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Leaf Morphology- An Interpretation of Fractals in Architectural Design

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Abstract

Nature is the primary source of inspiration for human mind. Our world is full of interesting natural phenomena, organisms and systems that are essential for the existence of life on earth. Learning from nature is not a new concept. However, with the passage of time and the advancement of technology, the world has shifted to high tech strategies that are not sustainable in our natural context any more. Hence, scientists and designers are rethinking about sustainable solutions by taking inspiration from nature and with the help of advance technologies. Mathematics of self-similar shapes has existed for centuries. We have now realized that it is a natural phenomenon and is known as fractals. It is found everywhere, from trees to river networks, clouds to coral reefs, lighting to bird's wings and vascular system of lungs to leaves. Fractals are never ending and infinitely complex patterns that are self-similar across different scales. Fractals create infinite complexity but in mathematics, it can be formulated thorough relatively simple equations. The idea is to study leaf morphology to understand the fractal pattern in leaf. Further, we want to explore the properties of leaf fractals so that we can use these arrangements in our architectural design.

Keywords: fractals, fractal geometry, morphogenesis, Voronoi diagram, Voronoi polygon

Introduction

The world is full of natural phenomena. We are trying to take inspiration from nature and trying to find out the ways we can interpret natural patterns in our design in an appropriate and effective way. Natural patterns are not just there to be imitated for the sake of aesthetics but also to develop an understanding about design strategies. In this way, we can design efficiently in accordance with our natural context. (Paearce, 1980).

Bio-mimicry is the science and philosophy of learning from nature.

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From nature and natural phenomena we take inspiration. There are three categories of bio-mimicry. In the first category, ideas and inspirations are developed from natural forms and shapes. It is about the shape and formation of a natural object, such as the shape of a flower or a fish. In the second category, natural mechanisms of organisms, articulation or structures are the source of inspiration, such as the movement of worms or the structure of a bird's wing. In the third category, natural phenomena and systems are the main sources of design inspiration. For example, the process of photosynthesis in leaves or wave formation in water.

Nature has several complex phenomena which can be either regular and/or irregular. To understand nature, we have to investigate the morphology of natural elements or compounds (Hartvigsen, 2000). To develop their understanding and to analyze them, designers and engineers often combine nature with mathematics. Mathematics provides rules and guides to understand their complexity and to develop ratios and geometry. In this paper, the design concept is derived from a natural pattern known as fractals. Fractals are present everywhere from the simplest and smallest scale to complex systems. Leaf fractals and morphology are the sources of inspiration that will be further interpreted into an architectural design with a new, efficient and natural design approach (ICDC, 2013).

2. Background

The world is fascinated by the beautiful patterns of nature known as fractals. Fractal geometry is the amalgamation of art and mathematics. Using mathematical equations and ratios, various natural patterns can be interpreted geometrically. Fractals are an interesting natural arrangement that can be found in microscopic organisms, flowers, petals, leaves, human body, coastlines, mountains and sky lightening. Fractal geometry is now connected with artificial intelligence but before its invention, people worked with fractals with help of equation and practical geometry.

British cartographers, while measuring the length of the British coast, observed similarities in the coastline. When the coastline was measured on a large scale map, they observed that it was approximately half the length of coastline that was measured earlier on the detailed map. They looked closer and found that the more detailed and longer the coastline became, the more it started to repeat the same arrangements of shapes. Hence, they discovered one of the main characteristics of fractals but they did not realize this discovery at that time.

Fractals are continuous and complex patterns. They create self-similar and complex arrangements across different scales and angles. They can be created by a simple process repeated with a continuous feedback loop. Fractals are pictures of chaos, harmony and dynamic systems. Benoit Mandelbrot coined the term 'fractal' in 1975. A fractal is a form of geometry that exhibits self-similar ratios. The understanding of the clarity of smaller objects in the entire figure is related to the image size that is not readable in the totality of the figure. Infinite complexity is the beauty of fractals, but in mathematics it can be worked out with relatively simple equations and geometry. By repeating fractal ratios or fractal generating equations several times with different intervals, random outputs can create beautiful and complex fractal patterns.

Fractals have two significant characteristics, these are self-similarity and non-integer dimension. Self-similarity can be easily observed in fractals. For instance, if we take a fern leaf and observe it closely, it will be noticed that every smaller leaf is a part of a bigger leaf and it has the same form as the bigger fern leaf. We can say that the fern leaf is self-similar because every component shows similarity in formation. Fractal patterns can magnify themselves many times and after each phase they exhibit the same shape, which is the characteristic of that particular fractal (Mandelbort, 2013).

3. Morus Rubra – Leaf Morphology and Fractal Pattern

Plants have an elementary and significant role in our ecosystem. Every living organism and the whole environment of earth, all are directly or indirectly related and dependent on plants. Plants have two main systems categorized as shoot and root systems. Leaf is the most essential part of shoot system. Leaves perform two primary functions that are photosynthesis and transpiration.

Morus Rubra is selected to study the fractal pattern in leaf morphology. Morus Rubra is a local plant of Lahore, locally known as *shehtoot*. Morphologically, its leaf has three parts; base, petiole and lamina. Different plants have different types of venation in their leaves. Venation is described as the pattern or arrangement of veins and veinlet in a leaf. Primarily, there are two types of leaf venation in plants, that is, parallel and rectangular. Morus Rubra's leaves have rectangular venation and structurally, its leaves are thin and flattened.

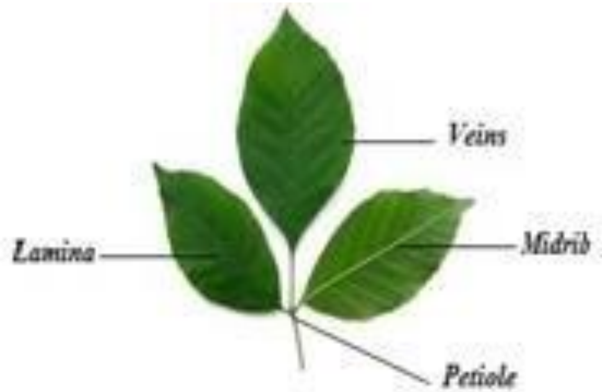

Figure 1. Morus Rubra plant

Midrib, primary, secondary and tertiary veins of the leaf can be seen easily and all these veins make an intricate pattern by following fractals. One of the basic characteristics of fractals is that fractal patterns can be magnified many times and the same basic module of the fractal shape will be repeated with specific rotations and ratios.

In the following figure, the analysis of veins can be seen; in different layers these veins are configured into primary, secondary and tertiary veins making a complex fractal pattern.

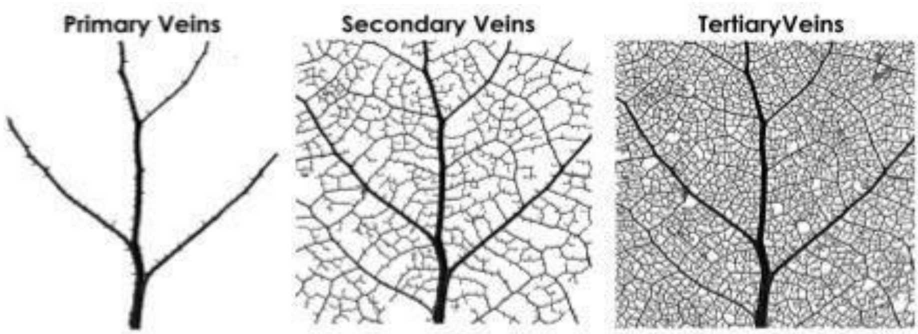

Figure 2. Morus Rubra venation (primary, secondary, tertiary veins)

4. Interpretation of Leaf Fractal Pattern in Architectural Design Via Voronoi Diagram

The main question is how to use fractal patterns in design. The idea is to use these pattern not just for the aesthetic purpose or to imitate a natural pattern but to explore the structural and functional aspect of fractals. In mathematics, there is a way to draw fractals diagrams, which represents such polygonal shapes as found in leaves' vascular structure. The process is carried out in a plane to make shapes and each shape acts as a plane to carry out the process again to make more shapes. This method is called 'Voronoi diagram'. It is named after Georgy Voronoi, and it is known as 'Voronoi tessellation' (Aurenhammer & Klein, 1991).

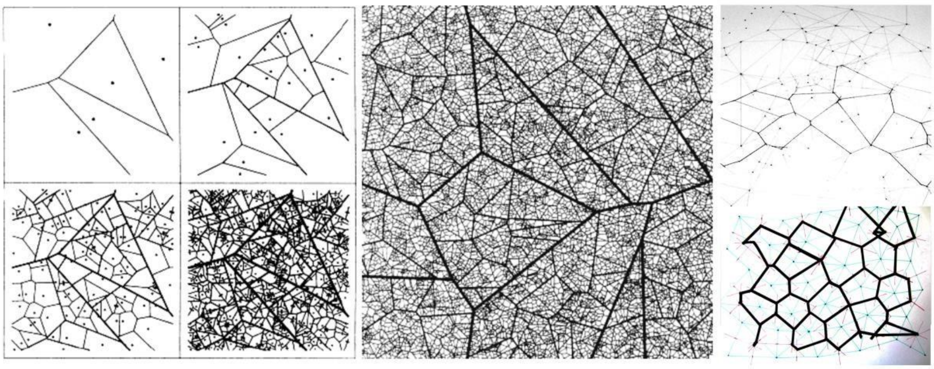

Figure 3. Generating Voronoi diagram

4.1. Generating Fractals from Voronoi Diagram

In the natural process of morphogenesis, cells divide and every cell fights for its own place. Throughout this fight, borders are generated between cells. Division of this type is called Voronoi diagram. You can discover this process all around in natural forms like leaves, trees, rocks, crystals, earth crust and even in the body of all living organisms. Voronoi diagrams are used to create fascinating fractal patterns which can be used to interpret natural fractals, like natural patterns of leaf veins, animal skin, water channels, mountain ranges and vascular system. The fractal patterns are generated with the help of Voronoi diagram.

A Voronoi diagram consists of the Voronoi region and a set of Voronoi polygons. Voronoi region is created by drawing three points in a plane; by interconnecting these points we get a specified region. Again in the former region, three sets of points are drawn; we start with a small set of points and draw Voronoi diagram. Then, we use a denser set of points and create a new Voronoi diagram inside each region of the former diagram. For drawing further Voronoi diagrams, only those points are considered that are located within the region. This process is repeated recursively in each region to attain a higher level diagram.

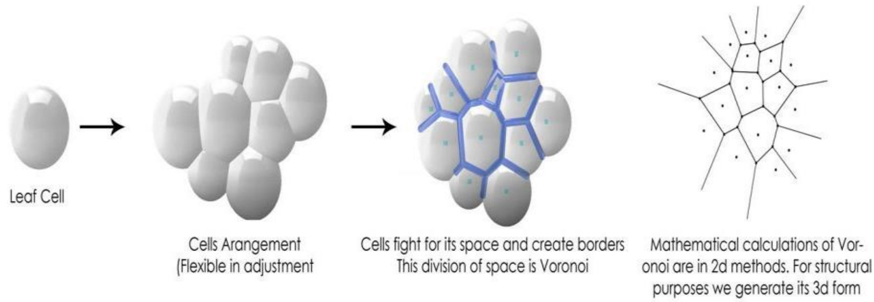

Figure 4. Leaf cells (process of morphogenesis)

5. Developing Architectural Design from Voronoi Diagram

The idea is to use Voronoi diagram in architectural design from various aspects, such as aesthetics, structural and environmental responsive designs. The major question was how to develop a structural sense for architecture through Voronoi diagrams that is used to draw 2D patterns. We want to use these irregular shapes of Voronoi as a self-supporting structure. Then, we thought of making adjustments and interpretations taking inspiration from leaf morphology and fractal patterns. In this process, we used the Voronoi plugin sketchup to generate Voronoi diagrams. Firstly, random points were created in Voronoi region. Afterwards, triangulation into the Voronoi region was created. Voronoi cells were formed, with each cell having its own boundary line and angles. 'Vornoi Conic Curve' was used to attain Voronoi diagram on a curved region. After generating Voronoi diagram on a curve form, in order to transform it into a structural form we used a 'JHS Power tool' to analyze its structural possibilities. A mesh was generated that can modify its triangulation with respect to the desired formation.

5.1. Structure: Self-Supporting Structure Through Layers

Primary, secondary and tertiary layers of Voronoi mesh were generated that overlap with each other to strengthen the structural stability of the structure (Shirriff, 1998). These layers distribute the load and lateral forces uniformly over the structure and make it a self-supporting structure. From outer to inner layers, all layers create the self-load bearing envelop. Leaf venation was the source of inspiration behind this formation, describing how the network of veins in leaf strengthens the structure and overall leaf formation in a plant. Midrib, the backbone and primary, secondary and tertiary veins encompass the total surface area and distribute the overall load by creating a self-supporting shape of leaf.

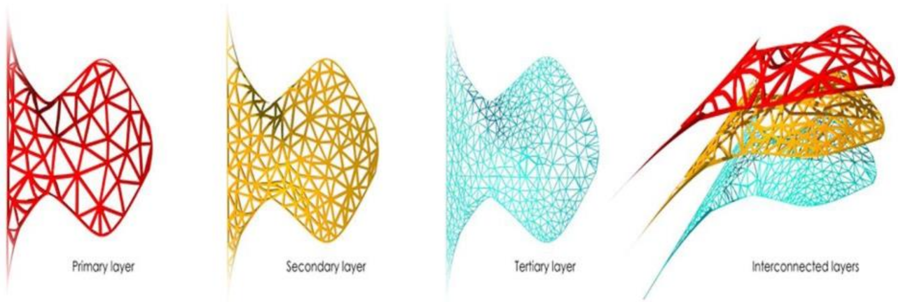

Figure 5. Self-supporting structural mechanism

5.2. Aesthetics: Porosity and Natural Lighting

Voronoi diagram generates cells in each layer and in a form of mesh. These cells are treated as void while the boundary lines between cells is extruded to make the skeleton of the structure. Porous surface of overlapped layers will allow the optimum exposure to sunlight through voids that will light up the indoor space and will enhance the overall ambience of the pavilion.

5.3. Environmental Responsive: Self-Cooling Skin

The proposed design will be located in Lahore. To make an environmental responsive design, firstly, we have to consider the climate of Lahore. The wind is most often blown from the north for 4 months, from February to May. The wind is most often blown from the west for 2 months, from May to July. The wind is most often blown from the east for 2 months, from August to October. The idea is to utilize the outer structural skin and interconnected layers to occupy the duct system along with the arrangement of cell's boundary lines. These ducts will contain cool water. Structure is placed in a north-west direction, so that in summers when the wind passes through the porous skin, the cold water present in the ducts will help to cool it. After passing through ducts, eventually cool breeze will be distributed into the enclosure through the porous surface of secondary and tertiary layers. In this way, the natural air conditioning process will help to control the indoor atmosphere. On the other hand, it is environmental friendly. Leaves are also responsible for transpiration and it is carried out with the help of veins that carry liquid to the leaf surface.

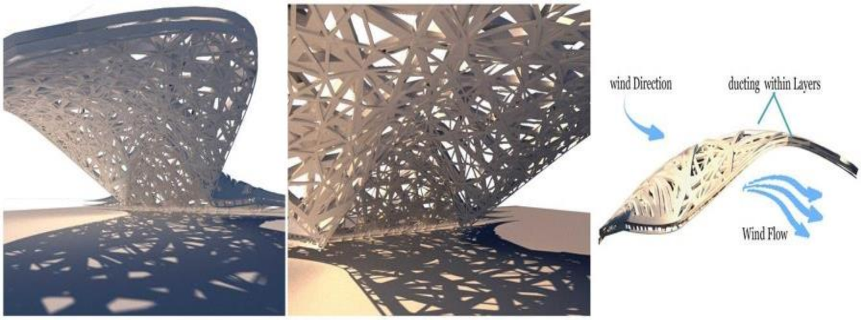

Figure 6. Self-cooling skin and wind flow

5.4. Voronax Pavilion

Voronax Pavilion is an interpretation of Voronoi diagram into an architectural design inspired from leaf morphology and fractal pattern. It consists of a self-supporting structure that incorporates the environment through its formation and orientation.

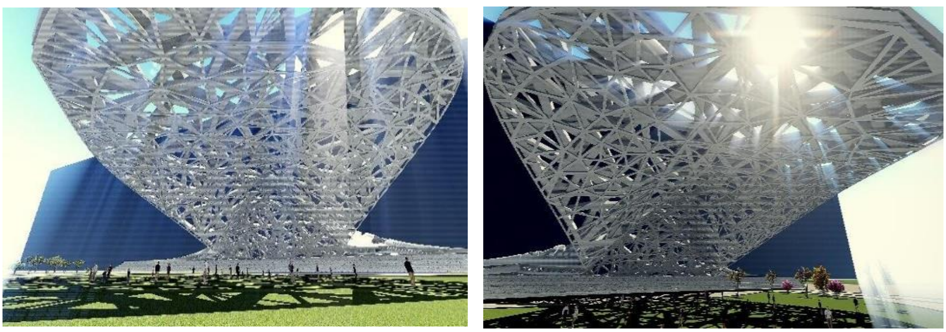

Figure 7. (Left) Porous overlapped Voronoi layers; (Right) sunlight through voids

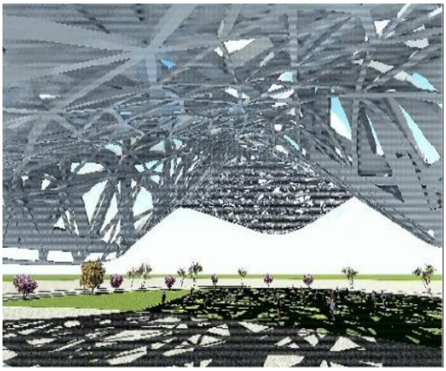
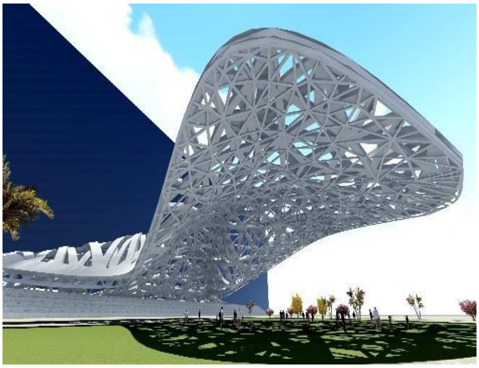

Figure 8. (Left) View from inside of the pavilion; (Right) exterior view of the pavilion

5.5. Site Location

The proposed Voronax pavilion is suggested as a public open space that will be located in Lahore. The proposed site is located in Johar Town, adjacent to the Expo Centre, Lahore. On the eastern side of the site, the nearest building is the Emporium mall. The site has access from two directions, that is, northern and eastern directions. The main entrance to the site is from Abdul Haq road and the side road will be used for parking space. The site has potential to attract users as the area is surrounded by Expo Centre and shopping mall. This space has major attractions for public use. Many people come to this location for recreational purposes. An open green space encompassing a public pavilion will add more attraction to this space.

This public pavilion is proposed in an open green space surrounded by trees and soft landscape. Voronax pavilion will be located in the centre of the green space. The idea is to place it in the centre of the site so that more green space can be added to the site in all directions and visitors have the axial visual permeability towards the pavilion. Structure is placed in the north-west direction keeping in view the environmental responsive strategy with respect to climate. When visitors will enter into the site they will feel the hierarchy of this place, this is how Voronax design will gradually amalgamate the open and semi-covered space in the form of a perforated enclosure. Even from the road, one will have the views and vistas of this pavilion it will attract more visitors. People could use this space for gatherings, concerts and different festivals.

Figure 9. (Left) selected site of the pavilion; (right) site plan of the Voronax pavilion

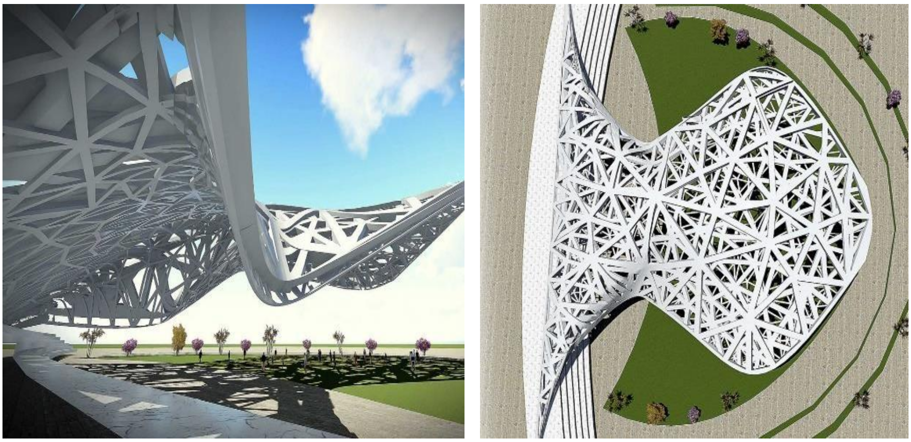

Figure 10. (Left) Side view of the pavilion; (Right) top view of the Voronax pavilion

6. Case Study - Icd/Itke Research Pavillon 2014-15

At the University of Stuttgart, the ICD/ITKE research pavilion was designed in 2015. This research pavilion exhibits the architectural potential of an innovative building design inspired by underwater nest construction of the water spider. The framework was built through a unique robotic fabrication process using carbon fiber. Initially, a flexible formwork was formed that was gradually stiffened from the inside by reinforcing it with carbon fibers.

The design concept is based on the study of biological construction processes for fiber reinforced structures. These processes are relevant for applications in architecture, as they do not require complex formwork and are capable of adapting to the varying demands of the individual constructions.

The design concept was developed by observing the biological construction processes of water spider. The biological processes creating fiber reinforced structures are highly material effective and functional. For this purpose, the web building process of the diving bell water spider (Agyroneda Aquatica) was reviewed. The web construction process of water spiders was thoroughly analyzed that included behavioral patterns and design rules of the fabrication process.

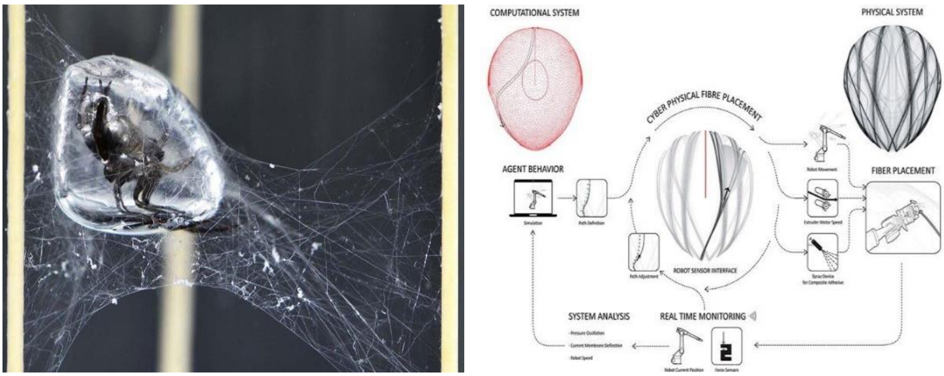

Figure 11. (Left) Water spider web; (Right) web formation process in design

The water spider lives its entire life under water. It constructs a reinforced air bubble to build up a shelter for itself. The spider builds a horizontal sheet web at which the bubble is placed. Then the air bubble is reinforced by creating fibers all around it from outside to inside. For reinforcement, fibers are placed in a hierarchical arrangement. This reinforcement results into a stable structure that can resist mechanical stresses like water movements and pressures. From this natural process, we can understand how fabrication mechanism can be used to create efficient fiber reinforced structures. Through this process, self-supporting structures can be developed consisting of a membrane and reinforced by carbon fiber. Such structures are flexible, light weight and adaptive.

Figure 12. (Left) View of the pavilion; (Right) view of research pavilion by ICD/ITKE

For the construction of this structure, shell geometry and main fiber bundle were generated by a computational form finding method. This method integrates fabrication constraints and structural production. Research pavilion consists of $40m^2$ area and an internal volume of $130m^3$ with a span of 7.5m and a height of 4.1m. The total construction weight is 260kg, which corresponds to a weight of $6.5kg /m^2$.

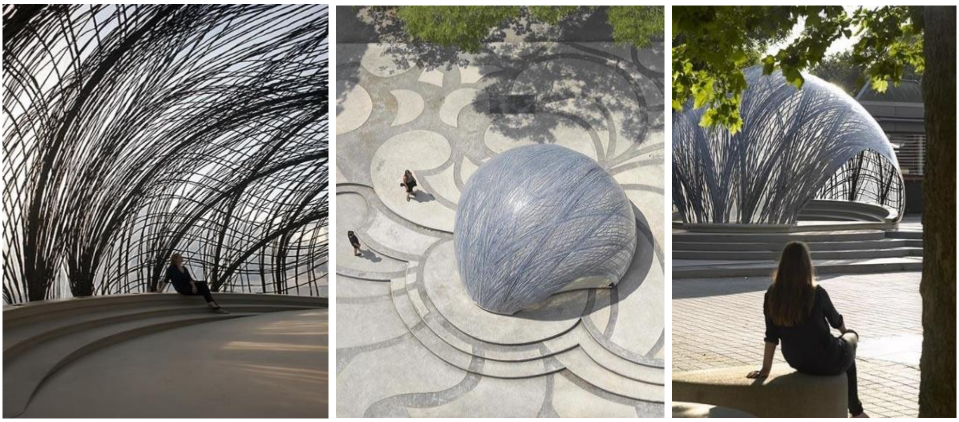

Figure 13. Interior view, top view and side view of the pavilion

6.1. Analysis

In this case study, we can observe that design concepts through different biological processes were developed. Not only the design concept but the mechanism and structural strategy was also developed by analyzing water spider web. With the advancement of technology, materials are formed with computational design techniques. This pavilion is an adaptive, selfsupported, light weight and flexible structure like a web of water spider. Its design is developed through different processes of biological arrangements consisting of fiber reinforcement.

7. Conclusion

Fractals that are derived from mathematical formulas or Voronoi diagrams are closer to our natural world but they are not perfectly applied on each natural object because natural phenomena show variations which are also rhythmic but complex. The fractal has dimension proved to be a powerful taxonomic attribute that quantifies the complexity of the leaf venation. Voronoi diagram is a methodology to generate fractals from the venation of a leaf. With Voronoi diagram, we attempted to interpret fractal patterns into an architectural design to generate a self-supporting structure that will incorporate the environmental responsive approach in it as well. Voronax pavilion is the interpretation/incorporation of fractals into architectural design. In its form and functional aspect, this pavilion incorporates aesthetics, structural and environmental approaches.

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