Design in Nature and Architecture

By

Dina Kasim Al Hussaini, B.Arch.

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Abstract

Structures and forms found in nature have evolved over billions of years and only the most structurally adaptable forms have survived. Their resourcefulness in utilizing material, innovative structural systems and their optimum response to a variety of climatic and environmental forces has made nature's evolving structures and forms inspiring exemplars for design.

This thesis focuses on structures and forms existing in nature that have and continue to serve as inspirational tools for man-made architecture. Examples such as the natural design and composition of the underside veins of a lily leaf and the outer and inner composition of bones and cells, all contribute to inspire architects to understand the principles that lead to strong, economic, efficient and elegant structural solutions in architecture.

Architectural feats such as the Crystal Palace constructed for the great exhibition of 1851, Eden project in Cornwall, England (completed in 2001) and the Museum of Science in Valencia, Spain (2001), are all examples reflective of architecture inspired by the structural principles that are common in nature and that became an integral part of man-made structural forms.

With the proposed design of the Museum of Nature along with accompanying research on the significance of natural forms for understanding architectural structures, this thesis argues that nature continues to be a relevant and appropriate inspirational medium for designing buildings that share structural principles common to both.

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Introduction

There is an upsurge in interest in forms that are derived from the physical characteristics of structures and forms found in nature, spurred on by modern science in general, and in the biological sciences in particular. As science sees further into the microscopic world of matter and uncovers more about the remarkable structures of living things, nature continues to surprise us and teach us how to build cleverly, economically, and subtly. In the animal, plant and mineral kingdoms, structures and forms help us to understand the basics of structural concepts, which can be, without doubt, the backbone for constructive design expressions within architecture.

Man –made architecture is a form of art that goes back to the origins, to nature itself. The meaning of the word is derived from the Greek, archi, meaning "first" or "original"; and tect, meaning the ability to put things together. It also implies the creation from the origins of nature, by putting things together in ways that express an understanding of nature's designs and its principles. In this, the natural expression of originality proceeds from the origins. Consequently, as architects, it is advantageous to acquire a general knowledge of the structural principles of nature that are common to architecture. The aesthetic, expressive and the technical aspects are frequently at odds with each other, yet an architect who is able to integrate the two may be more likely to create forms that satisfy the expressive and physical side of architecture. The physical nature and conception of architectural expression, and the structural principles of nature are inspirational tools towards form conception, it also contributes to inform and define this scope of study.

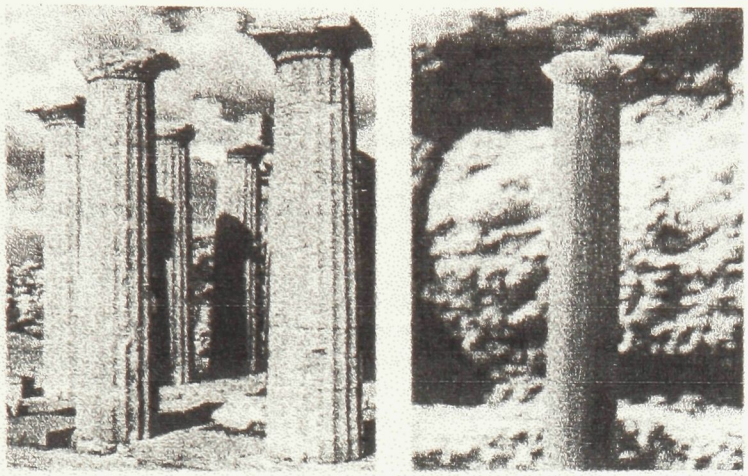


Figure 1 Structural principles common to both nature and architecture, here the stem of the forest angelica (native of Greece) plant has a base wider than the crown. (From Hersey's "The Monumental Impulse" 28)

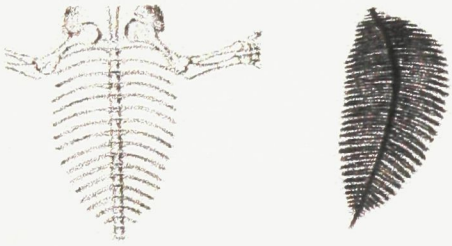
From the structural viewpoint, the master builders of antiquity rarely had a thorough knowledge of theoretical precepts in their architecture (see figure1). They relied on empirical intuition about the structural fundamentals of pure physics. In this way it was, possible to perceive how columns of a building must be wider at the bottom than at the top, because they support the accumulated weight of all the floors of the structure, or how an arch functions. One needs to have a structural design strategy in order to make calculations to determine the form and proportions of the structure and that requires imagination, intuition, experience and knowledge. With only a little theoretical knowledge, one can still know that a corbel supporting a balcony is well designed if the slope decreases the further it is away from the supporting structure (i.e. wall or column).

Structural expression in architecture represents one of many aspects of human creativity and cannot be imagined without a profound respect for natural laws. This can be seen in the construction of buildings or bridges with large spans or gaps, where structure is expressed like the spinal column. Robert Maillart, as Matilda McQuaid points out, was "*one of the first engineers of this century to break completely from masonry construction and apply a*

technically appropriate and elegant solution to reinforced concrete construction" [1]. His bridges, based on a simple but clear idea, are examples of engineering executed with common sense, and their shapes are characterized by economy in construction. Maillart is important in refining and reintroducing engineering and aesthetic beauty. His work is found principally in the remote valleys of the Swiss alps, linking areas separated by large chasms. (See figure 2).

Figure 2 Mailarts design for a bridge in the Swiss alps

Later, the works of modern engineers and architects reflected a continuation of this integration between engineering and architecture initiated by Maillart. Architects such as Eduardo Torroja, and Felix Candela, Frei Otto, Eero Saarinen (see figure 3), Pier Luigi Nervi and Santiago Calatrava derived their work equally from aesthetic choices, creative imagination, and science.



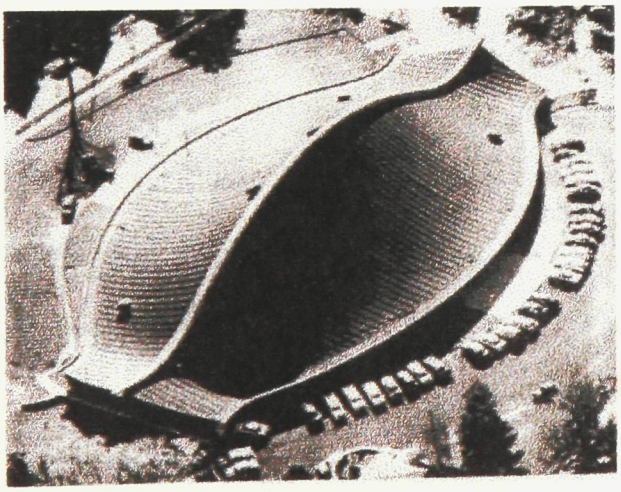


Figure 3 The antenna of the insect and part of the reptile Captorhinus as possible analogy is presented by Hersey for the structure of Saarinen's Ingalls Hockey Rink in 1957. (From Hersey's Monumental Impulse") 38

Hersey's comparison is incorrect and somewhat superficial as it omits structurally significant characteristics, namely, possessing dissimilar boundary conditions.

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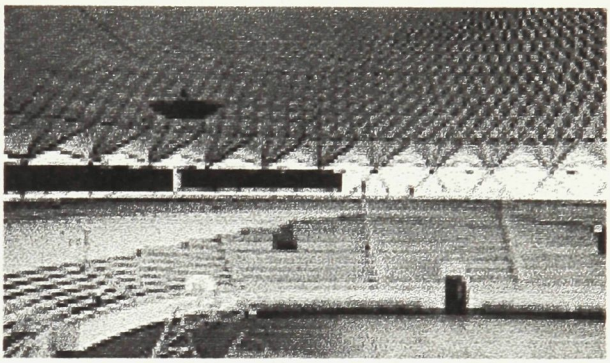
[1] Matilda McQuaid, Santiago Calatrava. Structure and Expression. 10

Torroja recognized that good structural design evolves only when its concerns go beyond science and techniques to include "*art, common sense, sentiment, aptitude and joy in creating pleasing outlines*" [2].

Pier Luigi Nervi, like Maillart, designed his works to be pleasing visually but also financially economical and efficient in construction. The modern design principles of efficiency, economy, and beauty became interdependent in his technical process, producing results such as the impressive roof pattern in Palazzatto dello Sport (1957) in Rome. (See figure 4).

Felix Candela drew on his experience as a builder to construct the thinnest conceivable shells. He created a variety of hyperbolic paraboloid, or saddle shaped shells, that were stiffer and easier to build than other shell constructions. The Los Manantiales restaurant in Xochimilco, Mexico, which was completed in 1958, represented the virtuosity with which he was able to manipulate this form into thin concrete shell roofs and walls. (See figure 5 on next page).



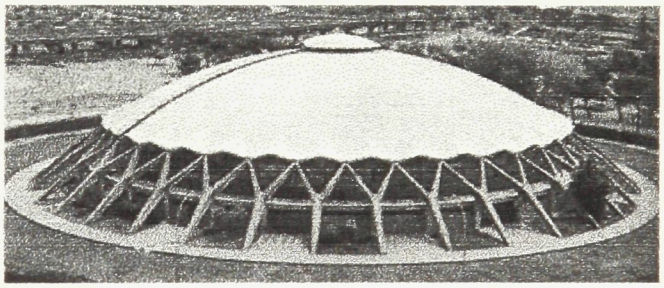
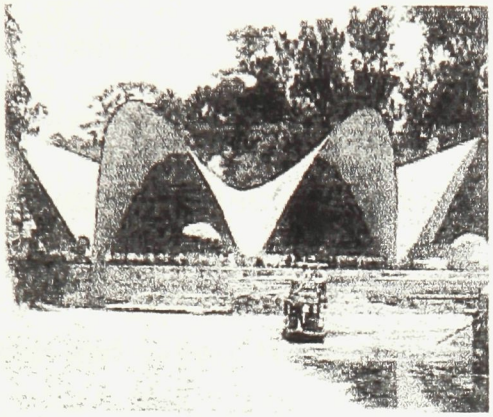


Figure 4 Palazzatto dello Sport (1957) in Rome. An interior and exterior view. http://www.monolithic.com/thedome/thinshell

[2] Matilda McQuaid, Santiago Calatrava: Structure and Expression. 10

The design approach of the architect/ engineer Santiago Calatrava, like those of his preceding generations- Maillart, Nervi, Torroja and Candela- is an integral part of this thesis. His structural forms are a source of inspiration and precedence to some of the concepts explored in this thesis. Throughout the different design phases, Calatrava incorporates methods and approaches that help to develop structural forms that are architecturally expressive. His architecture is one that engages the physical properties of natural forms and their aesthetics in order to reach a unique architecture. Philip Jodidio writes:



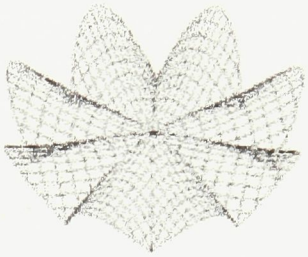


Figure 5 Felix Candela's design for the Los Manantiales restaurant in Mexico

"Although the technical idea in Calatrava's work is neither the primary motivation, as with Maillart, nor understated, it informs the overall expression of the structure. His work becomes an intertwinement of plastic expression and structural revelation, producing results that possibly can be best described as a synthesis of aesthetics and structural physics."[3]

Recurrence and rhythm, common characteristic found in nature, as in architecture, are often incorporated in the work of Santiago Calatrava. From the architectural standpoint, recurrence in design has an advantage in that it

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[3] Jodidio, Philip. Santiago Calatrava. Koln, TASCHEN. 2003. 12

provides a sense of order and, along with rhythm, it can be used to create movement and contrast. This has been successfully applied in most of Calatrava's works, and as a result, these characteristics (recurrence and rhythm) have enabled his work to reflect architectural clarity and structural integrity. Yet, whereas these characteristics have succeeded in some projects to bring about desirable effects, they have brought about monotony and repetition in the design of others rendering them visually lacking.

Philip Steadman and George Hersey investigate the historical significance of skeletal structures and cellular formations, among other natural forms, in the context of architecture. Their observations offer insight into the development of structural forms through the technique of observing nature's physical and aesthetic laws, yet, in some cases, the examples and comparisons between nature and man-made structures do not provide sound arguments as they omit structurally significant characteristics and make superficial comparisons. For example, George Hersey introduces the concept of '*self similarity*' at different scales that is inspired by designs in nature. According to Hersey, an example that illustrates this concept is the chapel designed by Bramante (i.e. the central vaults and dome of 1506 St. Peter's), (see figure 6) where the ribs of the dome are reproduced, and multiplied, just as one cell would reproduce and multiply in

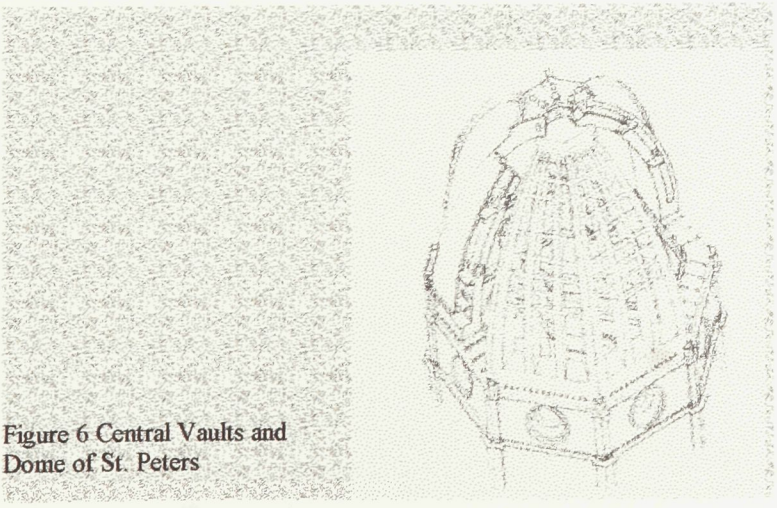

Figure 6 Central Vaults and Dome of St. Peters

nature). Here Hersey's example is somewhat far- fetched, as the design of the dome is dysfunctional, enormously wasteful, and not durable. It has been substantially rebuilt three times during its 400-year life. As a result, the dome of St. Peter's Cathedral represents bad structural design, primarily because it did not take advantage of construction methods that are obtained from studying nature's principles and other man-made architectural examples.

The thesis concepts are brought together in this study of structural form, through the design of a museum of nature. By studying the physical principles of structures and forms, and observing the work of architects, in particular Santiago Calatrava an approach to design is developed. With the principles and behavior of structures in mind, a structural form for the museum of nature culminates in one that is capable of withstanding stresses and reflects architectural clarity and structural coherence.

Chapter One

Historical Reference to Architectural expression and nature

Throughout the history of architecture, great interest has been taken in producing structures and forms inspired by nature. New materials were developed in order to fulfill the possibilities of refined structure. In the nineteenth century architects such as Viollet –le –Duc and Gottfried Semper thought it fit to adapt the anatomically based classification of organisms developed by the French naturalist Georges Cuvier to building types.

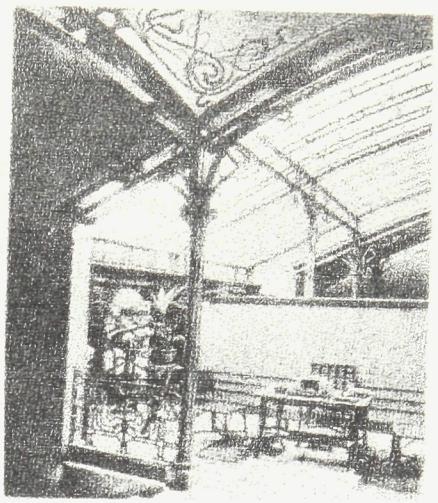

Figure.1 Victor Horta and the Art Nouveau style. Hotel Tassel,Brussels 1892. (From Frampton's "Modern Architecture") 68.

Later, the steel frame pioneered by Louis Sullivan and the Chicago school from the 1880's enabled internal structure and external cladding to be regarded as separate. Comparison with skin and bone in vertebrates was inevitable. Steel girders were exposed as structural members reminiscent of skeletal frames. Additionally, reinforced concrete, a material developed in France, made it possible for new challenging structures to be built. Following the demise of Art Nouveau (see figure 1) and the first World War there was a lull in interest. The revival in the 1950's was made possible by further developments in concrete construction as much as Art Nouveau was by the use of steel and glass.

Concrete became a well-developed building material in the late 19th century as a result of a few pioneers such as Francois Hannebique (1842-1921)

in France and G.A. Wayss (1851-1917) in Germany [1]. Their works stimulated scientific study of this composite material, and their construction procedures established its competitive economy. Hennebique and Wayss had shown by 1900 that concrete with steel bar reinforcement embedded in it was a universal construction material; it could be used in place of wood or stone, or even steel, except in long spans. Reinforced concrete was highly suitable for exploring an architecture of ribs and bones as it stretches and bends in all directions, the chief constraint on its use being the cost of building the timber formwork into which it is poured. (See figure 2)

> *"Although they created some unprecedented visual forms, these pioneers did not emphasize the appearance of concrete structures but rather their predictable performance in service and their low cost both to build and to maintain."*[2]

Arches for bridges and frameworks for buildings were their most prominent forms in the 1890's. Wayss had taken the thin arch designs of the French gardener Joseph Monier (1823-1906) while Hennebique simultaneously developed his ideas of beams and columns, beginning with metal elements protected from fire by concrete. The resulting building forms, with solid columns, beams, and

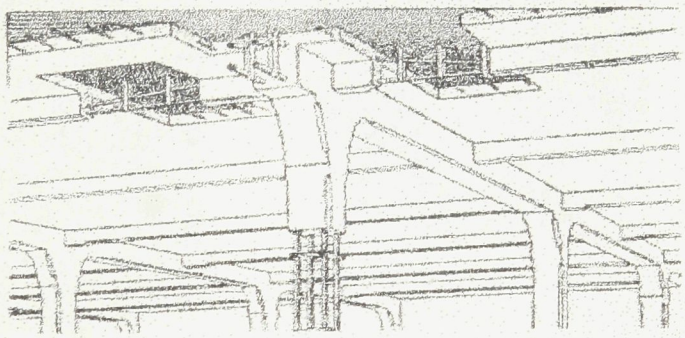

Figure 2 Hannebique's reinforced concrete system .`(From Frampton's Encyclopedia of Modern Architecture).235

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[1] Billington, D. P. Robert Maillart and the Art of Reinforced Concrete. 2
[2] Ibid. 2

joists supporting short span slabs, "looked like wooden construction"[3].

" What was clear to Hennebique then, was that reinforced concrete structures were monolithic, unlike those normally made up of steel or wood elements, but he designed frameworks that were not strong visual expressions of that monolithic nature.[4]

These developments eventually led to an eruption of structural forms inspired by natural forms. Although the designs of the Art Nouveau movement were shapes that were predominantly vegetal – there was also similarities with organisms. Ernst Haeckel's *Kunst -formen der Natur*[5], begun in 1899 at the height of the Art Nouveau and Vienna Secessionist movements, illustrated this resonance with its numerous obscure, often microscopic marine creatures (see figure 3 & 4).

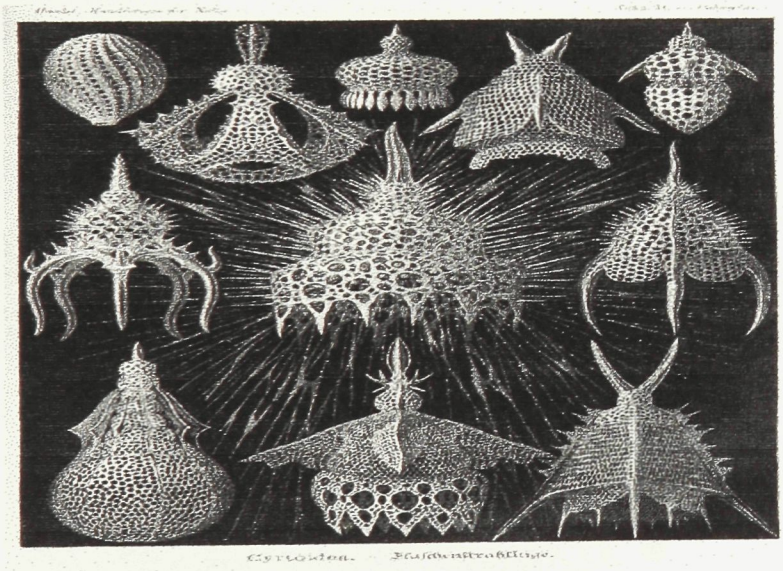

Figure 3 Microscopic marine creatures known as Radiolarians. (Form http://caliban.mpizkoeln.mpg.de/~stueber/haeckel/kunstformen/ natur.html

Figure 4 Ernst Haeckel. http://caliban.mpizkoeln.mpg.de

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[3] Ibid. 2
[4] Ibid.
[5] Philip Steadman. The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts. 20

The twentieth century saw architects and engineers such as Pier Luigi Nervi (figure 5) and Gio Ponti as well as Felix Candela exploiting reinforced concrete's structural potential. The decade's *'greatest triumphs'* were also manifested in the works of Eero Saarinen's aquiline TWA Terminal at New York's Kennedy Airport and John Utzon's polysemous Sydney Opera House.

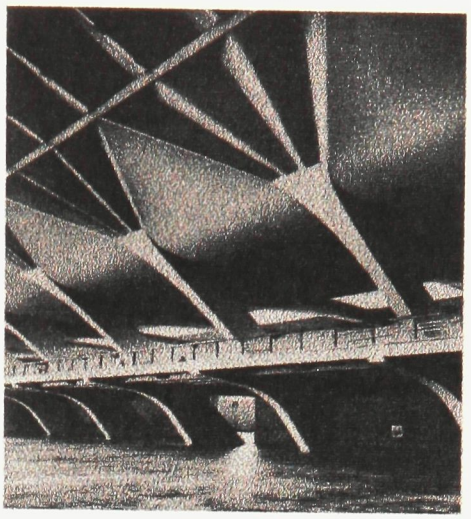

Figure 5 Pier Luigi Nervi's Exhibition hall, Turin, 1948-9. From Frampton's Encyclopedia of Modern Architecture).238

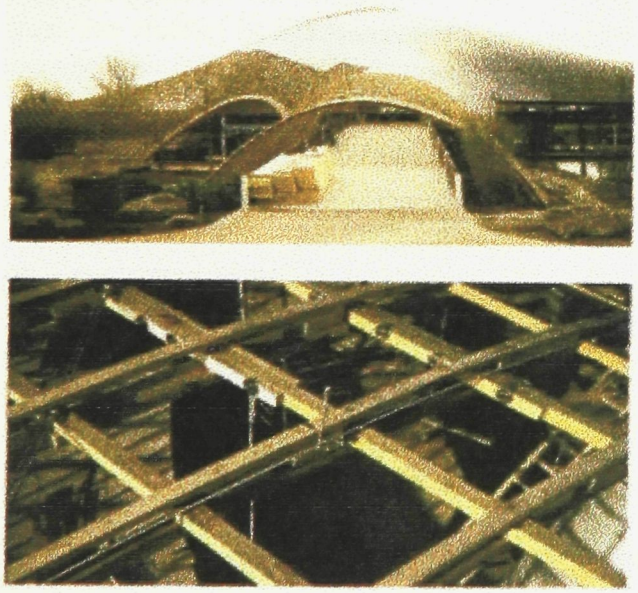

Figure 6 Mannheim Garden Festival, Germany, 1975
A translucent shell created by a timber lattice framework and clad in PVC coated polyester. (From Brooke's "Innovation in Architecture") 79

During the 1960's and 1970's, other new materials were crucial in shaping desired structural forms other than 'heavy' concrete. Flexible fabric – based structures held in place by tension cables or the pressure of inflation. The visionary work of Buck minister Fuller and Frei Otto were able to bring some of the most ambitious schemes to reality. Frei Otto experimented with pure tension structures through hanging chain models to define forms of minimal energy. The form was then inverted to form an optimal compression structure under uniform loads. An architectural

example that characterized this principle is seen in the form of the timber lattice structure for the Mannheim Garden Festival that was designed in accordance with the above-mentioned technique (see figure 6 on previous page). When inverted this form generated *'Catenery'* structure of pure compression under self weight.[6]

Nature's structures and forms continue to motivate architectural innovation whether it is aesthetic, functional or structural. For example, lightweight structures can be made more efficient and economical by observing nature's principles. Alderley William Hugh notes the significance of observing nature's structures and forms by stating:

> *"It is clear that taking natural forms as models can lead to lighter structures and more efficient use of materials as well as novelty of style, provided that the model is followed through appropriately."*[7]

Nature's significant role as an inspirational tool for new design solutions and technological innovations in the realm of architecture and engineering is made further clear in Powely's statement

> *For architecture or technology to emulate nature neither necessitates nor excludes using natural materials and vernacular, or biomorphic forms. But as science unravels nature's secrets, it is the leading edge of technology, which some may mistake for its most artificial and unnatural pole, that is most likely faithfully to appropriate nature, especially in artifacts expressly created of some high performance application. This artifact or component may have biomorphic form, not because it is styled that way, but because it happens to offer the economy, efficiency and exact fit for purpose found in organic creation.*[8]

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[6] Brookes, Alan & Poole, Dominique. Innovation in Architecture. 10.
[7] Hugh, Alderley- William. Zoomorphic: The New Animal Architecture. 15
[8] Brookes, Alan & Poole, Dominique. Innovation in Architecture. 10.

Backed by today's technological advancements in building materials and scientific discoveries in the field of construction, architectural achievements have aided in finding solutions to design and construction issues. According to Martin Powely in *Innovation in Architecture: "architects and engineers are responding to new opportunities offered by new materials and sophisticated means of prediction available to them"* [9].

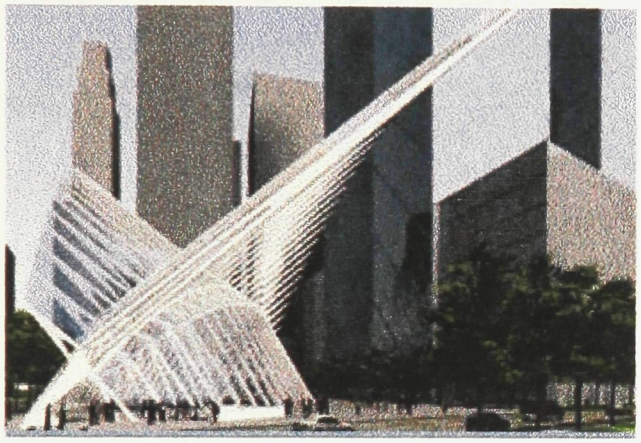

Figure 7 Path Terminal- New York. A landmark for New York City. (From http://www.aecom.com/marketsandservices)

Numerous examples exist of architectural achievements that have successfully merged today's modern technological advancements in design and construction with nature's inspiring principles. The design of the Grand Central & Penn Station by architect Santiago Calatrava is a prime example. His main goal with the PATH Terminal (see figure 7) was to create a landmark; a new focus for the city, and a grand welcome "gate" for those arriving in Manhattan for the first time by train. The structure and form gives the building, and by extension the place, a kind of personality.

A looser approach to structural form and expression inspired by nature is seen in buildings with an environmental agenda such as Nicholas Grimshaw and Partner's Eden Project (see figure 8), because of the nature of their contents, or because of the sustainability issues addressed in the project.

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[9] Brookes, Alan & Poole, Dominique. Innovation in Architecture. 10.

Another structural expression with reference to nature occurs when the structure strives to emulate nature's principles, and means to do so with the repetition of parts. The Museum of Science in Valencia, Spain, Stadelhofen station in Zurich and Milwaukee Art Museum (see figure 9), are few examples among numerous architectural projects designed by Santiago Calatrava that possess strong structural expressions and qualities inspired by nature's principles. All mentioned architectural examples, according to Calatrava, recall the "*principle of recurrence*" which is a principle that is characterized by qualities such as economy and efficiency. As in his architectural projects, nature is a guiding principle for his sculptural works that recall recurrence even if they appear reduced to abstract, elementary shapes like cones and cubes. "*The configuration of most of these works is derived primarily from the human body, which can still be discerned in their highly schematic combinatorial shapes*"[10].

Figure 8 Eden Project in Cornwal, England. (From http://www.edenproject.com)

Figure 9 Milwaukee Art Museum in U.S.A. interior view of hall. (From http://www.cac.es/cac)

[10] Anthony Tischhauser, Santiago Calatrava: Public Buildings. Introduction by the Architect.

Chapter Two

efficiency, is present in Santiago Calatrava's design for the roof of a multi purpose hall in Suhr, (see figure 1) Switzerland, with tensioned cables piercing in curved ceiling panels joined by the point of maximum stress. Relying on the principle of recurrence in his design of the roof for the Jakem factory , Calatrava achieved structural efficiency common to principles found in nature. The application of a curved steel structure enforced this further, where the structure followed the lines of force of the triangular trusses.[2] (See Figure. 2).

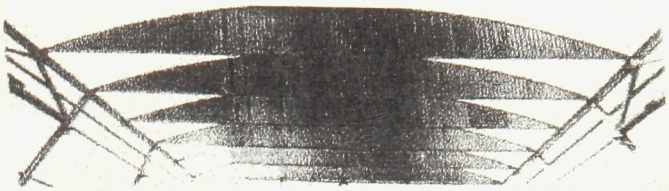

Figure 2 Balancing the curved steel structure on trusses on the sides for maximum efficiency in Jakem Factory.

Economy is another significant characteristic of structural forms in nature. Efficient structures, that are economical in conserving material, will not necessarily be economical overall. Man- made structures can be costly if they are difficult to construct. Thin concrete shells, for example, are efficient but usually costly due to the labor involved. In addition, economic considerations depend on the social setting – the specific time and place. Labor costs may vary from place to place, and from one era to another. Other variables, such as the experience of the contractor and workers, affect the cost of a structure. Overall, the architect must strive for efficient structures, but keep in mind economical factors that may require altering the *design.*

The structural forms of the engineer Robert Maillart's (1872-1940) are worthy of note [3]. Although not an architect, his structurally innovative designs

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[2] Dennis Sharp, Santiago Calatrava. 27

Structural Design in Nature and Architecture

Great technology has been at work for millions of years and in order for natural structures to adapt to different physical forces, like tension compression, shear and torsion, they have become fluid, ephemeral, and beautifully balanced, and their technology has been dynamic, lightweight, and efficient. The latter, an important characteristic of natural structures, is achieved by transferring the required amount of forces with the least amount of materials. In *On Growth and Form*, D'Arcy Thompson suggests that the shapes of living things are largely the result of "*adaptation to physical forces, not behavior and diet, as many biologists believed at the time*" [1].

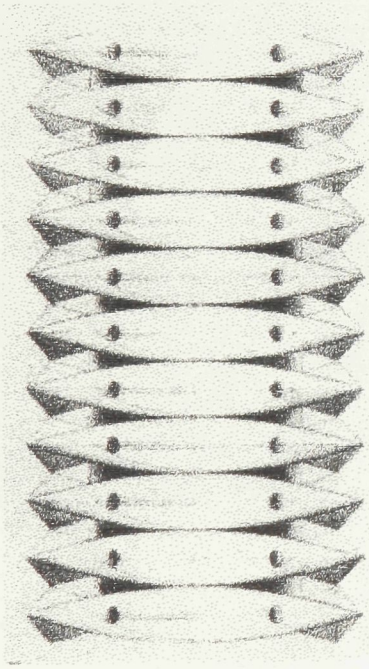

Figure 1 Design of the roof at Suhr represents efficiency in structure

To adapt and increase efficiency, natural forms prefer tension members because compression members have a propensity to buckle. Using the maximum amount of tension, members concentrate compression into localized regions. Man-made structures such as shells and tents provide maximum efficiency. Some architectural examples that express efficiency in structural design include Frei Otto's Olympic Stadium in Munich, Germany, where the steel wire nets are in tension and the large steel masts carry the compression. Another example of structural

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[1] Willis, Delta. The Sand Dollar and the Slide Rule: Drawing Blueprints from Nature. New York, NY: Addison-Wesley Publishing Company. 1995. 27

have contributed greatly to structural design and architectural concepts with reinforced concrete as the primary building material for construction. Through several bridge designs in his native Switzerland, his contribution to structural design was made in 1908 when he invented the mushroom slab (see figure 3). In this method, Kenneth Frampton states:

."Columns, beams and floors are no longer treated as separate units as in timber or steel structures, but column passed organically into the beamless floor slab, the resultant structure culminated into a "mushroom shaped column" that is highly expressive of the world of nature." [4]

Adding that:

"This structural system exemplifies a practical, uniform structure that facilitates economic construction in the use of materials, it also permits flexibility in application and helps to ensure a light and elegant design"[5].

Figure 3 Filter building interior at Rorschach, 1912, without water. The columns support the heavily loaded roof through wide octagonal capitals.

Frank Lloyd Wright later adopted the structural form of the 'Mushroom columns' or 'dendriform columns' in his design for the Laboratory tower for S.C. Johnson and Son in 1949 [6] (see figure 4). These slender columns that were constructed of concrete reinforced with steel mesh and shaped to taper down at the base supported the building. When arranged, the 'forest of mushrooms' provided a system that acted as an

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[3] Frampton, Kenneth. Encyclopedia of Modern Architecture. 181
[4] Ibid. 182
[5] Ibid. 182
[6] Frampton, Kennith. Encyclopedia of Modern Architecture. 325

upside down spread footing enabling the vertical loads of the cantilevered floors to distribute evenly in order to provide balance and help stabilize the overall structure of the building, in particular the central core. Wright's innovative design for the columns became technically successful and architecturally gratifying.

Another important characteristic of natural structures, that influences man-made structures, is its ability to reflect beauty and elegance through structure. In the architectural realm, the personal expression of an architect's vision should be consistent with nature's logic of 'beauty', efficiency and economy. Further more, in the process of designing structural forms, architectural elegance and beauty, like efficiency and economy, must not be achieved by giving up requirements of materials and competitive costs in favor of a separate search of architectural beauty. Architectural beauty and structural elegance comes from within the discipline that incorporates lessons learnt from nature.

Figure 4 Interior, main room with Mushroom columns looking up of the Johnson Wax Company in 1949.

If efficiency reflects the forces that are learnt from observing our natural world and economy relates to local patterns of social behavior at specific times, then architectural elegance and structural beauty stands for a unique and personal creative process that learns from the lessons nature presents.

Principles Common to Nature and Architecture

As in nature, structures have been applied to man-made forms and examples abound. Bridges are typical examples of structures found in nature: the beam bridge made by a fallen tree; the arch bridge created by the erosion of rocks; and the hanging bridge formed by different types of vines. These three types of structural principles have remained unchanged for thousands of years. (See figure. 1).

Every living and non-living form contains a structure. A structure's purpose is to transmit forces towards solid bases, usually land. This is the case for trees, bridges, buildings and other forms, whether natural or manmade. The forces that act on the structure produce five basic types of stresses: compression, tension, cutting (shear) and torsion.

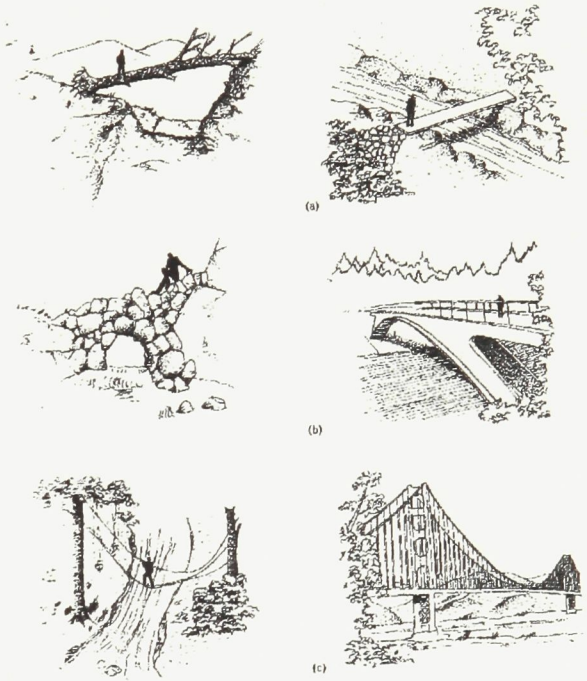

Figure 1 The three types of structural principles found in nature and their application in man made structures.(from Bio-Architecture by Senosian).

In his book titled *Bio- Architecture*, Aguilar Senosian takes the *Tree* as an example for all five stresses at work, explaining that:

"The upper surfaces of the wood fibers tense in the branches. Gravity pushes the branches downwards while the fibers on the lower surface compress.

Flexion is produced inside the wood when gravity attracts the branches; when the wind bends them, torsion is produced. A cutting force is also generated during movement between the wood fibers, caused by the branches and trunk swaying in the wind."[1]

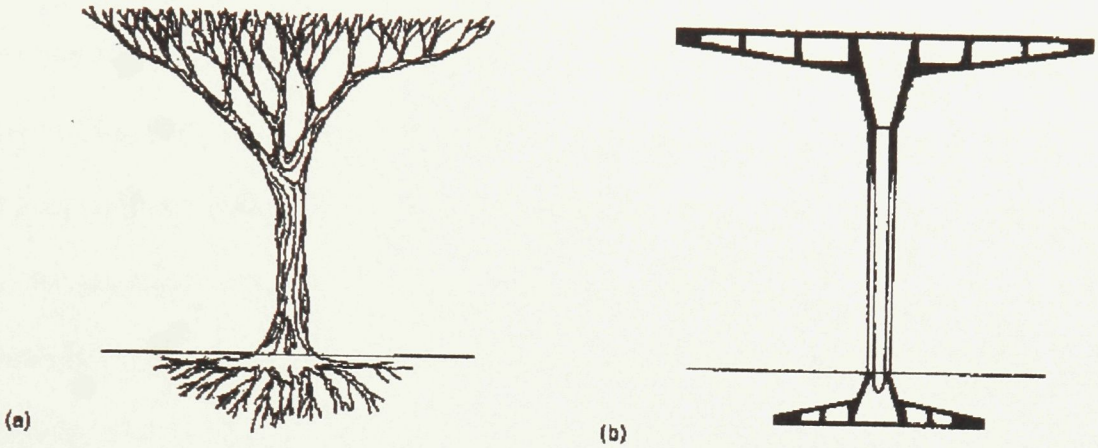

Figure.2. Arrangement of branches, ramifications.(from *Bio-Architecture* by Senosiain).

Senosian further adds that:

"Relying on the natural laws of stress distribution, in a tree, the stresses (weight) of the highest branches (corbel) are transmitted downwards, increasing until they reach the trunk (spinal column), which transmit these stresses downwards (compression), increasing until they reach the ground. After that, these stresses (weight) are transmitted into the ground through the roots (foundation)."[2] (See figure.2).

Just as in nature, the scale and intensity of forces pose a unique influence on man-made forms (architecture). Structures such as large buildings produce immense forces resulting in constructions largely organized to balance those forces with compressive bearing material. Tension exists, of course, but is often not as apparent or as overtly expressed in most building forms. With a few notable exceptions, tension forces remain a hidden character in the play dominated by compression but can be regarded as acting in different

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[1] Aguilar Senosiain, Bio-Architecture. 28
[2] Ibid. 28

levels of a structure.

Tension and compression are common terms used to describe the direction of forces within the continuous medium of a form. The relationship between tensile and compressive forces forms the basis of all operations that describes the stability of form and structure. The equilibrium of a structure requires that the arrangement of forces should be static, meaning that the interaction of tension and compression forces maintains a stable relationship even under the influence of external forces acting upon its form. The magnitude of the forces that act on the equilibrated structure is determined by the overall mass of the structure and any additional forces it may be subjected to.

In general, structures that undergo compression are short and thick. In order to support its great weight, pillars, something like an elephant's legs, gravitate outwards vertically from a point on the body close to its center of gravity. Conversely, structures that use tension are slim and fragile, like cobwebs. These structures can support more weight with less material. An example is given to illustrate this principle by Aguilar Senosiain:

> *"If we imagine an insect growing considerably larger than it does in real life, its legs would have to be shorter and thicker to cope with the increase in weight; its wings would also have to undergo modifications. If an elephant decreased in size its weight would be less and so it would no longer need such thick legs and feet for support".*[3]

In the architectural realm, a key aspect in shaping our conception of structural form is that the primacy of gravity is not a forgone conclusion, especially in natural structures. D'Arcy Thompson observed that, in the case of the water beetle's form, gravity is less persuasive than are the forces of the

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[3] Ibid. 29

surface tension of water.[4] More Importantly, the idea and conception of scale provide a framework within which one can more accurately define the science of structural form. At the macro scale of a building, the gravitational force assumes its primary role in shaping the behavior of matter because of the building's substantial mass.

According to Thompson:

"Gravitation influences both our bodies and minds. We owe it to our sense of vertical, our knowledge of up-and-down; our conception of the horizontal plane on which we stand, and our discovery of two axes therein, related to the vertical as to one another; it was gravity which taught us to think of three- dimensional space. Our architecture is controlled by gravity, but gravity has less influence over the architecture of the bee; a bee might even be commended, if it referred space to four dimensions instead of three!" [5]

In nature, the wholeness of a form indicates that the forces of stress are always in some sense of equilibrium. The internal tensions are balanced against one another into a stable configuration. The human body is an example of design in dynamic balance. The skeleton is the internal structure of the body, the basis of which is the backbone supported by the pelvis. The whole structure is held together and moves by the muscular system: ligaments, membranes, tendons and muscles- a whole network in tension. Almost all bones are flexible at both ends and rigid in the middle. Stresses are distributed through the use of internal fibers that range in consistency from soft to hard- they allow some animals, to perform movements during which the muscles and tendons are tensed and the bones are compressed. A structure that is rigid will break more easily than one that is flexible or elastic.

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[4] D'Arcy Wentworth Thompson, On Growth and Form. 67
[5] Ibid. 67

Bone structure can actively resist or re-guide the stresses and strains of subtle and extreme loads. These loads contribute to create its resultant shape. That is to say, bone structure abounds with forms whose makeup is produced by the direction and intensity of stresses and strains. A bone, in some cases, comes with a pre-determined shape, yet it does not conform to that shape throughout its lifetime. (See figure.3)

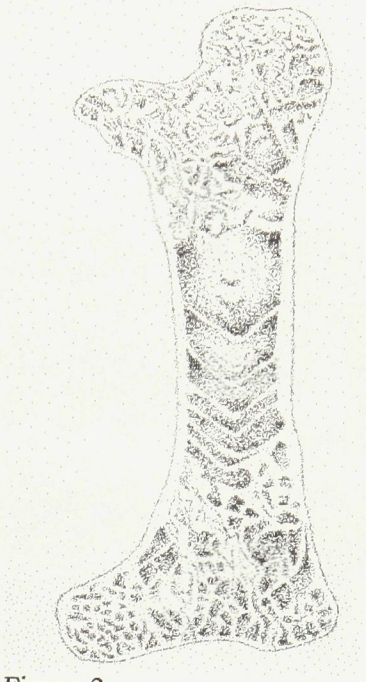

Figure 3
Longitudinal cross section of a thigh bone. The distribution of the fibers at both ends gives the bone its required flexibility. (From *Bio Architecture* by Senosiain). P.30.

The human body' s structural resistance can be explained through the linkage of its structural system, with those that tolerate pressure, and those that resist it. (i.e. Hard (bone) and soft (muscles, ligament, tendons), rigid and flexible)

People are now seeking materials that will offer as much resistance as possible to both. Cartilage is an example of a material that resists the stresses of compression and tension up to a point, helping to maintain the shape of some organs like the ear and the nose.

Santiago Calatrava

The work of the Spanish architect Santiago Calatrava abounds with designs that illustrate structural principles in architecture. Dennis Sharp describes Santiago Calatrava's work in his book titled *Santiago Calatrava* by stating that:

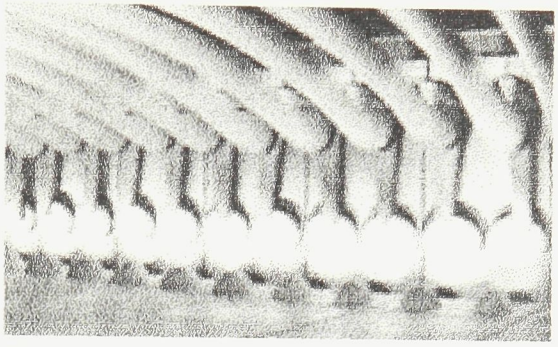

Fig.4.Santiago Calatrava. Concrete Pavilion. *From Creatures from the Mind of the Engineer* by Robert Herbison. p.15..

" His designs incorporate highly articulate members that, like organisms, express rounded corners and avoid abrupt, sectional contrasts. His sections adapt to varying bending moments; where his columns are broader in their middle, and taper gradually towards both ends. Most frequent in his work is the use of highly differentiated elements; composed of non-uniform materials, where each material –again like the members of organisms- assumes the task it can best perform. As a result he stretches the structural capability of building materials, concrete and steel in particular, in order to design such members to create challenging spans."

Furthermore, Calatrava's designs clearly reflect structural principles inspired by bones and other natural forms of nature. Although, in some cases, his work becomes prone to imitation of the outer form of bones rather than the principles with which they inform, as is evident in the Concrete Pavilion project (see figure 4). Calatrava's structural applications also combine natural characteristics such as symmetry and order, with the solidity and malleability of building materials to achieve three-dimensional structures with an impressive visual impact. On that, Calatrava notes:

"Frequently my designs recall the form of skeletons. Behind this is the principle of recurrence. In the case of vertebrae, one finds the form dictated by the universal structural law that the base is thicker than the crown. The recurrence

of this principle expresses economic efficiency. But it also arises from something beautiful, namely rhythm- the rhythm one finds in musical compositions ".[6]

Equilibrium of the structures/members is largely dependent on the characteristic of these materials to resist tensile and compressive forces. Calatrava's knowledge of the forces acting on a structure is expressed in terms of this principle, which he best observes in the human body. Some of his designs appear directly transmitting in pictorial terms. Others attempt to 'geometricize' human poses in his quest to understand a wider dimension of the forces at work.

Anthony Tischhauser writes in *Calatrava:*

"Calatrava's structures give the impression of being built of sections strung together, having first unfolded in the eye of the mind. They are not unfolding systems but movement drawn out into form, one curve blends into another without losing its identity".[7]

Calatrava's intuitive application of materials appears to transform their physical characteristics. His architecture is almost always stripped down to its basics, with its precise structural and architectural logic in full display. The parallels with body forms of animals and humans stops with Calatrava's rejection of skin. The texture of concrete, steel and glass is expressed through the weight of the materials brought to bear; the heaviness expressed not necessarily being real. Steel is often made to seem lighter and heavy granite stones can appear even heavier when contrasted with the slender chromium cable, balanced on thin cones, as is the case with the steel supports of Stadelhofen's promenade.

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[6] Sharp, Dennis, Santiago Calatrava. 12
[7] Anthony Tischhauser, Santiago Calatrava: Public Buildings. 18

Rod Usher of *Time Magazine* comments on Calatrava's Architecture:

"A Calatrava object is an event, occupying its own clearly demarcated space, marked out by its distinctive white forms. They do not invite addition, subtraction, or adaptation. His buildings are, he admits, "autonomous."[6]

Nevertheless, buildings are like living beings to Calatrava and are treated as entities- they have a top and a bottom, and upper side and an underside, a beginning and an end. His buildings are legible and appear simple, clear and self-contained and concerned with the whole.

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[6] From Rod Usher's interview with Santiago Calatrava for Time Magazine. http://www.time.com/time/europe/specials/ff/trip3/calatrava2.html

Lightweight Structures

Throughout the history of architecture, great interest has been taken in models for structures that nature offers. At the end of the twentieth century, technological advances and research by some architects and engineers made it possible to build lighter structures on the same principles as those of the natural world. One of the greatest achievements of architecture and engineering is in the development of lightweight structures. An integral part of this research is to explore methods of Lightweight construction.

There are basically four light structures derived from natural models: Cable networks inspired by spider's webs; pneumatics inspired by bubbles; vaults inspired by shells and eggs and finally, geodesics inspired by radiolarians. These light structures are characterized by low cost materials, low dead weight, and possibility of large clear spans, simplifying constructive details, simple assembly and short building time.

Cable networks

Spiders produce elastic, resistant webs with a minimum amount of material and at phenomenal speed. These viscous – elastic structures absorb impact and resist the struggles of insects without breaking, providing prototypes for 'new structures.' The static principles used in building a web are the same as those used in 8000 BC by the nomadic tribes making tents from animal skins to protect themselves from the wind. Our ancestors also applied skin covering that sheltered small areas or enclosures to protect themselves

from the elements. Later, they designed primary structures with synthetic material. Later still, to shelter in larger spaces, they designed a network of cables as the principle structure, covering it with a membrane in materials such as acrylic, canvas and fiberglass.

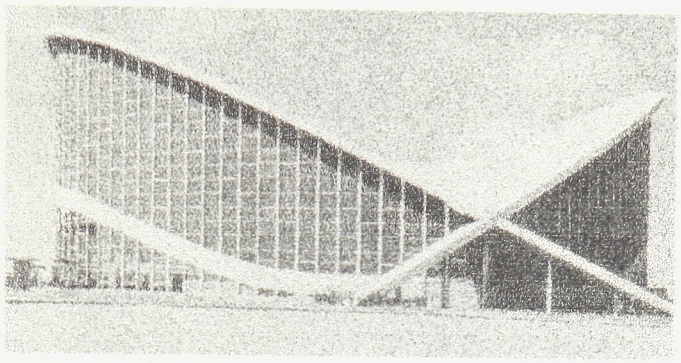

Figure. 1. Matthew Nowicki's Arena.1952-3 (from *Encyclopedia of Modern Architecture*.p.279.).

In 1950, the architect Matthew Nowicki (see figure 1) designed the first network of cables. This project was created for Cow Palace, Raleigh, North Carolina, USA, and was based on the principle whereby a cloth membrane was supported by four legs of crossed wood, pivoted at their half way point, two at the front and two at the back. Nowicki's construction used reinforced concrete arches pivoted at both intersections. The cable network is tightened in two directions; some cables curved upwards parallel to the legs of the arches, others hang down perpendicular to the others. This structure turned out to have the shape of a saddle. All the cables were stretched with the weight of the arches that hung over the same braces and finallythe framework was covered with a network of wavy acrylic domes.

Another example is the Yale University Hockey Rink (1956-1958) (See.figure 2). Eero Saarinen built a concrete arch as the main part of a structure that serenely crossed the whole shell. The dorsal column (arch) where the vertebrae (steel cables) are secured is very liberal. These vertebrae hung in a perpendicular fashion like a hammock and are anchored in the walls,

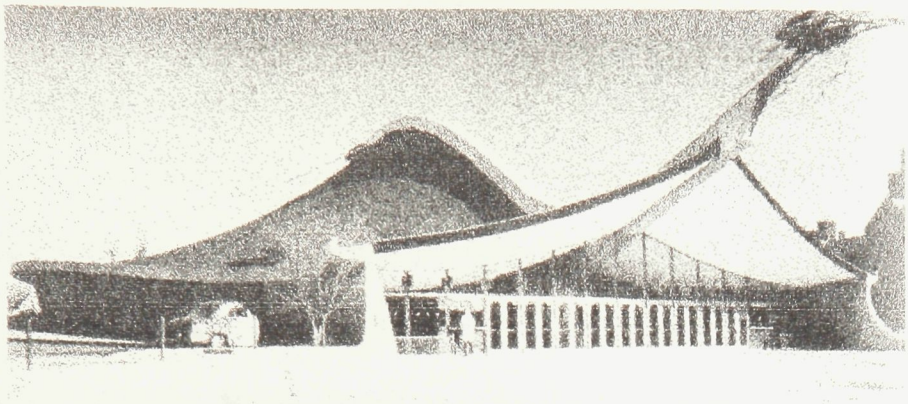

Figure.2. Eero Saarinen. Yale Hockey Rink. 1958 (from *Encyclopedia of Modern Architecture*). P.246

curved and slanted outwards. The walls worked like dead weights, staking that anchor down, and at the same time working like counterweights for the roof. In this way the architect was able to achieve balance of the cables as if they were lengths of silk with a beautiful fall. The entrance's gullets are arranged hierarchically by the projection of the roof, becoming a sort of corbel. Inside, the elements of the roof can be distinguished: the steel cables, the wooden lining that covers the ceiling looking like the hull of a ship, and the concrete of the arch, all of these take on a clean and harmonious appearance.

Saarinen also designed the roof of Dulles Airport in Washington, DC. The cables hang in only one direction from the top of columns tilted outwards to raise the cable roof with prefabricated slabs, which in their turn keep the columns from falling. In this way, balance of forces is achieved in the structure.

Pneumatic structures

In nature a great many forms are made up of micro spheres (pneumatic structures). The microsphere behaves like a soap bubble in water, with a

consistently flexible and resistant layer around a watery or gaseous content. Every animal or plant cell is a pneumatic structure made up of membranes and contents- the protoplasm. One of the fundamental properties of liquids is surface tension, the strength of which gives shape to typical bubbles. When a bubble presents minimal surface, its shape results from a minimal amount of material. Besides being resistant, these light, flexible structures attain great plasticity.

According the Senosiain, we could consider ourselves pneumatic structures susceptible to puncture by sharp objects [10]. Other examples of such structures are found in the conduction systems of plants: in viscera in general (the placenta, intestines, heart, stomach and lungs); in soft fruit such as grapes, tomatoes, and kernels of corn; in egg-yokes or the soft eggs of reptiles and insects.

In toads that inflate their throat, the air behaves like an element of compression acting inside the membrane in tension. The use of air as a structural material is therefore, not new. In everyday life there is pneumatic structures in which air inside a resistant, protective shell like covering supports a heavy weight. Such is the case of balloons, balls and other items inflated by air. The pneumatic covering-*pneuma,* Greek for lung- is always soft. The original cells of wood and bone are actually soft but accumulate solid material like the bony or cellulose substances, becoming rigid 'pneumatic structures' that can hold up under certain pressure.

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[10] Ibid. 36

"It is no accident that the forms of pneumatic constructions developed by humans resemble natural shapes. Some of the techniques of abstract mathematics have slowly been lost, as time has elapsed. Nevertheless, the result is still getting closer to the shapes found in organic life. Over the past three decades, air has become recognized as an important component of many structures." [11]

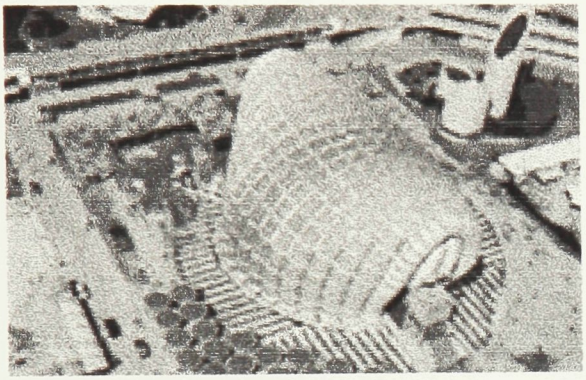

Fig.3. Fuji Pavilion, Yutaka Muramata, 1970.
retrieved from http://www.earthstation9.com/index.html?1970_osa.htm. (On Oct.12,04)

At Expo '70 in Osaka, Japan, Yutaka Muramata designed the Fuji Pavillion that was built in 16 sections, each section being 4 meters wide The perimeter measured 50 meters, and the Pavilion was 25meters high. When the inside pressure was increased, the building was able to resist winds of hurricane intensity. (see.fig.3).

David Geiger conceived an idea for the roof of the United States Pavilion that was made of a vinyl membrane reinforced with fiberglass, anchored to an oval shaped, tilted wall. (See figure 4). When the membrane is inflated, the suspended cables begin to tighten. The roof is held up by air pressure that can resist winds of up to 240 kilometers an hour.

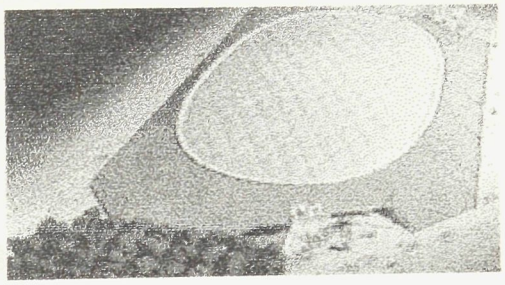

Fig.4. USA pavilion in Osaka.1970.
(retrieved from http://www.earthstation9.com/index.html?1970_osa.htm. (On Oct.12,04)

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[11] Aguilar Senosiain, Bio-Architecture. 36

Vaults

One of the most interesting structures in nature is the egg. Its shell is associated with two specific properties: curved shape and hardness of material. The shells of nuts such as pecans, almonds, or coconuts; crustaceans; the external bodies of insects; and the pods of numerous seeds, are similar. These natural structures generally have greater rigidity than flat structures. They protect life yet use a minimal amount of material.

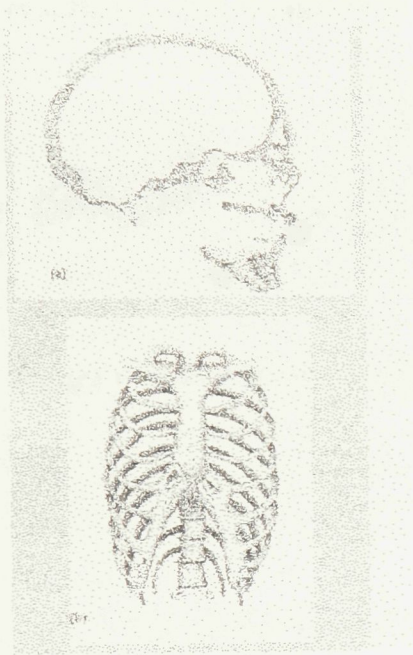

Fig.5. The human cranium and thoracic vault. (From *Bio-Architecture).* P 37.

Inside the human body, bone structures protect vital organs. The cranium protects the brain, and the thorax protects the heart, lungs, and other organs. The same is true of the central bone structure of a bird, which has similarities to a shell- it is nearly transparent and rigid- and serves as armour to protect internal organs. (See figure 5)

Mollusk shells provide protection form predators, and their consistency means that they can withstand water pressure at great depths. The strength of a shell can be explained by the design of its structure: a thin plate with a curved surface that transmits stress throughout itself towards the supports. Shells can be built either with moldable materials (clay, concrete, plaster) or from other materials (wood, metal, brick, or stone) that can be put together and shaped into curved surfaces.

The application of the structural principles of the shell is common to architecture as it is in nature: a curved, three-dimensional shape of rigid material and minimum thickness under the law of maximum efficiency and minimal material. Some examples of large roofs built using this method are resistant, due exclusively to their shape.

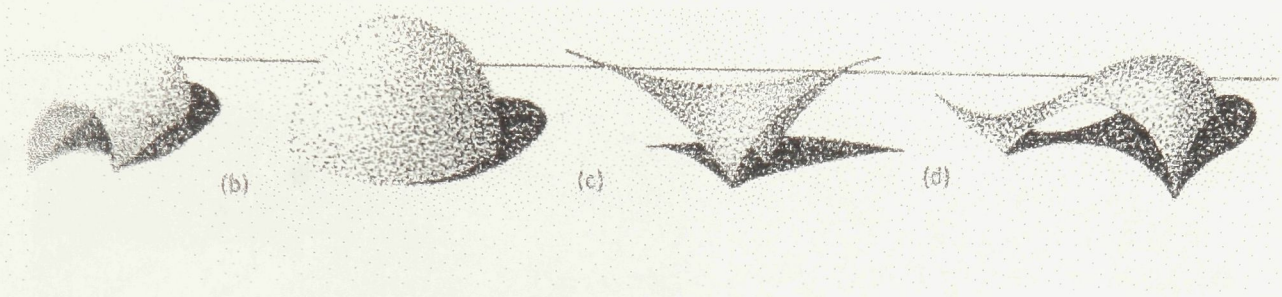

Figure 6 The different resulting shapes of shell curvature.

The flatter the curvature of the shell, the less load it can hold; the greater the curvature, the greater the load it can hold. In this way, shells can be architecturally classified into four different types: roof arches, with single curvature; domes, with double curvature; hyperbolic paraboloids, with double, inverse curvature; and free standing forms, a combination of all three (see figure 6).

Domes represent yet another kind of shell structure. In general, domes of double curvature can resist twice as much, or more, than barrel vaults with curvature in a single direction. At present, with the use of more efficient material, it is possible to reduce the thickness of structures for roofs and overcome clearings.

Another variety of shell shapes is the hyperbolic paraboloid designed by Felix Candela (see figure 7) in Mexico during the 1950's and 60's, which covers churches, gas stations and warehouses. The relative simplicity of design and construction is due to the use of straight elements (ruled surfaces) to form a double inverse curvature. The construction of a saddle is a classic example.

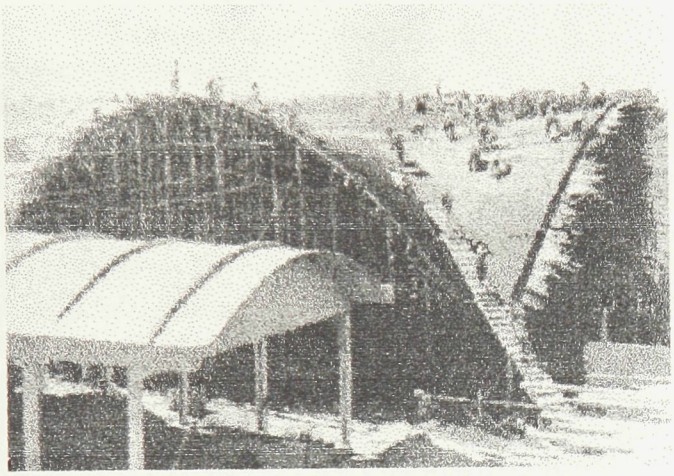

Figure 7 The process of constructing a shell structure is visible in this photo.

Colin Faber points out:

"During his career Candela began to gather everything that had been written on shells, seashells, and eggshells and to study their resistance to pressure, why they do not break, and so on."[13]

Candela did not favor meticulous and detailed calculations, or at least he did not base his work on them. At certain stages of his life, he trusted intuition:

"When I began constructing roofs, my mind was barely leaving the student stage. As students we believe everything we are told. For example, we believe we have exact methods to calculate structures. At that moment I began to lose faith in everything I had previously believed. This is a necessary starting point for anyone who is going to make something of his own."[15]

The crests, like the wrinkles or creases that pass toward the inner part of a shell, increase rigidity and resistance without increasing overall thickness too much. Structures can be resistant by being light in weight - like natural structures such as seashells- rather than by mass and reinforcement.

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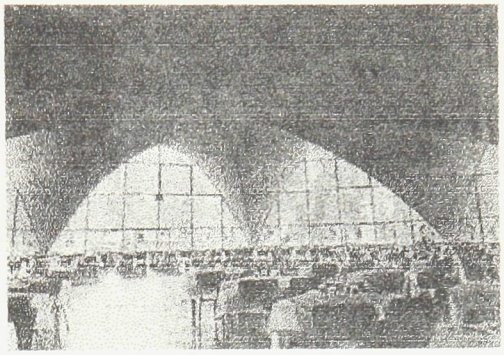
13 Colin Faber, The Structures of Candela. 2nd ed. Mexico: Editorial C.E.C.S.A., 1975, 210

15 Ibid. 212

Furthermore, the clear and straightforward structure delineates space thereby achieving overall harmony and the resultant form from the application of the structural principles that Candela applied generated natural or organic looking forms.

The principles of shell structure is stated in Candela words:

"It may be said there are two basic criteria for a proper shell:
The shell must be stable and of a shape which permits an easy way to work. It should be as symmetrical as possible because this simplifies its behavior. Either interior groins (as in the restaurant in Xochimilco) or exterior edges should be able to send loads to points of support, or else there should be a continuous support along certain edges.... A comparatively rapid, simple method must be found to calculate the membrane stresses. At the moment this seems possible only with the hypar shell, if by 'simple' one infers a procedure which mathematics, or specifically, in every case having to solve a system of differential equations to comply with previously selected boundary conditions."[17] (See figure 8).



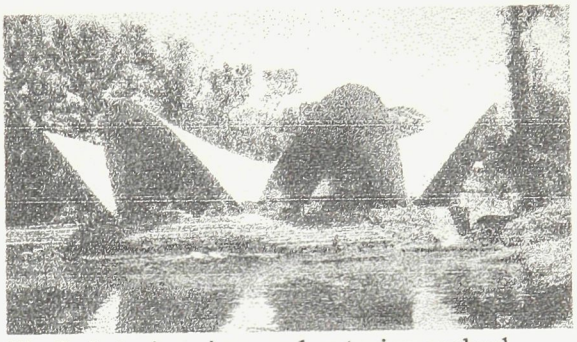


Fig.8. Interior view and exterior arched work of reinforced concrete of 4 cm thick concrete covers the 'crests'. Designed by Felix Candela. 1957-58.

The last variation of the shell is found in the free forms characterized by a combination of double curvature. The project of the architect Eero Saarinen for the TWA terminal in Kennedy Airport in New York City exemplifies a free structural design and represents a formal unit that is comparable to forms in nature, yet to Saarinen the structure was a determining factor in the expression of the form (see figure 9).

Michel Ragon in his book *Where shall we live tomorrow?* Points out that:

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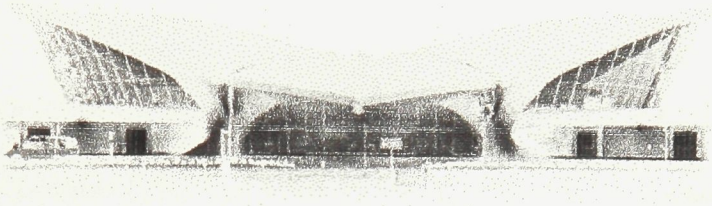
[17] Faber, Colin. Candela/ The Shell Builder. 199

"Eero Saarinen with his General Motors factory, called the Versailles of the twentieth century, had perfected the parallelepiped box of Mies van der Rohe, who changed the style completely a short while before his death... Following the school of Antoni Gaudi of Spain, he carries out his architectural work on the boundaries of expressionist sculpture. He conceives the idea of whirlpools starting from curved forms of concrete that suction and transport all the way to the vast shell of the interior where a comfortable and dramatic space is found...and in the word dramatic we include the ideas of surprise, mystery, and poetry".[19]

Eero Saarinen explained his designs:

"It could be said that it is all about structural forms that are derived from the laws of the curved shell. It is about an aesthetic will that seeks continuity in all architectural elements...The flow of all the elements makes it impossible to design it with drawings. The rehearsals will be made in the model all the way to the final solution...."[20]



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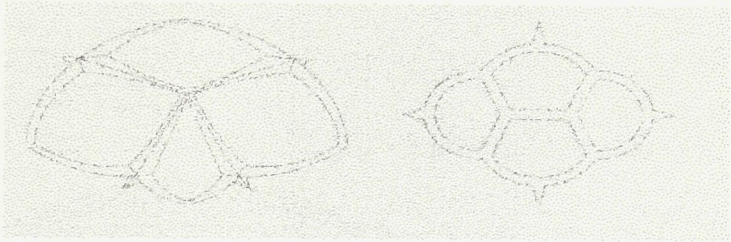

(b)

Fig.9. (a)TWA terminal at Kennedy Airport, N.Y. Saarinen,1958-61, (b) horizontal section of the roof of the TWA building compared to that of a Dictyonema 200x natural size.(From Senosiain' Bio-Architecture.p43.

Author of *Bio-Architecture,* Senosian notes that the top view of the airport seems visually and structurally similar to a Dictyonema cell found in nature. I find this comparison or analogy incorrect because by careful observation one can clearly observe that the structure of the cellular form and Saarinen's Terminal (top view) possess dissimilar angular conditions and are hence structurally different, though visually alike at a glance.

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19 Michel Ragon, op.cit., pg. 97

20 Curt Seigel, Structural Form in Modern Architecture, 2nd ed. Mexico D. F. Editorial C.E.C.S.A., 1967. 274

Geodesics

The natural origin of the hexagon is found in bubbles or spherical cells: whether they're the cells of complex organisms, viruses, or whatever, when grouped together and compressed by crowding, they adopt hexagonal shapes the intersections of which form angles of due to surface tension. This same pattern can be seen in the tortoise's shell and the giraffe's skin. It can also be found in the beehive.

Common to nature' structural principles, several architectural structures have incorporated the principles of geodesics to achieve desired forms to cover large spans. Among the most famous is the Eden project in Cornwall, England, where the entire structural framework applied in the making of the final form consisted of a network of hundreds of hexagonal units connected together in order to create the large 'Bioms'.

Chapter Three

The Structure of the Lily leaf and the Crystal Palace

Figure 1 The underside of the lily leaf which inspires Paxton's subsequent Two-way spanning structural system

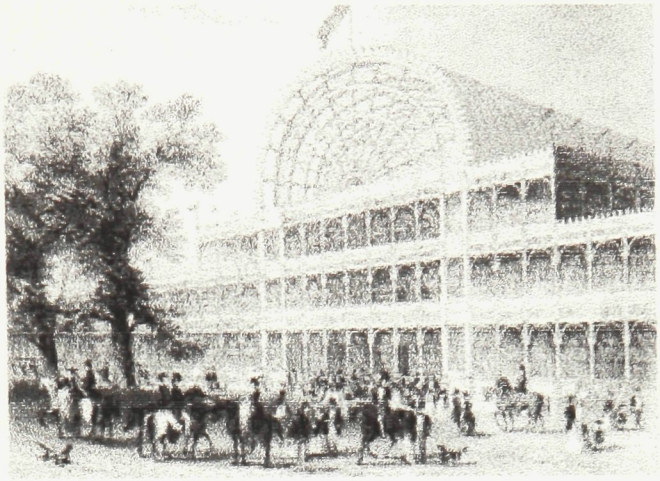

Figure 2 The Crystal Palace and Exhibition of 1851 in Hyde Park. (From McKean's Crystal Palace, P33)

Built in London for the first World's Fair in 1851, the Crystal Palace was a technological marvel of glass and iron. The Palace was 108 feet high and enclosed about 18 acres that housed fine arts and industrial goods brought by 17,000 exhibitors from all over the world.

The Crystal Palace was developed by landscape designer Joseph Paxton, whose idea for the basic structure was sparked by a water lily called Victoria Amazonica (known as *V. regia*). This water lily was famous for having huge leaves--more than a yard across that are so strong people can stand on them. When Paxton examined the underside of the leaves, he noticed that they were supported by ribbing where each leaf had radial ribs that were stiffened by slender cross ribs. This observation inspired him to make a glass and iron roof that was light but also stiff enough to span a large gap. Altogether, the Crystal Palace contained more than 200,000 12-by-49-inch panes of glass supported by iron.

Although neither engineer nor architect, Joseph Paxton's design and construction for the Crystal Palace raised doubts about the structure's safety from prominent scientists and engineers. They feared that the constant movements of large crowds inside the Crystal Palace would cause resonance, making the structure vibrate and eventually collapse. To test the Palace's safety, Paxton built a model and had 300 workmen tromp back and forth and then jump in unison. After his measurements revealed that the girders had moved by only a quarter inch, construction of the Palace was permitted to proceed.

After nine months of construction, the Crystal Palace was officially opened to the public in May the 1st 1851, on the grounds of Hyde Park, later to be dismantled and moved to Sydenham. It continued to house exhibitions and other social events for 85 years until its destruction as a result of a massive fire in 1936.

The construction of the crystal palace was a great fete of engineering and architecture in the 19th century. As a man-made accomplishment, it was a symbol of efficiency, economy, and architectural elegance at its best. Just as there is clarity in nature's principles and designs, the Crystal Palace presented an architecture that was structurally clear and expressive. It followed the program imposed upon it by need and introduced revolutionary methods of construction by employing the materials and structural components according to their qualities and properties. It also presented the concept of how iron construction may be made architectural without any system of disguise, paving the way for other architectural achievements to take form.

The Structure of Bones and Gothic Architecture

The expression of the anatomical similarity as applied to architecture can be traced back as early as 1770, when J.R Perronet said of Gothic cathedrals that:

> *"The magic of these latter buildings consists largely in the fact that they were built, in some degree, to imitate the structure of animals; the high, delicate columns, the tracery with transverse ribs, diagonal ribs and tiercerons, could be compared to the bones, and the small stones and the stones and voussoirs, only for or five inches thick, to the skin of these animals. These buildings could take on a life of their own, like a skeleton, or the ribs of a boat, which seem to be constructed on similar models".*[1]

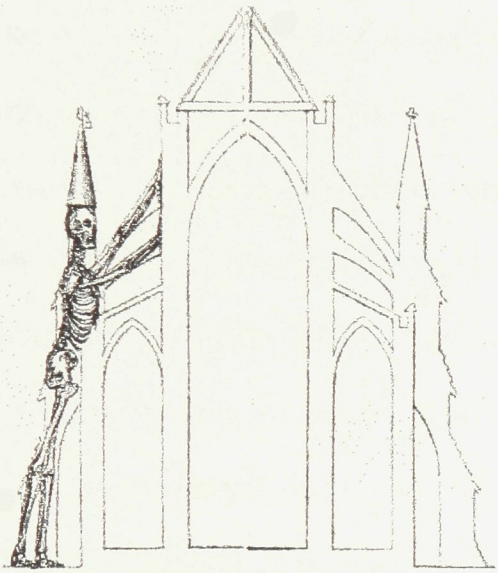

Figure 1 A.Bartholomew, diagram comparing the counter abutments of Gothic vaulting with the human skeleton. From Steadman's "The Evolution of Designs". 42

Perronet's image was dismissed by architect Patte, on the grounds that the static equilibrium of a construction in such a hard and unyielding material as stone could not be properly compared with the way the muscle and elastic, living structure of the body keep it in balance. Nevertheless, it was one that was used repeatedly throughout the next one hundred years, and with special reference to Gothic architecture [2]. (Figure 1)

Rationality and economy of structure were the primary principles that guided Gothic architecture. Viollet Le Duc was the greatest nineteenth century exponent of 'Gothic Rationalism'. R.D. Middleton, in a dissertation on '*Viollet le Duc and the rational Gothic Tradition*', traced the theme back to the same quoted passage from Perronet:

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[1] Philip Steadman. The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts. 42

[2] Ibid. 42

"Where Perronet put the view that in Gothic- unlike the mass and bulk which characterized for example Roman building- weight was pared down to an irreducible minimum, and opposing structural forces were exactly reconciled in the ingenious systems of counterbalanced vaulting, piers and buttresses which the Gothic builder has evolved".[4]

Spanning the enclosed volume was the primary structural problem of Gothic architecture: of closing the roof of the Church, while at the same time reducing to a minimum the area of supporting walls by which the roof was held up. The loads from the vault were brought together and concentrated onto a number of point supports, the columns, which transferred these forces to the ground. Meanwhile, the intervening area of the wall which in Roman and Romanesque architecture would have played the main structural role, was dissolved, removed and replaced in Gothic by the progressively larger areas of glass which in the end came to fill the entire space between external buttresses. The form of the vault was thus important and determined the whole supporting system that it crowned.

Figure 2 E. Violet le Duc, 'Cathedral ideale' - intended to reveal structural principles common to cathedrals. (from Steadman's "Evolution of Designs". 71

Viollet le Duc saw the pattern of ribs in Gothic vaulting, gradually elaborated into a hierarchy of interlaced primary and secondary members, resisting structurally in the most economical way and reflecting the exact pattern of distributed forces in the vault's warped surfaces. These ribs

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[4] P. Steadman, The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts. 42

were collected together at the head of each column, and their number, relative sizes and positions, distributed around the main shaft were therefore, determined by the pattern, proportion and dimensions of the whole vault. The compound profile of the column in cross section was determined logically by the conformation of the roof whose loads were carried down that column. (See figure 3)

It was the structural principles and the intellectual bases of Gothic building, which Viollet le Duc demonstrated in his writings. Although sensitive to the qualities of Gothic architecture which 'heightened spiritual feelings, to its symbolic language and the artistic expression of religious themes in its forms, decoration and carving'; although he had a 'sensuous and romantic appreciation of the style' [5], he disapproved of any attempts at systematizing architectural style through sets of rigid or mathematical rules. Steadman notes that:

Figure 3 St.Gimers in France.
(From www.carcassonne.org)

"It was understanding of function and structure that, for Violet - le- Duc was not only the key to historical interpretation, but provided lessons which were learned from Gothic and applied in modern architecture". [6]

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[5] Ibid. 43
[6] Ibid. 45

In addition to the structural framework of the Gothic vault which was designed on rational principles; the decorative features, including the moldings and other small details played their own functional parts, in throwing off rain, for example, and in providing counter weights to resist lateral thrusts.

Violet le Duc's writings on the structural principles of Gothic architecture had its pronounced impact on the works of Antonio Gaudi among other late nineteenth century architects, like Victor Horta and Hendrick Petrus Berlage. His writings, in particular L'Art *russe* (1870) influenced Gaudi's works, where the constituents of the national style were seen as being contingent on the principles of structural rationalism. Examples of Gaudi's architecture, like the Sagrada Familia Church, reflected Violet le Duc's writings, and yet, while Gothic in it's structural architecture, it had it's inspiration rooted in nature's principles. (See figure 4).

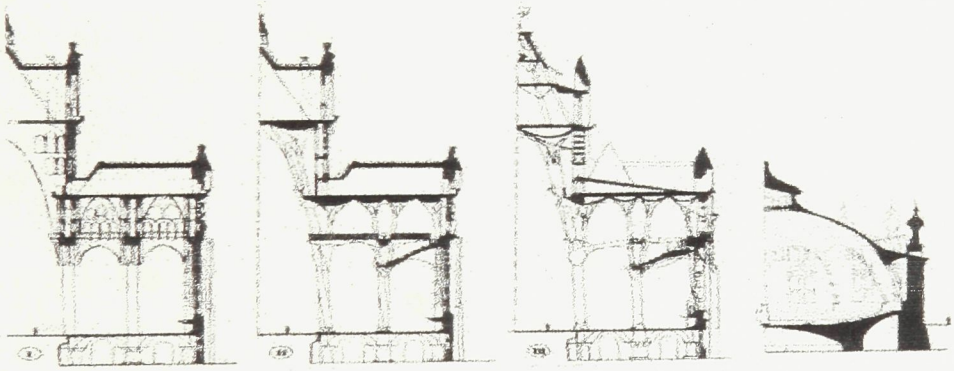

Figure 4 Gaudi, three progressive stages of the Sagrada Familia Church, Barcelona (left to right, 1898, 1915, 1918) and Viollet le Duc, Section for a Cathedral , from his *L' Art russe*, 1870. (From Frampton's "Modern Architecture: a critical history". 65

From the *Dictionnnaire Raisonne de l'Architure Francaise,* Violet –le-Duc confirms his rational philosophy of architectural structure by stating:

"Just as when seeing the leaf of a plant, one deduces from it the whole plant; from the bone of an animal, the whole animal; so from seeing a cross section one deduces the architectural members; and from the membranes, the whole monument".[7]

This method of deduction, which followed Cuvier's anatomical principle of the ' correlation of parts' [8], was illustrated in the relation of the vault to column in Gothic. Since the pattern of the ribs followed logically from the shape of the vault, and the exact profile of the column in cross section was determined by the ribs and how they were brought down onto the head of the column. As for the construction of the flying buttress (diagonal shoring of masonry on the outside of the building), its design acted as a practical solution to lateral forces. The buttresses, which were a new solution to a construction problem, became an integral part of the Gothic style, so much so, that in architecture as in nature an organism is an assemblage of interdependent parts of which the structure is determined by function and of which the form is an expression of the structure. Cuvier's rule of the correlation of the parts states that:

"This character of the organisms of nature is shared by at least one of he organisms of architecture. A person sufficiently skilled in the laws of organic structure can reconstruct, from the cross section of the pier of a Gothic Cathedral, the whole structural system of which it is the nucleus and pre-figurement. The design of such a building seems to me to be worthy, if any work of man is worthy, to be called a work of creative architecture. It is imitation not of the forms of nature but of the processes of nature."[9]

So in principle it was possible, for Viollet-le-Duc to work through the process backwards, and from the one part of the structure alone infer or construct all the others just as Cuvier did with the reconstruction of fossils.

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7 J. Summerson. "Violey-le-Duc and the Rational Point of View", Heavenly Mansions and other essays on Architecture, '*style*' , vol. 8. 482

8 By the 'Correlation of the parts', Cuvier meant the necessary functional interdependence between the various organs or systems of the body. Philip Steadman. 35

9 Ibid. 47

Trabeculae and the Eiffel Tower

Constructed for the 1889 World's Fair in France, the 984-foot Eiffel Tower was the tallest building in the world until 1930, when the 1,046-foot Chrysler Building was completed in Manhattan. This feat of engineering was inspired by work on the anatomy of the thighbone or Trabeculae, which was begun about 40 years earlier in Zurich, Switzerland.[10]

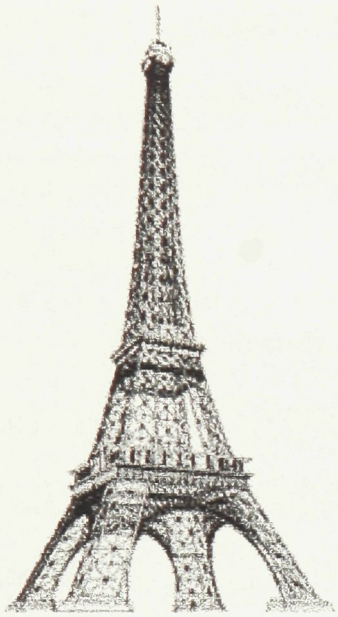

Figure 7 Eiffel Tower. (From http://www.paris.org/Monuments/Eiffel)

During the early 1850s, anatomist Hermann von Meyer was studying the part of the thighbone, or femur, that inserts into the hip joint. This joint was interesting because the femur head extends sideways into the hip socket, and so it bears the body's weight off-center. Von Meyer found that the inside of the femur head contains an orderly latticework of tiny ridges of bone called trabeculae.

"The trabeculae spread in beautiful curving lines from the head of the hollow shaft of the bone; and these linear bundles are crossed by others, with so nice a regularity of arrangement that each intercrossing is as nearly as possible an orthogonal one: that is to say, the one set of fibers cross the other everywhere at right angles" [11]notes D'Arcy Thompson in Growth and Form.

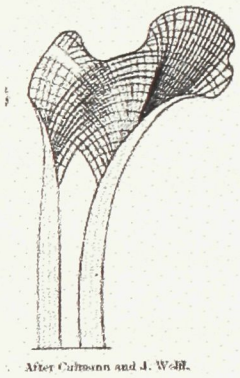

Figure 8 Thompson's diagram of the stress lines in a crane and a femur. The femur represents a kind of engineering optimum, an excellent balance of lightness and strength. (From http://pharyngula.org/index/bone_and_pattern/

In 1866, Swiss engineer Karl Cullman visited von Meyer's dissecting room. The anatomist

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[10] http://nationalzoo.si.edu/Publications/ZooGoer/1999/4/designsfromlife.cfm
[11] Ibid.

showed the engineer a section of bone.

> *"The engineer saw in a moment that the arrangement of the bony trabeculae was nothing more nor less than a diagram of the lines of stress, or directions of tension and compression, in the loaded structure: In short, that Nature was strengthening the bone in precisely the manner and direction in which strength was required,"* [12] notes Thompson.

Besides showing that the trabeculae were effectively a series of studs and braces arranged along the lines of force generated when standing, Cullman also showed that this is one of the most efficient ways of supporting off-center weight, a finding that underscores the benefits of designs inspired by nature.

This basic concept of building along the lines of force inspired French structural engineer Gustave Eiffel to design the flared tower that bears his name. Like the curve in the head of the femur, the famous iron curves of the Eiffel Tower are supported by an intricate latticework of metal studs and braces. Eiffel calculated the curve of his tower's base pylons so the bending and shearing forces of the wind would be transformed into compression, a force the pylons could withstand more effectively. The same principle was used to design other skyscrapers.

We can thus conclude from the example above that nature has perfected ingenious designs that are ours for the taking. Nature's principles and designs continue to inspire and spark the creation of structures and forms that are becoming increasingly efficient, strong and economic. Furthermore, there exists a purpose in design in living forms and as a result architecture will benefit greatly from studying nature's principles and designs.

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[12] Ibid.

Case Study: Santiago Calatrava and the City of Science- Valencia, Spain.1991-2000.
Science Museum and Planetarium.

Calatrava's 'Museo de las Ciencias' is part of an arts, culture and leisure complex, alongside the now dry bed of the River Turia, all commissioned by the City of Valencia in an effort to create a national cultural center that exemplifies the finest aspects of contemporary Spanish architecture. In addition to the museum, there is the Palace of Arts, a cinema and a planetarium. This has given back a new focus to an incoherent and under developed area, while linking and providing a marker for the outer areas of the city.[1] (See figure 1)

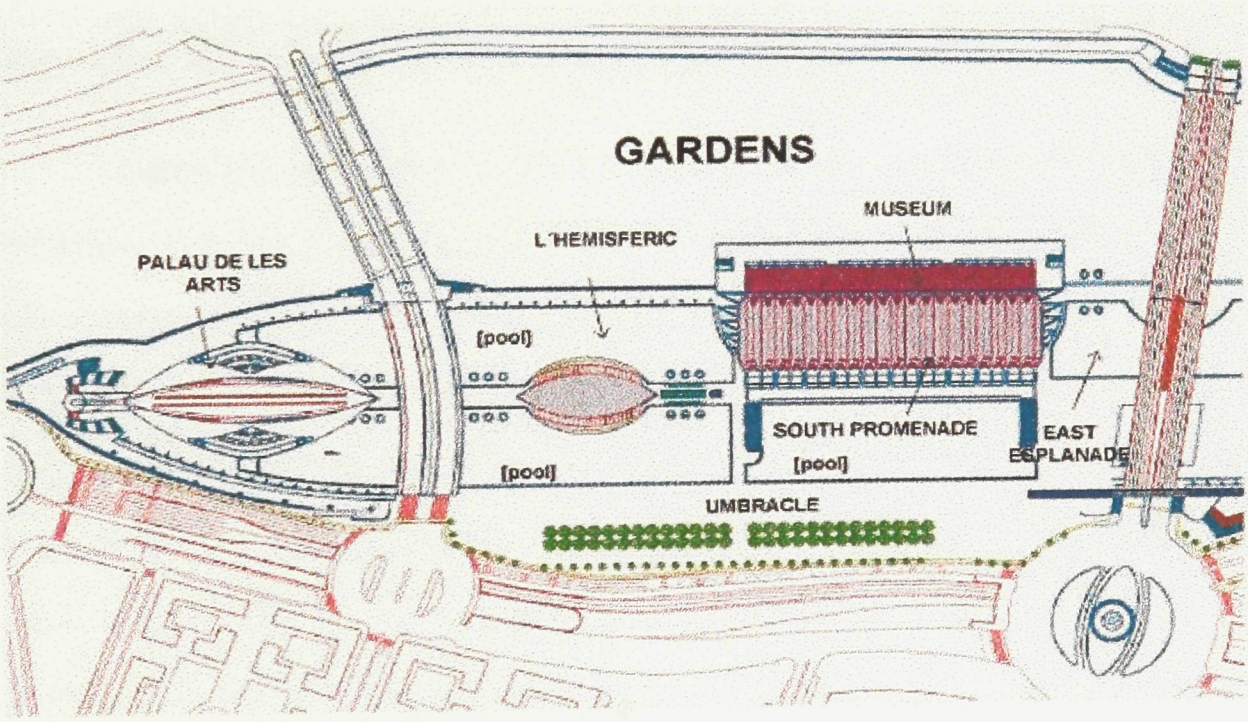

Figure 1 Final site proposal for the City of Science. From http://www.cac.es/cac

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[1] Tischhauser, Anthony. *Santiago Calatrava: Public Buildings.* 1998. 154-155
2. Usher, Rod Santiago Calatrava Time Magazine.2002.
<http://www.time.com/time/europe/specials/ff/trip3/calatrava2.html>

Figure 2 View of the City of Science showing Planetarium, Museum of Science and South Promenade viewed from the Palau de les Arts. (From http://www.cac.es/cac)

Santiago Calatrava notes:

"As the site is close to the sea, and Valencia is so dry, I decided to make water a major element for the whole site using it as a mirror for the architecture."[2]

Organized from east to west, the original individual components of the scheme comprised a planetarium, museum and library. The library and the planetarium however, were later combined to form a single unit between the museum and the tower (now the Palacio de las Artes (See figure 2). Two principle buildings were organized around a central raised promenade running from the foot of the tower to become the longitudinal axis of the site, offering views out towards the sea. This walkway, an integral part of the overall landscaping, served as an ordering element with gardens extending to either side and, as a reminder of the site's fluvial past, shallow reflecting pools embracing the planetarium, and covering the library, cinemas, several auditoria and restaurants beneath. Further strips of water marked the northern boundary of the science museum.

Calatrava states that:

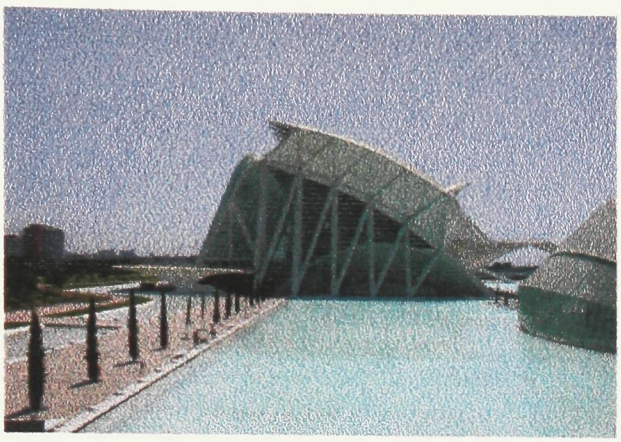

Figure 3 Enforcing the element of water into the design in the City of Science, here a view of the Museum of Science in Valencia .(Photo courtesy Manuel Baez)

"What I have tried to create is a city that is within Valencia, but lives by itself. I wanted to give it the character of a park. I am proud of the fact that people can walk through and around the main buildings without paying. It is a city to be discovered by promenading. There are more than 7 km of promenade. This is very Mediterranean, very adequate for the climate of Valencia. So is the water, which offers freshness and also mirrors and duplicates the buildings." [3]

The science museum was contained in a large linear volume (see figure 4). The sunken garden extended beneath the walkway to optically connect the museum to administrative buildings originally organized along the full length of the Camino de las Moreras and now relocated to the main science museum building. Two levels of car parking replace this administrative center, while a new motor bridge, crossing the river bed to the north east, is arranged to pass over a shopping mall of the south east corner at the planetarium's initial location.

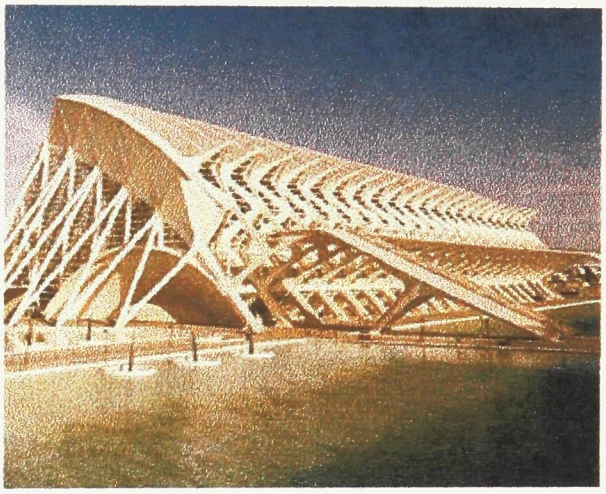

Figure 4 Museeum of Science in Valencia, Spain, designed by architect Santiago Calatrava. (From http://www.cac.es/cac)

The first proposal for the planetarium included a low slung, flat roofed structure that, in plan, resembled and isosceles triangle with concave sides. In the reworked scheme, the globe – the heart of the planetarium – is roofed over

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[3] Ibid. 2

by an elliptical shell structure. In a subsequent version, longitudinal sections of this shell can open to the sky, while in a further development; this globe is placed within an elliptical pad, cradled like the pupil of an eye. Its "pupil" is a planetarium, also containing an IMAX cinema and a lazerium. The concrete socket of this eye is modified to incorporate elongated, aluminum awnings that differ in length and fold upwards to form a brise- soleil roof that opens along the curved, composite, above the central axis of the eye shape. In the final design, the concrete encasement has been extended upwards, and the brise – soleil has been narrowed and replaced by a system of slats mounted on each side of pivoting, central stems to imitate the structure of a feather. To either side of the base, elongated doors of vertical, articulated slats can be raised to permit views across the pool. The planetarium, set slightly below grade to avoid visual conflict with the science museum and the opera House, is entered through the sunken gallery – formed by concrete arches (case in situ) that support the transparent roof- which in turn houses ticket booths, a restaurant and other services.

The original scheme had envisaged an underground connecting system between the buildings. This concept was resolved in three pathways: the central promenade along the axis of the site; and two further promenades, one to the north along the banks of the former river, and one to the south, raised to give views over the excavated area. The pools have been extended to replace the garden beside the museum. Water now stretches from the Palacio de las Artes in the west to the shopping in the east.

Covering 41,000 square meters and resembling a prehistoric-skeleton the science museum is a longitudinal building, with the repetition of the modular, transversal sections along the whole length of the site, is a special tour de force. The Science Museum, a building of white concrete and cascades of glass that from some angles conjures a 220-m-long dinosaur's spine caught in an ice floe. From another standpoint, it's a soaring forest of petrified trees [4]. (See figure 5)

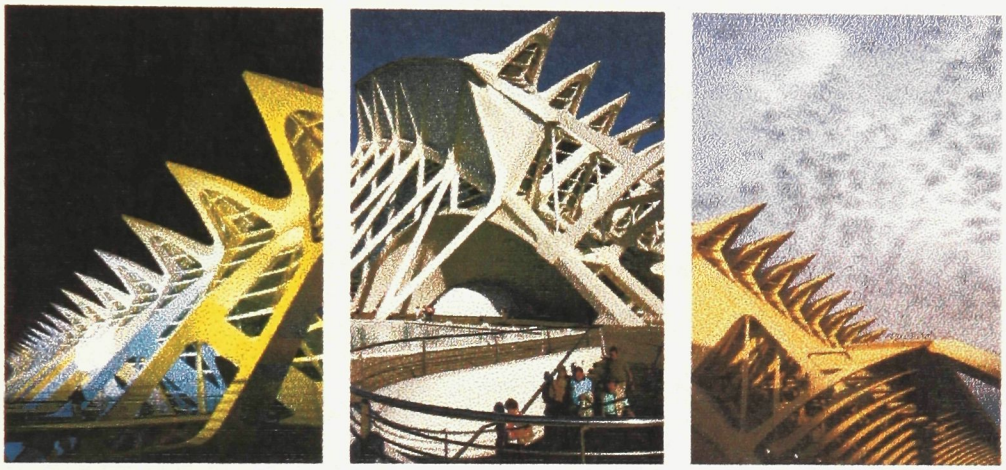

Figure 5 Museum of Science , viewed from different angles
(From http://www.cac.es/cac)

Like Frank Gehry's Guggenheim in Bilbao, container tends to compete with content, in Valencia's case a brilliant series of scientific "edutainment" displays where the main rule imposed by director Manuel Toharia is that "*it is prohibited not to touch the exhibits.*"[5]

The first impression of the interior of the museum is of a delicately arched space whose structure admits a flood of natural light. This impressive,

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[4] The Museum of Science: Case Study, Valencia , 2002
<http://www.corusconstruction.com/page_9113.html>

[5] Usher, Rod Santiago Calatrava Time Magazine.2002.
<http://www.time.com/time/europe/specials/ff/trip3/calatrava2.html>

extensively glazed building runs parallel to the former riverbed and the repeated concrete 'rib bone' perpetuates the biological analogy. Like the grand and traditional pavilions of the great exhibitions of the past five linearly organized concrete "trees" branch out to support the connecting line between roof and façade on a scale that permits the integration of service cores and lifts. With a series of 21 arched saddle roofs running in parallel, Calatrava reduced this immense roof area to acceptable proportions (see section of the roof on figure 6). At the same time, performance was at the forefront with a functional system for the draining of rainwater via central 'gutters' between each rib of the roof. A total of 21 concrete spans embrace each section of the roof (see figure 7).

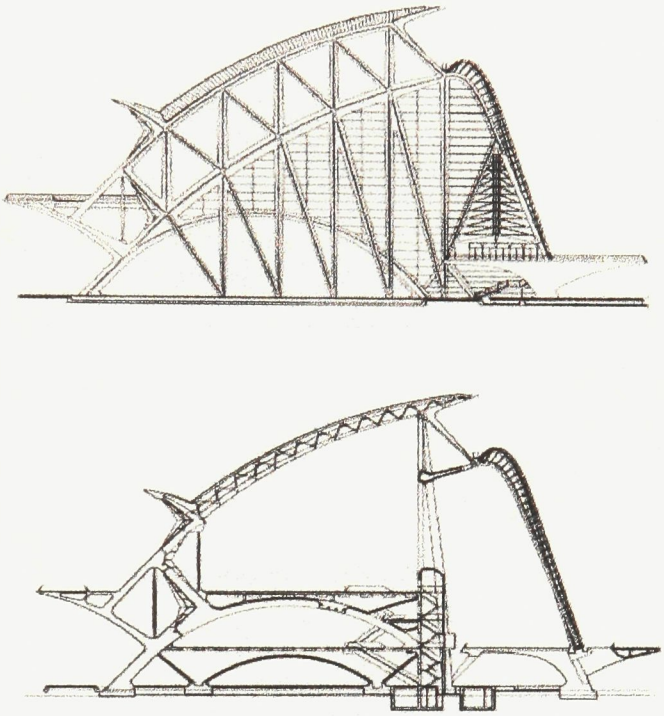

Figure 6 Elevation (top) and structural detail of the Museum. (From Tischhauser's "Santiago Calatrava: Public Buildings".152

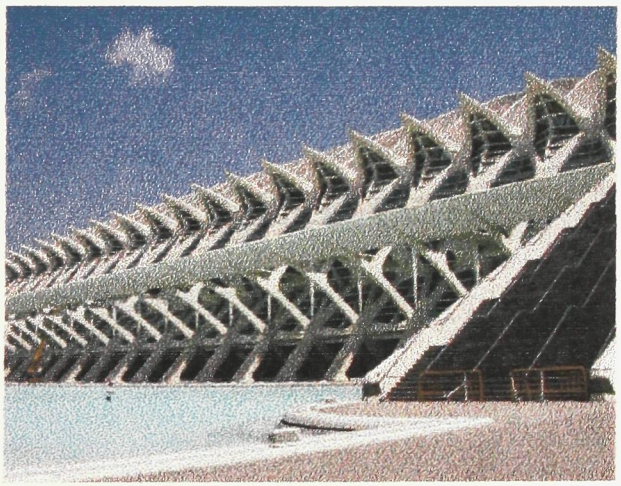

Figure 7 Showing ribbed roof of the Museum of Science. (Photo courtesy Manuel Baez)

Calatrava's design specified a built up roof system with a smooth inner skin – this was achieved by the

installation of polyester coated steel pan ceiling profiles. Each pan was fitted on-site and supported 60mm of semi-rigid thermal insulation. The convex ridges of the roof structure are clad in aluminum flashings color coated in white to complement the concrete structure. The supporting structure comprised 60mm deep omega profiles mounted within the pan profiles. The omega profiles, pan profile brackets and the insulation were then overlaid by a vapor control barrier. The ST 50 clips, with thermal barrier pads, are fixed through this sub-structure to allow the fixing of the Kalzip outer sheets. The thermal insulation of the roof comprises a 80mm layer of mineral wool compressed to 50mm. The outer skin of the roof comprises a total of 11,500 square meters of Kalzip 65/333 profiles, 1mm gauge, and stucco embossed finish installed in sheet lengths of 5.4 meters. The ridge detail was executed in the conventional manner by means of lock plates.[6]

The cladding of the rising bays of the museum is the same as that used for the roof to give an overall integrity of design and appearance, interspersed by the same lateral concrete arches. Reflecting a diffuse light, the large glazed areas, light concrete spans and water features – all reacted to the dramatic effects of the Mediterranean sun.

The symmetrical ends of the building are braced firmly by triangulated structures that also mark the entrances (see figure 8). The white supporting concrete framework of the south facing façade is filled with glass; the north façade is a glass and steel screen that forms a continuous curtain along the full

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[6] The Museum of Science: Case Study, Valencia , 2002 <http://www.corusconstruction.com/page_9113.html>

length of the building This is a modular development of 104 meters width and 241meters in length.[7]

The surface of the water on the southern side of the museum not only projects filtered light into the vaulted hall of the museum but also assists the air-conditioning system by cooling and humidifying the air flowing into the hall.

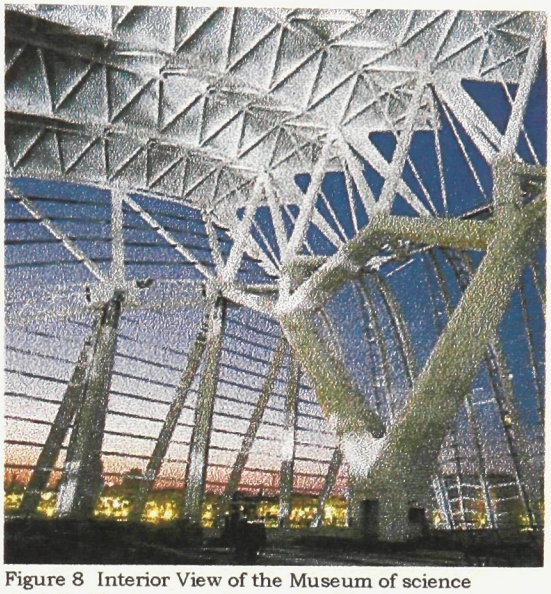

Figure 8 Interior View of the Museum of science showing the structure supporting the roof. (From http://www.cac.es)

The primary interior finishing of the Calatrava's Museum of Science consists of granite floors, glass walls and other hard surfaces (see interior view of the finishing on figure 8). In some cases, critics have noted that the building becomes a vast echo chamber. With voices of hundreds of visitors, the center becomes noisy. The acoustical aspect in a large building such as the Museum of Science must be considered. Yet regardless of such problems, Santiago Calatrava's Science museum is regarded as a demonstration of the opportunity that extends to modern architects today. His architecture is one that is reflective of the advancement in the fields of science and technology. Furthermore, Calatrava's architecture is strengthened by his refined aesthetic sensibility that is informed by his engineering skill.

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[7] Ibid.

Cells and Tissues and Architecture

Cells have frequently been called architectural- and they are according to David Goodsell, a molecular biologist, even makes them into practicing architects.

"Cells are inventive architects... To build these elaborate structures... one can find examples of any engineering principle in use today, Fences are built, railways are laid, reservoirs are filled, and houses are constructed complete with rooms, doors, windows, and even decorated in attractive colors. Lap joints, buttresses, waterproofing, reinforcing rods, and valves, concrete, adhesive-each have a molecular counterpart. "[1]

The word "Cell" was first used in something like its biological sense by Robert Hooke (Cosmographia, 1665). He was describing the rows of tiny cavities in a slice of cork. But the primary meaning of *Cella* is "small room". Hooke's conception ties in, too, with the notion of tight packing since that is how cells are arrayed.

The post-Neolithic Cypriote house-plans are considered among the oldest remains, anywhere, of human habitations.[2] The people of Lamba-Lakkous (see figure 1) organized their houses in a cell- like way, with an outer membrane, a nucleus hearth, various "organelles" or household elements such as

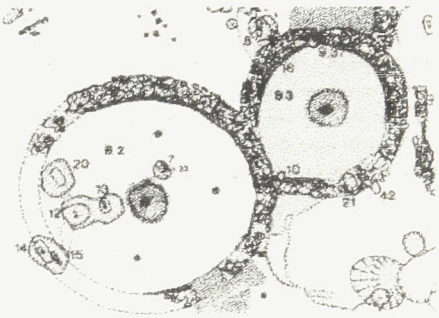

Figure. 1 Lemba- Lakkous, Cyprus. Detail from 1980 plan of excavated remains of Chalcolithic I (c3900 BCE) settlement. (From Karageorghis's "Cyprus from the Stone Age to the Romans". 33

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[1] Goodsell, Our Molecular Nature. 81
[2] Vassos Karageorghis, Cyprus from the Stone Age to the Romans. 33

fireplaces, and sleeping and cooking equipment in between. All these elements are essential devices for survival and reproduction. The house plans are in fact sections through spheroids- prolate, oblate, or otherwise stretched- much like body cells. This is true only of the plans, however: as for the houses' elevations, masts draped with vines or hides were raised in the central socket as protection against the weather.[3]

The builders of these dwellings would have known similar forms in their immediate surroundings- things that, unlike true body cells, were visible to the naked eye. On prototype would be the egg, which begins as a container for a single- cell embryo embedded in the nourishing matter it will need in order to reproduce and grow. And then there are cell- like beehives, bird's nests, and plants. To the Greeks, moreover, and therefore maybe even to the Chalcolithic residents of Lemba, the word for cell (Kutos) also meant Uterus, and even the whole human body. This does not, according to Hersey, necessarily mean that the Lemba cells are the extended phenotypes of builders whose own bodies, though they did not consciously know this, were put together similarly.

The idea has continued down the centuries. One architect who felt it strongly was the German expressionist Hermann Finsterlin. Around1919, he was to write *Francesco di Giorgio Martini.*

"Tell me, have you never regarded your holy body as a building composed of the tiniest, most emancipated single-cell structures? What if we are only living architectural cells, Lilliputian elements that build themselves into the

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[3] George Hersey, The Monumental Impulse. 19

giant proliferation of their organic machinery...[W]e could follow the thousand –times more beautiful example of lice and beetles when they build their breeding- palaces directly out of the bodies of living plants- *greenly glittering, sap- swollen domes in which the chorus of the world rings out no less beautifully than in the columned halls of a solar system."*[4]

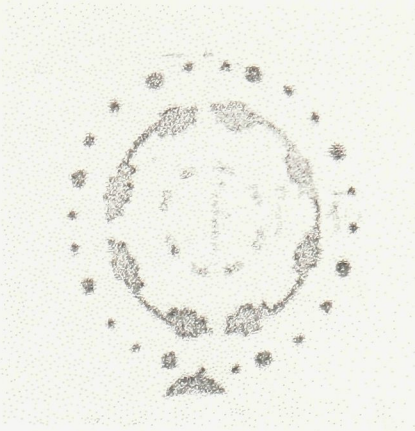

Figure.2 Plan of a Church by Francesco di Giorgio Martini. From Hersey's " The Monumental Impulse" 19

In this sense the Cypriot village is another instance of humans creating their architecture as body parts or clusters of such parts writ large. The village's site plan, particularly recalls modern diagrams of cell division and aggregation – meiosis, mitosis, and so on. Thus there is a fractal or tensegral chain leading from tissue cell to natural cell- like entities created by animals to human body parts, all of them rather similar in form, and in several cases with the smaller forms composing the larger. [5]

In his book, *The Monumental Impulse*, George Hersey, states that cellular architecture is not limited to monasteries, prisons, and prehistoric villages by presenting an example of a plan for a domed cylindrical church by the Renaissance architect Francesco di Giorgio Martini (see figure 2). Here an outer colonnade with large columns containing pairs of smaller columns act as the cell's outer sheath. Within that, and concentric to it, is the wall proper, articulated with clustered pilasters matching the outer column- pairs. Inside this is the space, labeled nave, for the congregation. It is screened from the alter area or *tribuna* by further column-pairs.

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[4] Hernan Finsterlin, undated letter to lain Boyd Whyte, ed. The Crystal Chain Letters: Architectural Fantasies by Bruno Taut and His Circle (Cambridge, Mass.: IT Press, 1985). 91

[5] George Hersey, The Monumental Impulse. 18

Like the Lemba house plans, Francesc's "cell" has its interior "origanells" of furniture (including on e or more organs), its outer membrane – the masonry and architectural equivalents of the real cell's outer plasma membrane – the masonry and architectural equivalents of the real cells' outer plasma membrane- and a nucleus in the form of a central lantern. Other organelles in the church would be the cornices, entrance, entablature, windows, steps, and so on. In cellular language, the dome's inner surface of coffers could even be given the cytological name of "endoplasmic reticulum" (a reticulum is a net or grid), and dome interiors normally are reticulated on their inner skin into coffers. That the church was to consist of four identical versions of this cell in other words, that it was to be a tight packed array- reinforces its cellular nature.[6]

Buildings and cells, then can resemble each other; but so can whole cities. As James E. Rothman and Lilio Orci recently put it: " All nucleated cells- whether in colonies of yeast of in plants and people- have complex internal organization resembling that of a well run city."[7] In their drawing, the long, densely folded interior rapping constitutes the endoplasmic reticulum. The Golgi apparatus is a series of globules, a kind of industrial zone connected by channels where proteins are processed. Small, independent globes near the front of the drawing are vesicles that transport proteins from place to place inside the cell. The Lysosome is a lobed chamber in which worn out component

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[6] Ibid. 19

[7] James E. Rothman and Lelio Orci, "Budding Vesicles in Living Cells," Scientific American, March 1996. 17

molecules are recycled. Thus the whole organism is an urban industrial complex.

A cutaway view through a cell in completed form resemble a soft irregular blob. Only by cutting it open (and using a microscope) can one actually sees the concentric walls, the central rounded keep or citadel with its batted bank of ear shaped battlements, the walled streets, the outer gardens (i.e. the area filled with cytosol or fluid in the cytoplasm surrounding the cell's nucleus), the semi-independent suburbs and the bastions on the perimeter. Rothman and Orci liken all these elements to the gated fortifications of an ancient city. The whole set up controls the entry, distribution, and exit of food and other supplies to and from the "city". (See figure 3).

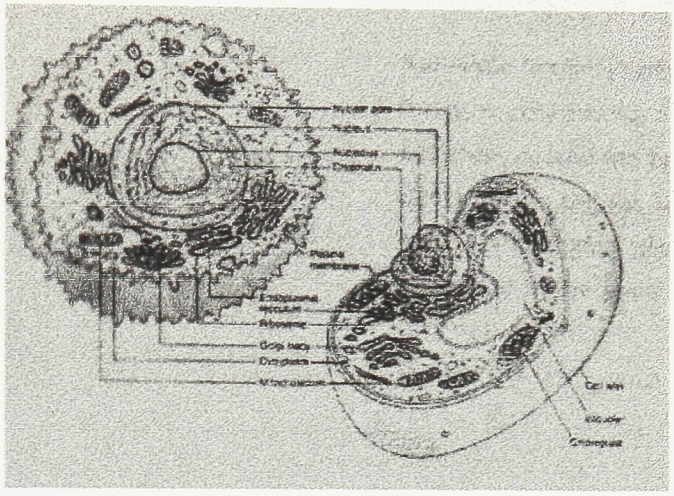

Figure.3 Cross section of a typical cell. From Rothman and Orci, "Budding Vesicles in Living Cells." Drawing by Toma Narashima. (From Hersey's " The Monumental Impulse" 20)

Though Pieter Bruegel could not see such a view of a cell, this whole cross section does resemble that artist's famous vision of the Tower of Babel (figure 5). The rising walls of Bruegel's city have the same curved concentric and the city itself, though clearly made of masonry, has the rounded elasticity that we see in cell.

But the possibility that in drawing out his image of the cell, the *Scientific American* Artist, Tomo Narashima, was influenced by Bruegel's image or something similar. He pushed the cell's perspective upward and pulled the nearer parts of it downward to display as much as possible of its interior. As a result, the cell's urban configuration- it's concentric walling, the cistern like vesicles, and the spiraling orientation of the whole toward its nuclear center- are given special focus. Four hundred years earlier, Bruegel had given Babel the same flowering thrusts, and for the same reason (see figure 4). But, Hersey notes here, if Narashima was influenced by Bruegel or one of his imitators, so what? That only reinforces what binds the images together. And of course the cells of Narashima's own hand, brain, and body are just as Babel like as Bruegel's were.

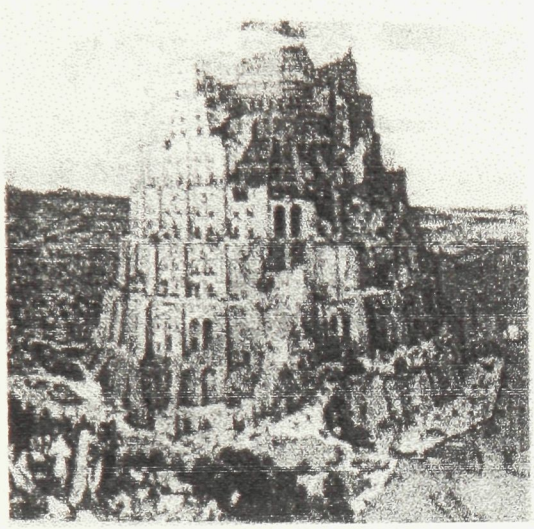

Figure.4 .Structure as the cell's endoplasmic reticula; Pieter Bruegel the Elder. The Tower of Babel, 1563. Vienna , Kunsthisstorsches Museum. (From Hersey's " The Monumental Impulse" 20)

Single Celled Organisms

Compared to ordinary tissue cells in multicellular organisms, the one – celled organisms called protozoans exist at a slightly larger scale of size and complexity. Protozoans have fascinated artists and architects ever since Leeuwenhoek began looking at them [8] (see figure 5). Their bodies, though consisting of a single cell, may develop parts and articulations that approximate the separate organs of metazoans, or multi-celled animals. Just as a virus is a single molecule with a head, tail, and legs, so a one-celled organism gestates its means of locomotion, its stomach, its reproductive system and all its other functioning parts from its single cell. Paradoxically, and in contrast to the orderly, tight packed arrays of metazoans' cells, protozoans can be among the most flamboyantly ornate of nature's shapes.[9]

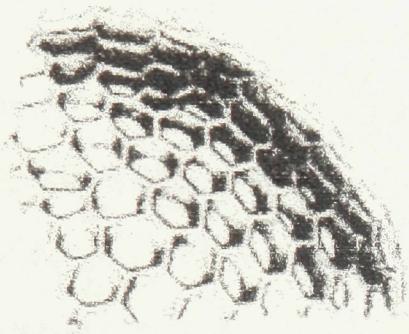

Figure.5 *Ceriosphaera*, From Haeckel, Die Radiolarien.(From http://caliban.mpiz-koeln.mpg.de/~stueber/haeckel/radiolari

As source of architectural inspiration, the protozoan's heyday came during the age of Haeckel, from about 1800 to 1920. His drawings of microscopic sea creatures greatly affected the art nouveau movement. They were published between1899 and 1904 in an influential work that was translated into many languages.[10] As a result, the years around 1900- the

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[8] Ibid. 21

[9] See O. Roger Anderson, *Radiolaria* (New York: Springer,1983), though according to Hershey, his micrograghs are less glamorous than the drawings in Ernist Haeckel's classic *Die Radiolarien*, 3 vols. (Berlin: G. Reimer, 1862-1888).

[10] George Hersey. 23

years of art Nouveau in France, Jugendstil in Austria, Florence in Italy, and Louis Sullivanin the United States, saw any number of buildings and other artifacts take their forms and colors from oceanic and other micro organisms.

In an article by Erica Krause, in the catalogue to the 1993-1994 French exhibition *L'Ame au Corps: Arts et sciences 1793-1993,* shows off this side of Haekel. Krause also influenced the French architect Rene Binet[11] and reproduced a drawing by Haekel for his monograph on the Radiolaria. Haekel's image represents a *Dictyopodium scaphodium.*" (scaphe= bowl; dictyopodia= "net-feet"). Like the dictyopodium itself, Binet's triumphal gateway is a tightly swollen lattice curved into a huge, three- legged truss, with two legs in front and one behind. The gate, again like the animal, forms an open, webbed dome. Binet's structure is outlined with arrays of light bulbs beaming light to the world in the manner of a sea creature's organs of luminescence. [12]

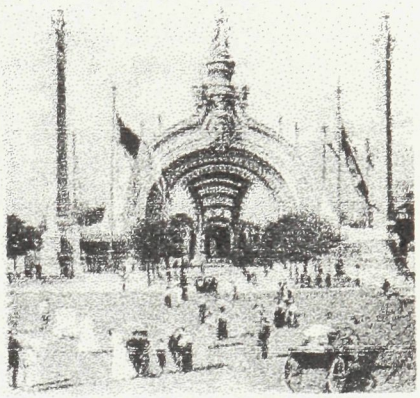

Figure 6 Rene Binet. Porte Monumentale for the Paris Exposition of 1900. (From Hersey's "The Monumental Impulse" 23)

Figure 7 Haeckel's drawing of *Dictyopodium scaphodium.*(From Hersey's *Monumental Impulse,* p 32)

A more recent architectural example of cells / architecture resemblance is the Fuller's USA Pavilion at the 1967 Montreal Exposition illustrated the architecture of this cell.

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[11] George Hersey. 22
[12] Ibid. 23

Like many molecular formations, that resemble cellular structures, the *buckyball* is an Archimedean sphere made out of the frames of pentagonal and hexagonal surfaces (see figure 8). The normal unit consists of five hexagons surrounding a pentagon. When enough of these shapes are assembled with all edges touching, the result will be a faceted spherical surface like that of the U.S.A Pavillion.[13]

Knowing that the principles of the buckyball multiplies tiny shapes and aggregates them into successively larger ones, suggesting self - similarity, indicates something comparable to the way protozoans reappear in human architecture.

Figure 8 United States Pavilion by Buckminister Fuller 1967 at Montreal Expo.
(From http://www.collectionscanada.ca

Today's human architecture continues to be influenced and inspired by the works of nature. One prominent example of cell formation transformed into architectural interpretation can be seen in the Eden project, in Cornwall, England.

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[13] Ibid. 44

CASE STUDY: Nicholas Grimshaw -Eden Project, Cornwall, England (completed 2001)

"Is there anybody out there who doesn't, in quiet moments, feel in his or her heart that the future lies in working with the grain of nature? We are creatures. We may live in concrete burrows, and cover ourselves up in a million different ways, and talk of our command over all we survey. Yet nothing can disguise the fact that we are part of nature, indivisible from it. At Eden we want to explore what that means" [1]

Figure 1 Eden Project in Cornwall, England.
(From http://www.edenproject.com)

The primary aim for the Eden project was to promote the understanding and responsible management of the vital relationship between plants, people and resources leading to a sustainable future for all (see figure 1). Through the design of a theatre, that tells the story of human dependence on plants a series of giant conservatories were built to stand high, wide and high enough for the towering trees of the rainforests.

According to Eden's Chief Executive, Tim Smit, Eden has become a symbol of regeneration, bringing life and community where there was none in that particular area of Cornwall.

"Yes, we wanted a cauldron where science, technology and the arts could be cooked into an entertaining and educational experience, inspiring us to look at the world with fresh eyes. We are working with partners in Development, the Environment, Industry and Science, creating a new Foundation to explore and champion an understanding of the interdependence of people and plants."[2]

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1 Tim Smit-director of Eden Project.
2 Eden Project, on www.edenproject.com, retrieved on Jan.2, 2004.

More so, Smit believes that the project became more than the previous statement. The project was built to promote solutions to the world's challenges.

" We want Eden to become a meeting house where we can ask: what do our best possible futures look like- and how do we get there?"

In January 1999 the land (see aerial view on figure 2) where the Visitor Center stands now ran into some serious complications, as a result of 43 million gallons of underground water filling an existing pit. Yet the enthusiasm for the project was the driving force towards its successful completion. Smith notes:

"In a world of -isms and -ologies, of expertise so refined that only experts understand it, we have brought together scientists, artists and technologists to create a distinctive culture, one that makes the possibilities of the future come to life in a way that we can all comprehend." [3]

A 50-meter deep crater is home to thousands of important and exotic plants. Three of the world's climate zones ("Biomes") have been chosen for interpretation: The Humid Tropics (Rainforests and Oceanic Islands) and the Warm Temperate regions (the Mediterranean, South Africa & California) are contained within the two giant Conservatories. The third, or

Figure 2 Aerial view of the site, while work was in progress. (From http://www.edenproject.com)

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[3] Ibid. 2

"Roofless Biome", is the temperate zone that thrives on the climatic advantages that Cornwall offers. There, a wide range of plants from the India to Chile with the native flora of Cornwall, the Atlantic rainforests, and many of the more familiar crops.

The site was a south facing, sheltered location, with a sea view. The site resembled a crater with 60m deep the area of 35 football pitches. That said, it also possessed disadvantages, the most prominent problem was that the site curved in an inverted cone shape with little level ground and the second disadvantage was that the ground was all rocks and insufficient and unstable soil. (figure 3 shows a model of the site). With a pit area of 15 ha, out of a 50 ha site area, 1.8 million tons of soil was shifted to create a level bottom in the pit in order to create the stage on which to plant. All the soil on site was made from china clay waste and composted green waste 85,000 tons of soil in all. As for the foundation for the Biomes, they were in the form of a huge necklace in the bottom and continued up the back of the wall of the pit, 2metres wide, 1.5 meters thick and 858 meters long.

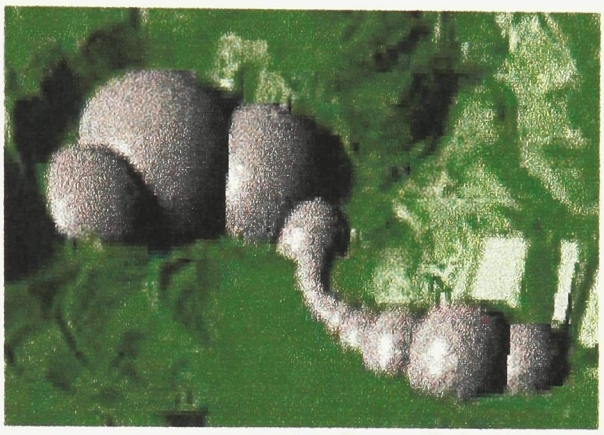

Figure 3. Locating the project within the site layout. (From http://www.edenproject.com)

The building process of the Biomes, required the construction of the largest scaffolding in the world- 12 levels; 25 meters across. According to Tim Smit :

"The largest Biome is 240m long, 55 m high and 110m wide - with no internal supports. It is large enough to house the Tower of London and tall enough for a tower of 11 double decker buses. It is also long enough for a nose to nose traffic jam of 24 buses."[4]

The early concept for the design of the Eden project conservatories consisted of structures that evolved over several months. Grimshaw notes that "designs were done on the drawing board, on computers and even on napkins." The first design by Grimshaw was initially asked to prepare proposals for the Eden Project because of their work on the international terminal at Waterloo. The influence on the design at Waterloo (see figure 3) had come from techniques developed in the 19th century for the design of glasshouses that had been transferred and developed for the demands of the latter19thcentury; the large railway sheds, Glasshouses to railway halls and back to glasshouses.

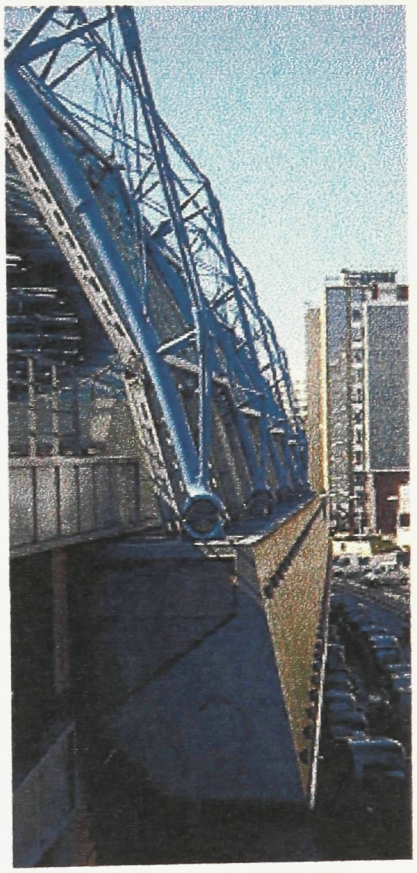

Figure 3 Waterloo Terminal by Nicolas Grimshaw. (From http://www.galinsky.com/biuldings/waterloo

At Waterloo the challenge was to design a roof structure and envelope that could deal with the sinuous shape of the track. Working with the engineers Anthony Hunt Associates Grimshaws developed a steel and glass roof structure. Knowing Grimshaws previous successful design, the question that was put forth at the time was; would design based on the principles of Grimshaws

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[4] Ibid. 3

previous project work in the site allocated for the Eden project, which is basically a pit?

Models were built, and numerous meetings took place. While the Eden team was in Cornwall working on funding, purchasing and accessing the site Grimshaw had time to go over the proposals. After a careful study by the Grimshaw's team, it was found that bubbles would settle perfectly onto any shaped surface, so the team started to think bubbles. Tim Smit, director of the project explains, that:

Figure 4. Preliminary model of the Bioms.
(From http://www.edenproject.com)

" The Biomes were 3D space frames made up of giant hexagons and pentagons. Each side of each hexagon and pentagon was machined to a unique specification to fit its position in the sphere. The whole structure was based on a complex 3D computer model which was linked to a machine shop, where a computerized production line calculated the length each of the sections needed to be, and automatically cuts them to exactly the right specification."[5]

The lightweight galvanized steel tubular frames went up like a giant Meccano set to form enormous self-supporting shells. The giant conservatory's whole structure was designed to efficiently capture solar energy using the back wall as a heat sink to radiate heat at night. (See figure 5 & 6).

For added weight support the covered Biomes sat on very solid foundations that weighed more than the Biomes themselves. One of the complications the project faced was attaching the foundations to the sheer wall at the back of the Biomes. A huge shelf had to be cut out of the cliff face in

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[5] Retrieved on Jan, 2,2003. www.edenproject.com/3440_3470.htm

order to make room for not only the foundations, but for the construction team to put it there.

A full 3D-computer model was also constructed of each Biome to predict the behavior of the frame. Forces from the wind, snow and other loads are transferred through the shell to the foundation. The models helped to finalize the design. Wind tunnel tests carried out on a scale model showed that the wind blowing across the top of the crater would suck up the covered Biomes, rather than blow them down.

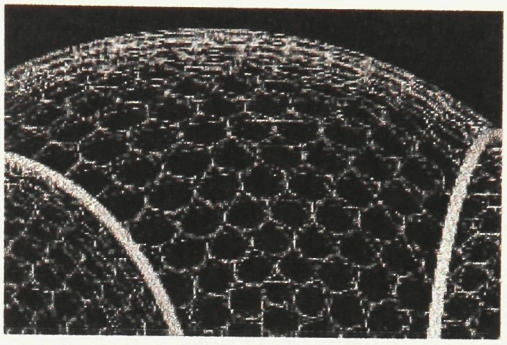

Figure 5. Structure known as hex tri hex based on Geodesic principles.
(From http://www.edenproject.com)

Principles of 'hex-tri-hex' were applied in the construction of the conservatories (see figure 5). A geodesic line was the shortest distance between two points on a curved surface. It was much easier to have straight bits of steel frame than curved ones, as a result, the design concept moved on and the final design comprised a two-layer steel curved space frame with an outer layer of hexagons, (with the occasional pentagon thrown in to make it all fit together like a football) and an inner layer of hexagons and triangles (resembling huge steel stars). Diagonals connected the node points of the layers together to make the structure rigid. This structure - the first of its kind on this

Figure 6 Final design for Eden Project
(From http://www.edenproject.com)

scale in the world – was called the 'hex-tri-hex'. [6]

The final designs were all based on geodesic principles. Knowing that one of the most interesting ways to enclose space economically was to make use of the concept of a geodesic dome (see figure 6 on previous page for a view of the final design). Geodesic domes gave the appearance of a sphere, yet all the surfaces were planes and all their edges were straight lines. Drawing geodesics on the sphere and connecting the points at which they intersect with straight lines formed a geodesic structure. Additionally, forces within a geodesic structure are uniformly distributed and nature continually forms hexagonal structures as the most efficient way of absorbing stress (see part of the constructed dome on figure 7).

An early architectural example of a geodesic sphere was Walter Bauersfelds Zeiss Planetarium in Jena, Germany in 1926. Later in the 1950s, Buck Minster Fuller, an American engineer and architect, further demonstrated the capabilities of geodesic structures Bucky Balls. Innovative architecture based on nature.[7]

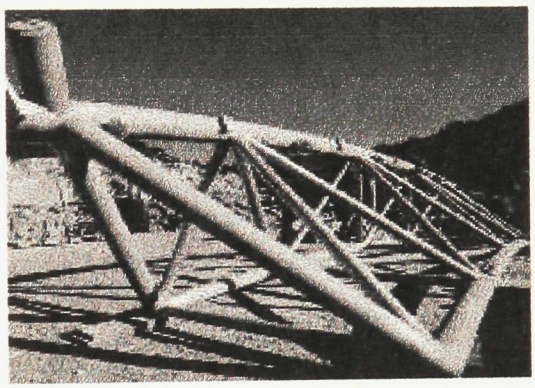

Figure 7 Part of the constructed dome. (From http://www.edenproject.com)

The spheres that were incorporated in the design process worked well as they could be molded neatly into the bottom of the pit. However there was still

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[6] Ibid. 3
[7] Ibid. 4

work to be done on the design of the framework of hexagons and pentagons. The design team looked at several ways of fitting them all together including; a fully braced single layer, an unbraced single layer with large diameter tubes, and various double layer arrangements.[8]

The larger the diameter of the sphere, the larger the hexagons and pentagons. The side lengths were fitted together through a series of universal connectors ball joints at every node position that allowed for connection in all the different configurations. Side lengths varied from 1 meter up to 5.4 m. The largest uninterrupted clear panel was nearly 11 m from point to point. The inner lighter shell was braced to the main outer frame to give it rigidity using diagonals connecting the node points of both layers. Having two shells connected vertically made it a curved space frame. This three-dimensional curved space frame acted like a shell, the forces from the wind, snow and other loads were transferred through the shell to the foundation.

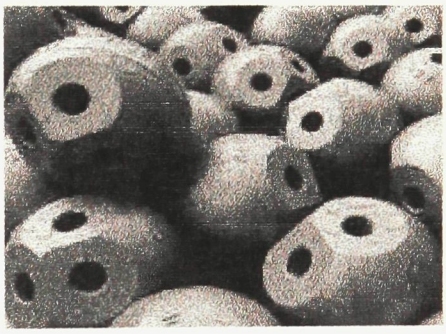

Figure 8 Metal connectors. (From http://www.edenproject.com)

When working out the way to fit the spheres together the team looked at some very advanced computer programs and bubbles to find the answer. According to Barry Johnson, of McAlpines constructions:

[8] Ibid. 4

"It's a natural fact that where bubbles intersect they do so vertically in a plane, which means that you can put an arch between the two bubbles and it will automatically be vertical and straight".[9]

Around the perimeter of the structure the top and bottom booms of the truss met to form a true pin-joint to the foundation (see figure 8 for detail of the connectors). This simplifies the forces being transmitted to the foundation strip. Bubbles aside, the complex structural design required millions of calculations and would not have been possible without advanced technological design and computers. The whole structure was based on a complex 3D-computer model developed jointly between Grimshaws, Hunts and Mero. This model was linked to a machine shop where a computerized production line calculated the length each section needed to be and automatically cut it to exactly the right specification to fit its unique position in the structure. The giant construction kit consisted of thousands of individual components. Each was numbered and accommodated its matching mate with minimal tolerance.

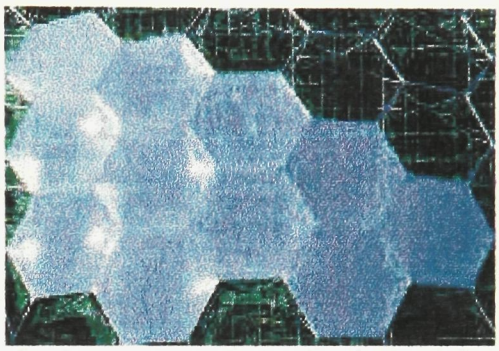

Figure 9 Intersecting domes clad with inflated cushionsof ETFE
(From http://www.edenproject.com)

To cover the structure, Structural engineer Anthony Hunt developed a series of intersecting domes, clad with inflated cushions made from a lightweight transparent foil, ethyltetrafluroethylene (ETFE)[10] (see figure 9).

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[9] Ibid. 4

[10] ETFE is strong, as well as light. The foil is 1 per cent of the weight of glass, but can take 400 times its own weight. ETFE has impeccable green credentials: it is recyclable and because it is so slippery it is, in effect, self-cleansing From http://www.ajplus.co.uk/eden/building/

Each biome has four domes, strengthened by steel arches where they intersect. The shape provided maximum size and strength, using minimum steel.

The space frame has an outer layer of hexagons (the 'top cord'), connected to a secondary inner skin, which is built up from a series of hexagons and triangles. The 'hextri-hex' structure has the advantage of flexibility and can be tailor-made to fit the site's irregular topography.

This gave scope for considerably larger areas clad with ETFE than glazing would have allowed, with the largest hexagons measuring 11 m from point to point. At the same time, the foil lets in a plant friendly 97 per cent of UV light.

When asked why this shape for the Eden project, the Grimshaws pointed out a number of points that were all advantageous. Efficiency was primary for the project and the shape provided maximum size and strength with minimum steel. It also assists in energy savings by providing maximum volume with minimum surface area (minimizing heat loss). The spherical shape is also adaptable as it moulds to the shape of the site. It enables the application of transparent materials by letting through more light than glass, even including UV light and it is light weight, for the weight of the steel was almost the same as the weight of air it enclosed. And finally, the shape provided large spans to be

accomplished, spans 110 meters at its widest point with no internal supports - allowing complete freedom for the plants and the landscape architects. [10]

David Kirkland, of Grimshaws considers the advantages derived from observing nature for the Eden project by stating. 'A biologically inspired building that drew as much from nature as it did from traditional architecture'. And on the final structure of the project

Kirkland notes:

> *"The best structures, demonstrating beauty and function, are built by the animal kingdom. Termites' and wasps' nests have air conditioning, and they have farms. Nature takes what is available and produces a natural solution. We felt the biological form of the structure was suitable for plants, the way the whole thing fits into the cliff face and the landscaped bowl of the old pit".*[11]

The lessons derived from the nature of the Eden project are considered important as they all contributed to its success. What is noteworthy here, this is the efficiency that was reached as a result of the coordinated work of the two disciplines, Architecture and Engineering under the guidance of nature's principles and today's advanced technology.

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[10] Ibid. 4
[11] Ibid. 4

Chapter Four

Public Museums and Architecture

"The concept of museums opening to the public began in the Enlightenment. The Louvre became the international standard after its Grande Galerie opened in 1793 for the public free of charge. From then the museum increasingly became a mirror of architectural possibilities in the second half of the twentieth century."[1]

The purpose of a museum in the past, as it is today, was to acquire, study and display art and other precious or educational objects. A museum building looked elegant, but never elegant enough to overshadow the collection. Buildings that were built for other purposes often made the best museums then. Most museums were converted European palaces or great private houses, made into museums more or less by accident. Aside from the Louvre, the classic case is the Uffizi in Florence. Giorgio Vasari designed it in the 16th century as offices for Cosimo I de' Medici, but today it's the home for a large collection. One room leads logically to another in an organized manner. Another example includes, the *Musée d'Orsay* in Paris, which was a converted railway station, and the *Frick Museum* on Fifth Avenue in New York was designed as a millionaire's home.[2]

Recently though, simplicity and efficiency have no longer become the most desired qualities. " *Communities want their museums to express civic pride and power, as cathedrals once did*"[3]. I maintain that a museum design must be

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1 Fulford, Robert. In the age of museum building. The National Post, 4 December, 2001. http://www.robertfulford.com/MuseumArchitecture.html.
2 Ibid.

3 Fulford, Robert. In the age of museum building. The National Post, 4 December, 2001. http://www.robertfulford.com/MuseumArchitecture.html.

powerful enough to impose itself on the public imagination. As such, it is unacceptable to think that architecture should take second place to the contents when it comes to designing a museum.

In his book titled, *Museum Buildings: A Design Manual,* Paul von Naredi Rainer's confirms that, the connection between the '*museumization*' of our society, and the dynamics of the civilization process generates that field of tension in which museums as the showplace of cultural development turn into the identifying locale by which towns and regions define themselves.[4] Further more, for society as a whole, museums provide valuable intangible benefits as sources of national, regional, and local identity. They have the singular capacity to reflect both continuity and change, to preserve and protect cultural and natural heritage while vividly illustrating the progression of the human imagination and the natural world.

As they are places of public gathering, I find that museum design must be, in such a manner, that it contributes 'architecturally' to the enrichment of local cultural life and make communities more attractive places to live. Prominent museum architecture contributes significantly to reviving whole districts, as is the case in 'The City of Science' in Valencia and the Centre Georges Pompidou did for the Marais district of Paris in the 1970s [5]

"Increasing globalization and claims to qualitative sophistication associated precisely with the museum and its architecture have long since led to

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[4] Naredi- Rainer, Paul . Museum Building : A Design Manual. Berlin: Birkhauser Publishers for Architectur, 2003. 13

[5] Fulford, Robert. In the age of museum building. The National Post, 4 December, 2001 .<http://www.robertfulford.com/MuseumArchitecture.html >.

the museum buildings becoming an issue of not only public interest, but also international sophistication, against the standards of which the local intentions must compete." [6]

Earlier, museums were identified by their most famous objects, like the Mona Lisa in the Louvre, yet ever since the design of the Guggenheim Museum in 1950, the connection has grown stronger between architect and museums. Wright was noted saying, *"Architecture was "the mother art" and the Guggenheim's visitors should appreciate a magnificent example of it".*[7] Examples include Gehry's Balbao museum, Calatrava's Science Museum in Valencia - Spain, and Foster's Eden project, all of which are identified by the architect who designed them.

To represent an architecture that provides a place for exhibits from the past shown and conserved for the future that adequately represents the present requires, in each case, an architecture that is unique and sensitive to the requirements bestowed upon it.

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[6] Naredi- Rainer, Paul . Museum Building : A Design Manual. Berlin: Birkhauser Publishers for Architecture, 2003. 13

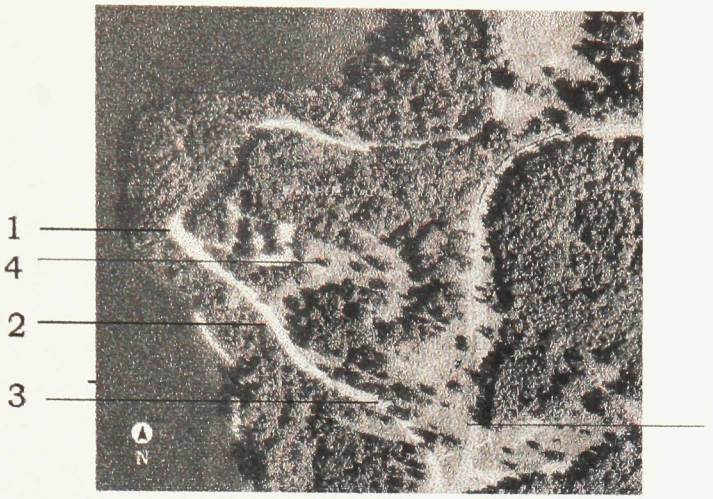
[7] Fulford, Robert. In the age of museum building. The National Post, 4 December, 2001. <http://www.robertfulford.com/MuseumArchitecture.html >.

Proposed Site

The propose site is part of a land located in Rockliffe Park, situated east of the city of Ottawa. The topography of the land for the project is partially hilly, sloping gently towards the Ottawa river. The natural contour (sloping) of the land is an added advantage to the project as it provides greater potential for creativity in design and interesting design possibilities.

Set against the backdrop of the Ottawa river, the site of the museum of nature has the capacity to generate a unified correlation connecting the museum visitors and anticipated architecture with the natural environment. The site supplies a harmonious link between architecture and nature and will encourages visitor interaction to take place. Although the site is presently devoid of any establishments, it is suggested that the structural form and ultimate architecture of the building, upon realization, will attract visitors and increase the sites potential. Once inserted into the natural landscape, it is anticipated that the architecture will enhance the uniqueness of the landscape without subjugating its natural character. The site exemplifies harmony and balance with its environment and, without a doubt; it plays a crucial role in designing a rewarding venue.

As a cultural institution, the museum will become a part of a chain of museums situated along Sussex Parkway. To the west, a few kilometers from the proposed site, is the *Canada and the World Pavilion* and further east is the *Aviation museum.* This will contribute in attracting a greater number of visitors to the area. The museum will become a place to enjoy, to contemplate, and to inspire.



Site Photos

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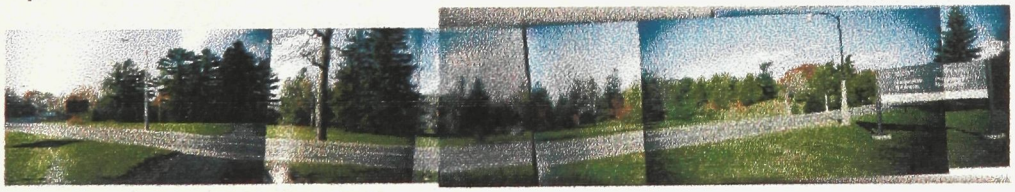

Figure1 Aerial view of Rockliffe Park and below photos of Site of the Museum of Nature (Photos by Author)

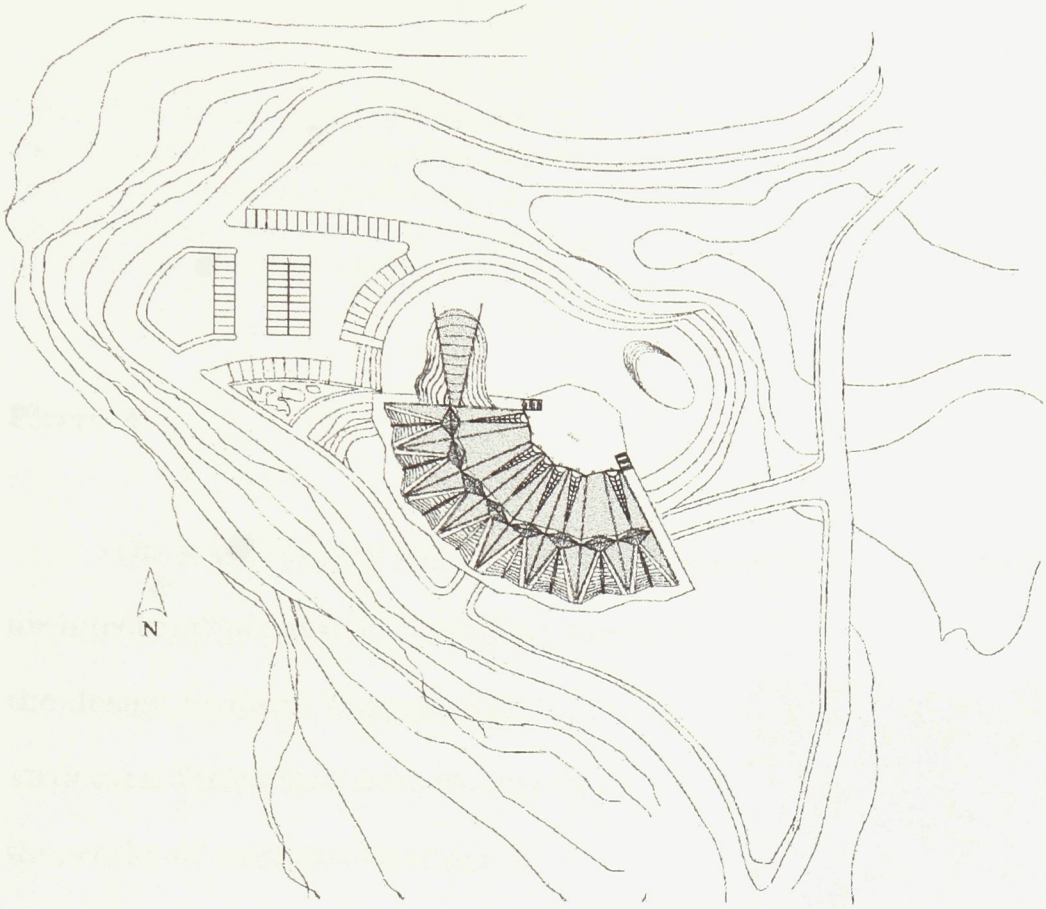

Figure 2 The proposed museum building in site.(Drawings by the Author)

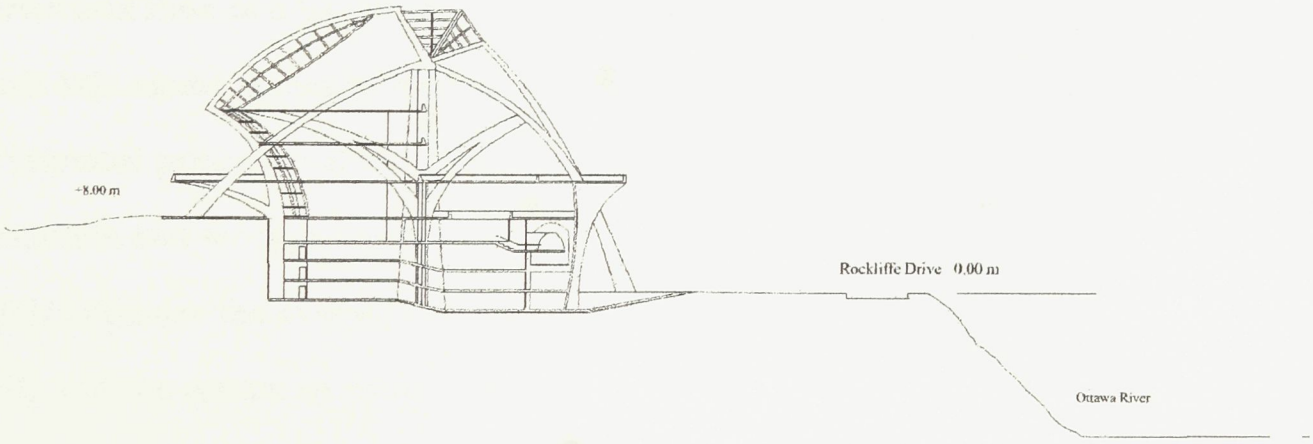

Figure 3 Longitudinal section through the site.(Drawing by the Author)

Architectural Proposal

"Sketches are sometimes followed by scale models –or what Calatrava refers to as 'Toys and games'. Used as experiments and preliminary inspirational tools for resolving a technical problem, such as dynamics or tension, they can also be seen as sculptures that borrow the language of engineering. They are creative statements about structural forces." [1]

Phase A

On searching for the initial inspiration to direct and 'structure' the architectural proposition, the first phase of the design involved observing examples of structural forms that were incorporated in the works of architect Santiago Calatrava's, in particular, the Museum of Science in Valencia- Spain. By observing the structure through numerous sources of the project drawings, a model was made, to represent the structural form of a bay of the museum. Through this model, a clearer understanding of the physical principles of structure -forces (compression and tension, torsion, gravity, etc.) that influence the overall structure was realized, and the means by which the architect, in this case Caltrava's structural

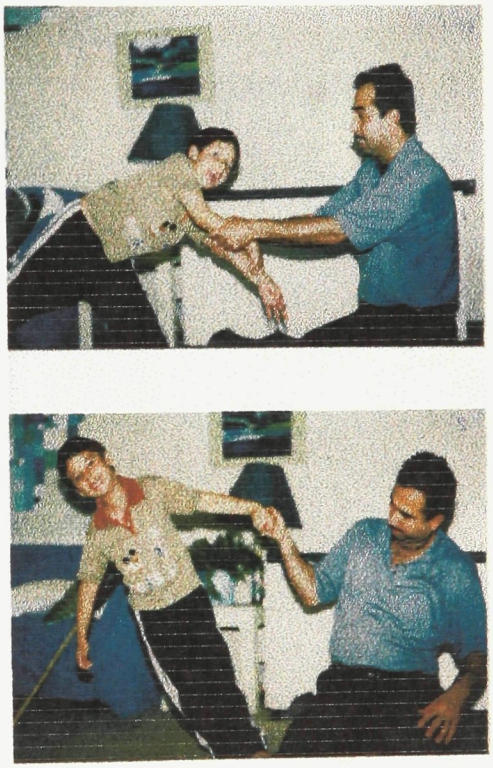

Figure 1 Demonstrations in the behavior of forces were part of the preliminary experiments towards understanding Calatrava's work in the Museum of Science.

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[1] Anthony Tischhauser, Santiago Calatrava, pg. 27

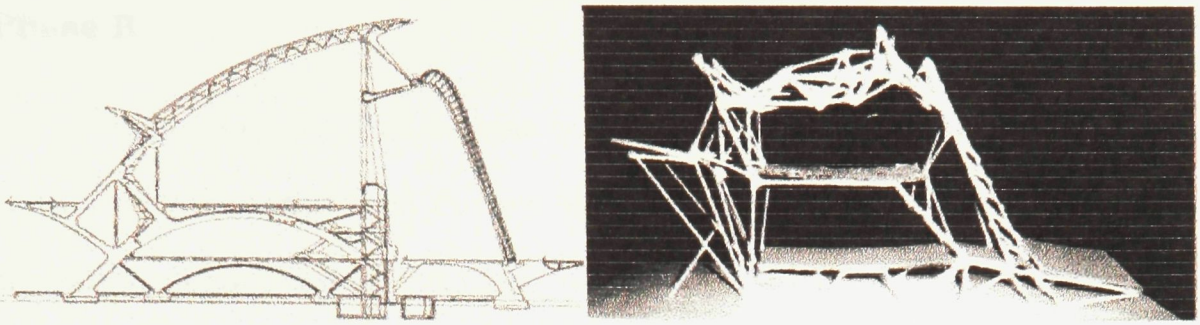


Figure 2 Section of Museum of Science and a model made to study structural balance .

design counter balances these forces to produce the desired architectural work. Following this phase a series of individual "Toys and Game" models[2] were constructed in order to reach the right structural balance and architectural elegance for the project. A series of embodied physical manifestations of the structural principle were developed. As a result, it became easier to understand and sense the forces at work on the models that gave inspiration to design strategies and modeling techniques.

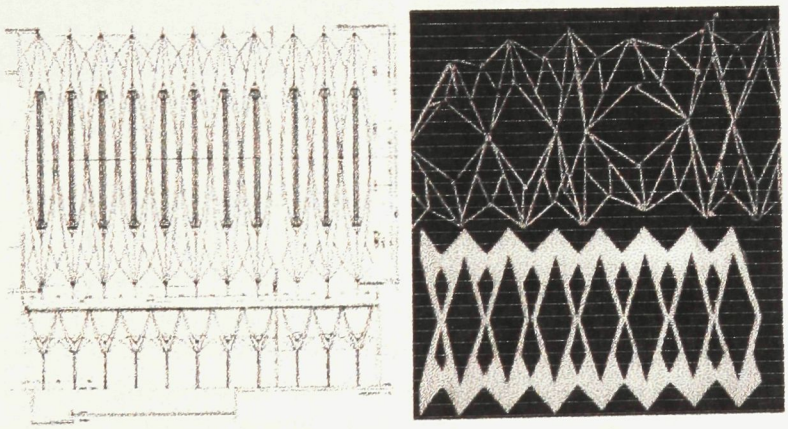
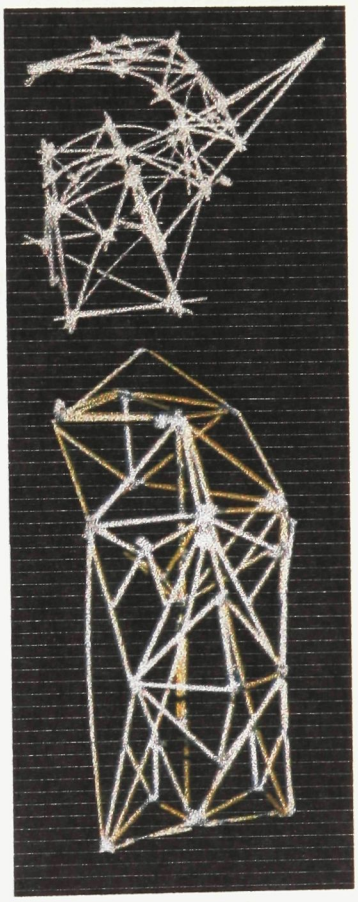


Figure 3 Roof plan and longitudinal section for Barenmatte Cultural Center by Santiago Calatrava and a model exploring structural design in two design mediums. (Models by the author)



Two 'Toy' models in structural design.

[2] Refer to quote on beginning of page.

Phase B

Phase B consists of designs of a bay for the museum of nature that is repeated five times to form the overall building. The design process focuses on developing structures for primary and secondary members that lead to the development of an architectural composition that is in line with the concept and is reflective of the theses work. Three models of the bays were designed in accordance with revisions to the proposed design. Sketches were made at this stage to reflect desired ideas for the interior spaces of the museum. These drawings also aided in visualizing the interior spaces of the museum once the design of the structural system were emplaced. (See drawings below).

Figure 4 Interior conceptualized spaces for the Museum of Nature (Drawings by the author)

"White is in fact the color which intensifies the perception of all of the other hues that exist in natural light and in nature. It is against a white surface that one best appreciates the play of light and shadow, solids and voids. For this reason white has traditionally been taken as a symbol of purity and clarity, of perfection. Where other colors have relative values dependent upon their context, whit retains its absoluteness. Yet when white is alone, it is never just white, but almost always some color that is itself being transformed by light and by everything changing in the sky, the clouds, the sun, the moon. Goethe said, "color is the pain of light." Whiteness, perhaps, is the memory and the anticipation of color."[1]

Whiteness is a characteristic of the design work for the museum of nature. It's application assists in clarifying the architectural concept and

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[1] Richard Meier, Richard Meier Architect 1964/1984. New York, NY: Rizzoli, 1984. 9

heightening the power of the visual form while leaving space for light (natural and artificial) to play its role in giving character to the interior and exterior spaces. It has also aided in the primary preoccupation for this design, which was creating a space with structure in mind- not an abstract space, but space whose definition and order were related to nature's principles. The examples studied in this thesis (of leaves, bones and cells), possessed visual clarity in their structuring so their principles became an integral part of the project. Exposing the structural system of the museum will enable the visitors to observe and comprehend the system at work and understand the means by which the spaces within are formed.

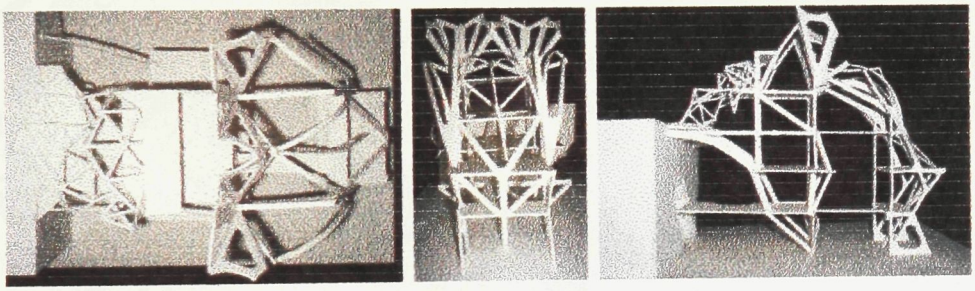
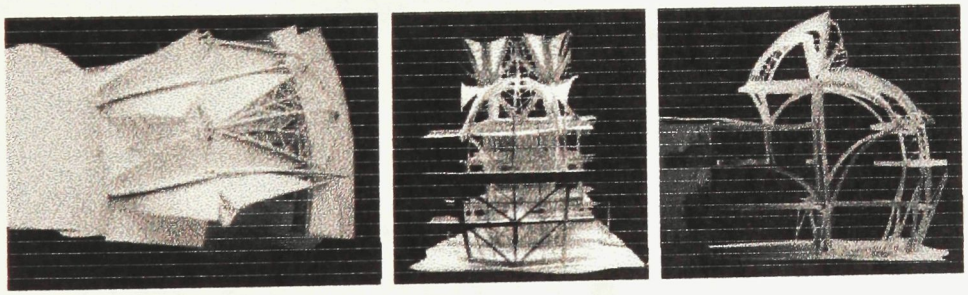
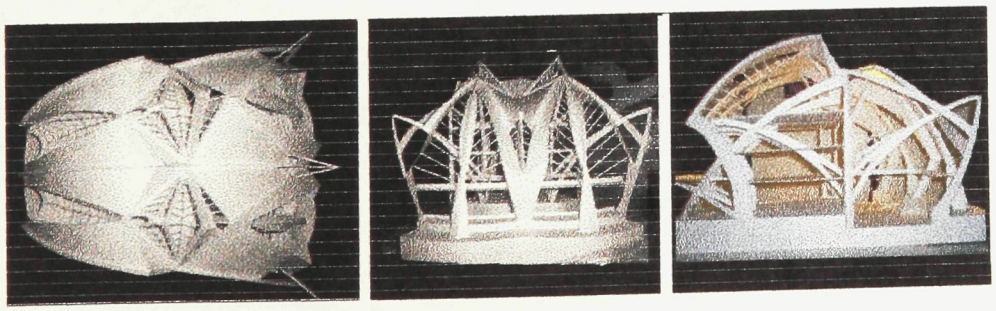


Figure5 Three models by the author. **Model of a single bay** viewed from left to right, top, frontal and section showing structure and floor levels.



First iteration to model showing design of structure, from, top, front, section.



Second iteration to Model of bay showing top, front and section.

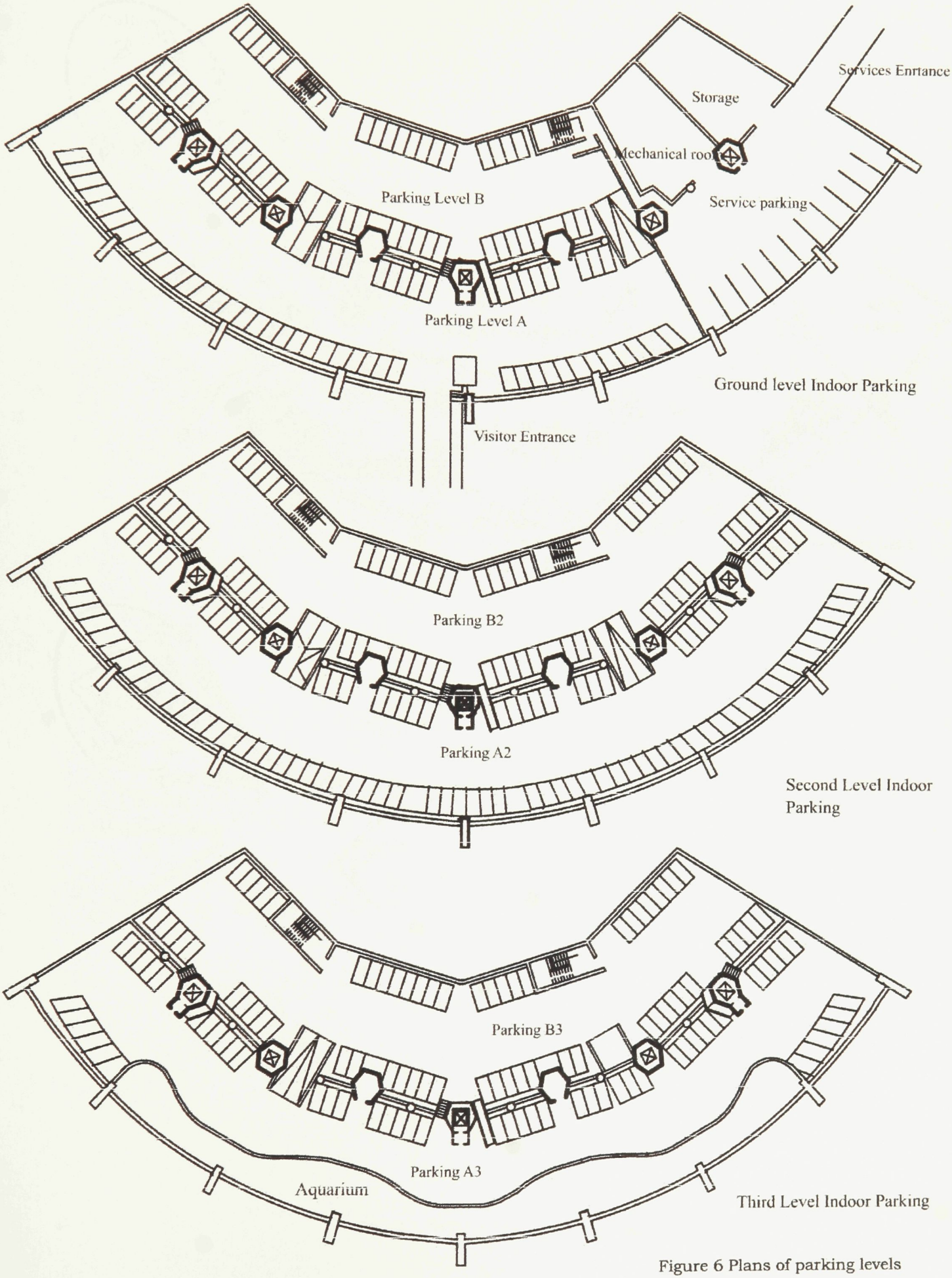
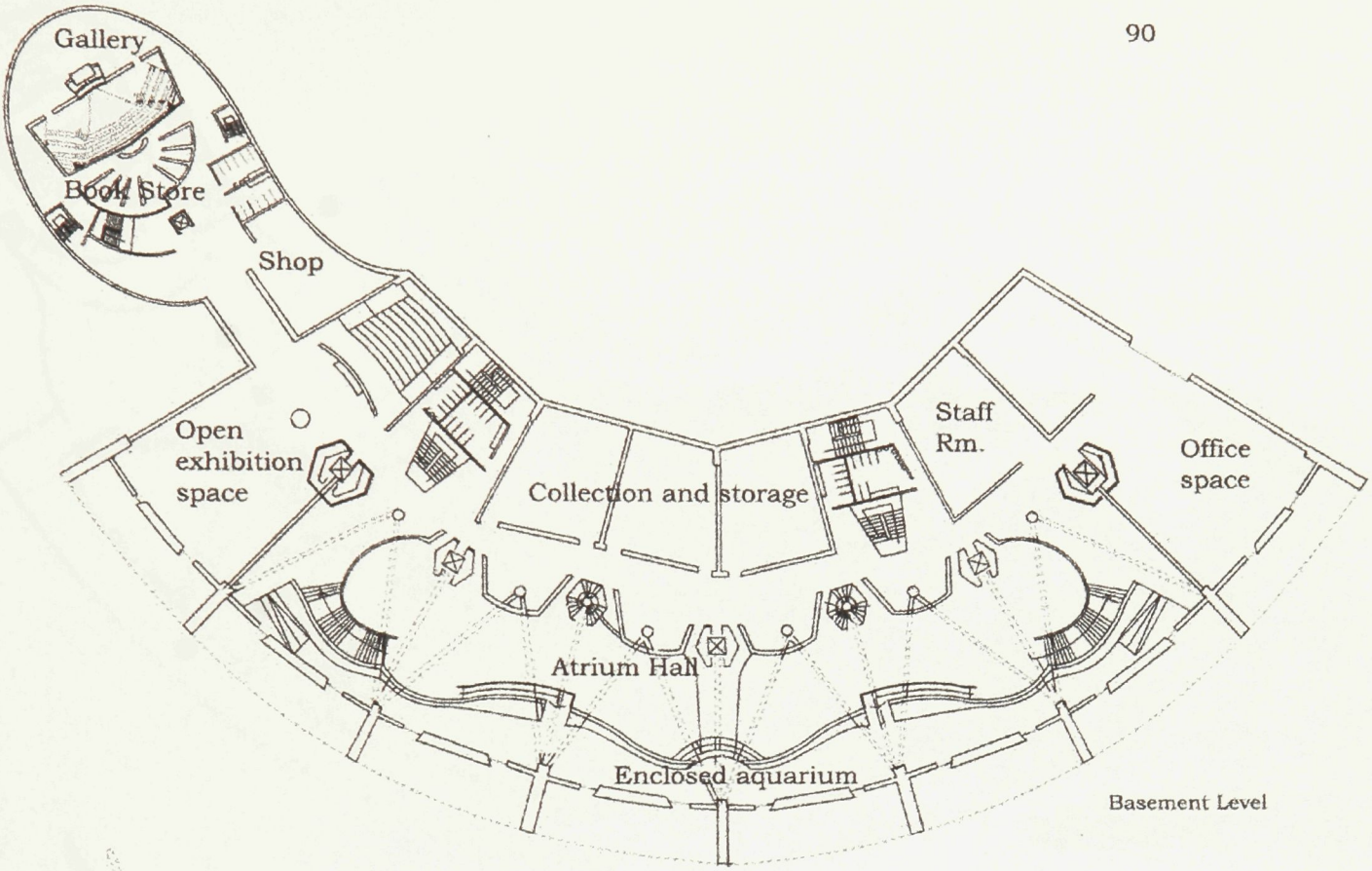


Figure 6 Plans of parking levels



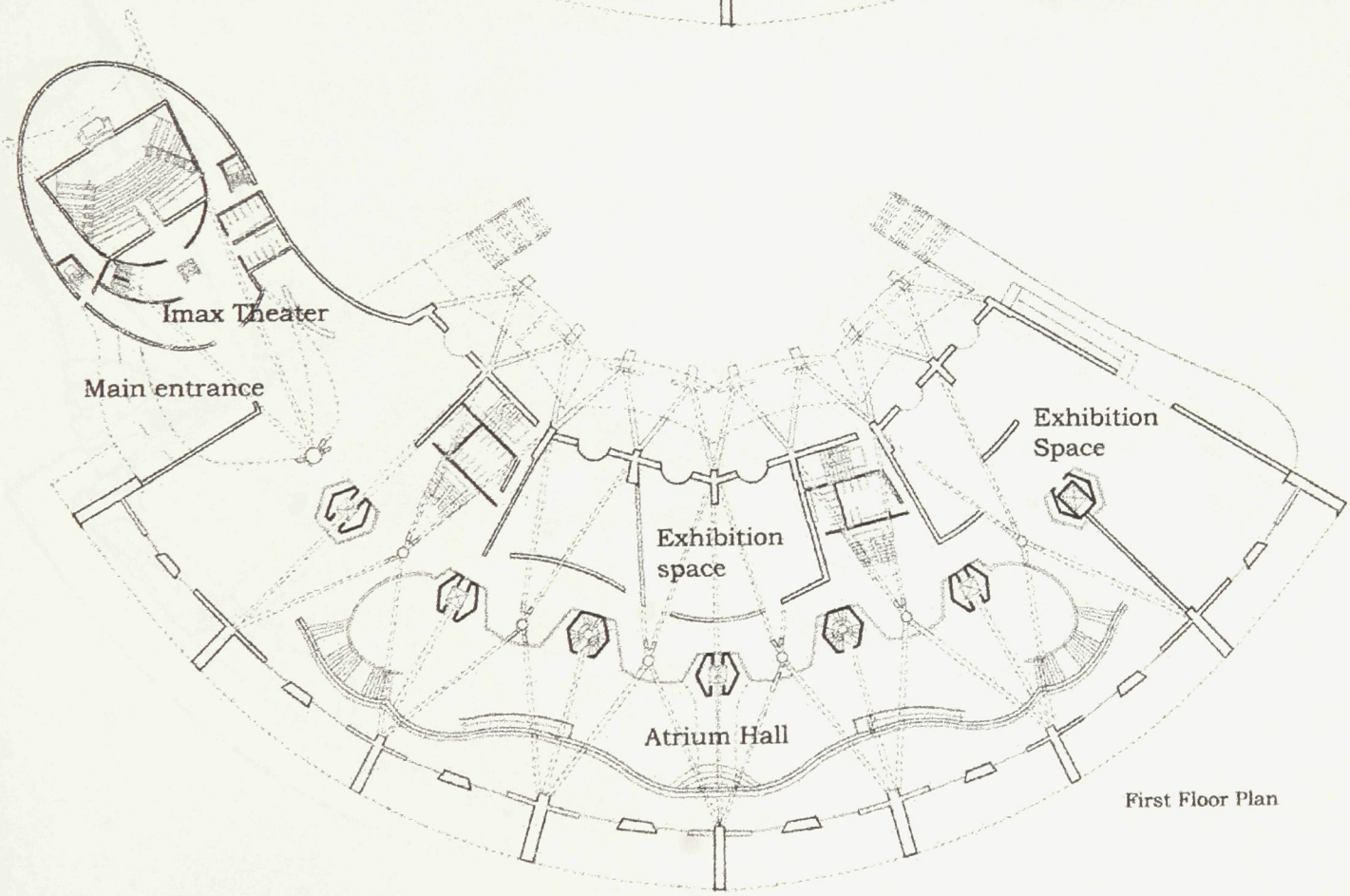
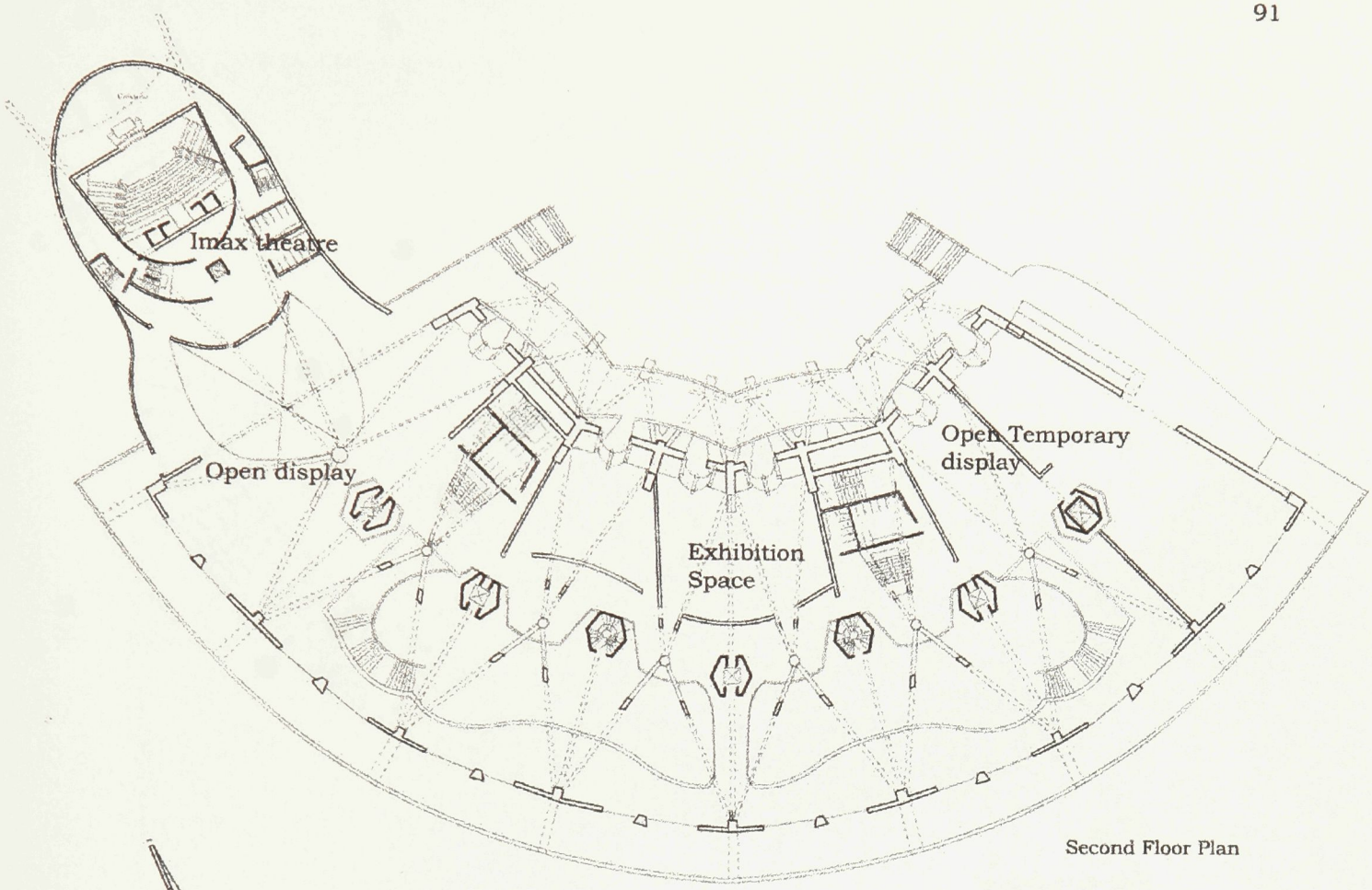


Figure 7 Plans for Basement and first level for the Museum



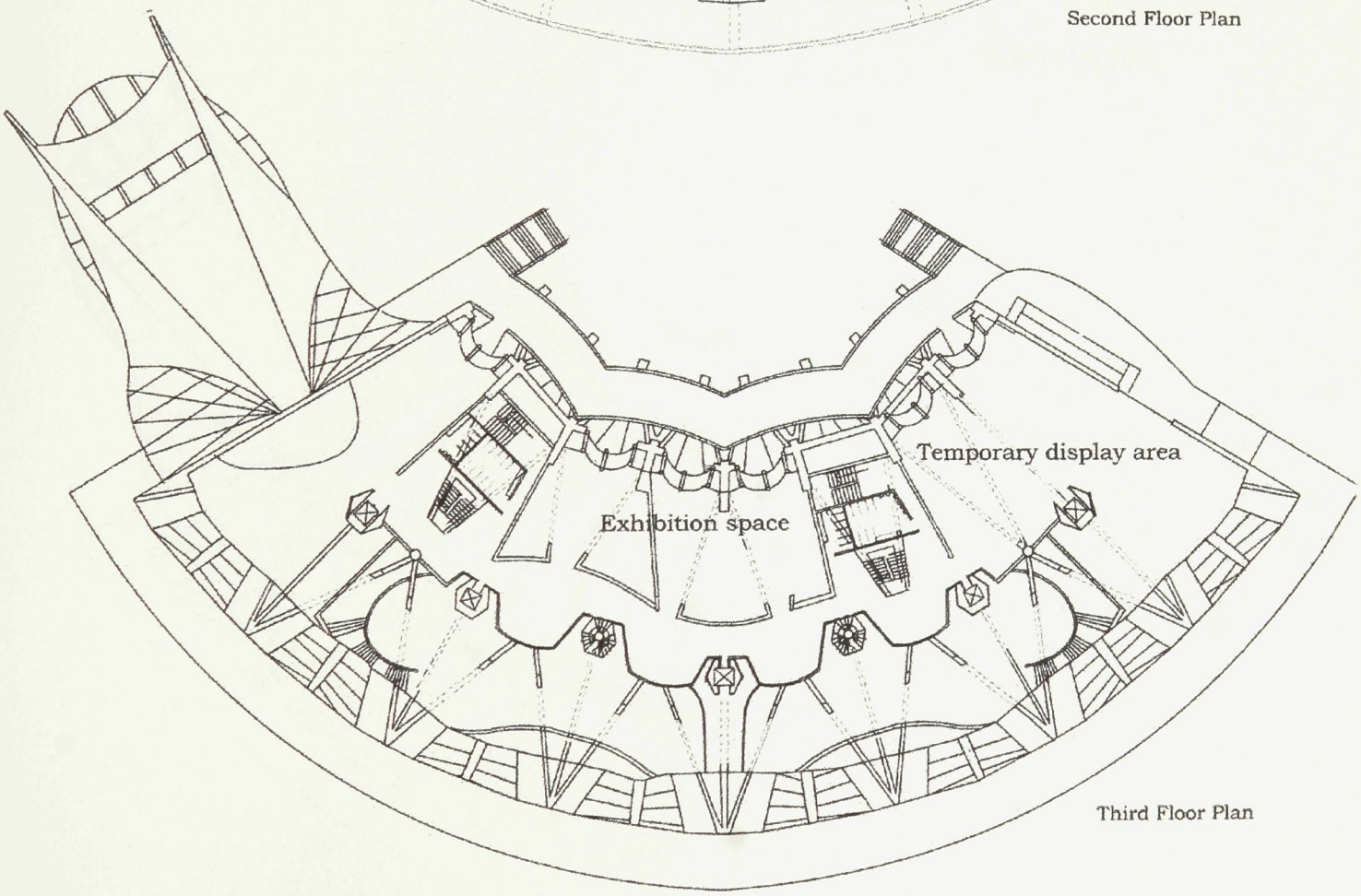
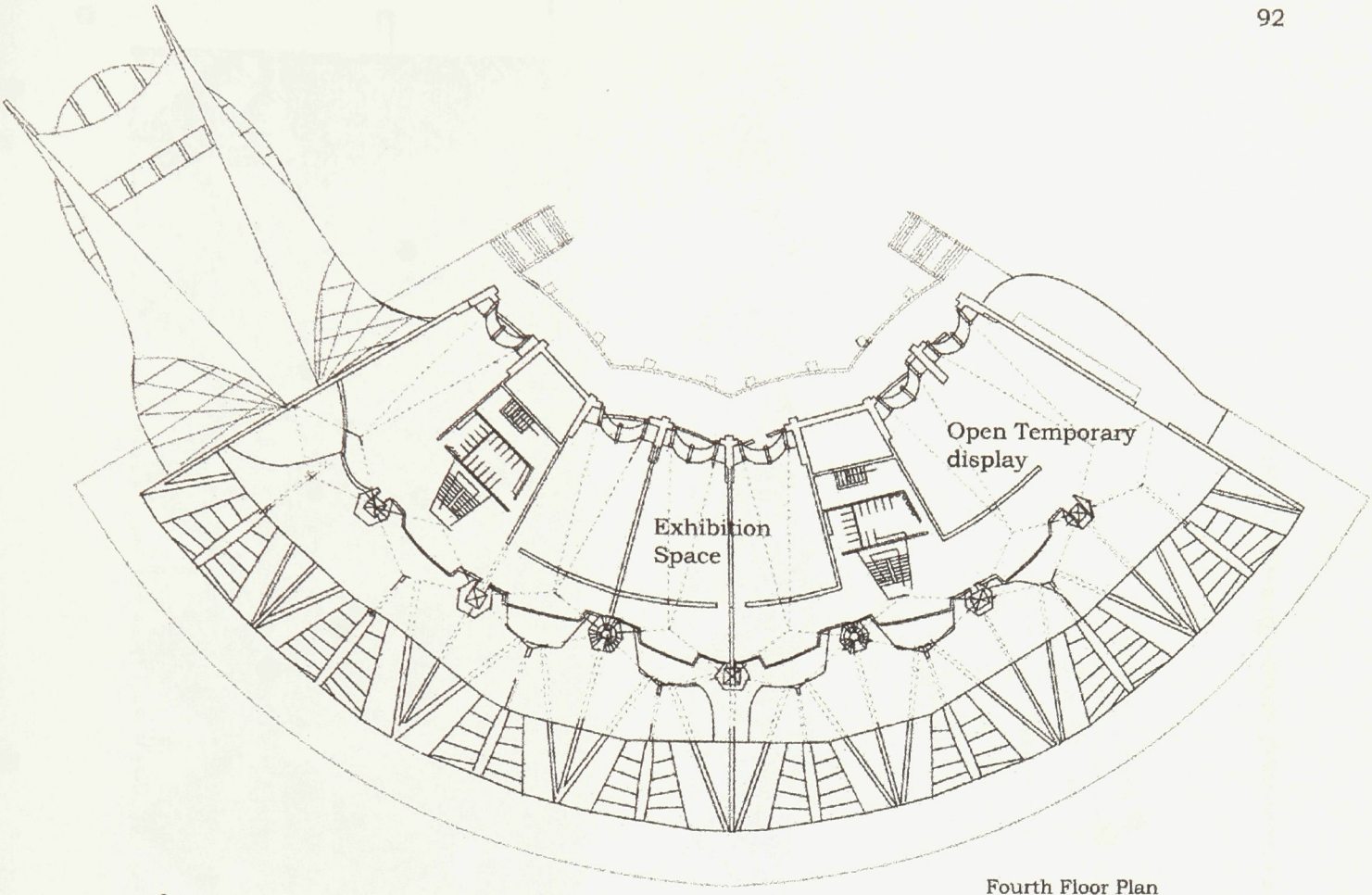


Figure 8 Plans for the second and third level of the museum



Fourth Floor Plan

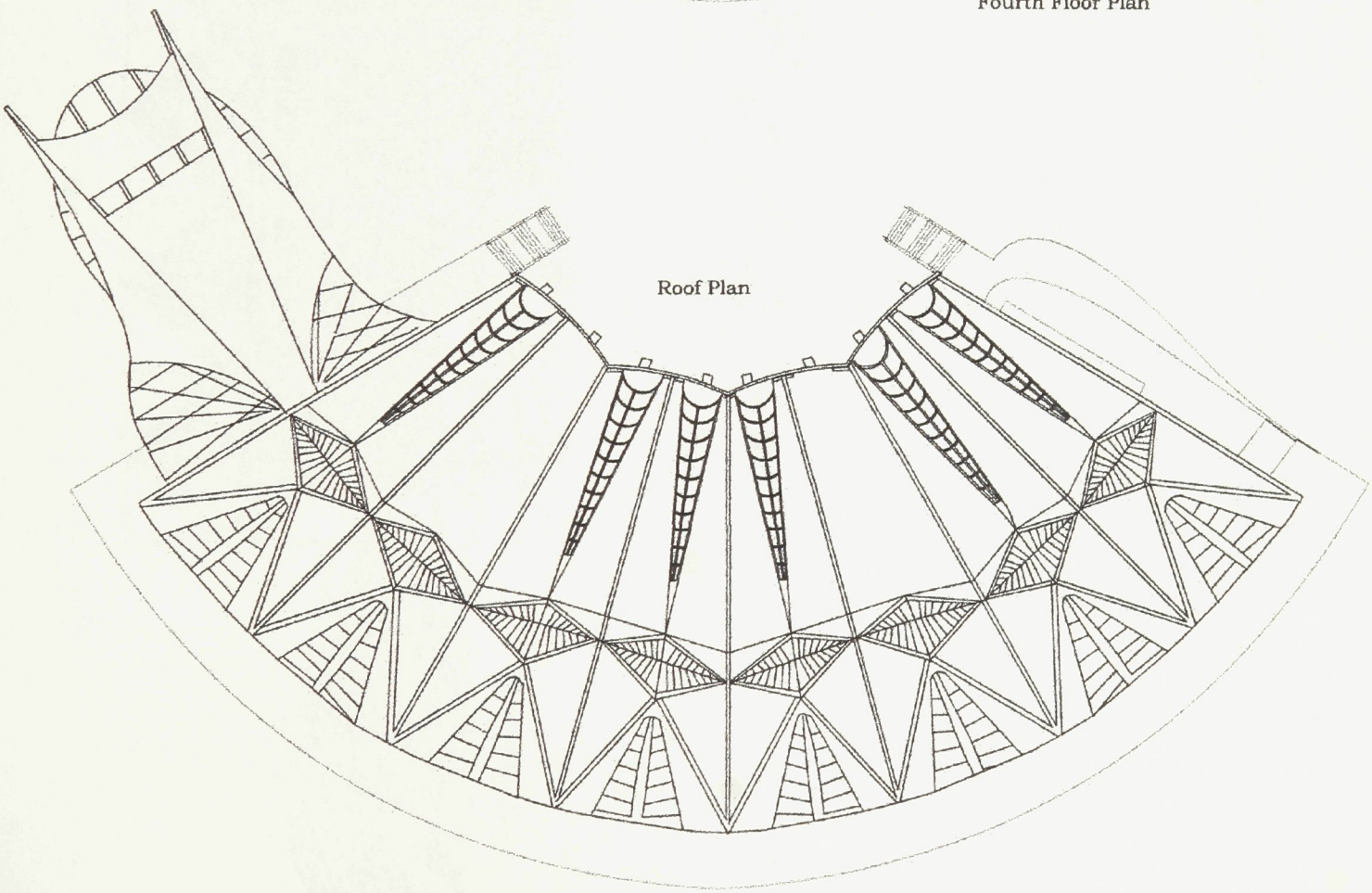


Figure 9 Plans for the fourth level and roof level of the museum

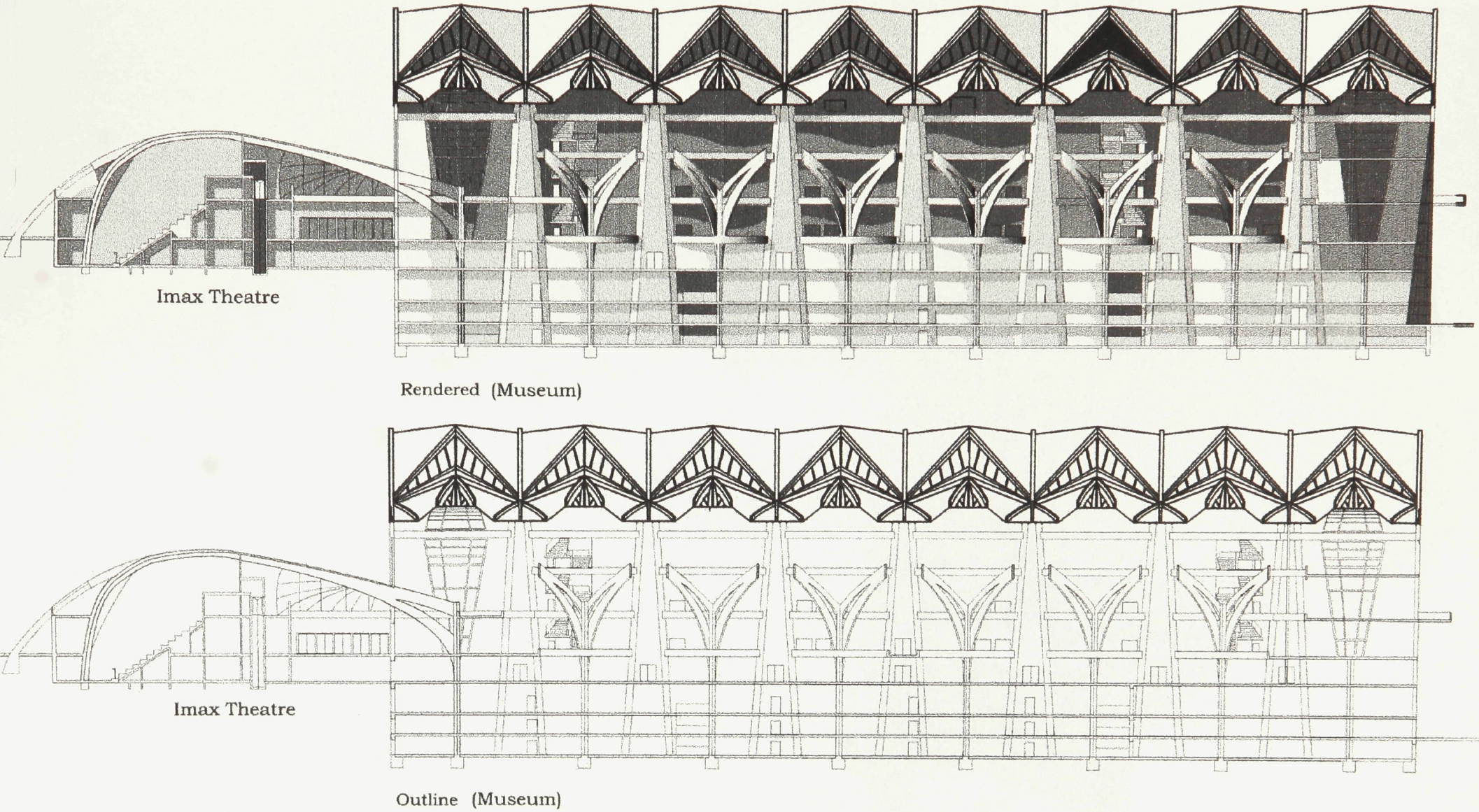
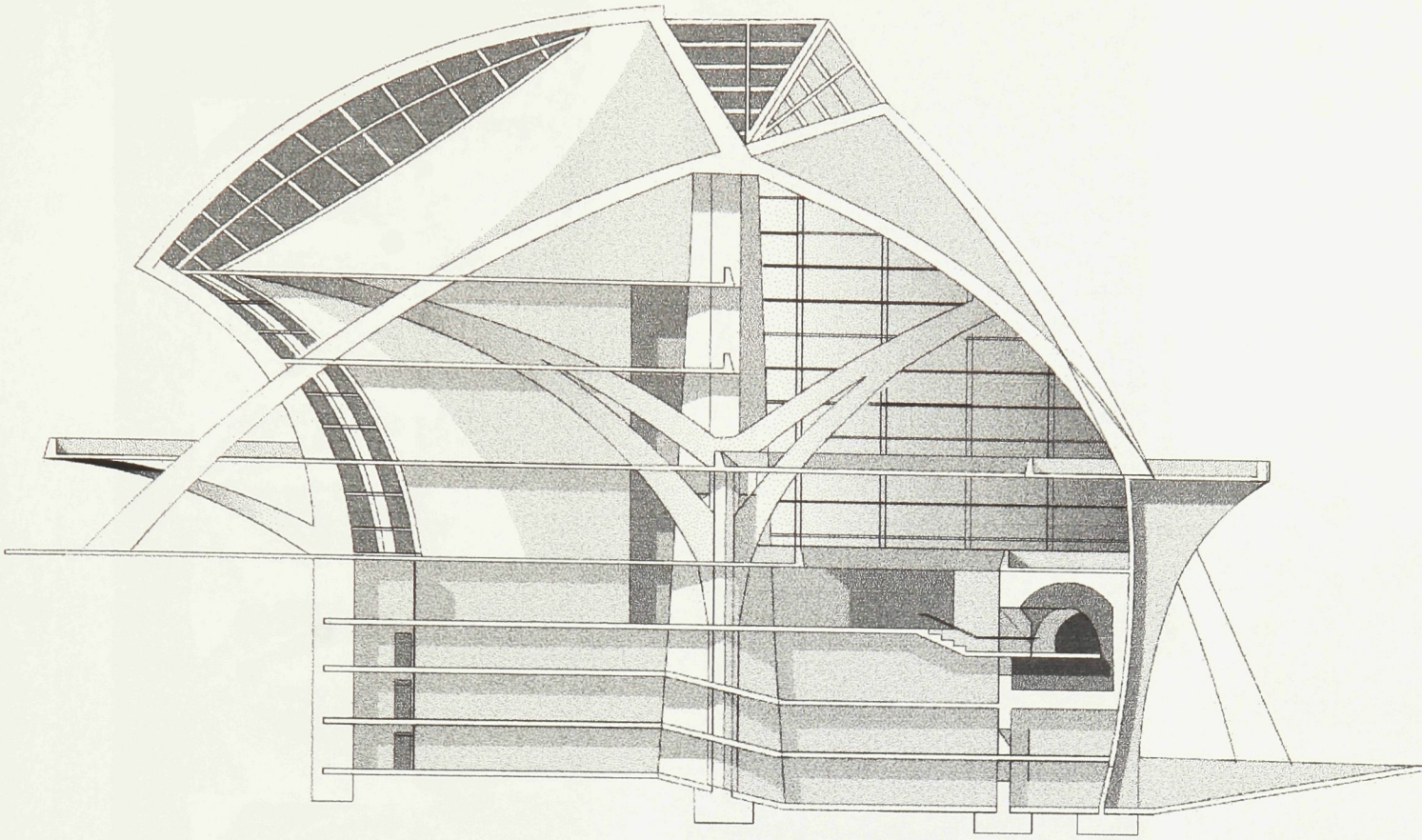
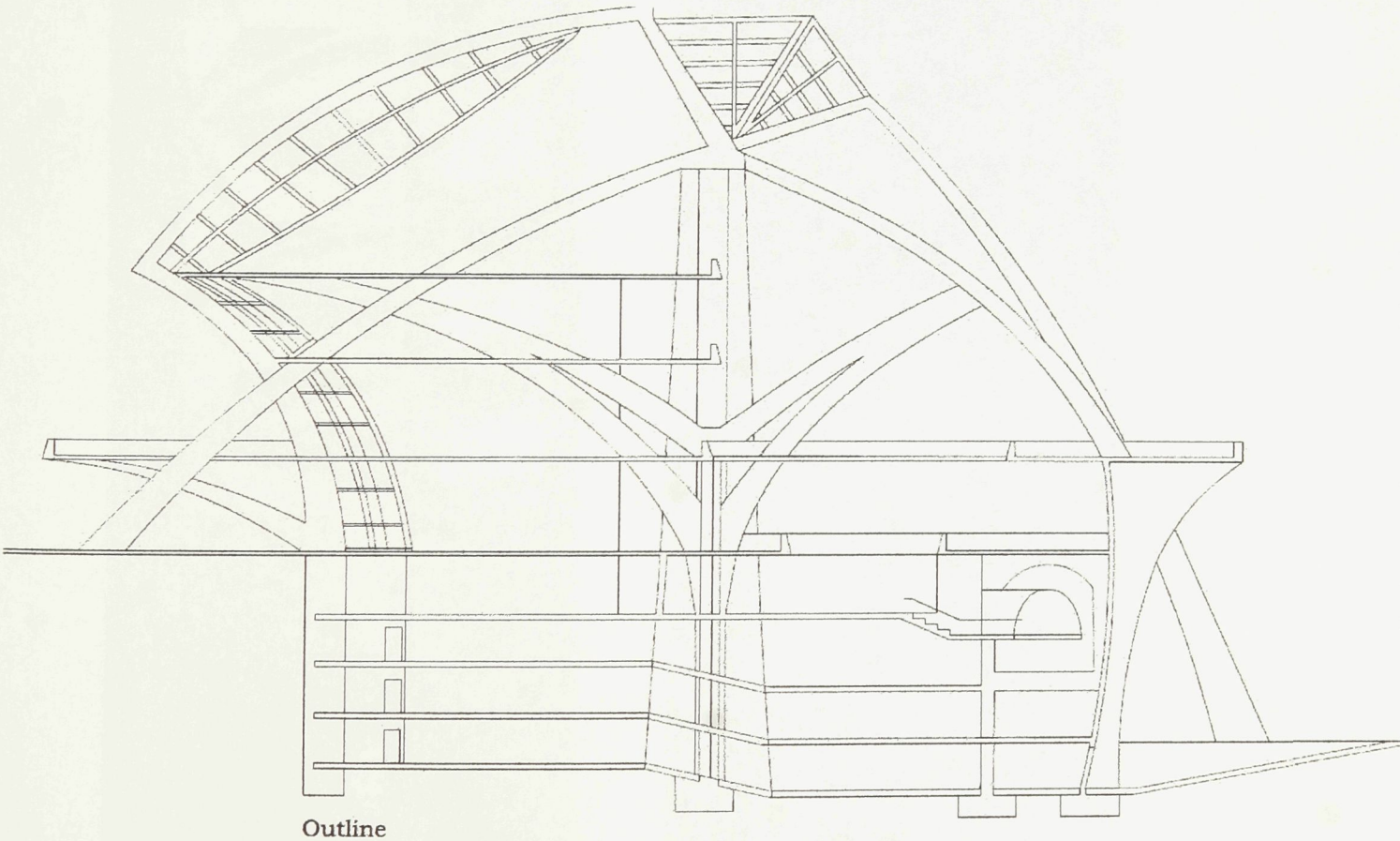


Figure 13 Drawing of a longitudinal section through the museum of nature (Drawings by author)



Rendered



Outline

Figure 10 Cross section through the museum

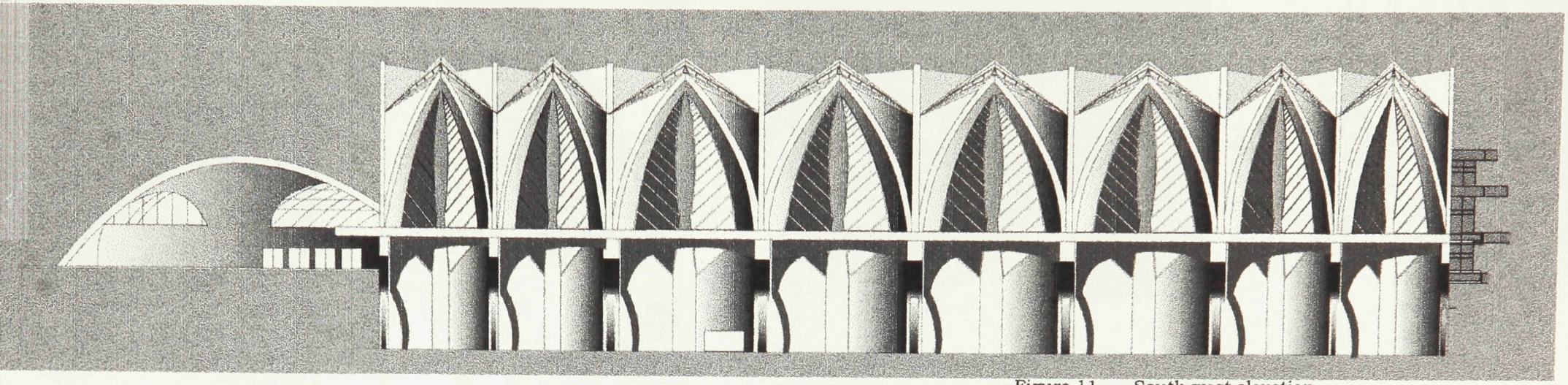


Figure 11 South west elevation

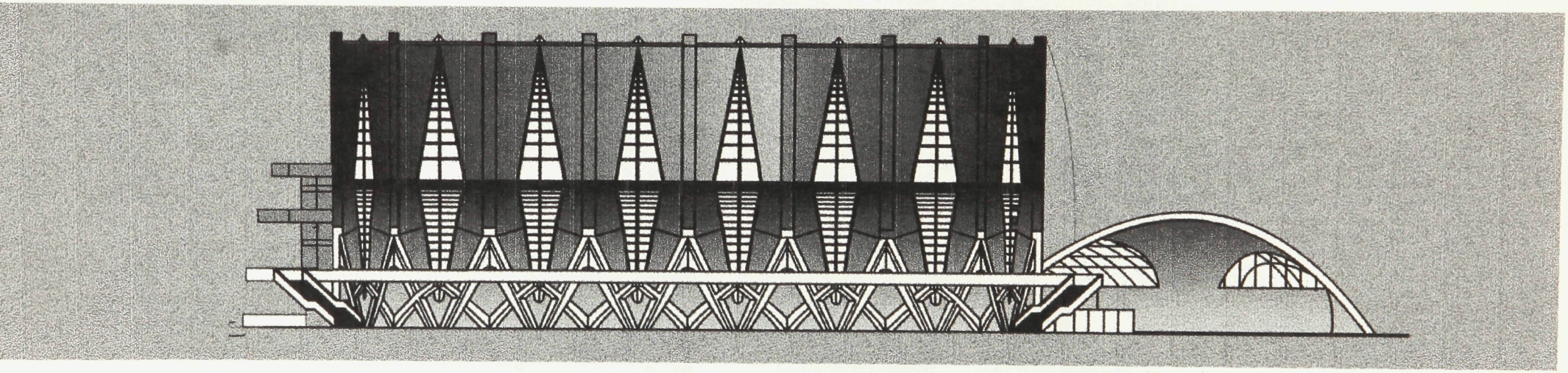


Figure 12 North east elevation

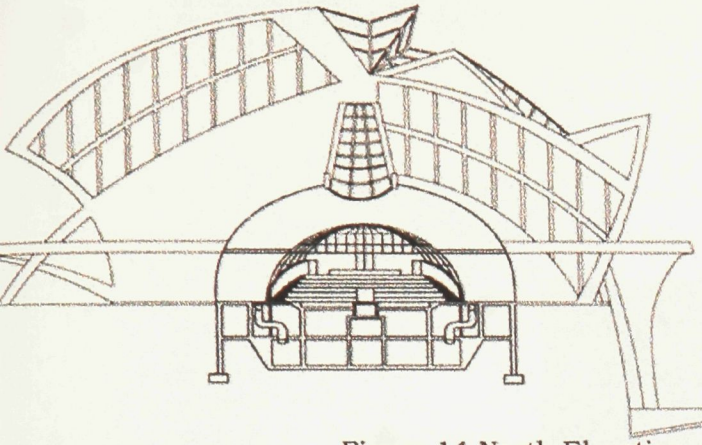


Figure 14 North Elevation

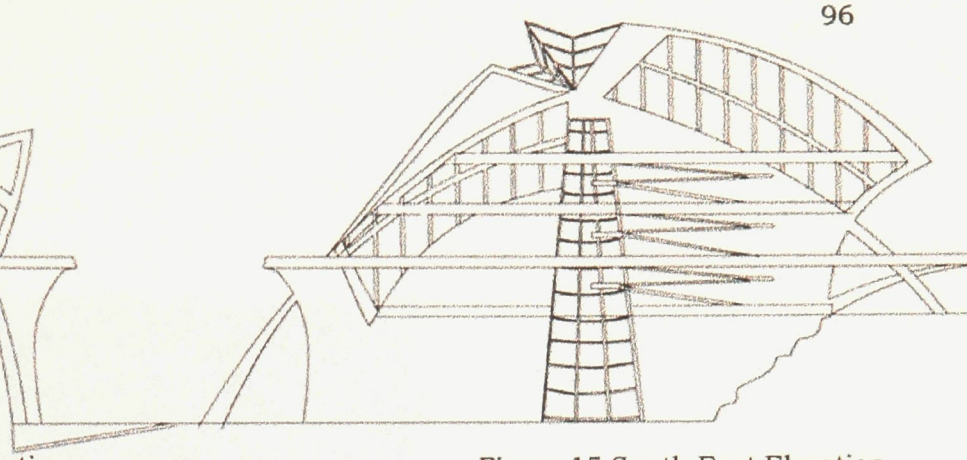
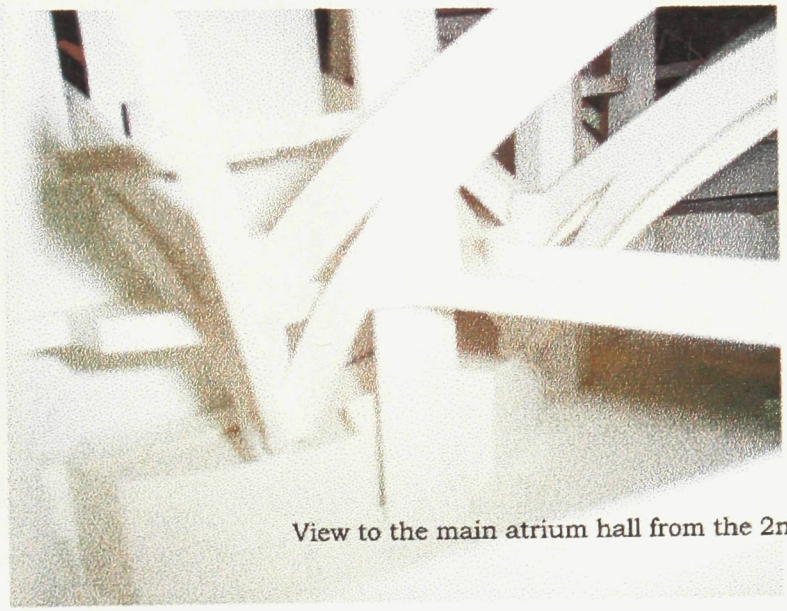


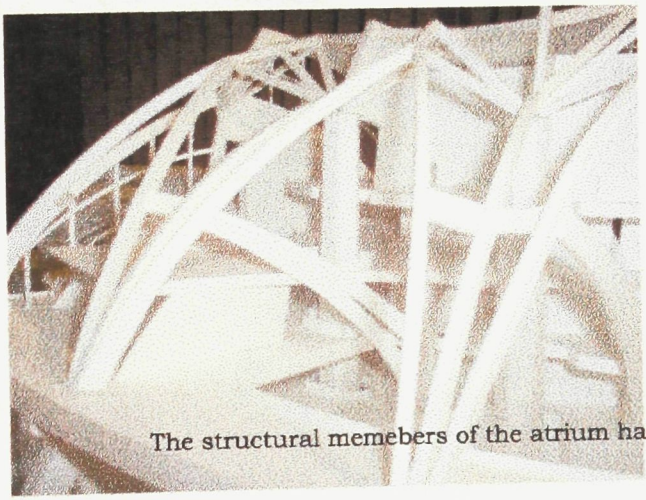
Figure 15 South East Elevation

Interior view of the second level

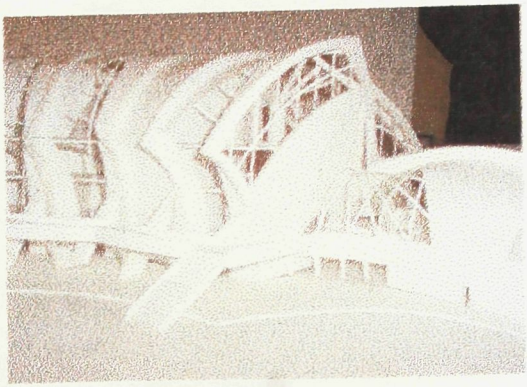


View to the main atrium hall from the 2nd level

A view to the First level and atrium hall from the 2nd level terrace



The structural memebers of the atrium hall expose



North East side of the museum

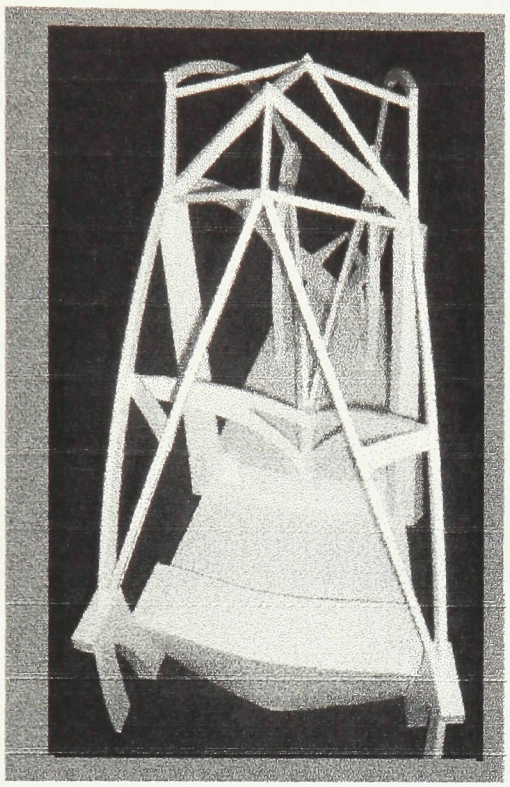
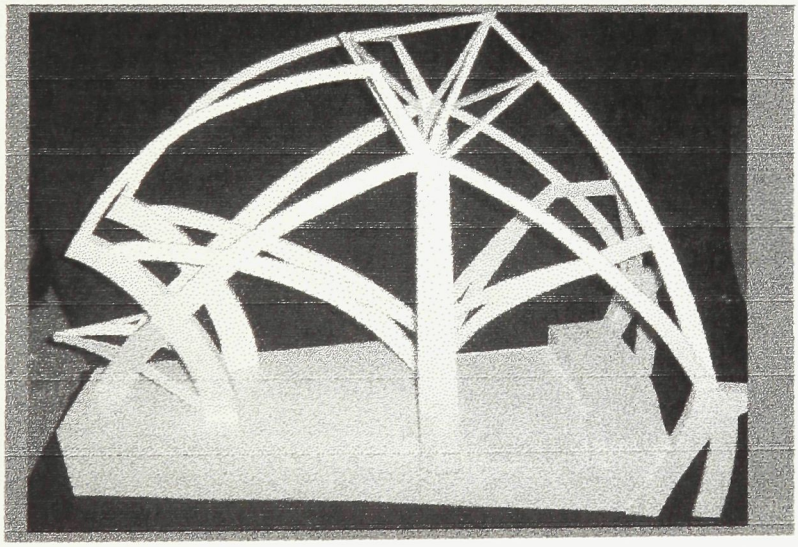
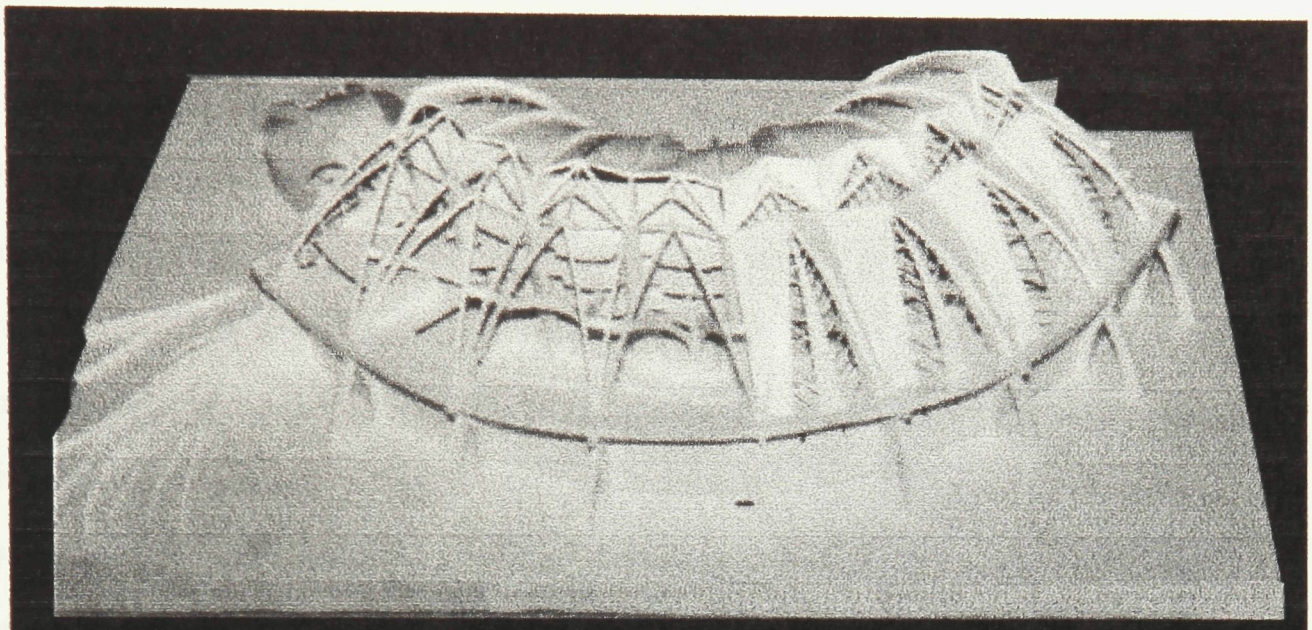
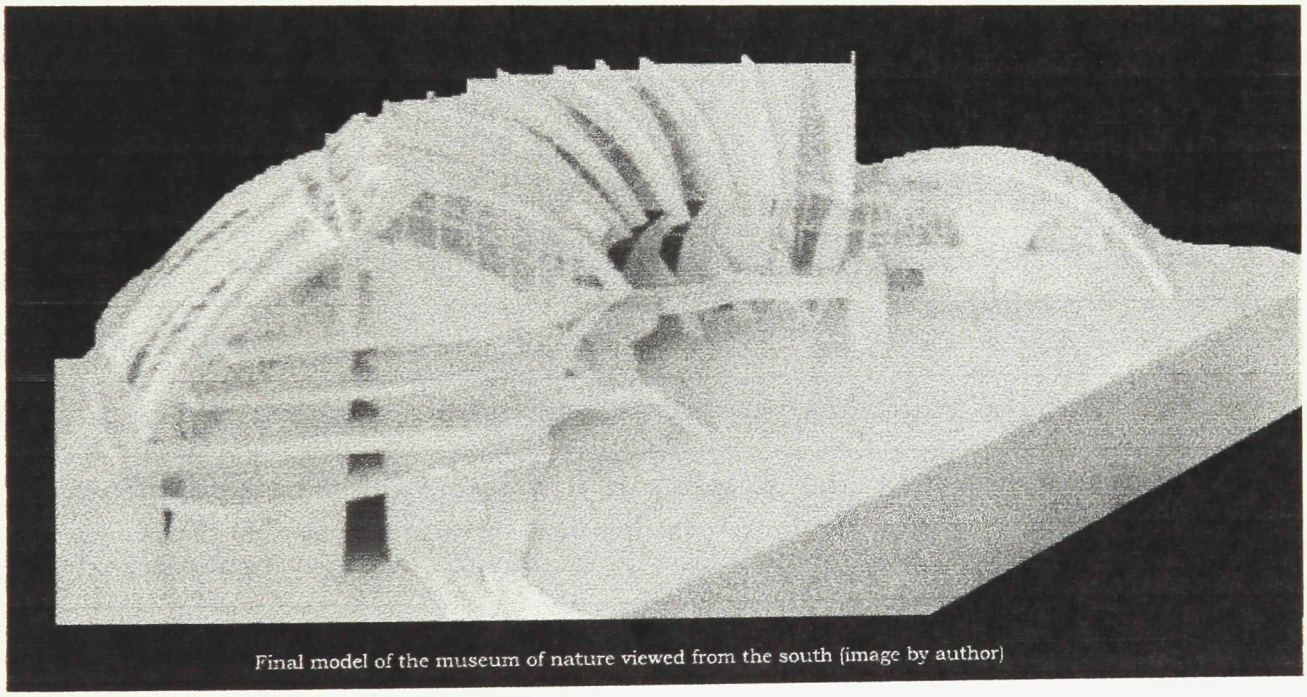


Figure 16 Constructed model showing structural members in a single bay of the museum of nature (image and model by the author)





Final model viewed from the south west (image by author)



Final model of the museum of nature viewed from the south (image by author)

Closing Words from the Author

This thesis has explored structural principles common to natural structures that contribute to the conceptualization and realization of structural design in architecture. By examining the works of architects, one concludes that each architect has applied the principles of structures and forms of nature in order to create an architectural expression that is unique to their work. In the case of this thesis, by looking at these principles and works of architects, the research evolved into an exploration of structures and forms akin to nature, and designing and making became reflective of nature's design in the process. Models that experiment conceptual ideas and sketches were developed through out numerous phases of the project to assist in order to understanding how these principles come to be applied in the design of the museum of nature to achieve desired results.

Through the design of the Museum of Nature, this thesis has found that structural design in architecture has been inspired, in different degrees, by forms of design in nature. In order to increase the understanding of the relationship between structural design in nature and in architecture it was important to observe plants/ architecture, bone/architecture, and cells/architecture, in order to connect these two fields, and to create a basis for a comprehensive perspective in the design of the museum of nature.

From the disciplinary side, this thesis has argued that the structure of architectural expression is more than abstract and literary ideas, visually striking renderings and illustrations of finished work. It aims at achieving

balance by parallel and complementary aspects that are acquired from the knowledge of nature's principles, and recognition of their importance in the development of man-made structures and forms. A successful architectural expression can be realized when it has a strong connection with nature's principles. Structures and forms found in nature provide endless possibilities for inspiration that can spark architectural innovation.

The qualities of structural design in nature – aesthetics, efficiency, and economy – are all desirable attributes of design in architecture. Using innovative ideas inspired from nature, architects can become proficient 'structurally', and ultimately, contributing significantly to the growth and enrichment of the profession and architecture.

Reflecting back on this thesis, then, what lies ahead is the need to further explore and study the sciences and in particular, biological science on the discipline of architecture. This goes beyond the pragmatics of practice and extends into more conceptual questions. Can we produce other kinds of structures inspired by the sciences and nature? If so, what might they look like? Can biological science contribute to the strategy of constructing forms in architecture?

In my view, there is a myriad of design possibilities that can assist in the development of new man-made structures and forms inspired by what the sciences present. This is supported by our continuing drive to discover new design methods that heighten the quality and performance of architecture

through efficiency and economy and what better way can this be achieved other than to acquire and share the knowledge attained from nature and science.

Nature is a continual source of knowledge to our built environment and the study of the sciences have enabled us to look further into means by which microscopic life, for example, contrives structures and forms akin to their environment. Through science, we continue to delve further in our knowledge of nature's principles and it is not surprising to learn that life forms are unique because they have managed, through millions of years, to develop strategies of their own to live by, structure themselves and attain their unique forms, as a result, architecture continues to benefit from this by implementing nature's strategies in its designs.

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Appendix A

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Museums-Chronicle of Events

Ancient Greek

Figure.1 Delphi, Athenian Treasure Chamber After 480BC (Rebuilt in 1906).

The term ' museum' originates from the Greek place of muses: place and dance floor of the muses and their mother Mnempsune. The Greek goddess of memory- was initially used in the ancient world to designate the schools of poetry and philosophy that came to be attached to the shrines of the muses (see figure 1). Later the term came to refer to the research facilities that were attached to collections such as the museum in Alexandria. [1] The famous library of Alexandria was part of the museum and contained a huge collection of manuscripts from the Greek world. The museum and most of its library were destroyed about AD 270 during civil disturbances.

The Middle Ages

Christianity was the focal point for collecting. Collections were held in treasure chambers. Cathedrals, churches, and monasteries became repositories for religious relics, jewels, precious metals, rare manuscripts, and fabrics. Beginning in the 7th century, spoils of the Crusades augmented these

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[1] Naredi- Rainer, Paul . Museum Building : A Design Manual. Berlin, Germany: Birkhauser Publishers for Architecture, 2003. 13

collections, as well as private collections. Collecting in the Islamic world and Asia followed similar patterns.

The Renaissance

Many of the famous European museums of today trace their beginnings to the rich private collections that developed during the Renaissance. During the 14th century in Italy, the rise of commerce created a new class of wealthy merchants who amassed large collections of sculpture, paintings, and the art of antiquity. The nobilities and the dignitaries of the church also began to collect on a large scale. In Rome the initiative in founding collections was taken by Popes Paul II, Julius II, Leo X, Clement VII, Pius V, Sixths V, and Clement XIV. In Florence, the wealthy Medici family assembled an unrivaled collection of antique Roman and contemporary Italian sculptures, manuscripts, tapestries, paintings, bronzes, and gems as well as objects of scientific and technological interest. The Medicos displayed large pictures of mythological and religious subjects in a long narrow corridor called a *galleria.* By the end of the 16th century, the galleria was invariably part of the residences of Italian princes. Today the term *gallery* means a place where works of art are hung or arranged for viewing.

17th Century

In the households of wealthy collectors, small art objects or nature collections were often arranged in a *cabinet* [1]. These cabinets began in the 16th

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[1] Originally the term *cabinet of curiosities* referred to a piece of furniture where small valuables were stored for safekeeping. The term later came to designate a small room or small private museum where such things were kept. Although these arrangements were often haphazard, they nevertheless represented the first efforts to chronicle the full spectrum of human achievement and the natural world. (http://encarta.msn.com/encyclopedia_761557357_4/Museum.html)

century but came into their own in the 17th century, when the burgeoning interest in science expanded the realm of interests and opportunities for collectors. With the discovery of the Americas and newly opened trade routes to Asia, rare tropical birds and animals, plants, rocks, and insects rapidly found their way into the eclectic and encyclopedic cabinets. Collectors often organized their holdings according to classification systems, presaging the collection management practices of today's museums. The *Ash Olean* collection was the first public natural history museum in the world and marked the first English use of the word *museum* (See figure 2).

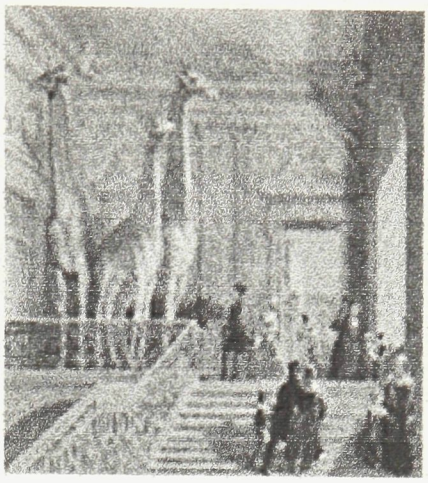

Figure.2.British Museum opens to the public.

18th Century- Britain

The 18th century saw the beginnings of the public museum in Europe and, at the close of the century, the establishment of the first museums in the New World. The growth of mercantilism, the decline of the court patronage system, and the rise of a new affluent class led to the emergence of a more sophisticated style of living and greater interest in the arts. At the same time, the dawn of the Industrial Revolution in the mid-18th century stimulated public fascination with the marvels of science and technology. The new "public" museums, however, were generally inaccessible to all but the aristocracy. The British museum opened in 1759. At first, it contained only a library and natural history collections. An act of parliament declared the museum an issue of public interest.

18th Century –France

In 1793 the French Republic opened the Louvre with its art treasures collected by the French royalty. It was accessible to the public on three days of one "decade" (the 10-day unit had replaced the week in the republican calendar).

Figure 3 Hubert Robert:Grande Galerie in the Louvre, 1794/96; Paris, Louvre.

The *Conservatoire de Musée National* (National Museum Conservatory) was charged with organizing the Louvre (see figure 3) as a national public museum and the centerpiece of a planned national museum system Louvre opens to public in 1794 free of charge- then the word *museum* was exclusively used to refer to art collections. The Louvre had the first administrative structure that is typical today.

19th Century

The concept of the public museum began to flourish in the 19th century. In Western Europe, beginning in the mid-1800s, nearly every nation formed an encyclopedic national museum of art, science, or natural history on a grand scale. In Canada, the Geological Survey of Canada, started in 1842, began collecting natural history specimens that would form the basis of National Museum of Canada (later renamed the National Museum of Natural Sciences and now called the Canadian Museum of Nature); and in 1880 the government launched the National Gallery of Canada.

A dominant force in the change that permeated European and American institutions was the popular success of the world expositions, which spawned important museums, revolutionized exhibition techniques, and signaled a new trend in public participation. The profits from the Great Exhibition of 1851 in the Crystal Palace in Hyde Park, London, were used to acquire land on which to build museums, including the South Kensington Museum of Industrial Art (later the Victoria and Albert Museum).

The dramatic growth in the number and scope of museums during the 19th century stimulated active discussion about their role in society. This discussion persisted through the 20th century, as changes in museums continued to parallel global political, economic, and social changes.

20th Century

After World War I (1914-1918), museums in the United States, Great Britain, France, and northern Europe began to shape more and more of their programs to satisfy the increasing need for public education. However, political changes retarded the development of many central, southern, and eastern European museums. World War II (1939-1945) devastated many museums, both physically and philosophically. It was not until after the war that the museums of Europe were able to free themselves from the monolithic state supervisory structure and begin to develop into cultural institutions vital to their own communities.

Museums became focused more on concepts and ideas than on collections of objects—such as *children's museums*, *science-technology centers*, *art centers*, and *outdoor history museums*—became popular throughout the world. In the states, large special exhibitions, termed *blockbusters*, appealed to

a general audience, and museums began to adopt marketing techniques to promote their many offerings. Museums also expanded the range of topics they addressed to include significant contemporary social issues and controversial historical questions.

21 Century

At the beginning of the 21st century, museums throughout the world enjoy popularity and public respect. Millions of people visit museums each year to see, enjoy, participate in, and learn from their collections, exhibitions, and programs. Millions more visit museums' Web sites on the Internet, which has allowed museums to expand beyond their physical walls and reach out to vast audiences. Museums continue to be challenged by the diversity—ethnic, economic, educational, and generational—of the public they serve. They are responding by striving to be accessible cultural and educational centers that engage the public as part of their traditional missions to collect, preserve, and interpret the world's heritage.