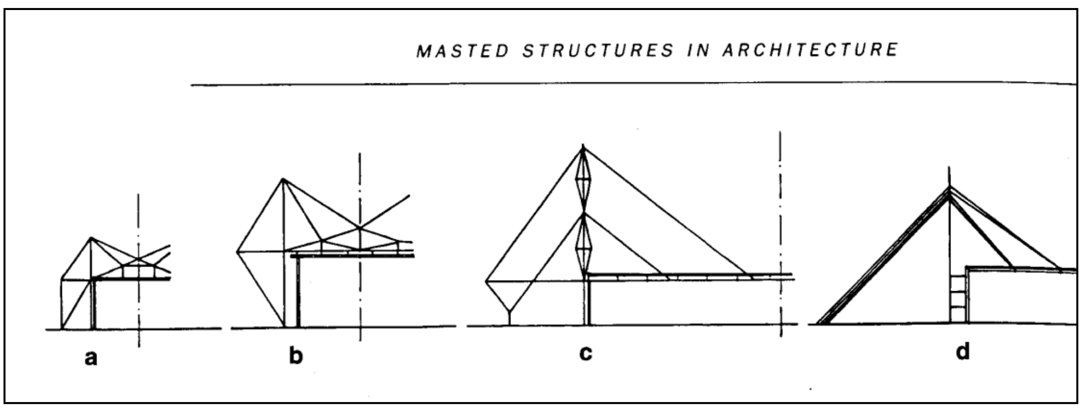


Figure 3: Masted structures in Architecture (Source: Harris& Pui-K 1996)

Mast structure can be seen in all manner of material, sizes, shapes and colors and also in any range of size as small office building to vast supermarkets, they can be extensively charming and impressing and always eye-catching .Although most of the significant examples are in Europe it is worldwide structure addition to the present day architectural language in a way that elements of this language are structural. (Harris& Pui-K 1996).

The development of mast structure arrayed over the post war period this has come about five reasons:

- The need for unobstructed and large spaces such as sport halls, exhibition halls, factories supermarkets and warehouses.
- Practical understanding of how tension structures behave under varying conditions of loading and the aim of computers for making the necessary calculations.
- The availability of new materials and techniques.
- The need for new innovative buildings new ‘image’.
- Presence in the UK engineers who were interested in architect/engineer collaboration and were capable of the intellectual effort required in achievement of excellence.

In fact masted structures made a great impact in a variety of functional and formal types of buildings.

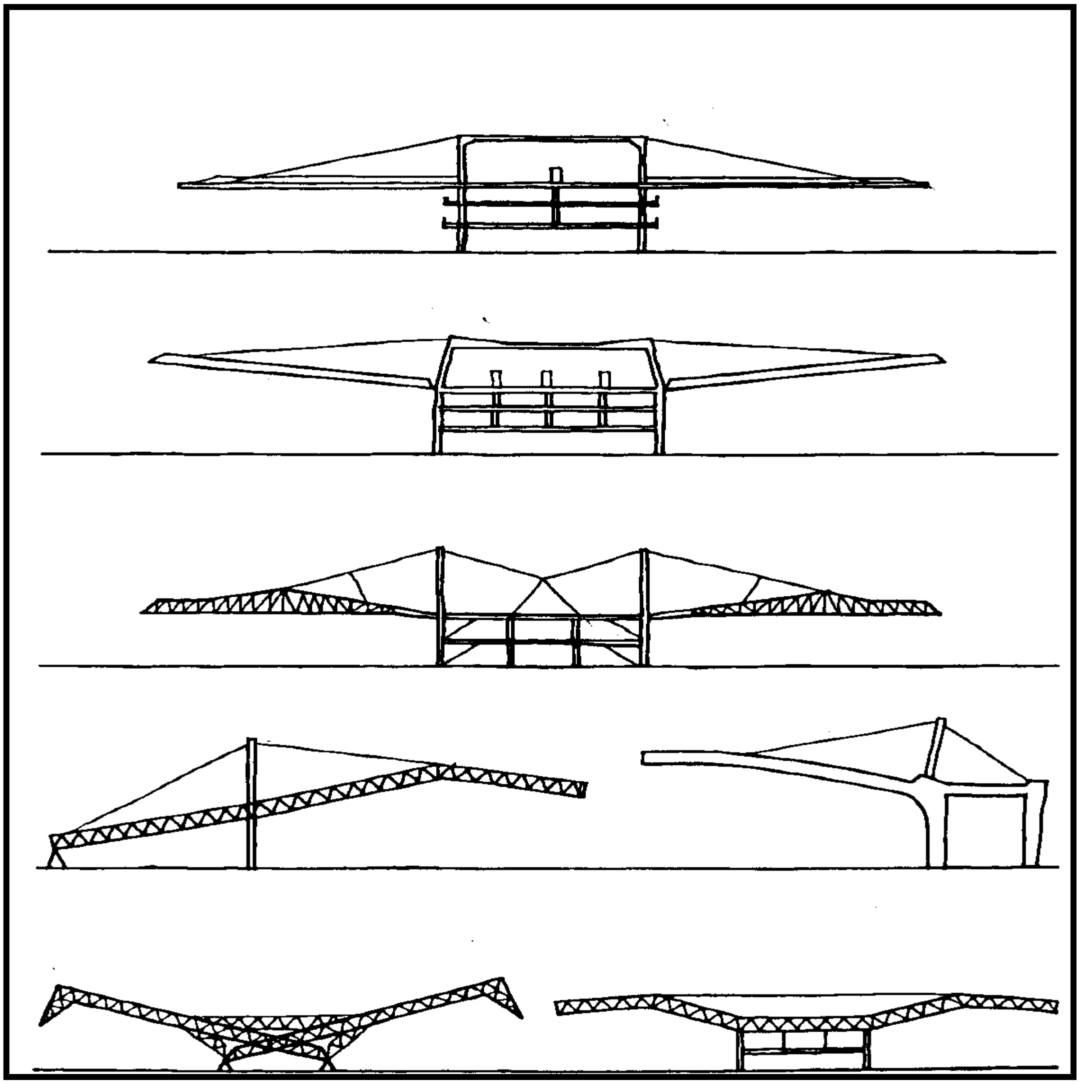


Figure 4 : Types of Mast Structure (Source: Harris& Pui-K 1996)

Mast structure in its evolution have got two different ways .First are those which took historical precedents such as vernacular tent and grew in size from simple shelter of people to the complex, from circus tents and even the ships tent. The second group has its background from the cable-stayed version of the suspension bridge which was originated during the19th century. “In parallel with the arched and framed structures of the architectural iron revolution, suspension bridges of more substantial and permanent form than hither to were introduced and the cable-stayed, radiating cable form made its appearance.” (Harris& Pui-K 1996).

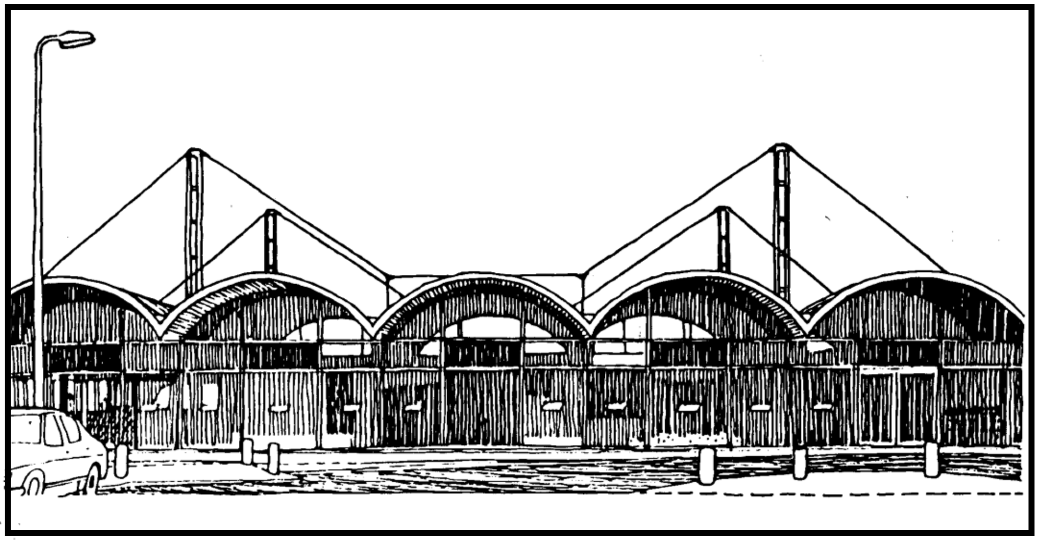


Figure 5: Sketch from Mast Structure building (Source: Harris& Pui-K 1996)

To define the architectural system in mast structure, we have to make a distinction between the buildings envelop and the building structure. In frame-structure buildings, including most of masted structures, there are two criteria's, First to make enclosing space envelope and weather protective building, Second to make an appropriate structural frame work.(Harris& Pui-K 1996).

In order to reveal the information about mast structures, we need to know the taxonomy of Masted Structures and there will be variety and analysis on how they vary.

There will be an organization of framework of basic concepts; the categorization will be based on physical attributes. There will be three basic structural elements: Mast cables and roof membrane and the number of their position and relationship will be analyzed. (Figure 6, 7, 8).

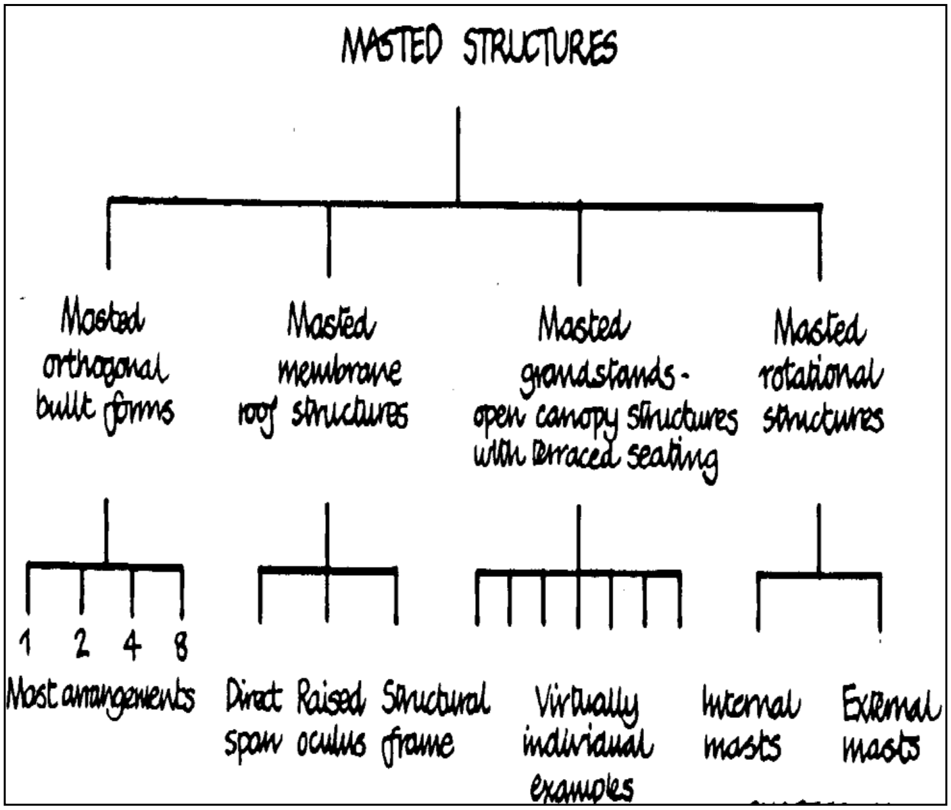


Figure 6: A formal taxonomy of masted structures (Source: Harris& Pui-K 1996)

Standardized topological relationships of structural systems based on up to eight masts, with typical one-way and two-ways translations is divided into three main groups:

a. Orthogonal Mast Structures

1. single mast origin: internal mast ,perimeter mast, external mast.

2. Two mast origin: side masts ,end masts ,adjacent cornet masts, opposite corner masts.

3. four mast origins: corner masts, intermediate masts ,spinal masts ,side masts.

4. eight mast origin: side masts, side and corner masts.

b. Rotational Mast structures

Rotational forms: internal masts, external masts.

c. Multiples Mast Structures

Typical one way translations: basic cell, longitudinal translation, laternal translation.(See Figure 7).

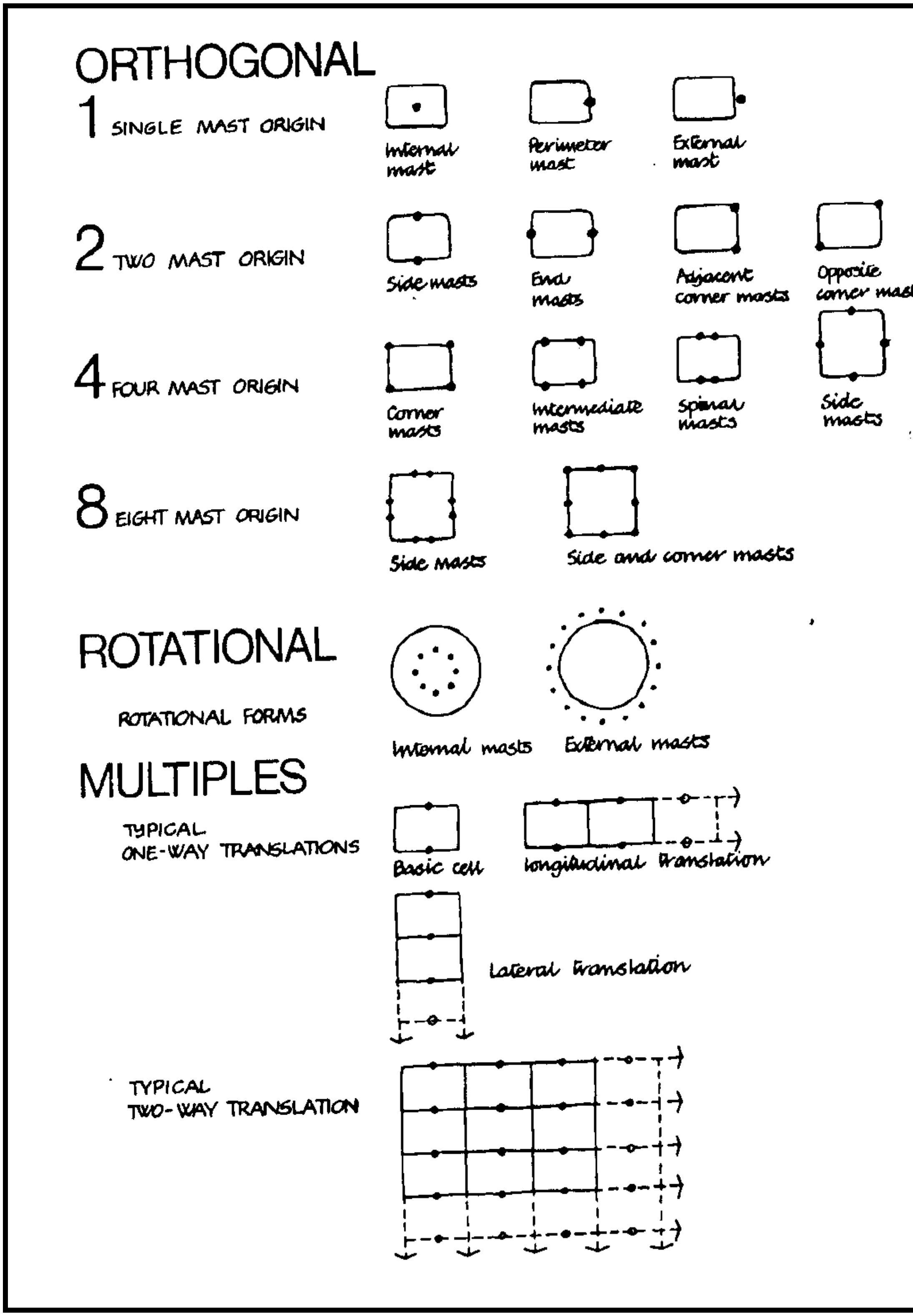


Figure 7: Standardized topological relationships of structural systems based on up to eight masts, with typical one-way and two-ways translations. (Source: Harris& Pui-K 1996)

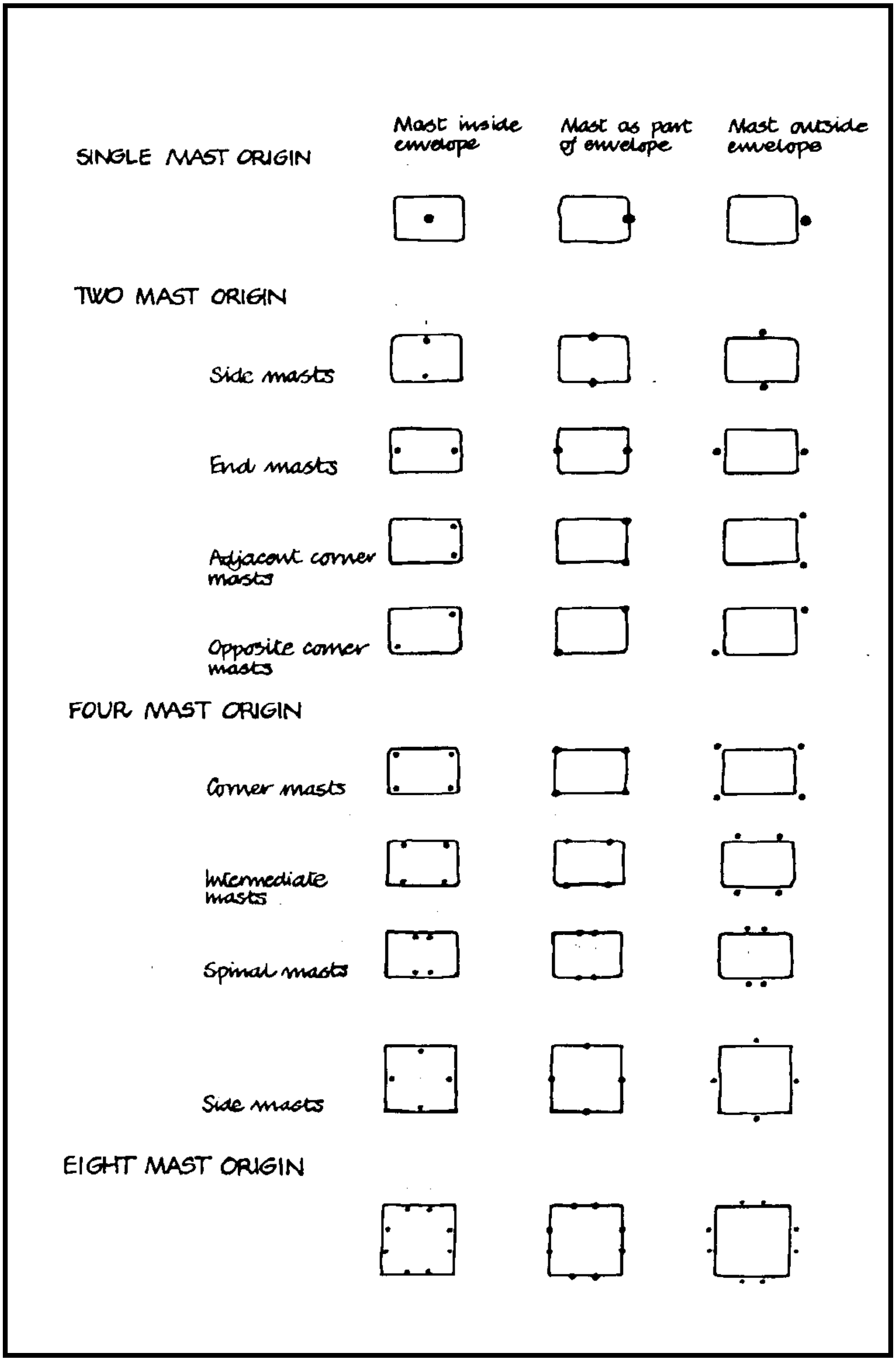


Figure 8: Standardized topological masts in relation to the building envelope. (Source: Harris& Pui-K 1996).

- **Typical Two Way Translation, in relation to the building envelope**

In membrane roof structure the characteristic features are different from other categorizations and needs to justify separately.

- Membrane supported directly from the masts.
- Membranes supported by cable networks.
- Membranes attached to an external framework.

1.3.1 Tension Structures 'Architectural Umbrellas'

"In most framed buildings, the building itself defines the form of the structure to a large extent: columns, walls, beams, and slabs are arranged and sized to suite the application using basic rules which are directed by the plan form and structural efficiency. "But there is more freedom in the choice of form to the structure and it's mostly external to the building envelop. (Trebilcock, Lawson, 2004).

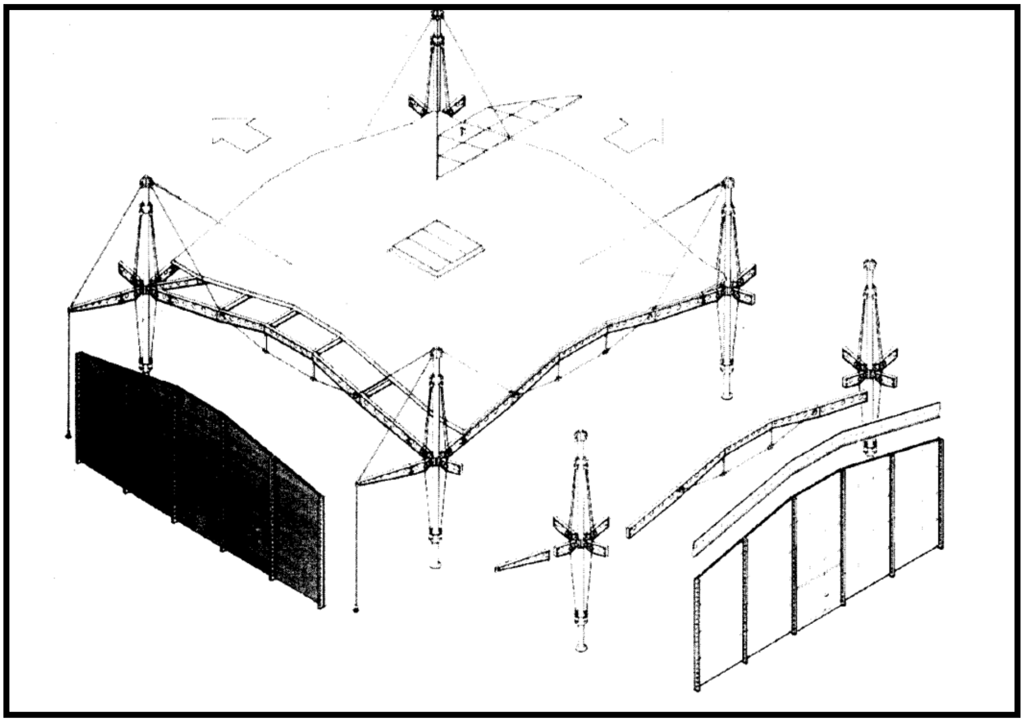


Figure 9: Tension Structure (Source: Harris& Pui-K 1996)

- **The Benefits of Tension Structure Are:**
  - They are a simple and well-organized structural form.
  - They are capable of creating long –span enclosures.
  - They can be erected quiet easily.
  - They are able to accommodate flexible cladding materials or membranes.
  - They have separate supports, primary to concentrated foundation forces.
  - **Their Disadvantages Somehow Related to Their Advantages:**
  - Foundation forces are heavy in both compression (under the masts) and in tension (at the tie holding down points).
  - There is a need for additional spaces around the structure for the holding down arrangement.
  - The structural elements or ties often pierce the enclosure.

- Tension elements can be easily introduced into other forms of construction, which are not strictly ‘tent-type’ enclosure. These are:
- Arch structures with ties at their base or at middle locations.
- Entrance frames, with ties at or close to roof space level.
- The bottom harmony of roof trusses, which is subject to tension .
- Elements of tension in bracing system.
- **Different Forms of Tension Attachments:**

Head detail at masts or column by direct attachments:

Saddle Support**:** A saddle stand for horse saddles that can be used in various ways, either set at rest against a wall or stood upright to hold a saddle. The saddle stand provides a convenient place to store valuables in its interior as well as a saddle holder that can be used in cramped areas where it takes up little space.

- Middle attachments to columns or masts.
- Foundation attachments.
- Middle tie attachments.
- Attachments of column bases.
- Cross-over ties.

1.3.2 Fabric Structure

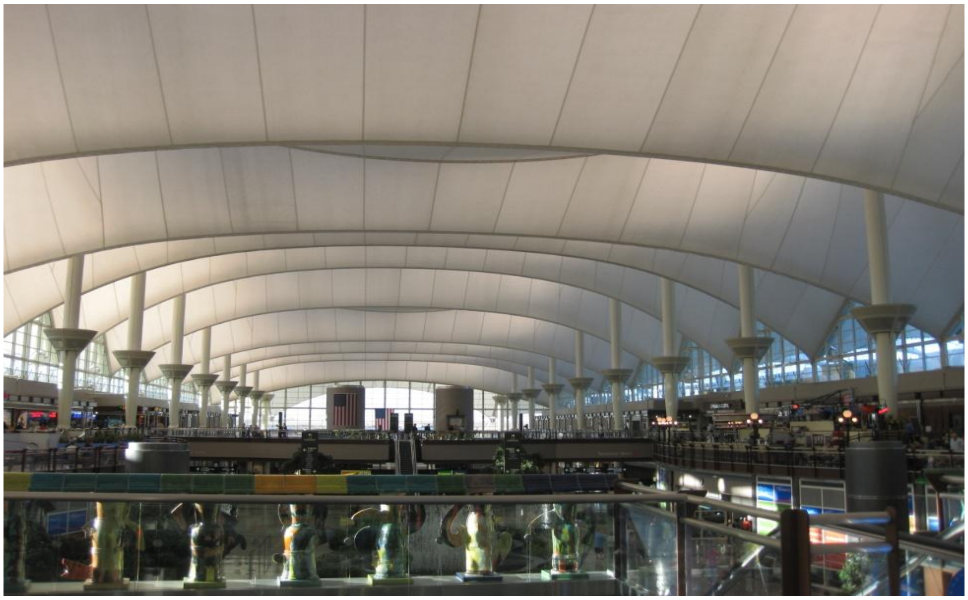


Figure 10: Fabric Structure, Denver International Airport (Photo: Personal Archive)

Another type of surface structure is fabric or membrane structures. Like shell structure there is no difference between the architectural and the structural forms. Their density linearity and solidity contrast with the flowing double-curved, light-weight and transparent fabric surfaces, which sometime's disturbs the overall softness of form. (Harris& Pui-K 1996).

1.3.3 Catenaries

Figure 11: Catenaries Structure, Washington Dulles International Airport
(Photo: www.wikipedia.com)

Catenaries like fabric structures transfer load to their supports through tension catenaries that support roofs It is usually designed so that the roofs self-weight exceeds the wind suction or boost pressures that would otherwise cause extreme vertical movements. (Harris& Pui-K 1996). Catenaries tension members are usually different from the cladding and showing within or outside the building envelope.

1.3.4 Ribbed Structure

Ribbed structures can also become architectural and structural forms although their skeletal character often necessitates a separate enveloping system. Ribs usually cantilever from their foundations or are propped near their bases. In general ribbed structures enclose single volumes rather than multi-storey constructions. By restricting the height of these structures efficiently to a single storey, although very high, designers stay away from potentially.(See Figure12).The **Allen Lambert Galleria**, sometimes described as the »crystal cathedral of commerce«, was the result of an international competition and was in corporated into the development in order to satisfy the City of Toronto's public art requirements. Designed by Spanish architect Santiago Calatrava, it is one of the most photographed spaces in Toronto's financial district; the interior illustrates Calatravas's signature organic style, with a vaulted ceiling that is intended to evoke an avenue of trees.

Figure 12: Ribbed Structure shown in Allen Lambert Galleria
(Source: http://eng.archinform.net)

1.4 Conceptual structure

"On a philosophical level nature has "bridged the gap" between structure logic, efficiency, best use of material properties ,functionality-and beauty proportions, color, smell, shape, volume-to a level that no man-made built form has achieved to date" .(Larsen, Tyas, 2003).

Conceptual structures are those that sources of inspiration for developing structural form are due to:

- Learning from natural forms.
- Applying our own perception.
- Looking for inspiration from patterns.
- Applying understanding of structural principles; when the case is too difficult or new for any of the others method to work, learning from physical models.

It should be noted that this section is most categorically not intended to be a state-of-the-art history of development of structural form, nor it is intended to give a full explanation of all available structural concepts.

The studies here intend to identify different examples of conceptual structures .this will help to have better image of conceptual structures:

1. Contrasting forms [trees], 2.Arches [Natural Stone Arches, Eggshell], 3.Shell Structures (Sea Shells), 4.Space Frames [Chemical Compounds], 5.Framed Structures [Bones, Skeletal Structure].

1.4.1 Contrasting Forms [Trees]

Figure 13: Contrasting forms. Colorado Airport, USA (Photo: Personal Archive)

Where a Juxtaposition of architectural qualities such as scale, materiality, geometry and texture are observed, Architectural and structural forms contrast “As one approaches a building and becomes aware of its architectural form, one usually expects to discover a certain structural form based on one’s previous architectural experience. If the actual form is considerably different from what is anticipated, then it is likely that architectural and structural forms contrast.” (Larsen, Tyas, 2003).

Elegant contrasting forms provide many opportunities for innovative architecture.

When we look at trees apart from its beauty, there are structural lessons to be investigated. Larsen stated that “A tree is, in effect, a large vertical cantilever, which is supported at one end only by it roots.”(Larsen, Tyas, 2003).There is lots of examples in structure which have inspired by the logic of tree structures.

1.4.1.1 Arches [Natural Stone Arches, Eggshell]

Figure 14: Arches, Eggshell (Photo:www.greayer.com)

Arches also offer a potential synthesis of architectural and structural form. There are lessons in the nature from different locations," how efficient an arch can be at carrying heavy loads over a long span Pont d'Arcy (France), Rainbow Bridge (Arizona, USA) and landscape arch (Utah, USA). Their shape is the solution to their endurance –rock is strong in compression, weak in tension. "An arch is the perfect shape to transfer loads across a span purely in compression. It should be no surprise that we don't find flat or inverted rock arches –these would generate unsustainable tensile stresses and would collapse." (Larsen, Tyas, 2003) .By observing the existing natural shapes, designer can apply the same rule into their own design.

Eggshells also apply similar principle in miniature. The driving force is to protect the developing young with the least material and more material will be on mother's body and make it harder for the young to finally break out of the shell. "The shell can be thought of as a three dimensional (3-D) arch, again transmitting the forces efficiently in compression. This 3-D version of an arch is the essence of domes and shells produced by human designers."(Larsen, Tyas, 2003).

1.4.1.2 Shell Structures (Sea Shells)

Figure 15: Shell Structure (Source: www.farm4.static.flickr.com)

Shell structure achieves the most wholesome combination of architectural and structural forms .They are also known as ‘surface structures’, they rely upon their three-dimensional curved geometry and correct direction and placement of supports for their sufficient structural performance. Shell structures can also be constructed from linear steel or timber members, as in the cases of geodesic or other braced frames. (Charleson, A.W.2006). In shell structure projects, structure acts as building skin in a very minor way; it defines an organic architectural form when it is achieving economic, rational, transparent construction.

In many cases because of the organism of the shape it is not possible to use the arch effect and bending must be avoided by some other means."Many sea shells solve the problem of how to minimize material while providing bending strength by having corrugations in the plane of the shell." (Larsen, Tyas, 2003).

1.4.1.3 Space Frames [Chemical Compounds]

Figure 16: Space Frames (photo: www. farm1.static.flickr.com**)**

"The generic term 'space frame' is often used to describe two structural types: space trusses, with inclined 'web' elements, and space frames, comprising three-dimensional modular units. They both reply primarily upon full triangulation of the structure, provided the primary loads are applied directly at the node joints." (Trebilcock, Lawson, 2004).

- **The benefits and advantages of space grids:**

Some of the advantages of using space frames are outlined below:

- Loads are distributed more evenly to the supports.

- Deflections are reduced compared to two-dimensional structures of alike span, size and loading.
- Because of the open nature of structure it allows the mechanical and electrical services and air condition ducts within the structure .
- Details are simplified- secondary members can be attached at the nodes and secondary elements such as purlins may not be needed.
- The structural interminancy of space grids means that. failure in one part will not lead to the whole structure.
- Modular space grids are ready factory made so they are easy transportable and simple assemble on site.
- They may be extended without difficulty or dismantled because of their modular nature.
- There is a considerable freedom in space planning, although approximately square.

Bays are preferable structurally, because they act like a two –dimensional grillage.

- Space frames can be assembled at ground level and then lifted into place.
- Most of space grids have a regular grid for the ease of construction, this regular grid pattern which may be exploited architecturally – particularly striking effects can be achieved when the color of the structure contrast with the color of the cladding.

Space grids are not appropriate for all roofing applications and their disadvantages have been summarized below:

- Space grids are more expensive than alternative structural systems, particularly when they Rae use for short spans (up to 20 m) or where there is no advantage of two-way spanning action.

- Because of the fixed geometry, it is problematic for irregular shaped buildings.

- Visually, space grid structures appears very ‘busy’ ,at some viewing angles the lightweight structure can appear to be very cluttered grid size ,configuration and depth can have considerable influence on the perceived density of structure.

When space grids are used to support floors, some fire resistant’s is necessary to use and because of the large number of relatively small sized components this is more expensive to achieve economically. (Trebilcock, Lawson, 2004).

- **General forms of space grids:**

In space grid structures, where two plane grids are separated by inclined members, the top and bottom grids do not necessarily need to have same patter or orientation.

The general forms of doubled –layer grids are divided into five groups as:

1. Square on square—where top and above space grid totally cover each other and they cover each other in the plane of the grid lines.

2. Square on square offset—where the bottom grid is offset by half a grid square relative to the upper grid, with web members connecting the intersection points on the top and bottom grids.

3. Square on diagonal square—where the lower grid is set as 45degree s to the lines of support and its mostly larger than the top grid and again with web members connecting the intersection points on the top and bottom grids.

4. Triangle on triangle offset—where both grids are triangular but the lower grid intersections occur below the centroids of alternate triangles in the upper grid ,with web members connecting the intersection points on the top and bottom grids.

Triangle on hexagon—where the upper grid is triangular and the lower, more open, grid is hexagonal due to the removal of some joints and web elements from the grid type. (Trebilcock, Lawson, 2004).

> *"In fact it happens in chemistry as in architecture that 'beautiful' that is, symmetrical and simple, is also the most study: in short, the same thing happens with molecules as with the cupolas of cathedrals or the arches of brigs."*(Larsen, Tyas, 2003).

The same detail that happening in chemistry between the components of the molecules can be applied into architectural structure. Levi understood the "beauty "in the structure of buckminsterfullerene, the phenomenology of carbon, which was first produced using nana-technology in the 1990s,and it gave the promise to the future of structural material of hitherto undreamed- of strength.

1.4.1.4 Framed Structures [Bones, Skeletal Structure]

Figure 17: Example of Bone Skeletal Structure (Photo: Personal Archive)

Synthesis of architectural and structural form enlarges ahead of curved forms. Consider the close relationship between orthogonal skeletal structural frameworks and rectilinear forms.

"Bones are the components of the skeletal frame which carry the weight of an animal, and, as such, are analogous to the structural framework of beams and columns in modern office blocks, structure-components of the frame which are not efficient in helping support it are nothing but a burden, and are slowly eliminated."(Larsen, Tyas, 2003).Santiago calatrava was inspired by nature and bone-like structures such as the Kuwait pavilion in Seville, Spain.

"There is a structure comprising an outer skin it keeps the external environment out and holds the contents in, and a separate, rigid main structure, which is a hidden skeleton (Larsen, Tyas, 2003).”This is like an animal structure the skin and structure and it’s like the façade to skeleton beam and column.

- **Replication from Nature**

There are two approaches in replication form nature:

a. Environmental Control

First designer demonstrates the inspiration of nature it will reflect the natural beauty of the form.

b. Image

Second the process which is nature’s responses to the environment will be the tool of inspiration for designer.

In both cases there is no guarantee for good quality architecture .considering only technical part of nature will produce dull and lifeless architecture .at the same time imitation will lead to thoughtless foolishly results for those which seek to copy nature only in appearance.

The most interesting architectural examples from nature are tree structures in a recent structural development. Artificial tree structures have to respond to different types of issues mostly they are used in buildings with wide spaces with structural support to give the free space allow for desired functions.”They work best for large open areas, with a sufficiently large floor- to- floor or floor- to- roof height to faceplate the separation of the branches.”(Larsen, Tyas, 2003).

The equivalence with the natural form of trees can be seen on two levels. The artificial look of tree is obvious but it is understandable that designer is responding to the point which is designing an appropriate structural form, the same way that a tree is Nature’s is appropriate to its own design point.

On the other hand trees and building columns are similar in their operation and they don’t carry similar loads. Trees are true cantilevers, and cantilevers are typically relatively flexible structural members. Buildings on the other hand, usually are required to be much stiffer when loaded.” (Larsen, Tyas, 2003).

1.5 Free-Form Structure

“Since the development of the structural technologies of steel and reinforced concrete it has been possible to design buildings, at least to a preliminary stage of the process, without considering how they will be supported or constructed.” (Macdonald, A.J.2001).

The explanations above refer to the Free-form structure and its possibility to build is due to the strength properties of steel and reinforced concrete in a way that practically any form can be built. The view that free-form buildings should give is tectonic and the visual vocabulary emerged from, or at least be directly related to, the structural framework of the building. The consequence of this was that the forms of most buildings were relatively basic from a structural approach-derived from the geometry of the post-and –beam framework.

Further factor which privileged the use of simple forms that the design and construction of very complex forms was difficult and costly, thus the potential offered by these new materials.

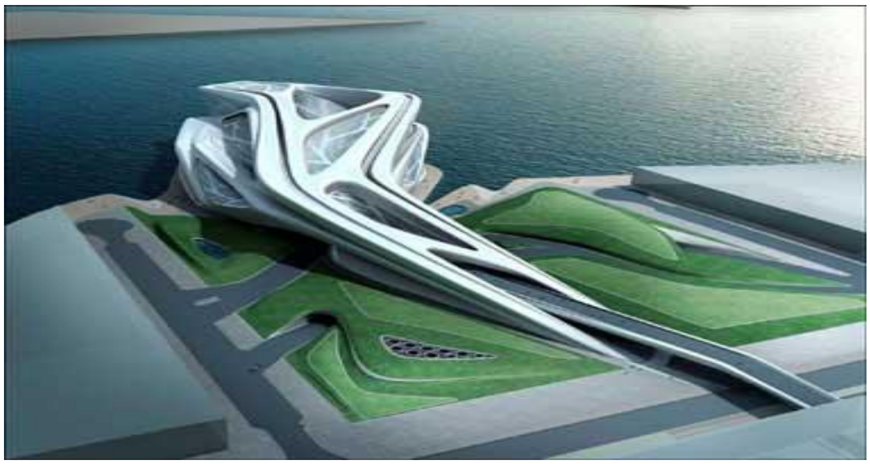


Figure 18: Hadid Performing Arts Centre Abu Dhabi
(Source: http://www.arcspace.com)

Expressive form challenges prevailing ideas of architecture, as well the limits of Understanding in engineering by encouraging the development of innovative fabrication solutions the synthesis of design conception and fabrication has always been integral to the process of creating architecture (Klinger, 2006). As Le Corbusier reminded us, “almost every period of Architecture has been linked to research in construction” (1931). Further, “the architect should have construction at least as much as his fingers’ ends as a thinker his grammar”. (Le Corbusier, 1931).

1.5.1 Free Form Structure system

The introduction of computer in the late twentieth century, firstly as a tool for structural analysis and consequently as a design aid, which allowed very difficult forms to be expressed and cutting and fabricating processes to be controlled, gave architects almost boundless freedom in the matter of form. This was a key issue in the preamble of the very complex geometries which appeared in architecture towards the end of the twentieth century. A good example is Frank Gehry's highly complex and spectacular Guggenheim Museum in Bilbao, Spain.

Wolf Prix, of Coop Himmelblau, was another late-twentieth –century architects who entirely oppressed this freedom:

"…we want to keep the design moment free of all material constrains…"
"In the initial stages structural planning is never an immediate priority…"
Enormous inventiveness was often needed of the engineers who developed the structural solutions for buildings whose forms had been created in a purely sculptural way. (Macdonald, A.J.2001).

Two important considerations must be taken into account when form is developed without choice to structural requirement:

Firstly, as the form will almost indeed be non-form –active, bending-type internal force will have to be opposed.

Secondly, the degrees of the internal forces which are caused are expected to be high in relation to the load carried.

The suggestion of both of these considerations are that structural material will be wastefully used and that the element sizes essential to produce enough strength will be high .This is a situation which can result in structures which are clumsy and ungainly. (Macdonald, A.J.2001).

A scale effect also operates because the strength of structural material remains constant even though the size of the structure increases.

1.6 Synthesis of Architectural and Structural Form

This discussion is considering the envelope of the building as an architectural form "in these cases structure defines architectural form and often functions, at least partially, as the building envelope."(Charleson, A.W.2006) all the three structure classes will be included in this subsection.

- **Walls**

Wall is another structural system capable of integrating architectural and structural forms.

- **Consonant forms**

Most of the buildings belong to this category where the Architectural and structural forms neither combine nor contrast. A contented and usually typical correlation exists between them. The form of these buildings cannot be considered synthesized, they are however highly incorporated.

In order to understand the relationship between structural and architectural form we should start from the massing or enveloping form. "The fact is structure rarely generates the architectural form, but instead responds to it in a way that meets the programmed and preferably is regular with design concepts." (Charleson, A.W.2006) In order to synthesize the design process it starts with architectural sketches, from architectural sketches to architectural structures is the right interpretation of these sketches. The structure should respond to the form and have a relation to the design initial ideas.

In general there are seven structural systems in terms of load transfer sequence for the architectural structures: (table 14)

1. **Form-active Structure Systems:** Its basic components are primarily subjected to but one kind of normal stresses, either compression or to tension. Structure acting mainly through material form: [Catenaries', Ribbed Structure, Cable Structures, Tent Structures, Arch Structures].
2. **Vector-active Structure Systems:** The system members are subjected with one part to compression, with the other part to tension: [Space Trusses].
3. **Section-active Structure Systems:** The system members are primarily subjected to bending, to inner compression, tension and shear. Structures acting mainly through cross section and continuity of material: [Sectional Profile and Framed Structure].
4. **Surface-active Structure Systems:** The system members are primarily subjected to membrane stresses, to stress acting parallel to the surface. Structures acting mainly through extension and form of space**:** [Structure &

Space Enclosure & Surface Shape: Shell Structure, Fabric Structure, and Surface Design].

5. **Height-active Structure Systems:** Are devices for the control of the height loads.
6. **Hybrid Structure Systems:** the redirection of forces is effected through the coactions of two or several- in their structural function basically equipotent mechanisms from different structure 'families'**.**
7. **Geometry Structure Form:** Descriptive Geometry, Geometry of structural forms and Geometry of lines, planes and solids. [Flat Surfaces/ Folding, Dome Surfaces] (Engel, H. 2007).

1.7 Synthesis of the Building Exterior

Many buildings take their architectural form from urban locations site boundaries and recession planes. Apart from the site influence on design some architects take the structures to enrich their architectural form which doesn't have ties to the surrounding built environment and make the building indifferent from surrounding**.** In fact Architects expose the structure in the building façade with awareness of enriching the exterior architecture.

"Structure plays numerous roles in contributing to the visual appearance of a building façade, through modulation, adding depth and texture, and acting as a visual screen or filter." (Charleson, A.W.2006).In order to enrich the design architects often use the building envelop and structural elements and try to relate them with using aesthetic values.

1.7.1 Modulation

"Modulation generates patterns that potentially introduce variety, rhythm and hierarchy, and generally increases visual interest." (Charleson, A.W.2006) modulation can be provided by beams and columns and in some cases the outcome would be sculptural.

1.7.2 Depth and Texture

"Structural depth is a prerequisite for and a major contributor to modulation variation of space depth relieves plainness, and in conjunction with natural and artificial light, creates opportunities for contrasting bright and shadowed areas that visually enliven a façade."(Charleson, A.W.2006) Designer's usually present structural depth to façades using ribbed or separate elements continues structure like an undulating wall presents other possibilities.

If it is folded or curved in plan, the structural depth and the stability and strength normal to the plane of a wall increase. Therefore wall can be understood as a vertically cantilevered folded-plate when resisting facade loads. Shaping a wall in plan provides opportunities for architectural enrichments. Consequently the interior will be regarded for the qualities of its interior space and urban setting. The smooth curving wall gives an attractive softness and naturalness. Texture implies variation of surface depth and it has a relation with materiality. Each material possesses a one of a kind texture depending on the way it is prefabricated finished or formed.

According to the construction constrains and planning arising from placing a new stand over existing one, some unusual structural solutions were required.

1.7.3 Screening and Filtering

Depending on its density, depth in plan and elevation, and its spatial relationship to a building envelope, exterior structure can be read as a filter or screen, contributing another set of aesthetic qualities to a façade.

1.7.4 Structural Scale

Structural scale has a great influence on how exterior structure contributes aesthetically to a façade .the dimensions of structural members can lie anywhere on a range between the extremes of mesh-like fineness and massive monumentality. Lots of buildings, beginning with utilizing small-scale structure demonstrate different approaches to structural scale.

"Where steel is used most efficiently, in tension, members invariably fall into the category of small scale – a consequence of sufficient of sufficient strength gained from minimal cross-sectional area. "(Charleson, A.W.2006).

1.7.5 Connecting the Interior to the Exterior

In contemporary architecture, structure that is expressed on an exterior elevation sometimes bears some resemblance to the interior structure. This may be a consequence of a design development that begins by attending o the interior structure and then letting those results in union with other ideals like clearness, inform the exterior design.

1.7.6 Entry

Provisions and expression of entrance, very significant aspects of architectural design, supply continuous opportunism for structural participations at a basic level, structure might supply little more than the support of an entry canopy.

1.7.7 Expressive Roles

Exterior structure has a long tradition of playing expressive roles. Reflect on gothic cathedrals. Their theories, flying-buttresses and buttresses express how the horizontal thrusts from masonry roof vaults are opposed and transferred to the earth. (See igure19).

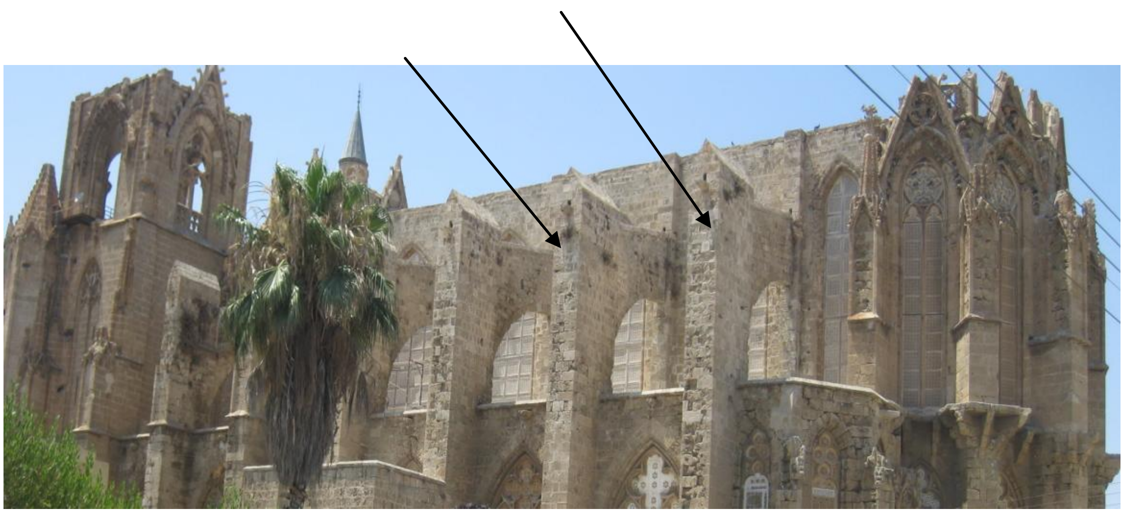


Figure 19: Flying buttresses in Gothic church, Famagusta, Northern Cyprus (Source: personal Archive)

Contemporary exterior structure continues this meaningful tradition by communicating a varied range of ideas, architectural qualities and actions exterior structure can to some level convey any architectural ideas. The simplicity with which such an idea might be communicated is quiet another matter .this definitely depends on an architect’s talent.

These theories are helping to illustrate how the structure can enrich the exterior visual qualities of buildings.

1.8 Meaning in Structure -Representation and Symbolism

This subchapter investigates how exposed structure improves architecture when structural forms and details add meaning by good quality of their representational and symbolic qualities. Structural representation is understood as structure characterizing a physical item, like a tree or a crane, while symbolic structure reminds an idea, a worth or a condition. Similar to attractiveness, representation and symbolism lie in the eye of the beholder.

“Both representational and symbolic structure encompasses different degrees of explicitness.”(Charleson, A.W.2006).

Although some of the examples of representation are generally recognized, others are not. And this situation is more obvious in the case of symbolism.

Severe Fen demonstrates the deeply personal nature of human answer to structural representation and symbolism. He sensitively imagines an individual’s reaction to an exposed structural member, a column: In the church the fisherman enters his pew. From his seat he recognizes that the column has the same dimension as his mast.

Through this recognition he feels secure. On the open sea, the tree was a symbol he trusted, as it brought him safely home. The same representation assists him now in turning his thoughts towards prayer. Within his spirit the sea is calm. In his search for the stars, the column offers him a personal dialogue. "(Charleson, A.W.2006).

This passage exemplifies structure, column in this case playing both representational and symbolic role. In the following section each role will be explained separately.

1.8.1 Representation

Examples representational structures can be divided into two irregularly sized groups. "In the far larger group, sources of representation include objects and processes found in the natural world. Artifacts that comprise the smaller group also become sources of design inspiration and invite attempts at representation." (A. Charleston, 2006).both nature and artifacts are sources of inspiration for the representational structures. This can be categorized into conceptual structures those with replication from nature or physical models.

Plant forms that remind the shapes of well-developed trees are certainly the most general. In the Eden Project structure founded on natural microscopic or molecular forms, where hexagonal structural biomes are scaled-up adaptations of bumblebee eye structure. There are still other sources of inspiration in nature, forms from plants, skeleton of insect's animals, birds and marine life, and forms from naturally occurring solids like metals and crystals are all hidden bases of representation.

a. Natural World

Discussion of the design of young Finnish architects, Antoniadis suggests that one may categorize as a uniquely Finnish obsession, the introduction of tree-form elements into architecture. From all natural forms, forests and trees are by far the most likely to be represented structurally, the structural trees tie the exterior and interior architecture of the building.

b. Artifacts

There are examples of structural representation originating from aeronautical, nautical, and automotive engineering, and industrial and historic structures but there are very few.

“With this building fresh in our minds, a building whose structure defies categorization, that can be interpreted in many ways, and possesses a palpable and tantalizing sense of both representation and symbolism. (A. Charleson, 2006).

This difference is understandable through examples where structures play more obvious symbolic roles.

1.8.2 Symbolism

“The practice of people imbuing structure with meaning is commonplace both outside and inside the architectural community.” (A. Charleson, 2006). The observation of people filling structure with meaning is ordinary both outside and inside the architectural district the illustration of this activity is the different examples from different sources including the world of vernacular architecture.

In Rangiatea church, Otaki, New Zealand oldest church religious symbolic meaning is attached to the exposed interior structure (See Figure20). “The ridge-pole, fashioned from a single tree, symbolizes the new faith and a belief in only one god .the ridge-pole is supported by three pillars symbolizing the Christian trinity.”

Figure 20: Rangiatea Otaki church Newzealand (Source: http://www.geocities.com)

Angus Macdonald also recognizes the symbolic role of structure in architecture. In his categorization of possible relationships between structure and architecture he includes ‘structure symbolized’. here structure is emphasized visually and forms an critical element of the architectural vocabulary .the “structure symbolized” approach has been employed almost completely as a mean of expressing the idea of technical progress.(A.Macdonald,1997).he describes that symbolic aim can include issues other than celebrating technology and investigates the implications of structure symbolizing a principle like sustainability.

An implicit assumption that structure plays symbolic in architecture lie behinds this research .for example, the main categorization of architectural structures is according to their meaning and expressional attitude of this structures. Structure in fact plays a wide range of symbolic role. However some of symbolic readings are not intention of architects and in the other hand architecture is enriched pretty clearly by exploiting the symbolic potential of structure.

Representation examples inspiration comes from the natural world. The most common source is trees, but also zoomorphic and anthromorphic forms are included. Representation based on human is less general but boat, ship; space-craft and book forms are represented by structure indeed. Structural symbolism, inherent in the concept of reading structure, is implied during this research.

a) Reading a Building as a Structural Object

"The idea that structural criticism should be an aspect of the standard critical appraisal of a work of architecture requires an ability, on the part of the critic, to read a building as a structural object." (Macdonald, A.J.2001). the classification system proposed in chapter 1 provides a basis for this. The system is based on a categorization of structure according to building envelope.

b) Types of Relationship between Structure and Architecture

Structure and architecture may be related in a broad variety of ways ranging between the extremes of complete authority of the architecture by the structure to whole disregard of structural requirements in the determination of both the form of a building and of its aesthetic treatment. (Macdonald, A.J.2001) .The unlimited number of possibilities is argued here under six wide headings:

- Ornamentation of structure
- Structure as ornament
- Structure as architecture
- Structure as form generator
- Structure accepted
- Structure ignored

This research is mainly focused on structure as form generator and explore the ways it affect the design and its relationship to the form as a whole.

1.9 Effect of Structure in Architectural Spaces

The relationship between structure and building functionality depends on structure of the building, by considering how structure located on the edge of a building maximizes spatial planning freedom (See figure21). A general approach for achieving large structure-free floor area is to place primary structure either outside or just inside the building envelope. The more a structure is organized; its parts assume hierarchical organization into subgroups aesthetically successful forms are those that permit a maximally articulated simplicity of organization.

Different roles of structure in architectural spaces are as followed: structure is observed subdividing interior space, increasing of functional flexibility; it can be used as subdividing space, expressive circulation effect and finally disordering function.

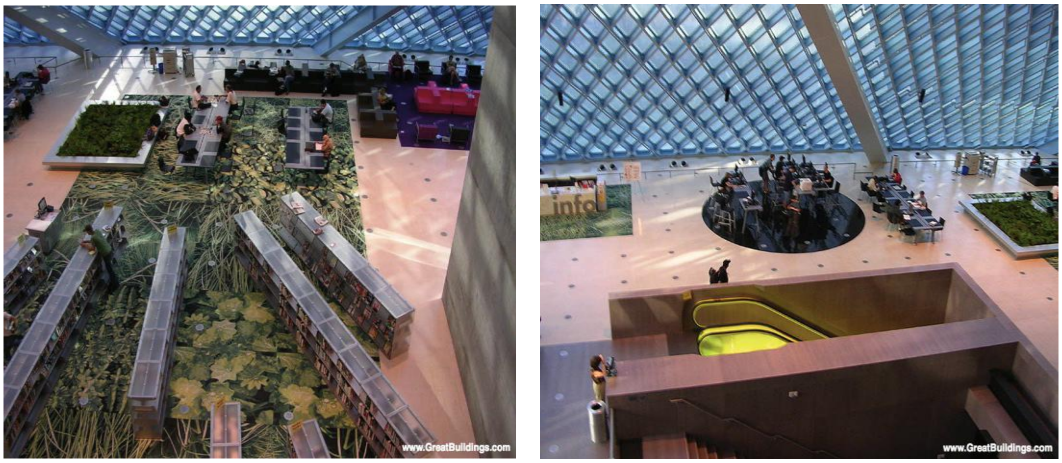


Figure 21: Seattle public library Rem Koolhaas (Source: www.gretbuildings.com)

1.9.1 Structure is observed Subdividing Interior Space:

- First, where the subdivided spaces accommodate similar functions and are distinguished as being part of a larger space.
- Secondly, where structure divides different building functions, like circulation and exhibition space, from each other.

This guides on to a section that examines how structure’s physical presence, including its directional quality, defines and increases circulation. Finally, examples demonstrate structure disrupting function, both purposely and unintentionally. (Charleson, A.W.2006).

Several architectural texts acknowledge the need for thoughtful integration of structure with building function. ”At an essentially pragmatic level, Schodak explains the concept of ‘critical functional dimensions’.” (Charleson, A.W.2006). In this approach designer should determine the minimum structure –free plan dimensions for a given space or series of spaces. Once these dimensions are decided ahead,’ basic functional modules’ can be drawn in plan.

Spaces between the modules then establish where vertical structure can be placed without intruding upon function. Minimum clear spans across modules can then be readily identified and, together with modules shapes, can propose appropriate structural systems such as load bearing walls or moment-resisting frames in combination with one- or two-way floor or roof horizontal spanning systems. Different-sized modules are often needed within one building.

Krier take a wider architectural approach towards structure and function. He calls attention to the spatial qualities of different structural systems and insists upon structure and function being integrated: construction is closely related to function. A clearly defined concept of spatial organization demands an appropriate structural solution. The more harmonious this unity, the closer one comes to the architectonic end product." He categorizes structure which he mainly recognizes as a spatial organizer, into three different types:

- Solid wall
- Skeletal construction
- Mixed construction comprising both walls and skeletal structure

Each type holds a different architectural character. For example, solid walled construction with its introverted and more intimate character contrasts with skeletal structures that are more open and flexible. Mixed system, in contrast, present opportunities for a hierarchy of interior spaces, greater spatial complexity and 'differentiated tectonic character. ' (Charleson, A.W.2006)

Krier highlights how interior structure, by virtue of its design and detailing influences spatial character, and as a result function; this chapter concerns itself more directly with the relationship between structure and the physical or practical features of building function ,consequently effect of structure in architectural spaces.

1.10 Functional Flexibility Increasment

Maximum flexibility of space planning and building function is due to the freedom from structural restrictions. Architectural elements such as partitions walls or screens can organize a clear space of interior structure. Obviously, maximum interior architectural flexibility is reached by positioning main structure outside the building envelope. But this strategy is often not easy to achieve according to possibly unnecessary structural depths and other architectural implications like cost that are related with spanning across the whole width of a building. A far more frequent and rational move toward to attain a high degree of planning freedom involves adopting the 'free plan'-that combination of structure with interior space inherited from the Modern Movement. "Spaces that once would have been enclosed by load-bearing walls now flow almost completely unimpeded around and between columns that are usually located on an orthogonal grid. " (Charleson, A.W.2006).

The spatial objectivity of structure allows the 'free plan'. That is the impact upon interior architecture by structure, perhaps in the form of columns or short walls, whether evaluated by its effect upon function or aesthetics, is considered minimal.

“More profound disturbances to building function form so-called ‘free plan’ structure also arise.” (Charleson, A.W.2006) for example, the oft studied Tugendhat House designed by Mies van der Rohe (Fig17). One review suggests rather uncritically how the architect used the columns to help identify places: two of the columns, together with the curved screen wall, frame the dining area; two others help define the living area; and another column suggests the boundary of the study area at the top right on the plan. (Unwin, S.1997).

Figure 22: Tugendhat House, by Ludwig Mies van der Rohe, at Brno, Czech Republic, 1930(Source: www.greatbuildings.com)

On the other hand, an option reading could view that identification of places as being as unconvincing as to edge on the accidental. additionally, after observing the columns placed close to walls but playing no exacting spatially defining architectural roles, and other columns located uncomfortably in secondary spaces, one could conclude that the interior architecture would be much improved if the existing walls were to become load-bearing and as many of the non-perimeter columns as possible were removed!

As already mentioned the maximum freedom in planning occurs when vertical structures are located on a building perimeter. This option suits single storey construction better than multi-storey buildings for two reasons:

1. Outside structure certainly results in long spans necessitating reasonably deep structure and consequent large inter-storey heights. A deep or high roof structure of a single-storey building does not usually have such harsh outcomes upon building height as do several layers of deep floor structure. This may refer in some examples to Mast Structure as well.

2. Roofs in general weight far less than suspended floors so they can span larger distances more easily.

Categories of perimeter structure include:

1. Exoskeleton structures where all structural members lie outside the building envelope.

2. Where to differing degrees structure imposes upon interior space.

In the second set of building:

- Structure either potentially disturbs function around the boundary of the floor plan.

- It is well integrated with occupancy.

1.10.1 Subdividing Space

Since old ages, load-bearing walls have divides building plans into part spaces. However, since the introduction of metal skeletal-frames in the nineteenth century, non-structural partition walls have provided another method. Yet, as observed in contemporary works of architecture, structure still subdivides space. In the analysis section, first buildings are considered where the interior structural arrangement within a single large volume produces several smaller spaces with similar functions. Further examples then illustrates how interior structure can be arranged to create spaces with different functions.

1.10.2 Expressive Circulations

Structure has long story in expressive circulation such as arcades and colonnades. Structure has capacity to bring order to a plan, and often functions as the backbone that unavoidably describes the major circulation route.

"By virtue of their physical presence, columns, walls or other structural members can literally and virtually restrict movement to along a single axis." (Charleson, A.W.2006).

Structure can also play less order roles by simply recommending a circulation route. These additional subtle roles are done by horizontal structure, such as beams, that display a directional quality.

1.10.3 Disordering Function

Irregularly, structure dislocates some feature of the function of a building. In a few cases an architect may cause this disruption pretty intentionally. (Charleson, A.W.2006). At the same time functional disordering is like a side-effect from medication, unwanted, but admitted as the cost of achieving a certain architectural objective.

There are two design strategies to achieve building functionality:

1. Derived from discovering and applying ‘critical functional dimensions’.
2. More general architectural approach.

The maximization of functional flexibility is addressed with indication to the ‘free plan’.-0[Illustration on how outside structures with different spatial relationships to their building envelopes allow the most flexible planning and usage of interior spaces.

Two groups of buildings demonstrate how structure also supplies to building function by subdividing space.

1. The spatial subdivision of a large volume allows similar functions to take place in each small space. Numerous buildings are famous for the variety of spatial experience and architectural qualities they offer.
2. Interior subdivision guides to a different space-use in each of the subdivided areas. Distinctive examples include the structure separating circulation from other spaces such as waiting areas and galleries.

Structural elements such as arcades and frames define or express the circulation which is a necessary function of any building.” Depending on numerous factors including structural spacing, scale, and materiality and detailing, structurally defined routes can be read and experienced very differently.” (Charleson, A.W.2006).for example, while one corridor displays silence, another expresses senses of simplicity and sadness, still if the physical incidence of structure is not enough strong to identify circulation, it can improve it by suggesting a sense of directionality.

Structure equally characterizes and limits the activities inside a building .the amount of detail with which this is attained depends upon the extent of the structure’s physical existence both in plan and section. Whether it is maximizing functional flexibility or interrupting it, subdividing space or articulating function, structure must be comprehensively combined both with the design concept and the functional necessities of the building.

CHAPTER 2

2.1 CASE STUDIES AND ANALYSIS

The studies here intend to investigate how certain criteria have affected the developments in architectural structures and spaces.

There are five recent projects chosen from well known architects for this chapter. Each of them will be analyzed according to the data that have been collected from the literature and the results will be concluded in the tables. For each of the case studies analysis has been done based on certain components and the table shows the relationship of this profile to one another.

2.1.1 Case selection

In order to get the best outcome from the case studies there was a need to select the cases appropriately. Therefore case selection is done according to Table 1.

Table 1: Generalized factors that are used for the selection of the case studies

Physical Qualities	Non-physical Qualities
Unusual Shape of Building Unusual Structural System New Material Large Scale	Costly Project Public Use Recent built Project(94-2005) Outstanding Architect

Physical qualities identify the visible qualities of the case studies, while the non physical looks at the intrinsic qualities of the cases. The case studies range from Museum, Recreation Centre, Science Centre and Terminal Station Projects.

The case studies for each type of architectural structures are selected in a way that the results can be generalized for any examples of the same architectural structure.

2.1.2 Analysis of case studies

The analysis of the case studies in this chapter is done in two stages; the first part of the analysis is based on descriptive research method,

a) Type of structure

b) Building type and synthesis of its exterior

c) Structure and architectural space relationship were described.

Second is the Vocabulary and Grammar method for architectural structure analysis, bringing out the structural qualities and making a comparison within each principle. A brief conclusion is made at the end of each table, stating what is learnt from the analysis. It mainly highlights the similarities of the case studies in each principle. For the vocabulary and grammar analysis the components are the outcome from synthesizing the structure and architectural form.

Table 2: Evaluation of the Eden Project 	**Case study one:** **The Eden Project** Location: St Austell. Cornwell England Architect: Nicholas Grimshaw & partners Created:1995-2001 Type of Structure: Conceptual Structure, Shell structure
BUILDING CONCEPT AND GENERAL INFORMATION	
Visitor attraction, including the world's largest greenhouse. The biomes demonstrate the degree of synthesis of forms possible with shell structures by the increasing structural depths of the biomes like this. Biomes interior structure consisting of outer primary hexagons and an inner layer of braced rods. Concept: a cluster of interlinked biomes.	
SYNTHESIS OF THE BUILDING EXTERIOR	
ENTRY(E):	There are signposted paths to the main entrance
MODULATIONS(M):	Structure modulates the whole facade
DEPTH AND (DT) TEXTURE:	Geometrical pattern, structural depth is associated with biomes
SCREENING AND (SF) FILTERING	Soften the façade (screening)
STRUCTURAL SCALE (SC):	Dimension of structure members are small
CONNECTING INETRIOR(CIE) TO EXTERIOR:	Interior structural system repeats on the exterior
EXPRESSIVE ROLE(ER):	Express the cluster of interlinked biomes

2.2 The Eden Project, England

The first concept was to create a giant glasshouse; it was quickly dropped because of the unstable site. The ultimate proposal fulfils the idea of structural engineer, Richard Buckminster Fuller, whose geodesic dome system expressed his mission to include the maximum volume within a minimal surface area, using the slightest material. (Cattermole, P.2007).

The source of inspiration in this complex is alienated into two major climate zones or 'biomes', it is specially selected to illustrate the range of plant life on earth: the warm and temperate regions [Californian, South African and Mediterranean] and the Humid tropics [tropical islands and rainforests].

Once the basic concept of interlocking geodesic domes and their overall sizes had been decided, the detailed designing was done using 3D computer modeling. The design was fed directly to the machine shop, where an automated production line computer controlled the accurate machining of all the components to exact size and specification. The same plant fabricated the nodes (drilled steel balls) used to join the sections together.

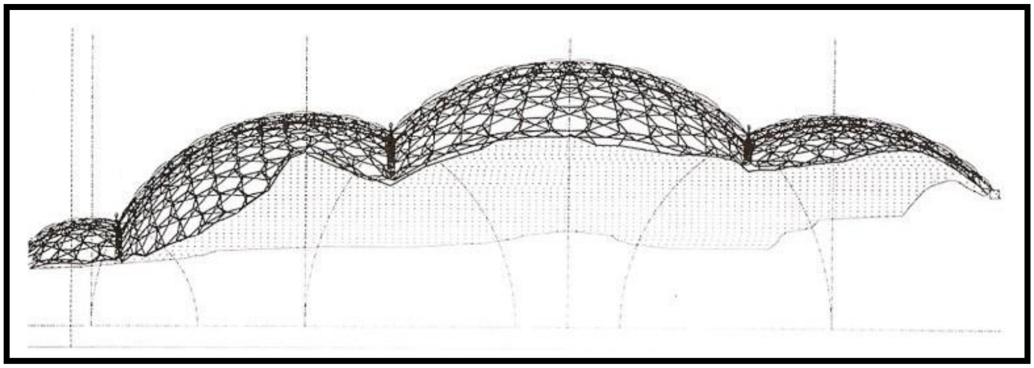
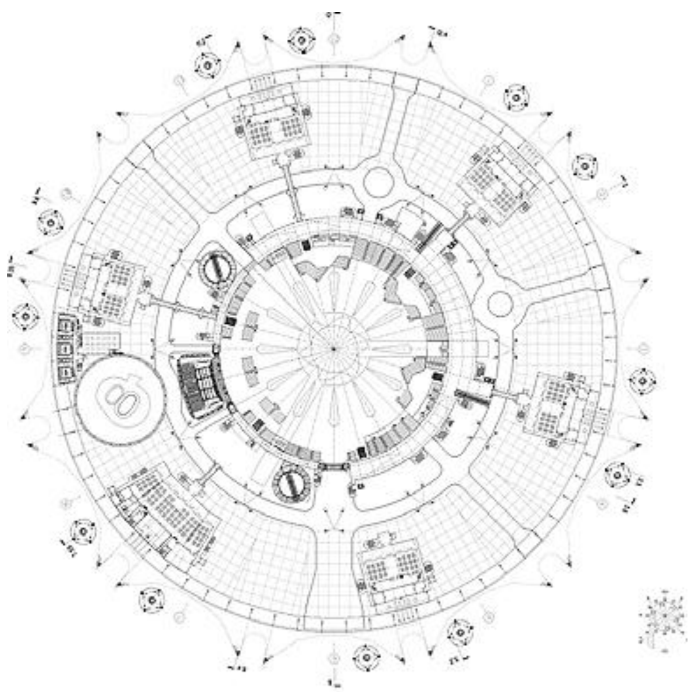


Figure 23: Section of the Eden project (source: http://en.wikiarquitectura.com)

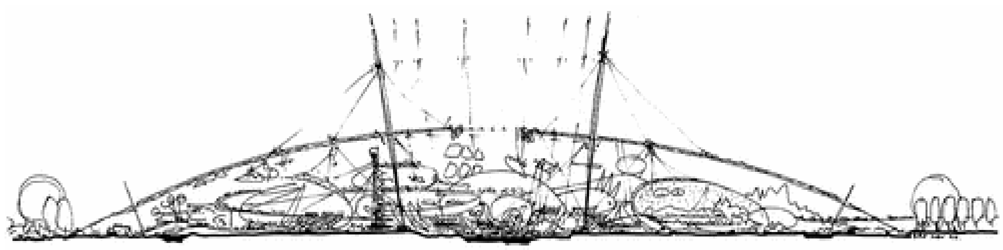
These are in fact huge structures, “the largest conservatories in the world”. The fundamental geometry of the biomes (**technical specification:** The biomes are essentially huge greenhouses) is base on enormous spheres, with their invisible projected centers all sharing the same frequent depth below ground level, following a forceful S-shaped line. The geodesic structures are made from steel. The panels are made from ethyltetrafluoroethylene (ETFE), a hi-tech transparent foil.

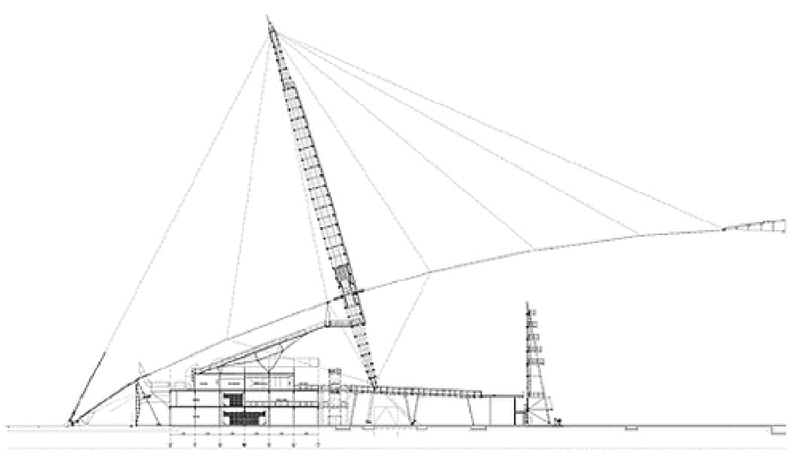
The biomes themselves are a model of sustainability, the ground water seepage used for irrigation and rainwater being recycled for humidification. (P.2007)

Table 3: Evaluation of the Millennium Dome 	**Case study two:** **Millennium Dome** Location: Greenwich, London England Architect: Richard Rogers Partnership Created:1996-98 Type of Structure: Mast Structure, Fabric covered Structure
BUILDING CONCEPT AND GENERAL INFORMATION	
A complex web of cables under tension hung off, yet more cables under tension. The whole building is effectively pulling itself out of the ground .with the twelve 100 m long cigar-shaped masts, each weighing 105 tons, suspended in the web of cables. Small wonder then, that the twenty-four reinforced concrete anchors around the circumference extend 24m into the ground Large enough to be noticeable from space and with its purity of form and straight logic of idea, the architecture of desire has never looked bigger, the dome's tent was the only cost-efficient structural answer that could face a suitably large area and still be competent of meeting the deadline.	
SYNTHESIS OF THE BUILDING EXTERIOR	
ENTRY	Circular columns signal the entry
MODULATIONS	Mast structure modulates the roof
DEPTH AND TEXTURE (DT)	Mast structure and membrane roof give two different textures to the building
SCREENING AND FILTERING.(SF)	Screening effect of mast structure on the roof
STRUCTURAL SCALE (SC)	Large scale structure
CONNECTING INETRIOR TO EXTERIOR (CIE)	Interior structural system repeats on the exterior
EXPRESSIVE ROLE(ER)	Expresses the strong sense of hanging.



a)





c)

Figure 24: a) Plan b) Section c) Zoom section (Source: http://architecture.about.com)

2.3 Millennium Dome Greenwich, London. England

"So much has been written in open hostility about the millennium Dome that it must be the most maligned structure in British architectural history." (Cattermole, P.2007).

Figure 25: Millennium Dome Entrance (Source: www.wikipedia.com)

The dome was a key model of a starship exclusive of a real captain at the bridge. According to the budget and time available, the dome's tent was the only cost-efficient structural answer that could face a suitably large area and still be competent of meeting the deadline.

Perhaps the biggest misnomer about the millennium dome is its name." Structurally speaking, it isn't a dome at all, as the canopy is not a ridged element, but a complex web of cables under tension hung off, yet more cables under tension. The whole building is effectively pulling itself out of the ground with the twelve 100 m long cigar-shaped masts, each weighing 105 tons, suspended in the web of cables. Small wonder then, that the twenty-four reinforced concrete anchors around the circumference extend 24m into the ground" (Cattermole,P.2007).

Figure 26: Detail of the structure of the mast (Source: www.arcspace, com)

Millennium dome is the largest fabric- covered structure in the world, large enough to be noticeable from space and with its purity of form and straight logic of idea; the architecture of desire has never looked bigger.

<table>
<tr><td>Table 4: Evaluation of the Guggenheim Museum
</td><td>Case study four:

Guggenheim Bilbao

Location: Bilbao, Spain
Architect: Frank Gehry
Created:1991-1997
Type of Structure: Free Form Structure</td></tr>
<tr><td colspan="2">BUILDING CONCEPT AND GENERAL INFORMATION</td></tr>
<tr><td colspan="2">Museum structure lies mainly hidden within its twisted sculptural forms. In several spots its sculptural steel structure is exposed the most visible one is at the tower. Simple triangulated steel frame work supports the geometrically complex skins. Structural details of nuts and bolts and standard steel sections are quiet simple comparative to the titanium clad three-dimensional curved surfaces.</td></tr>
<tr><td colspan="2">SYNTHESIS OF THE BUILDING EXTERIOR</td></tr>
<tr><td>ENTRY (E):</td><td>Glass and steel are used as the structure and they define the entry</td></tr>
<tr><td>MODULATIONS (M):</td><td>Structure modulates whole façade</td></tr>
<tr><td>DEPTHAND AND TEXTURE (DT):</td><td>Structure provides deep depth and rhythm</td></tr>
<tr><td>SCREENING AND FILTERING (SC):</td><td>Shining titanium cladding has a great texture</td></tr>
<tr><td>STRUCTURAL SCALE (SC):</td><td>Small scale structure</td></tr>
<tr><td>CONNECTING INETRIOR TO EXTERIOR (CIE):</td><td>Interior reflect the exterior. The fragmentation is also inside the building.</td></tr>
<tr><td>EXPRESSIVE ROLE(ER):</td><td>Irregularity and freestanding sculptural form is expressive</td></tr>
</table>

2.4 Guggenheim Museum, Bilbao, Spain

“Gehry in his studio transformed the energetic lines into hundreds, if not thousands, of models, created by folding, twisting and crumpling paper and card to create the apparently random forms that crystallized to become a building.” (Cattermole, P.2007).

A quantum jump in building design was only made possible by the wide utilize of CAITA, a French computer program borrowed from the aviation industry that had earlier been used to design the mirage jet fighter and the Boeing 777.

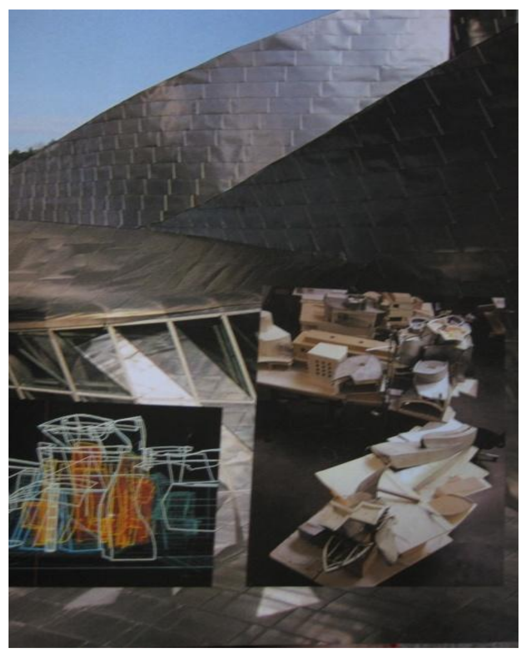


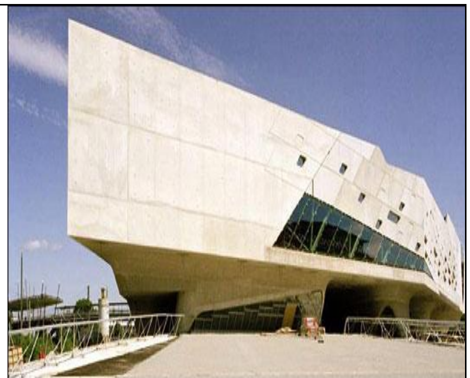
Figure 27: Interior of the Guggenheim Museum (Source: www.arcspace.com)
Figure 28: Design process of the Guggenheim Museum (Source: www.arcspace.com)

The models were translated into the virtual world by means of a laser that scanned and digitized their curves, turning them into three-dimensional computer models that could be scaled up to full size.

Figure 29: Atrium with primary, three-meter structural grid (Source: www.arch.ethz.ch)
Figure 30: Horizontally-curved structure (Source:www.arch.ethz.ch)

The fundamental structure is shaped from steel I-section beams that are used to construct a grid of sections approximately 3 m square. The sections were bolted, before welded together, as the holes could be pre-drilled to a supreme degree of exactness.

The building was divided into contoured layers and the numbered sections brought to the site for get-together, like a massive Meccano set. A projecting cover of curved steel tubes attached to the I-beam skeleton smoothed its faceted edges into elegant forms .to these contours were set vertical steel bars and above the bars, last layer of overlapping titanium sheets , held by stainless-steel crews, shaped the building's glittering skin. Gehry's innovative design leads the world's most famous signature building.

Table 5: Evaluation of the Phaeno Science Centre 	**Case study four:** **Phaeno Science Centre** Location: Wolfsburg, Germany Architect: Zaha Hadid Created:2000-5 Type of Structure: Free Form Structure
BUILDING CONCEPT AND GENERAL INFORMATION	
Science museum that could introduce the next generation with a aspiration of scientific exploration. Pure structure open plan, visual weight of the ceiling is intentionally increased by using its touching perspective lines to highlight the gigantic interiors.	
SYNTHESIS OF THE BUILDING EXTERIOR	
ENTRY	Defined by the canopy
MODULATIONS	Structure is selectively exposed
DEPTH AND TEXTURE	Gently curving wall possesses an attractive softness and naturalness
SCREENING AND FILTERING	Soften the façade (screening)
STRUCTURAL SCALE (SC)	Small scale
CONNECTING INETRIOR TO EXTERIOR	Interior structural system repeats on the exterior
EXPRESSIVE ROLE(ER)	The dynamic form is expressing the design process

2.5 Phaeno Science Center, Wolfsburg, Germany

Zaha Hadid statement about Phaeno Science Center:

"To create an urban field on the ground, with an object above, was a rare opportunity for us." (Schumacher, p. 2002)

Wolfsburg was built in 1983 for the state reason of housing the workers required to produce the Volkswagen, the 'people's car' that Hitler hoped would crowd the autobahns of Germany. The Phaeno Science Center Wolfsburg is a building that architecturally, geometrically and structurally pushes the boundaries of imagination regarding its design development and construction process. It is a reinforced concrete structure topped by a steel roof structure. Parts of the reinforced concrete structure could only be realized using a recently developed kind of self-compacting concrete. This required extensive testing of structural elements at the University of Brunswick. The exhibition building floats 7 m above street level. It rests on ten irregularly scattered room-sized objects that resemble inverted cones. The floor-slabs, spanning up to 22 m with a structural depth of 0.9 m, consist of a girder grillage with two sets of girders intersecting at an oblique angle. The steel roof structure is a girder grillage with two sets of girders intersecting at an oblique angle as well. The girders of each set do not run parallel to each other, they radiate like the fingers of a spread hand. The roof level does not continuously remain at the same plane but jumps to different heights. Maximum span is 35 m with a structural depth of 2.0 m.. The building is an extreme example for the prominent and vital role that structural engineers play in projects like these Parts of the reinforced concrete structure could only be realized using a recently developed kind of self-compacting concrete.(B.Tokaz.2007).

Wolfsburg has begun a search for a new identity in recognition, staging an international competition to design a science museum that could introduce the next generation with a aspiration of scientific exploration. (Cattermole, P.2007).

The project title was a Greek word Phaeno which means ‘cast light upon’ or to ‘discover’, was chosen for the project to express the of engaging sense of wonder.
A futuristic vision was found in Zaha Hadid’s project, she addressed the topography of the site, and the freely triangular plan is determined by the connection of road and rail links.

Hadid created additional space underneath by elevating the building on its irregular feet, like concrete vortexes sucked down from the floor slab above. It was an unexpected bonus that attracted the judges in the design competition. Hadid’s vision for this was to create a focal point for the local residents, a public room, a mock landscape under fluorescent stars.

The extensive use of self-compacting concrete [SCC] was made in the building. SCC has an ad-mixture of super plasticizer and chemical addition that improves the material’s flow qualities and allows it to be poured directly into composite form work.

In the façade of Phaeno the use of both SCC and pre-cast vibrated concrete can be seen clearly. There is a contrast between the hard edges of the slab sided walls and the curved underbelly of the floor slab upon which they rest.

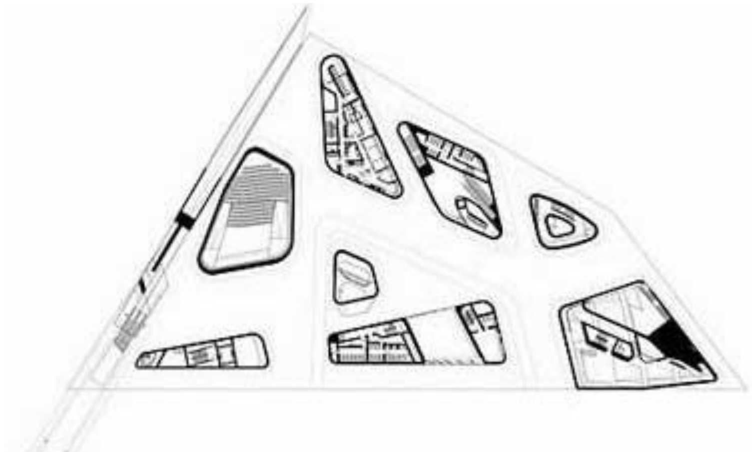
Figure 31: Interior of the Phaeno Centre (Source: www.arcspace.com)

The shafts are not solid structures, but settled by access points, cafes and shops, as well as the more ordinary building services. Six shafts support the weight of the floor though the remaining four extend upwards to support the roof .the grid is non-symmetrical and it is made of 4,700 different steel elements cut by CNC machinery and arranged above the main space, leaving it neat and open plan. The visual weight of the ceiling is intentionally increased by using its touching perspective lines to highlight the gigantic interiors, beyond pure structural necessity.


Figure 32: Main Entrance Hall of the Phaeno Central (Source: www.arcspace.com)

The rolling floor, like a dream cast in poured resin, makes for unreal moonscape even more innocent than the concrete plaza outside, with areas being defined not by static walls but by flowing ramps, hills and holes, at some points made friendlier by changes in ceiling height formed by the waves in the steel grid.

In Phaeno Hadid demonetarizes her theories on grand scale and create a landmark building that is combination of architecture and sculpture. Phaeno is the largest building constructed from "self-compacting concrete" (SCC) to date in Europe. Without this new type of concrete the diverse forms of Phaeno would have been difficult to achieve.



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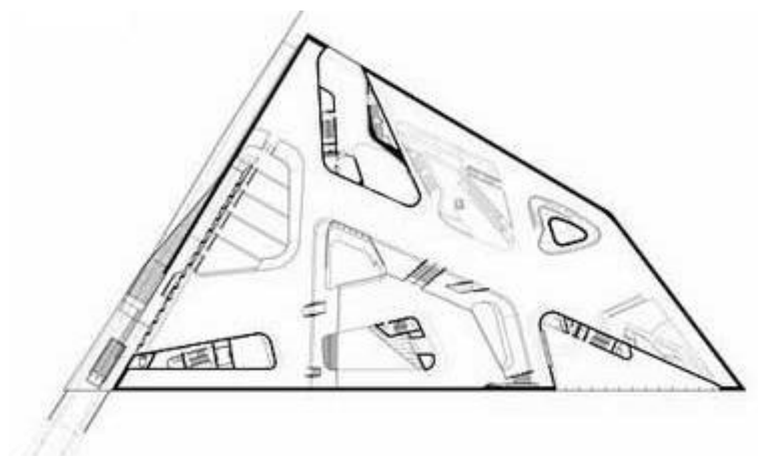

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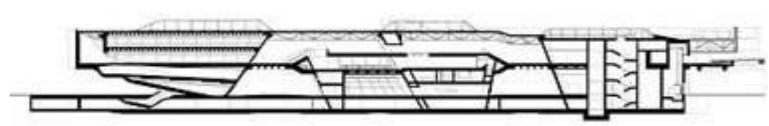


c)

Figure 33: a)Ground plan b)First floor c)Section drawing of Phaeno Science Center (Source:www.arcspace.com)

Table 6: Evaluation of the Lyons TGV Station	**Case study five:**
	**Lyons Satolas TGV Station** Location: Lyon-France Architect: Santiago Calatrava Created:1989-1994 Type of Structure: Conceptual Structure

BUILDING CONCEPT AND GENERAL INFORMATION

Created of three extensive steel arches, 120m long and 40 m tall at their maximum point, with the middle arch having a triangular section that generates the backbone. This is connected to the outer tubular steel arches by crossways bracing that forms a series of diamond-shaped glazed openings that admit natural light into the interior. Cambering the beams and the ‘sloping columns’ visually lighten the interior.

Concept: a balanced shape resembling a bird at the point of flight.

SYNTHESIS OF THE BUILDING EXTERIOR

ENTRY	Structure articulates entry
MODULATIONS	Structure modulates the whole facade
DEPTHAND TEXTURE	Structure provides deep depth , rhythm
SCREENING AND FILTERING	Structure functioning as a screen
STRUCTURAL SCALE	Large scale structure
CONNECTING INETRIOR TO EXTERIOR	Interior structural system repeats on the exterior
EXPRESSIVE ROLE(ER)	The structure of the building expresses the symmetry and skeletal form

2.6 Lyon Satolas TGV Station, Lyon, France

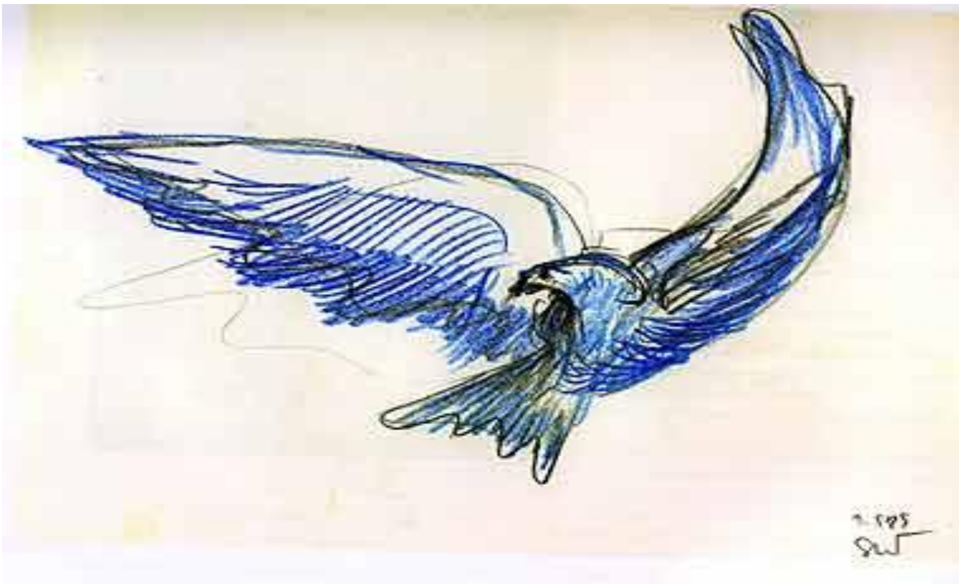


Figure 34: Showing the significance of Calatravas's artistic work as the basis of his Architectural design (source: http://www.arcspace.com)

"There can be little disagreement about Santiago Calatrava being an architect with the 'wow' factor". (Cattermole, P.2007). He is an outstanding civil engineer with an artistic talent, who has developed an international character for landmark building. The city of Lyons started on a competition for a design of a new TGV terminal to connect the rail and road networks to the Lyons-Satolas Airport with the plan of creating a 'Grande' statement, a triumphal entry for visitors landing on French soil. His concept was his own studies in sculpture and the human form, mainly the eye, making reference to our anatomy is a general idea to his work.

Figure 35: Detail structure elements inside the interior space (source: www.arcspace.com)

The size of the station has been built below ground in eagerness that a runway extension would have to be related to the site, leaving the bird-like head of the ticket hall to dominate the landscape. This hall is created of three extensive steel arches, 120m long and 40 m tall at their maximum point, with the middle arch having a triangular section that generates the backbone. This is connected to the Outer tubular steel arches by crossways bracing that forms a series of diamond Shaped glazed openings that admit natural light into the interior.

Figure 36: Interior of the terminal (source: www.arcspace.com)

Calatrava has created an example of how a building can become a work of sculptural magnificence. The structure has all the essential characters to be considered High-Tech sculpture.

2.7 Vocabulary and Grammar Method for Architectural Structures

As stated earlier the second stage of analysis in this thesis is vocabulary and grammar technique. It is used to analyze complex phenomena in analogy to the very complex structure of language. It is rather an old method for the study of language structures.

> *"By the method of vocabulary and grammar, the former comprising the primitives, whether noun or verb ranked in their several classes, the later teaching the forms of declension and conjugation with all possible plainness: to which is added the Harmonicon, viz. a table of those Latine words, which their sound and signification being nearly resembled by the English, are the sooner learned thereby"* (Groad, 1681)

As it mentioned above this analysis method mainly used for Language studies but the method can be applied to any other analysis as well. This analysis aims to provide an insightful table and detailed analysis on the structural components of each case study; each case study will be testified with the components of the synthesis of architectural structures.

In Table 6 the results of components of synthesis and the case studies are written randomly so arrows are used to define the relationship between them. Arrows connecting the each case study to the related component and it continues till the end of the table so by following the arrow from the top to the bottom we can read the results in Table 7. Results are written in organized manner and use of abbreviation helps to write shorter sentences.

This subchapter will report the results of analyzing these five architectural structures by this method.

What can be understood from this analysis is that:

1. Fundamental factors, which include syntheses of architectural structures and variants (case studies), are defined as vocabularies.

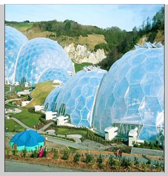
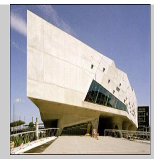
2. The relationship between variants (case studies) and components of architectural structure will form the grammar.

This analysis technique helps to have better understanding from the case studies and the concept of the developments of architectural structures within each case study.

Table 7: The case studies and results of the synthesis of the building exterior are written randomly and arrows are connecting them together.

VARIENTS / COMPONENTS	BILBAO V3	PHAENO CENTRE V4	LYONS STATION V5	EDEN PROJECT VI	MILLENIUM DOME V2
ENTRY (E	Signposted paths to the main entrance E1	Circular columns signal entry E2	Defined by the canopy E4	Glass and steel entrance structure E3	Structure articulates entry E5
MODULATIONS (M)	Structure modulates whole façade M1	Mast structures modulates the roof M2	Structure Selectively exposed M4	Structure mainly hidden M3	Structure modulates whole façade M5
DEPTH AND (DT) TEXTURE	Geometrical pattern ,structural depth is associated with biomes DT1	Mast structures and membrane roof gives two different textures to the building DT2	Gently curving wall possesses an attractive softness and naturalness DT4	Shining titanium cladding has a great texture DT3	Structure provide deep depth, rhythm DT5
SCREENING AND (SF) FILTERING	Soften the façade screening SF1	Screening effect of mast structure on the roof SF2	Soften the façade screening SF4	Soften the façade screening SF3	Structure functioning as a screen SF5
STRUCTURAL SCALE (SC)	`Small scale dimension of structure members SC1	Large scale structure SC5	Small scale SC3	Small scale SC4	Large scale structure SC2
CONNECTING INETRIOR(CIE) TO EXTERIOR	Interior structural system repeats on the exterior CIE4				
EXPRESSIVE ROLE(ER)	Express the A cluster of interlinked biomes ER1	Express the strong sense of hanging ER2	The dynamic form is expressing the design process ER3	The irregular and scultural form is expressive ER4	Express the symmetry and human form ER5

Table 8: Results of the Vocabulary and Grammar, the abbreviation is used to shorten the results

VARIENTS ***Components***	 V1	 V2	 V3	 V4	 V5
ENTRY (E)	**Signposted paths to the main entrance E1**	**Circular columns signal entry E2**	**Glass and steel entrance structure E3**	**Defined by the canopy E4**	**Structure articulates entry E5**
MODULATIONS (M)	**Structure modulates whole façade M1**	**Mast structures modulates the roof M2**	**Structure mainly hidden M3**	**Structure mainly hidden M4**	**Structure modulates whole façade M5**
DEPTH AND TEXTURE (DT)	**Geometrical pattern ,structural depth is associated with biomes DT1**	**Mast structures and membrane roof gives two different textures to the building DT2**	**Shining titanium cladding has a great texture DT3**	**Gently curving wall possesses an attractive softness and naturalness DT4**	**Structure provide deep depth, rhythm DT5**
SCREENING AND FILTERING (SF)	**Soften the façade screening SF1**	**Screening effect of mast structure on the roof SF2**	**Soften the façade screening SF3**	**Soften the façade screening SF4**	**Structure functioning as a screen SF5**
STRUCTURAL SCALE (SC)	**Small scale dimension of structure members SC1**	**Large scale structure SC2**	**Small scale SC3,SC4**		**Large scale structure SC5**
CONNECTING INETRIOR TO EXTERIOR (CIE)	**Interior structural system repeats on the exterior CIE1, CIE2, CIE3, CIE4,CIE5**				
EXPRESSIVE ROLE (ER)	**Express the cluster of interlinked biomes ER1**	**Express the strong sense of hanging ER2**	**The irregular and sculptural form is expressiveER3**	**The dynamic form is expressing the design process ER4**	**Express the symmetry and human form ER5**

2.8 Findings and conclusions from the tables

According to the (table7) Determination of grammar is written with abbreviation and the results are as below:

V1: In the first variant (the Eden project) the results are as below,

E1: In Eden project the entry is defined by the signposted paths.

M1: structure modulates the whole façade,

DTI: Geometrical pattern, structural depth is associated with biomes.

SF1: Soften the façade screening.

SC1: Small scale dimension of structure members.

C1E1: Interior structural system repeats on the exterior.

ER1: Express the cluster of interlinked biomes.

V2: In the second variant (Millennium Dome) the results are as below:

E2**:** Circular columns signal the entry.

M2: Mast structure modulates the roof.

DT2: Mast structure and membrane roof give two different textures to the building.

SF2: Screening effect of mast structure on the roof.

S2: Large scale structure.

CIE2: Interior structural system repeats on the exterior.

ER2: Expresses the strong sense of hanging.

V3: In the third variant (Guggenheim Museum) the results are as below:

E3: Glass and steel are used as the structure and they define the entry.

M3: Structure modulates whole façade.

DT3: Structure provides deep depth, rhythm.

T3: Shining titanium cladding has a great texture.

S3: Small scale structure.

CIE3: Interior reflects the exterior. The fragmentation is also inside the building.

ER3: Irregularity and freestanding sculptural form is expressive.

V4: In the fourth variant (Phaeno Science Center) the results are as below:

E4: Entry Defined by the canopy.

M4: Structure is selectively exposed.

DT4: Gently curving wall possesses an attractive softness and naturalness.

SF4: Soften the façade (screening).

S4: Small scale structure.

CIE4: Interior structural system repeats on the exterior.

ER4: The dynamic form is expressing the design process.

V5: In the fourth variant (TGV Terminal Station) the results are as below:

E5: Structure articulates entry.

M5: Structure modulates the whole façade.

DT5: Structure provides deep depth, rhythm.

SF5: Structure functioning as a screen.

S5: Large scale structure.

CIE5: Interior structural system repeats on the exterior.

ER5: The structure of the building expresses the symmetry and skeletal form.

There are some similarities with these different buildings; SC: Structural Scale is the same in V3, V4 (Guggenheim Museum, Phaeno Science Center) both have free-form structure.

All five case studies share one common similarity, structure connects the exterior to their interior. In table9 this results and the development in architectural structures is fully explored and the comparison chart (table 12) for the result of table 9 is drawn.

Table 9: Comparison of Evaluated Cases

Table 10:

Table 10: Results for the evaluation table

Table 11:guiding table for the evaluation chart

Table 12: comparison chart of the evaluated cases

Table 13: 3D Pie percentage charts of the evaluated cases

Table 14 classification of architectural structures and related structural systems in terms of load transfer sequence.

CHAPTER 3

3.1 FINDINGS AND CONCLUSION

The thesis so far has reviewed the developments in architectural structures, their effects on the architectural spaces and has suggested the architectural structure as integration of interior to the exterior of the building. These architectural structures play a major role in the both the physical and nonphysical aspects of design. Ignorance of structural issues in the determination of the form of a building can be problematic.

The enthusiasm of the architects to develop new sculptural forms in architecture by moving towards the principle of ‘total design,’ the integration of design and construction processes the developments in architectural structures.

In the evolution of the free-form architecture which became fashionable in the late twentieth century. It was the structural techniques which were developed and made such architecture possible, and gave architects the freedom to take advantage of geometries which in previous centuries would have been without a solution to comprehend. On the other hand without new technologies it would be impossible to create new buildings and architecture took a great benefit from the new technologies in design.

The above conforms to the aim of this thesis which is to formulate a general outline for the success of architectural structure design.

Among the objectives of this thesis was to find a developments in architectural structure and the role it plays towards better architectural structural design. What we need to understand are the developments in architectural structure. The main idea here is to restate the importance of learning from the principles of these three architectural structures. In chapter one, the principles of architectural structures are explained and case studies are selected accordingly.

Architectural structure is a unique way of design; its exclusivity lies in ability to reveal changes in people's cultures and lifestyles or reflection in technological innovation. The fact is nothing is impossible with new architectural structures.

Millennium Dome belongs to Mast structure group, In this case Mast structures modulates the roof and expresses the strong sense of hanging, Mast structures and the membrane roof gives two different textures to the building .the building in general has a mechanical vision.

The Eden Garden and Lyons Satolas Tgu Station both belong to the conceptual structure group. As the result of analysis in chapter 2 both the chemical compounds and skeleton structures are the concept of the structure. Both of them have wide interior spaces and the exterior is connected to the interior as a result of architectural structure.

The structure is screening the whole façade creating the building envelope; the biomes are texturing the Eden garden as the ribbed structures are texture for the Lyon station. There is rhythm and expressive role in their structural system.

Biome express the cluster of interlinked biomes and Lyon station express the symmetry and human form very well.

With the developments in construction techniques and innovation in building material the buildings became more dynamic, a quantum jump in building design was only made possible by the wide utilization of CAITA, a French computer program borrowed from the aviation industry that had earlier been used to design the mirage jet fighter and the Boeing 777.

Phaeno is the largest building constructed from "self-compacting concrete" (SCC) to date in Europe. Without this new type of concrete the diverse forms of Phaeno would have been difficult to achieve.

The Guggenheim Museum and Phaeno Science Center both belong to the Free-form structure group; sculptural attitude is a main feature for these kinds of architectural structures. The innovation in techniques and material was a key to these new architectural structures. Modulation differs relating to the design, In Guggenheim Museum is selectively exposed, but in Phaeno Science Centre the structure is hidden. Gently curving wall possesses an attractive softness and naturalness to the texture of Phaeno Science Centre same as shining titanium cladding texturing to the

Guggenheim Museum. Both building are having small scale structure achieved through the new structural techniques, the dynamism in Phaeno Centre and irregularities in the form are expressed with the architectural structures.

The four concepts (dynamic expression, screening, modulation and structural expression) have developed towards these three types of architectural structures.

- It can be stated that in mast structure the structure is dominant part in the overall shape of the building and eventually structural scale is larger.
- The innovation in materials such as SCC with high elasticity enabled designers to create more sculptural dynamic looking buildings.
- Representation is used in mast structure as well as the conceptual structure.
- In free-form structure the designer had more freedom rather than taking pattern from nature, so the architect had an opportunity to design more symbolic buildings.

All the above mentioned case studies show the developments in architectural structures, turns the images into real projects. It can be concluded from the case studies that there were developments in architectural structures, these developments are visible in buildings envelop. Started from mast structures with mechanical vision developed by conceptual structure, the image of the building has been softened with natural concepts. Finally with innovation in techniques and material, gives dynamism to sculptural buildings.

3.2 Recommendation and Further Study

Although the study was done on three different types of Architectural Structures to obtain a comparison and developments between them, focusing only on one type of Architectural Structure might be constructive in providing a detail framework readily usable for that type of architectural structure .Focusing only on one type of Architectural Structure as a subject of research would be more attentive in sense of new material and construction techniques..

The world of technology is full of innovation and surprises, hope that with an innovative techniques and materials other kind of comprehensive and successful architectural structures be involved in the future researches. It also recommended that the further study would be consideration of the developments of window as a component of façade in Architectural Structures. This would be a detail consideration of development of non structural element in Architectural Structures both from visual perspective and as an element of façade, contributing to new design.

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Development in Architectural Spaces

Table 9：Comparison of Evaluated Cases

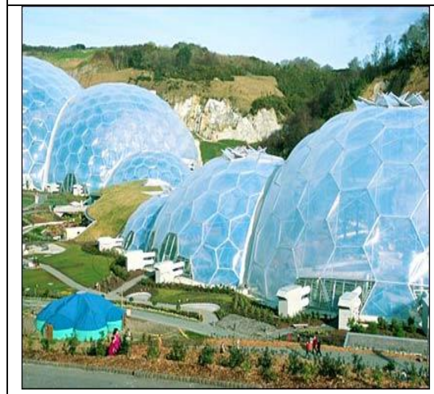
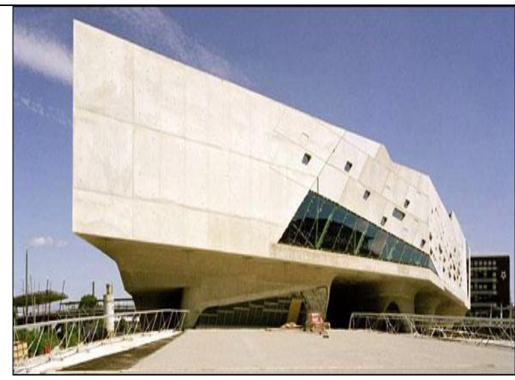
				
Design Approach				
Conceptual Structure Case one: The Eden Project	**Mast Structure** Case two:millenium dome	**Free-Form Structure** Case three:Guggenheim Museum	**`Free-Form Structure** Case Four:Phaeno Science Centre	**Conceptual Structure** Case Five: TGV Station
Characteristics				
• There are signposted paths to the main entrance • Structure modulates the whole façade • Geometrical pattern, structural depth is associated with biomes • Soften the façade (screening) • Dimension of structure members are small • Interior structural system repeats on the exterior • Express the cluster of interlinked biomes • **Representation**(natural world) • (chemical compounds)	• Circular columns signal the entry • Mast structure modulates the roof • Mast structure and membrane roof give two different textures to the building • Screening effect of mast structure on the roof • Large scale structure • Interior structural system repeats on the exterior • Expresses the strong sense of hanging • **Representation**(artifacts) • (Space craft)	• Structure modulates whole façade • Structure provides deep depth , rhythm • Shining titanium cladding has a great texture • small scale structure • Interior reflect the exterior. The fragmentation is also inside the building • Irregularity and freestanding sculptural form is expressive • **Symbolism** • (random crystallized forms)	• Entry Defined by the canopy • Structure is selectively exposed • Gently curving wall possesses an attractive softness and naturalness • Soften the façade (screening) • Small scale • Interior structural system repeats on the exterior • The dynamic form is expressing the design process • **Symbolism** • (aspiration of scientific exploration)Glass and steel are used as the structure and they define the entry	• Structure articulates entry • Structure modulates the whole façade • Structure provides deep depth , rhythm • Structure functioning as a screen • Large scale structure • Interior structural system repeats on the exterior • The structure of the building expresses the symmetry and skeletal form • **Representation**(natural world) • (Bird at the point of fly)

Table 10: Results for the evaluation table

	Depth & Texture	Structural Scale	Symbolism	Representation	Dynamic Expression	Screening & Filtering	Modulation	Structural Expression
Mast Structure	**Low**	**Large**	○	✓	**Low**	**Low**	**Low**	**Low**
Conceptual Structure	**High**	**Medium**	○	✓	**Medium**	**Medium**	**Medium**	**Medium**
Free-Form Structure	**Medium**	**Small**	✓	○	**High**	**High**	**High**	**High**

Table 10: results from the chart

From the table above it can be stated that:

- ○ The four concepts (dynamic expression, screening, modulation and structural expression) have developed more than the other concepts.
- ○ In mast structure the structure is dominant part in the overall shape of the building and eventually structural scale is larger.
- ○ The innovation in materials such as SCC with high elasticity enabled designers to create more sculptural and dynamic looking buildings.
- ○ In general it can be stated that architectural structure development clearly changed From the **mast structure** with straight furious masts to **Conceptual structure** with softer Image By using the concept of nature and finally with innovations in materials and construction technique in **free-form structure**.
- ○ Developments in three concepts (Dynamic Expression, Screening and Modulation) are due to the innovation of new materials and techniques
- ○ Representation is used in mast structure as well as the conceptual structure.
- ○ In free-form structure the designer had more freedom rather than taking pattern from nature and artifacts, so the architect had an opportunity to design more symbolic buildings.

Table 11: guiding table for the evaluation chart

	Depth & Texture	**Structural Scale**	**Symbolism**	**Representation**	**Dynamic Expression**	**Screening & Filtering**	**Modulation**	**Structural Expression**
Mast Structure	**Low (1)**	**Large (3)**	○ **(0)**	✓ **(1)**	**Low (1)**	**Low(1)**	**low (1)**	**Low(1)**
Conceptual Structure	**High (3)**	**Medium(2)**	○ **(0)**	✓ **(1)**	**Medium(2)**	**Medium(2)**	**Medium(2)**	**Medium(2)**
Free-Form Structure	**Medium (2)**	**Small (1)**	✓ **(1)**	○ **(0)**	**High(3)**	**High(3)**	**High(3)**	**High(3)**

Table 10: results from the chart

To be able to draw a chart from the table above, results are converted to numbers such as:

Low: (1), Medium: (2), High: (3) Small: (1), Medium: (2), Large: (3)

With these data's we can draw a comparable chart and the three different architectural structures are shown with three vertical axes in

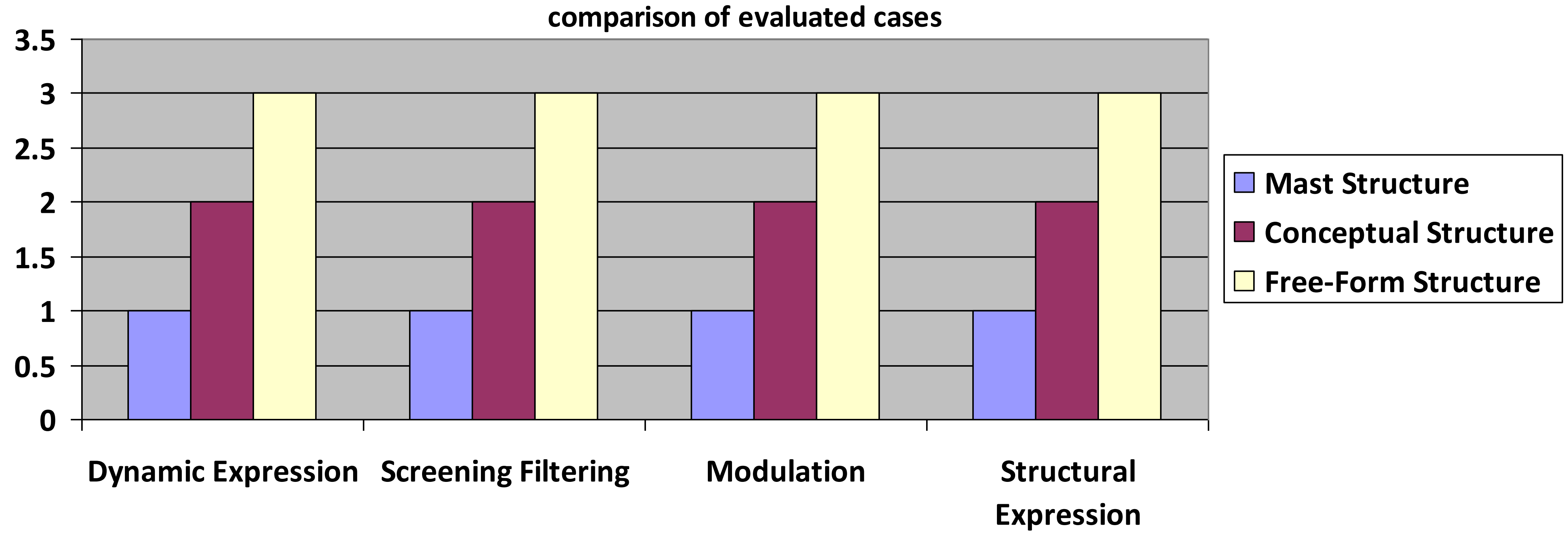
Three Different colors.

For example in the first chart from left Dynamic expression in architectural structure is equal to 3, conceptual structure is equal to 2

And in mast structure is equal to 1.

At the end the 3D pies are drawn to evaluate the percentage of the mentioned concepts in three different architectural structures.

Table 12: Comparison chart of the evaluated cases



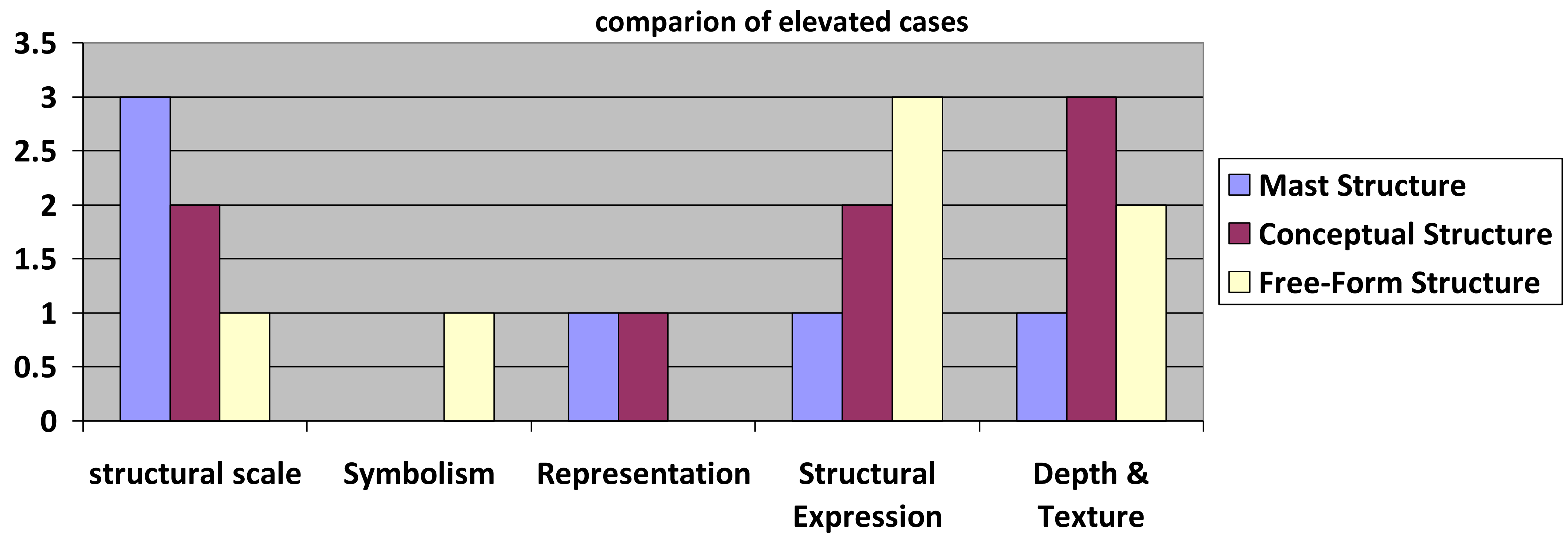
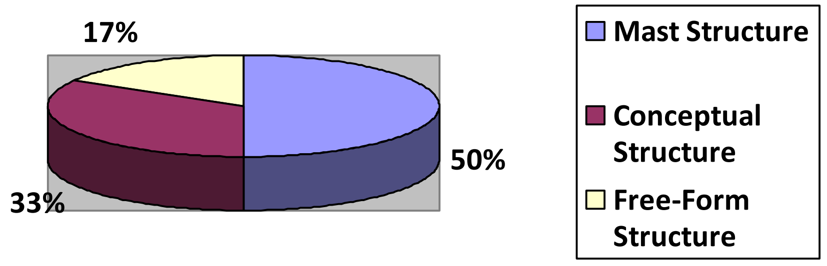
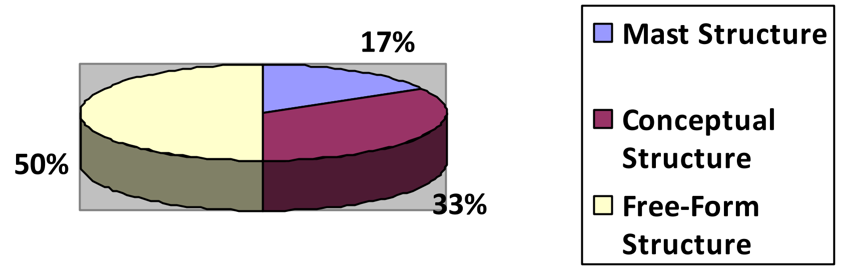


Table 13: 3D Pie percentage charts of the evaluated cases

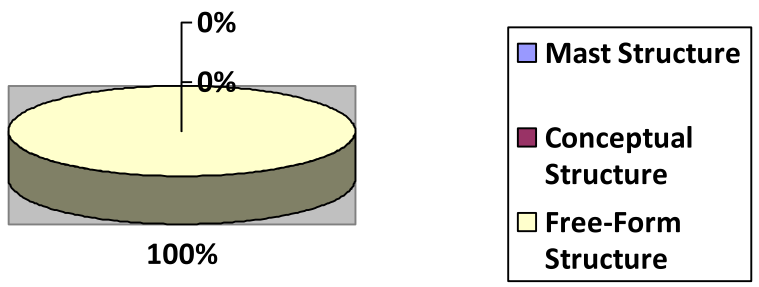
Structural scale evaluation chart



Percentage of the four concepts above.



Percentage of Symbolism evaluation in different architectural structures



Percentage of Representation in architectural structures

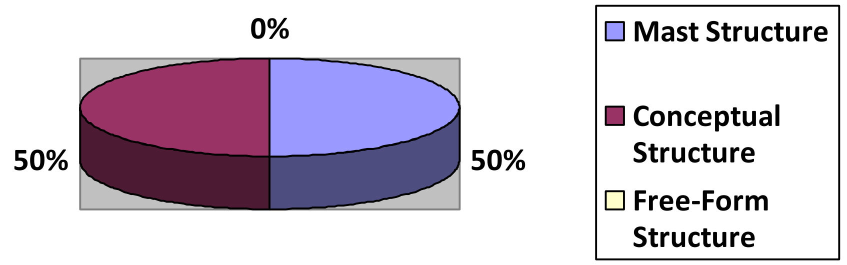


Table 14: Classification of Architectural Structures and elated structural systems in terms of load transfer sequence.