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Arboreal Architecture

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Abstract

The overall purpose of the study is to highlight the advantage of arboreal structures in case of its aesthetic and structural merits. Architects have been influenced by natural forms for ages and nature itself is a best solution giver for the existing problems. The tree is a perfect inspiration for a structural member as it itself have proven it's structural stability over ages. The inspiration from tree was first used as only as aesthetic elements, later on architects began to mimic one of the greater feature of the tree—its structural stability and mechanical properties. The purpose of this paper is to describe the arboreal structures, its effect on buildings and to find the different typologies in arboreal structures. Inferences from the study will help designers choose arboreal structures over the conventional load bearing structures.

Keywords: *Arboreal architecture, Dendritic structures, Evolution, Branching structures*

1. Introduction

Arboreal architecture is taking inspiration from trees. It comprises the imitation of the tree-like patterns used to build architectural structures, including their structural and mechanical attributes as well as their shape and form. From prehistoric times to the present, there has always been a relationship between trees and architecture. Through the development of technology and materials, the elements/structures have undergone numerous transformations over time, shifting from serving simply an aesthetic purpose to structural elements and then acting as both structural and aesthetic elements. For broad spanning constructions, it is currently considered to be quite useful without sacrificing its aesthetic feature.

2. Arboreal Structures

2.1. Biomimetics

Although the idea of learning from nature is not new, it has recently become more popular across many disciplines as a result of technological advancements. The concept of Biomimicry, considered as the science and philosophy of

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learning from nature (Benyusis, 2001) is used as a source of inspiration for architectural design in a variety of ways by architects and engineers. It is a representation of a tree form and shape. Tree like branching structure is also known as 'dendritic structure' (Schulz and Hilgenfeldt, 1994). Mathematics provides guidelines that help engineers and architects comprehend the complexity of natural shapes. The idea of complex, non-linear, and fractal geometries has made it possible to use mathematics to describe the irregular non-Euclidean geometry of natural trees (Casti, 1989). The term "fractal," first used in the 1970s by Benoit Mandelbrot, can theoretically be used to describe the geometry of numerous natural objects (Mandelbrot, 1982).

2.2. Branching Structures

Based on a tree's structure, a branching structure is created. A big surface area can be supported by the structure as it spreads out from one point to several branches (Figure 1). With great structural efficiency, the structure is able to shift the loads from a larger surface to a single column or point. Due to the separation of the components, the roof members' spans are reduced, resulting in smaller structural members. Additionally, each member's length is shrunk, shortening the buckling length. The dividing members provide for the support of a wide span or area. An ideal load path system is created by this member division.

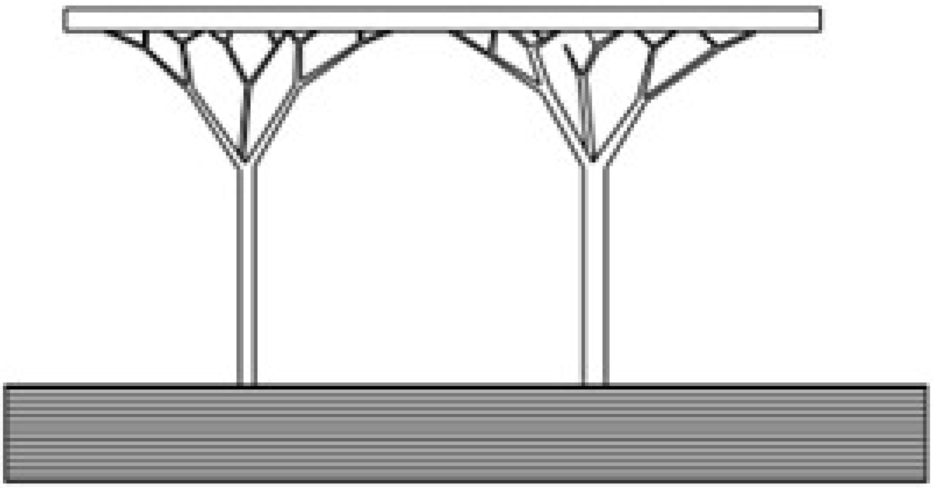

Figure 1: Branching as Structural System Design Sketches by Frei Otto

Source: Schultz et al. (2000)

2.3. Fractal Geometry

Fractal geometry is a branch of mathematics, which was created in the 1970s, examines abstract structures marked by recursive growth and self-similar patterns (Mandelbrot, 1982). Fractal objects exhibit the general property of being same or very similar at every size that is increased (Figure 2). Fractal objects are sets that have fractional dimensions, making them intermediary objects between one-dimensional shapes and two-dimensional shapes or two dimensional forms and three-dimensional forms (Falconer, 2003). No natural thing is completely fractal; instead, it exhibits "self likeness" and "self affinity" throughout a wide range of scales but a finite number of ranges (Bovill, 1996).

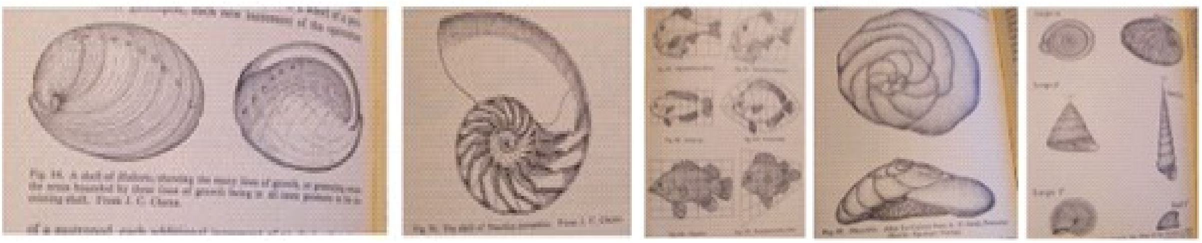

Figure 2: Fractal Geometry

Source: Growth and Form (Thompson, 1992)

2.4. Lightweight Structure

Frei Otto, a German architect and physicist, devoted his entire life to investigating how nature finds forms. He applied these techniques to create and construct numerous structures as an architect (Nerdinger, 2005). Frei Otto worked on the ideas of reducing material mass while maintaining structural effectiveness (Nerdinger, 2005). The introduction of suitable load bearing geometry offers enough strength and, as a result, lowers resource waste effectiveness (Nerdinger, 2005). Frei Otto focused on the model of branching structures and tree-like columns. His impressive creations include suspended architecture, dome and grid shells, inverting suspended drapes, and more. Frei Otto created a wide variety of branching structures. He molded concepts for the structural support of footbridges, conference rooms, and massive hexagonal grid domes using hanging models (Figure 3).

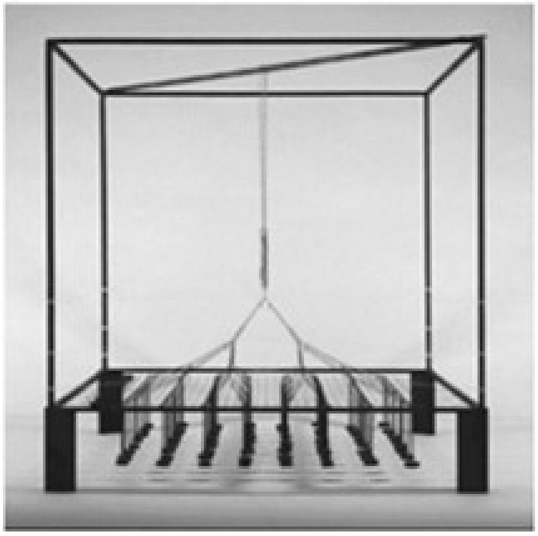

Figure 3: Frei Otto's Hanging Models of Branching Systems

Source: Nerdinger (2005)

3. Parameter Identification Through Literature Case Studies

As the research had been carried out as a part of four months academic project, the case studies with more information were selected on a random basis for parameter identification.

A. Sagrada Familia: Parameters identified: material, intersections or joints.

B. Johnson Wax Office Building: Parameters identified diameter, material, joints or connection.

C. Palazzo Del Lavoro: Parameters identified: material type, span, roof material, construction and erection techniques.

D. Cathedral of Our Lady of the Assumption at Karwar, Karnataka: Parameters identified: branches orientation, no of branching.

E. The Tote Restaurant, Mumbai: Parameters identified: roof material, orientation of primary structural members, angle of deviation at joints, foundation.

F. Atelier: Parameters identified: number of branching from a joint, material, type of connection used in joints.

G. Parameter Identified from Case Studies

- Branching pattern
- No of branches at the junction
- Levels of branching
- Joints or connection
- Angle of deviation at joints

- Material of structure
- Span
- Height
- Roof grid
- Diameter of the trunk and branches
- External radius
- Primary member
- Secondary member
- Roof structure and material
- Foundation
- Self weight of structure
- Bending moment
- Technology or technique used

4. Typology

Considering the parameter 'branching pattern' for typology identification.

4.1. Single Trunk Arboreal Structures

4.1.1. Mushroom and Umbrella Structures

Early examples of reinforced concrete mushroom and umbrella structures: 1930s (Figures 4 and 5).

Figure 4: Umbrella Structure

Source: Iasef Md Riann and Mario Sassone (2014)

Structure by F L Wright gave the column the label "dendriform," which is a botanical term for "tree-shaped," and he dubbed three of its four segments "stem," "petal," and "calyx."

Figure 5: Umbrella Structure

Source: Wikipedia

4.1.2. Baroni's Tree

Baroni's tree' in 1938, considered as the first known inverted reinforced concrete umbrella structures (Greco, 2001) (Figure 6).

Figure 6: Baroni's Tree

Source: Iasef Md Riann and Mario Sassone (2014)

4.1.3. Umbrella Column Shell

Felix Candela designed umbrella column shells which can be considered as the successors of Wright's mushroom columns. Candela's tree inspired column acts not only as a structural support but also as a shell structure like umbrella which covers a large span of the area. The secret of Candela's umbrellas was not only the shape, Each shell's design is based on the triad of external actions, shape, and boundary conditions.

The 4 cm thick umbrellas were created by Felix Candela under the presumption that a thin shell would function solely as a membrane (Figure 7). He did this by utilizing the parabola's capabilities to convert a uniform load into pure axial forces. The four hypars used to construct the umbrellas (hyperbolic paraboloids). Two primary parabolas of different signs are used to create each hypar, which is an anticlastic surface.

4.1.4. Umbrella Structures with Complex Column

Pier Luigi Nervi designed and constructed umbrella structures with a new construction approach where sometimes he used steel cantilevers as principal radial branches instead of monolithic concrete structure (Figure 8).

4.2. Multiple Branching Arboreal Structures

4.2.1. Lateral Branching Structures

The lateral buds of the main axis are where the branches are produced here. The primary stem's sides give rise to the branches. Here the primary stem are the members which supports the lateral branches (Figure 9).

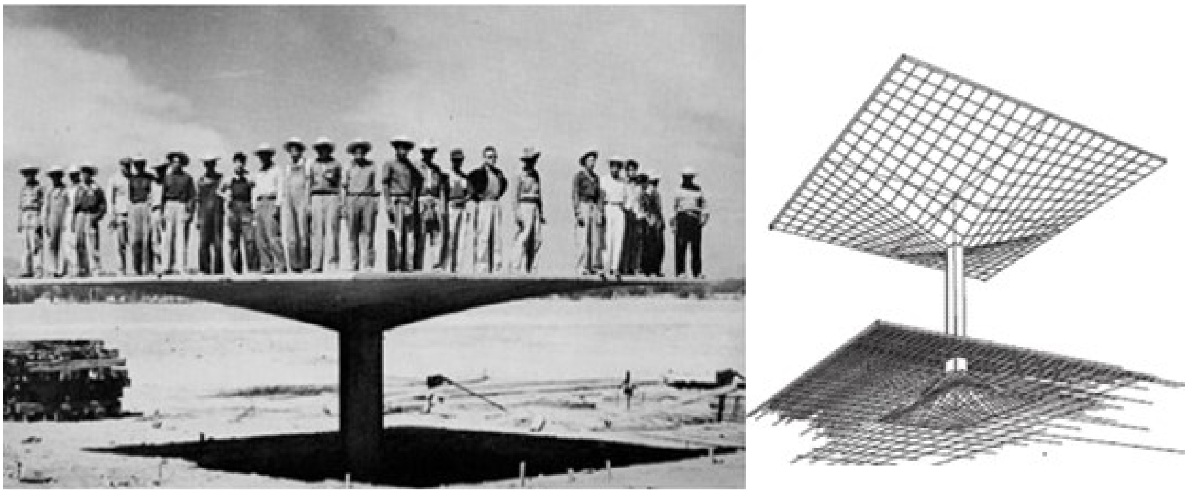

Figure 7: Umbrella Column Shell

Source: Garlock and Billington (2008)

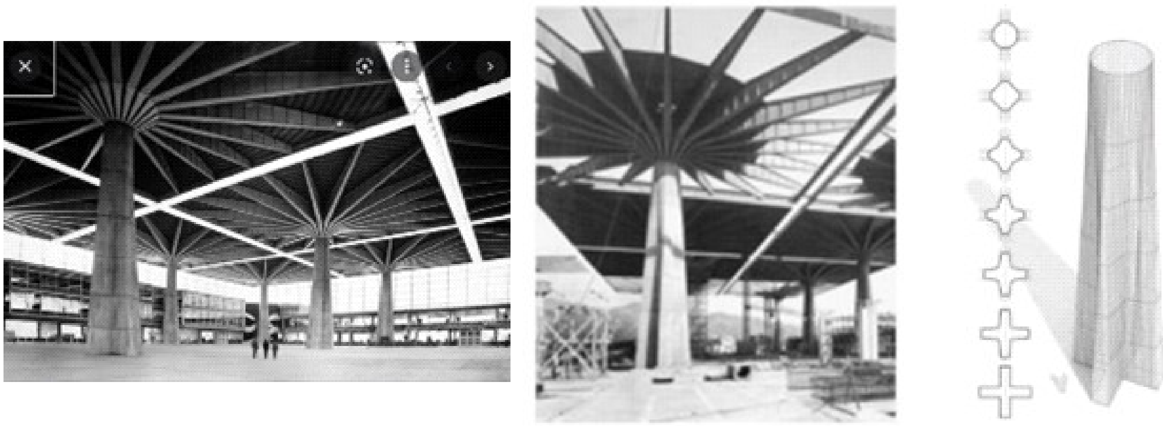

Figure 8: Umbrella Structures with Complex Column

Source: Perguni and Andreani (2013)

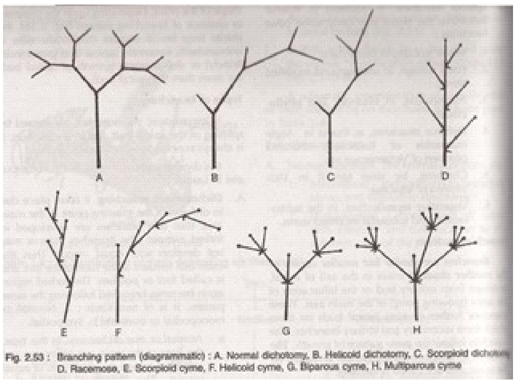

Figure 9: Branching Pattern

Source: Pteridophtes.ppt

Figure 10: Tote Restaurant

Source: Archdaily

4.2.2. Dichotomous Branching/Umbel Branching Structures

In this type, a branch that has already been divided produces two forked branches that are both the same size. Daughter branch tips may fork once more in the same way. An umbel is a racemose inflorescence that is characteristic of the carrot family cluster of spherical flowers (Figure 11). The umbel system can be thought of as a particular instance of the tree-like system, in which numerous short, equal-length branch stalks (known as pedicles) extend out from a central point to resemble the ribs of an umbrella.

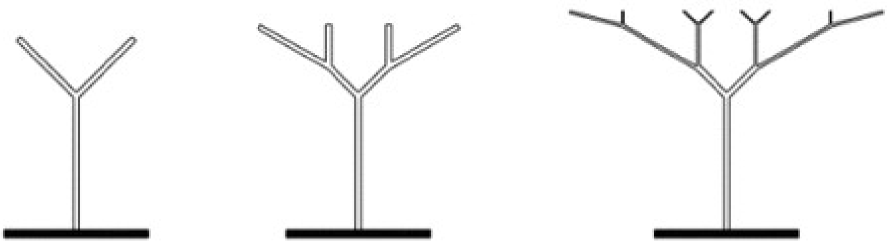

Figure 11: Structural Umbel Systems from Umbel Bifuricated System to Compound Umbel Systems

Source: Aseel Abdulhaleem Latif and Bahjat Rashad Shahin (2021)

Here the total load is distributed to one point and from there transmit the total load via a single member to a support point, the point of application of the reaction force providing total equilibrium.

Dichotomous branching structures were later used extensively. Its structure is to be studied in detail through case studies.

5. Dichotomous Branching Typology Case Study

To analyze the dichotomous branching pattern.

5.1. Stuttgart Airport Building (Figures 12-15)

Architect: Meinhard von Gerkan (GMP Architects)

Building Period: 1981-91 (planning and construction)

Structure: Tubular Steel

Figure 12: Interior of Stuttgart Airport Building

Source: Schlaich Bergermann Partner (2019)

The tiered roof is supported by a total of 18 steel trees (12 trees in Terminal 1). In this project, structural engineers and architects examine branching structures using "Genetic algorithms" (Gas) for minimal paths. Each pillar is made up of three separate levels and four connected tube columns that make up the tree's trunk (each column forms three branches, with four sub-branches each, to finally support the roof). By regulating the sizes and angles of those branches, they are dispersed so as to guarantee the transfer of loads with the availability of minimal bending forces.

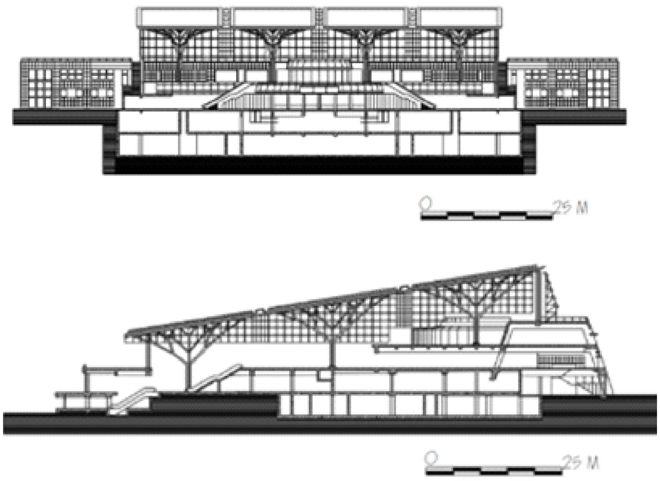

Figure 13: Sections

Source: Aseel Abdulhaleem Latif and Bahjat Rashad Shahin (2021)

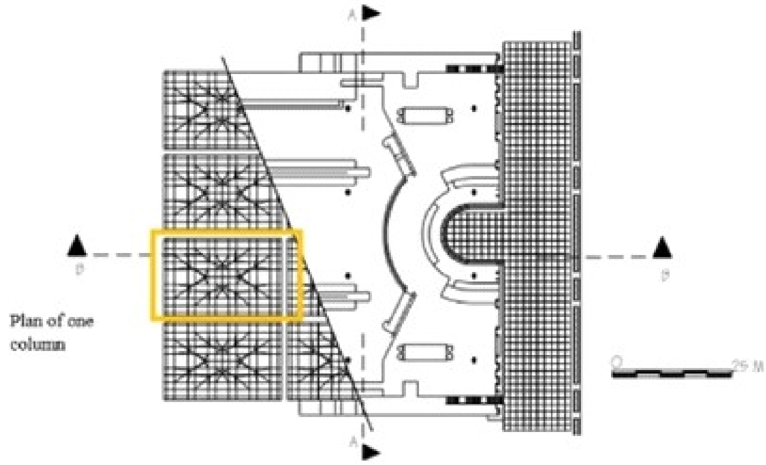

Figure 14: Plan

Source: Flamur Ahmeti (2017)

The distribution of these columns, despite their somewhat organic look, allows them to carry the roof loads in compression with few bending moments. The load may be observed descending through a complex hierarchy, starting from twigs and ending with the trunk, all of which are basically in compression. More specifically, the design of the terminal roof is inspired by the way trees are built.. The actual roof surface is divided into 12 equal, 26.6 x 43.4- meter sections that were built using a two-way steel section arrangement. The four tubular steel trunks that support each space act as a single unit. Each area is supported by a "steel tree" that is surrounded by glass strips. The numerous branching systems disperse the forces into smaller resultant points before they cluster on the trunks.

The building has a monopitched roof and a rectangular shape. There are three separate levels, and on each level, tubular tree-like columns are arranged to create a cascade and the roof's descent. The benefit of these umbel columns is that they achieve an uncluttered usable area below while offering closely spaced supports at roof level.

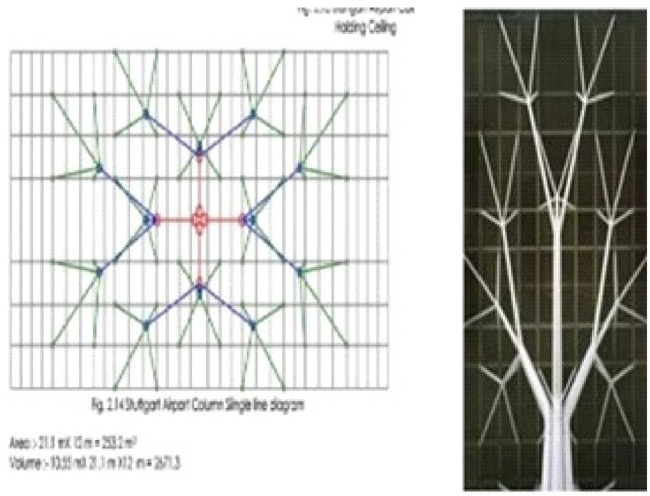

Figure 15: Stuttgart Airport (a) Column Single Line Drawing, (b) Column Holding Ceiling

Source: Rick Fairhurst Airport Case Study (2017)

5.2. The Changsha South Railway Station

Location: Changsha city, Hunan province

Architect: 3rd department of Central South Architectural Design Institute, INC

Figure 16: Interior of Changsha South Railway Station

Source: Wikipedia

Building Period: 2006-2009 (designed and construction)

Structure: Tubular Steel

Changsha South Railway Station has a total building area of around 447,000 sq. m. The shape of Changsha South Station's station building is modelled after the undulating curve of the mountains, and the platform canopy is modeled after the waves of the water. The curved roof is supported by 14 separate steel trees. Each pillar has two separate levels and four connected tube columns that make up the tree's trunk, each column forming four branches, with three sub-branches each, to support the roof. The sizes and angles of those branches are regulated so as to guarantee the transfer of loads with the availability of minimal bending forces. Despite their seemingly organic look, these columns are positioned to distribute the roof loads in compression with a minimum of bending moments (Figures 16, 17 and 18).

The branch-shaped steel structure support system has a strong sense of formal beauty, and its internal space design is succinct and straightforward with clear guidance, adding to the station building's distinctiveness.

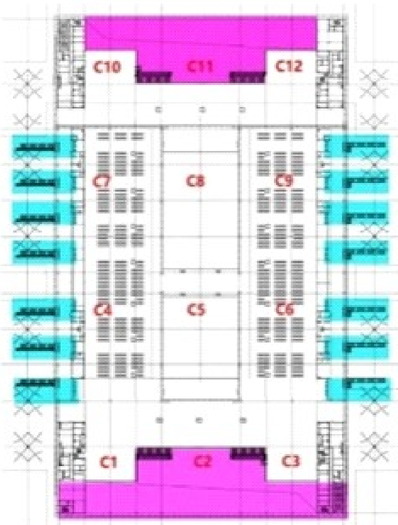

Figure 17: Plan

Source: Fucheng Zhu et al. (2020)

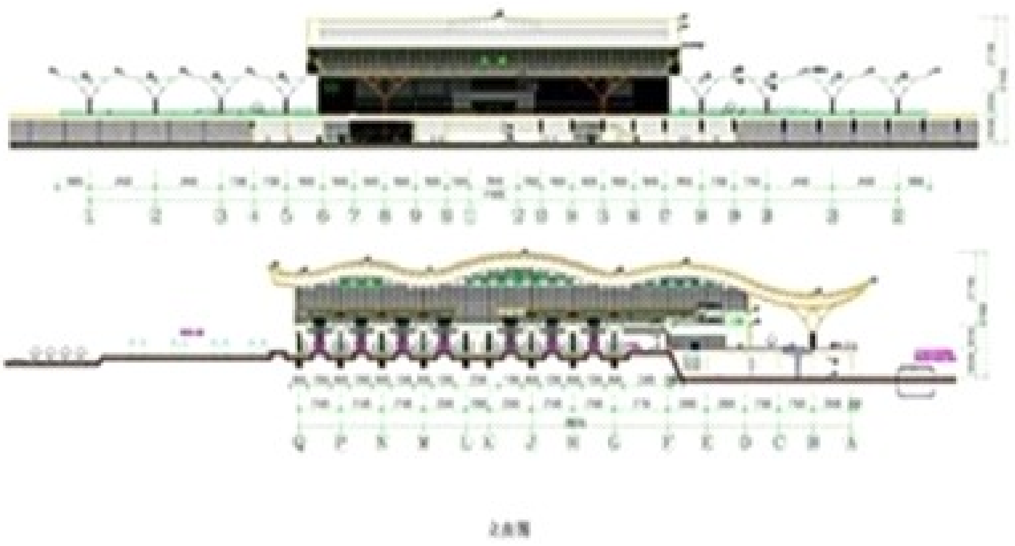

Figure 18: Section

Source: https://en.csadi.com.cn

6. Analysis

The dichotomous branching type arboreal structures are commonly seen in public structures, mainly in areas demanding large spanning spaces, making it material and economically efficient and creating aesthetically pleasing spaces.

Table 1: Comparative Analysis

	Stuttgart Airport	**Changsha Railway Station**
Material	Tubular steel	Tubular steel
Levels of branching	3	2
No.of branches from the node	4 (1st level),	4 (1st level),
	3 (2nd level),	3 (2nd level)
	4 (3rd level)	
Angle of branching (1st level)	130 °	130 °
Diameter of trunk (cm)	40 cm	40 cm
Diameter of branches (cm)	20 cm and 16 cm	20 cm
Type of roof	Sloped (to one side)	Curved (free form)
Span (m)	25 m x 17 m	16.5 x 15.5 m
Height (m)	13 m	13 m

6.1. Comparative Analysis

6.1.1. Analysis in Terms of Forms

- The four interconnected tubular columns that make up the primary pillars work as a single unit to distribute forces among the support locations.
- By regulating the sizes and angles of these branches, tree-like support systems with two or three layers are used to guarantee the availability of minimal bending forces.

- To prevent the creation of bending forces within the structural elements, small intervals are adopted between loading points and support systems.

6.1.2. Analysis in Terms of Materials

Columns made of hollow steel can be lighter than solid steel ones. The system's branching, which ranges from tree-like branches to four column support points, guarantees that the amount of structural material is kept to a minimum. Steel is the material that exhibits the best load bearing capability while also having the smallest volume and bulk, it is demonstrated. Therefore, despite having a higher specific weight, steel is the best performing lightweight material.

6.1.3. Analysis of Parameters

Literature case studies have been carried out taking buildings of different occupancies having arboreal structures as their structural members. And it has been found out that different structures are influenced by a number of parameters, and theses influencing parameters are listed. It is found that the parameters-branching pattern and numbers, branching orientation, material are common in varying uses of arboreal structures.

6.1.4. Analysis of Typology

From the parameter 'branching pattern' found from literature case studies, different typologies of arboreal structures are identified as Single trunk structures and Multiple branching structures.

7. Inference

- The parameters influencing the arboreal structures have been identified from literature case studies. The parameters are—branching pattern, no of branches at the junction, levels of branching, Joints or connection, angle of deviation at joints, material of structure, span, height, roof grid, diameter of the trunk and branches, external radius, primary member, secondary member, roof structure and material, foundation, self weight of structure, bending moment, technology or technique used.
- On the basis of identified parameter-branching pattern, typology of arboreal architecture are identified as Single trunk arboreal structures and multiple branching arboreal structures. These are further sub categorized as Mushroom and Umbrella Structures, Baroni's tree, Umbrella Column Shell, Umbrella Structures with Complex Column under the category of Single trunk arboreal structures,

And Lateral Branching structures, Dichotomous branching/Umbel Branching structures under the category of Multiple branching arboreal structures.

- From the case study of dichotomous branching structures the following where inferred.
- The four interconnected tubular columns that make up the primary pillars work efficiently as a single unit to distribute forces among the support location and the branched members supports a large surface area.
- Columns made of hollow steel are material efficient than solid ones, exhibiting best load bearing capacity. The tree like branching to four interconnected column support points guarantees the minimum amount of structural material.
- The diameter of the structure decreases as the level of branching increases.

	Case Study 1	**Case study 2**
Diameter of trunk	40 cm	40 cm
Diameter of 1st branch	20 cm	20 cm
Diameter of 2nd branch	16 cm	———

Proportion of diameter decrease is 40/16 : 20/16 : 16/16

The proportionate decrease in branching diameter is seen as 2.5 : 1.3 : 1 as (diameter of trunk : diameter of 1st level branching : diameter of 2nd level branching).

- The branching levels depends upon the span to be covered by the structure.
- Height depends on the span of the structure, as spanning increases so is the level of branching which results in the increase in height.

  No. of branching α distance to be spanned

  Increase in no. of branching results in increase in overall height of the structure.

  i.e., Height α Span of the structure
- From Table 1, the division of branching levels are found to be 4 in the primary division and the successive divisions as alternatives of 3's and 4's. Thus the pattern of no. of branching in each level is found as 4, 3, 4 in successive branching levels starting from primary branching.
- The angle of branching at first level is observed as 130° from the two case studies. Thus considered as a optimum angle for first level branching from the studied existing structures.

8. Conclusion

The ability of a natural tree to support a broad surface on a narrow element (trunk) through fractal-like branching structure is unquestionably its most inspiring characteristic. By comprehending nature's intricate forms, this concept has been instructing and directing architects to increase the effectiveness of their design realizations. However, the advancement of computational tools now enables the application of more logical and practical implementation approaches. Following the achievement of a minimal level of material and resource inputs needed, high structural efficiency is attained. Arboreal structures demonstrate the value of cost effectiveness and may play a significant role in future attempts to balance cost effectiveness, structure, and aesthetics. In recent years, with the rapid growth of science and technology, study on the characteristics of trees and plants, including fractals and other underlying geometric and mechanical elements, has opened a new arena for the inventions of forms and structures in architecture. More undiscovered facts and mechanisms of trees' forms and functions can be revealed by developing a deeper grasp of fractal-like form and its associated structural behavior. In order to solve both structural and spatial problems in architecture as well as to provide aesthetically innovative designs, researchers can now offer dendriform structures that are more innovative from an architectural and structural standpoint. The identification of influencing parameters helps us to identify what all features of the dendritic structures have to be concentrated for further future development of new technologies and classification based on the parameter branching pattern enables a better understanding of the structure for further future development.

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