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Geometric and Sustainable Analysis of the Hyperbolic Paraboloid of Félix Candela's Concrete Shell Structures

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Abstract: A shell structure, as its name implies, exhibits a curved, shell shaped appearance. In contrast to conventional framed constructions that depend on beams and columns, shell structures derive their strength from their inherent shape. The scarcity of concrete shell buildings globally can be attributed to the high degree of innovation necessary in various aspects such as design techniques, construction methods, and material utilization. Architects and engineers initiate the process by utilizing sophisticated analysis methods and approaches to identify the most suitable shape and curvature for the shell. Félix Candela was a celebrated figure in the mid-20th century, was globally recognized as an engineer, constructor, and structural artist specializing in concrete shell structures. The structural legacy Félix Candela plays a crucial role in engineering education and significantly enhances the practice of structural design. Through their innovative approaches and groundbreaking achievements, this contributes to advancements in structural engineering and inspires future generations of designers and engineers. This research studies and analyzes the geometric and structural analysis of two concrete shells structures that were made by Félix Candela. through the analysis study of his works, we conclude how this type of building promotes a new way of building that is highly sustainable and efficient. The research seeks to study how the application of the hyperbolic paraboloid can be an example of innovative, sustainable, and highly sophisticated structures through the study of the main works of Felix Candela.

Keywords: Hyperbolic paraboloid; Shell structure; Sustainable design; Geometry; Félix Candela

1. Introduction

A cruel reality that humanity is currently facing is climate change. This century is putting into debate how future generations will be able to live on earth through the actions we take now. For its part, the construction sector contributes about 30-35% of CO_2 emissions to the environment, which places it as one of the most polluting sectors in the world. That is why designs in the coming years must build differently using sustainability, materials and technology as tools to try to mitigate the effects of climate change. This is why, during the last decades, research in architecture and civil engineering has focused on building differently, considering current climatic adversities. A great example to try to mitigate environmental effects is centered on the optimization of structures, which simply translates to building more with less. With this premise, it is intended to be able to reduce construction materials, which translates to better structural performance through mathematics and much lower material expenditure. One of the principles of structural optimization is based on mathematical calculation and geometry, which in recent decades have been generating great results in trying to mitigate the effects of climate change. An example of these geometric shapes is the hyperbolic paraboloid; an example of the use of this geometric shape are the reinforced concrete shells of Félix Candela.

Félix Candela (1910-1997) was a Spanish born architect who in 1939 went in exile to Mexico after being imprisoned in a concentration camp at France due to his involvement with the Republicans during the Spanish Civil War. Candela lived in Mexico for thirty years and he obtained the Mexican citizenship [1]. In 1949, Candela, like the "innovative" masters of the history of architecture, had reached the conclusion that the most appropriate way to learn how to design and build thin shells was by experimenting directly with models. He also decided that the simplest and most immediate course that he should follow, because he was in a hurry to learn, was to build full-scale models with the materials used in actual construction, in the tradition of the Medieval master builders[2].

In 1949, following various professional pursuits including stints in Chihuahua, Acapulco, and Mexico City, and even a foray into film production he constructed his first experimental shell: a funicular or catenary vault. This innovative design was later applied in the construction of a rural school in Tamaulipas the following year. Buoyed by the success of this project and recognizing the vast potential in this pioneering field, Candela, along with his brothers Antonio and Julia, and Mexican architects Fernando and Raúl Fernández, founded a construction company dedicated to introducing concrete shells into industrial architecture. Thus, "*Cubiertas Ala*" was established, providing the platform for Félix Candela to act as architect, engineer, consultant, calculator, contractor, and builder, ultimately crafting the roofs that would garner him international acclaim. Félix Candela directed "*Cubiertas Ala*" from its foundation in 1950 until 1969, when his brother Antonio took over and directed it until it closures in 1976. In total, more than 1400 projects were carried out, of which almost 900 were built. Using only straight-line generation to create a warped surface, the hyperbolic paraboloid surface has negative Gaussian curvature which increases its resistance to buckling, while enabling construction with straight line formwork.

The work of the Spanish Mexican builder Félix Candela indicated new areas shell structures unifying the structural analysis and architectural ambitions into striking built forms. This allows for the possibility of slender sections. However, the use of thin shells introduces a concern for out-of-plane buckling, which becomes the primary integrity issue for such structures. The structural behavior of shells, compared to that of other types of structures, is characterized by a higher mechanical efficiency.

Concrete shells depend on their configuration, not on their mass, for stability[3]. Studies on double-curved surfaces date back to Greek times. The figure of the hyperbolic paraboloid was already known, but it was not really applied in the field of construction until the beginning of the 20th century. One of the first to experiment with these surfaces was the Spanish architect Antonio Gaudí (1852-1926), who would develop the first hyperbolic paraboloid vaults in the history of architecture in the crypt of Colonia Güel. In 1936, the French engineer Fernand Aimond (1902-1984) published a treatise on the static study of thin hyperbolic paraboloid vaults working without flexion, *"Etude statique des voiles minces en paraboloide hyperbolique trabaillant sans flexion."* Based on these treatises, new ways to calculate and solve hyperbolic paraboloid structures will appear and be perfected, especially those proposed by Félix Candela.

The use of hypar surfaces in shell structures is of course not new, as during the fifties and sixties Félix Candela revolutionized the thin shell concrete hypars around Mexico City[4]. During this period, Félix Candela became the most prolific designer and builder of reinforced concrete shell structures in the world. Candela was one of the pioneers of reinforced concrete shells in the world during the 20th century. Very interested in the structural performance, he affirms that: "for me the most important thing about the composition is the structure. What interests me most is the expressive potential of structural forms." It is in Mexico where he developed much of his work and where he made his greatest contribution to the history of architecture: the use of the hyperbolic paraboloid or hypar as he himself named it. Félix Candela demonstrated that geometric shapes, such as the hyperbolic paraboloid, could not only serve a structural function, but also contribute to aesthetics and sustainability in construction. Thanks to his work, the use of the hyperbolic paraboloid was adopted by other architects and engineers around the world, influencing the development of modern architecture, especially regarding the efficient use of materials and the construction of dynamic and lightweight forms.

2. Aims and Obejectives

This research seeks to contribute to the understanding of reinforced concrete shells through the hyperbolic paraboloid and to make known their advantages, their creation methods and sustainable /structural efficiency. Through the historiographic and structural analysis of the reinforced two concrete shells carried out by Félix Candela, an analysis of these shells, their geometry and how they present great sustainable advantages will be carried out. This research seeks to analyze the application of the hyperbolic paraboloid in the reinforced concrete shells of Félix Candela, explaining the advantages and applications that can be taken advantage of this geometric shape.

3. Geometrical Analysis of the Hyperbolic Paraboloid

The hyperbolic paraboloid is one of the types of construction that effectively uses the material, trusting its resistance more to its shape than to its mass. The double curvature makes it possible for the load to be transferred to the supports entirely by direct forces, so that all the material in a cross section of the sheet works uniformly. Although mathematical difficulties limit the use of the hyperbolic paraboloid for many years; the static principles on which it is based are not difficult to understand or apply, and that the project can be studied just as easily. Currently, thanks to technological advances, software and construction techniques, the application of geometry provides new tools when designing a light structure. The economic efficiency and structural simplicity inherent in hyperbolic paraboloid projects liberate engineers and architects from conventional constraints. Instead of conforming to traditional practices that rely on networks of linear members distributed in three perpendicular planes, engineers/architects can explore imaginative possibilities afforded by the graceful shapes derived from the basic element of the hyperbolic paraboloid. This freedom encourages creative expression and enables the realization of innovative architectural designs that defy conventional norms.

The surface of a hyperbolic paraboloid has a double anticlastic curvature, meaning the two principal curvatures bend in opposite directions, unlike synclastic or cup-shaped surfaces where the main curvatures bend in the same direction. The angle θ can vary, but when it is a right angle, the resulting paraboloid is termed equilateral, characterized by having two sets of main parabolas with identical curvature. When the angle θ is not a right angle, the parabolas in the acute quadrants are flatter than those in the obtuse quadrants.

A hyperbolic paraboloid is a surface that possesses both double curvature and double ruling. Its geometric construction involves defining four noncoplanar points (A, B, C, D) in such a manner that their projections onto the horizontal plane follow a clockwise arrangement (**Figure 1**). Each consecutive pair of points forms an edge of the hypar.

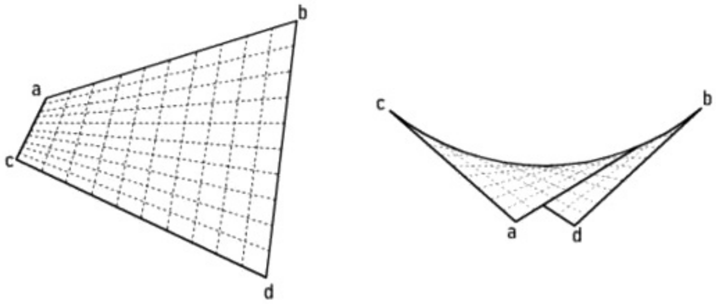

Figure 1. Upon connecting these pairs of points, excluding those that form the endpoints of the same edge, the diagonals AC and BD of the hypar aredetermined. The axis of the hypar, passing through the center O, is represented by the vector from the midpoint of diagonal BD to the midpoint of diagonal AC. This axis serves as a fundamental geometric characteristic of the hypar and directly influences its structural behavior.

When planes parallel to plane AOr and plane BOr intersect a hypar, they generate intersecting curves that delineate two sets of parabolas (**Figure 2**). The axes of all parabolas within a hypar are consistently parallel to its axis. The unique structural and visual qualities of hyperbolic paraboloids stem from their distinctive geometric attributes as surfaces that are both doubly ruled and doubly curved. To facilitate a clearer understanding of the structural analysis using graphic statics in subsequent sections.

The hyperbolic paraboloid is therefore a quadric, which, as its name indicates, is formed by containing parabolas. The hyperbolic paraboloid is the doubly ruled surface parameterized by:

$$z = \frac{y^2}{h^2} - \frac{x^2}{h^1}$$

Where:

$$\frac{\delta^2 z}{\delta x^2} = \frac{2}{h^1} \text{ and } \frac{\delta^2 z}{\delta y^2} = \frac{2}{h^2}$$

Therefore, h^1 and h^2 they are equal to twice the principal radii of curvature of the surface at the origin ($x = y = 0$) and serve as good approximations to twice the radii of curvature along the coordinate lines across the entire surface where it is flat. Then:

$$z = \frac{c_0}{a_0\, b_0}\, uv = kuv$$

A hyperbolic paraboloid is a ruled surface characterized by two sets of straight lines. The formation of a hyperbolic paraboloid can be visualized by considering two different plane lines and a third line that moves parallel to a specific plane through a point on the two plane lines. The path traced by this moving line creates the hyperbolic paraboloid. The lines AB and CD lie on different planes, while line AC is parallel to plane P. When AC moves along the directions of AB and CD, always remaining parallel to plane P, the resulting surface is a hyperbolic paraboloid. Additionally, Fig. 1 introduces another set of straight lines, which are perpendicular to the common vertical lines of AB and CD.

Since the hyperbolic paraboloid has curvatures of opposite sign in two directions, its Gaussian curvature is negative at all points, which characterizes its anticlastic shape. The Gaussian curvature is defined as the product of the principal curvatures in two perpendicular directions.

$$K = \kappa 1 \cdot \kappa 2$$

Where $k1$ is positive and $k2$ is negative. The hyperbolic paraboloid, due to its negative curvature and ability to distribute loads efficiently, is an ideal shape in the construction of light and strong roofs. Its ability to be constructed from straight lines makes it economically viable and structurally efficient.

4. About Shell Structures of Félix Candela

This research seeks to study two of the great works of Félix Candela in which the application of the parabolic hyperboloid demonstrated great advantages and these works made him known worldwide, these works are the restaurant "*Los Manantiales*" in Xochimilco and the "*Pabellon de Rayos Cósmicos"* at *Universidad Nacional Autónoma de México*. Many engineers and architects came to use the hyperbolic paraboloid in the history of construction, but without a doubt Félix Candela was one of the pioneers of the twentieth century.

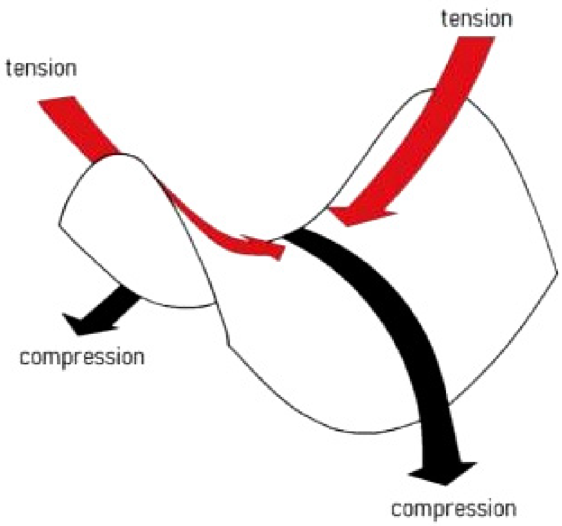

Figure 2. The forces are distributed directly to the rigidity arches of the shell and the tension and compression are appropriately transferred to the supports. This shows that Candela knew how to take advantage of these characteristics to obtain greater rigidity in the formation of the concrete shells

The "Pabellon de Rayos Cósmicos" is a collaborative project between Mexican architect Jorge González Reyna (1920- 1969) and Candela, was commissioned in 1951 by the Universidad Nacional Autonóma de México. This structure served as a scientific research center for the study of cosmic rays within the

Ciudad Universitaria campus. A significant structural consideration for the Pavilion was the necessity for an exceptionally thin roof to allow cosmic rays to pass through. The concrete shell needed to be an astonishingly thin 15 mm, as it was intended to facilitate the measurement of neutrons. Given the demanding requirement for extreme thinness, Candela opted for a geometry of double curvature the hyperbolic paraboloid. This choice offered greater rigidity compared to a surface of simple curvature and allowed for easy on-site redesign. Importantly, it could be executed using a wooden formwork of straight planks due to being a ruled surface.

Figure 3. Pabellon de Rayos Cósmicos, Felix Candela's first hypar structure

Candela ingeniously devised the final shape of the shell by combining two hyperbolic paraboloids. With this innovative approach, Candela achieved the goal of creating the thinnest shell ever built while imbuing it with undeniable and rational beauty. The disposition and form of its supports, along with its wavy facade, give the reinforced concrete shell the appearance of a delicate fabric softly draped over its frame a testament to Candela's mastery of form and structure. Additionally, the Pavilion's wavy and enclosed side walls further differentiate it from conventional structures, creating a striking contrast with the regular shapes prevalent in most other buildings. This unique combination of form and function establishes the "*Pabellon de Rayos Cósmicos*" as an icon of architectural innovation and scientific exploration.

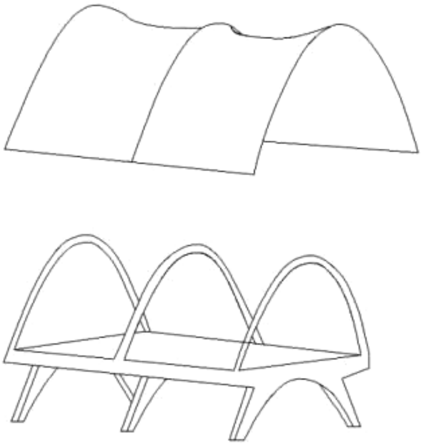

Figure 4. Diagram of the parts that make up the "Cosmic Ray Pavilion" which has two hyperbolic parabolics which transmit the load to three rigid arches

The roof structure is made up of two saddle-shaped enclosures, each 5.50 meters tall, supported by three parabolic arches with a thickness of 31 centimeters. These arches also support the single platform where the building's program is housed. The front and rear elevations of the roof form a parabola, a conical curve created by vertically cutting a paraboloid. The advantage of the hyperbolic paraboloid lies not only in its enhanced structural rigidity but also in its simplicity of construction, as the shell's geometry can be built using straight lines. This pavilion is composed of three key elements: the platform, the supporting arches, and the shell. The formwork for the rigid arches was left in place to provide support for the shell's formwork and likely to prevent any damage to the arches during curing. The entire curved structure was built using overlapping straight boards.

While this pavilion was being built in 1951, the famous critic Esther McCoy was in Mexico as coeditor of Arts & Architecture magazine no. 26. One of the objectives of that issue was to document the recently inaugurated Ciudad Universitaria. In this issue McCoy commented on the work of Félix Candela:

The designer, Felix Candela, architect and engineer, says that the general objection to shell structures «is based on the common confusion between massiveness and strength. Massive structures are not necessarily stronger than the lighter ones. On the contrary, the former are more subject to deformation and failure» . The dignity which characterizes the work of the Mexican architect does not prejudice him against new forms. Although he is limited by the concrete frame of his building, he has been able to push out its limits and endow with greater plasticity the material that is his to use[5].

Figure 5. Front view of the cosmic ray pavilion, which is made up of a reinforced concrete shell, a side wall in concrete waves and the pavilion's foundation.

In 1958, Félix Candela unveiled his most significant concrete shell structure, the "*Restaurante Los Manantiales*" located in Xochimilco, Mexico City. Revered for its remarkable slenderness and unencumbered edges, the restaurant's spatial composition has left an indelible mark on architectural history. The structure consists of an octagonal groin vault formed by the intersection of four equal hyperbolic paraboloids, where the curves of its edges are hyperbolic, intersected by planes inclined towards the outside. While visually appearing to have only one wavy free edge, Candela elucidated that each hypar segment requires two edges to transmit edge stresses to the supports. Thus, from a structural standpoint, the restaurant comprises a bold spatial ensemble of eight hypar fragments, each with eight free edges (**Figure 6**).

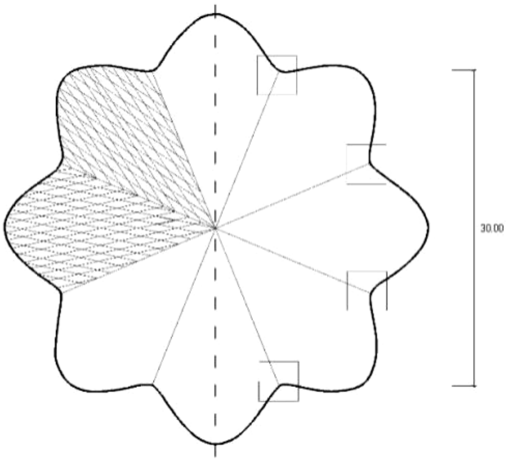

Figure 6. Restaurante *Los Manantiales* was built with a span of 35,50 m and thickness 6 cm. t was the first Candela structure which integrates 8 hyperbolic paraboloid

The restaurant project "*Los Manantiales*" was a project of remodeling where the architect in charge was Joaquín Álvarez Ordoñez, but not having the necessary knowledge that the architectural project required, he turned to the office for advice "*Cubiertas ALA*" directed by architect Félix Candela, who charge of project the shell of the building. *Los Manantiales* is an eight-sided groined vault composed of four intersecting hyperbolic paraboloid saddles. An elevation reveals canted parabolic edges, which display its striking thinness of 1-5/8" (40mm). Candela was taking a risk when he built *Los Manantiales*. The form was original, unexplored, and impossible to analyze precisely. Candela's career, however, habitually flew in the face of precise analysis [6].

The shell boasts eight identical canopies, with their supports arranged in a circular plan. Spanning approximately 30 meters, the outer projection of its edge measures 42 meters in diameter. Notably, the reinforced concrete shell was constructed with a continuous thickness of only 4 cm, making it one of the slenderest structures built during the Shell Adventure of Modern Architecture. To address the structural requirements of the shell, Candela employed a well-established strategy: he designed an "inverted umbrella" on the ground, consisting of four segments of hyperbolic paraboloids. After reinforcing the structure lightly, concrete was poured, creating an exceptionally efficient and costeffective foundation (with minimal material usage compared to traditional methods). Each of the eight foundations at Los Manantiales measures 4 meters per side and is connected by tensioners, forming an octagon with sides of 12.50 meters each.

Figure 7. It is worth noting that after the 2017 earthquake (one of the strongest recorded in Mexico City) Los manantiales suffered minimal damage, demonstrating the structural efficiency of this type of structures.

At the vertices of these foundations, the supports for the shell are placed, where all the loads from the four parabolic arches forming the edges are concentrated. Ingeniously concealed V-shaped reinforcements, using ¾ inch (19mm) rods, transform the edges into structural ribs, effectively transmitting forces from the concrete membrane to the foundation. These Vshaped reinforcements widen as the arch rises, nearly forming a plane at the top where the four edges intersect. The entire surface of the shell is reinforced by a grid of thin 5/16 inch (8mm) rods placed every 10 centimeters. Additionally, the free edge, which is 5 centimeters thick, is reinforced with two 5/8 inch (16mm) rods running along its sinuous ascending and descending line around the perimeter. The beauty of the Manantiales Restaurant lies in its spatial composition, free edges, and remarkable slenderness. The ingenious use of the hyperbolic paraboloid not only provides double curvature but also facilitates the use of simple straight plank formwork, making the construction process both cost-effective and rational. In the international architectural context of the 1950s, these factors set the restaurant apart. Another aspect that Félix Candela meticulously attended to be the junction of the concrete shell with its supports. Rather than visually merging the shell surface with the mass of the support, Candela opted for the shell to seemingly float over the supports. This design choice accentuates the structure's slenderness and free edges, preserving its aesthetic impact.

Figure 8. View of the main facade in which the formation of the hyperbolic paraboloids and their continuation of the reinforced concrete shell can be seen

5. Structural and Topology Optimization Through the Hyperbolic Paraboloid

Structural optimization in reinforced concrete structures refers to the search for efficient designs that minimize the use of materials, reduce costs and comply with safety and functionality regulations. This process involves finding the balance between structural capacity, construction costs and the behavior of the structure under loads. Optimization via the hyperbolic paraboloid refers to the use of a particular geometric shape that combines the properties of parabolas and hyperbolas to create structurally efficient surfaces. The hyperbolic paraboloid quadruples curved surface with double curvature, which gives it great advantages in terms of strength and efficiency when used in architectural and civil engineering designs.

The hyperbolic paraboloid can distribute loads more evenly along the structure, minimizing stress concentration points. This makes it an ideal choice for lightweight structures and large-span decks. In architecture and civil engineering, topology refers to the study and application of the form and spatial configuration of a building or structure, based on geometric and mathematical principles. Although the term "topology" comes primarily from mathematics, in architecture it is adapted to describe how spatial elements and shapes are organized and related to each other; to complement the above Fuller Buckminster says that: “topology is the science of fundamental pattern and structural relationships of event constellations”.

The reinforced concrete shells designed by architect and engineer Félix Candela not only represent an aesthetic and technical revolution in architecture, but also promote principles that are fundamental to sustainable architecture. Through their focus on structural efficiency and responsible use of materials, Candela’s designs

can be considered an early precursor to sustainable architecture. Candela was a master at using thin reinforced concrete surfaces to create lightweight, strong structures. The shapes he designed, such as hyperbolic paraboloids and other double-curved shells, distribute stress evenly, allowing him to minimize the thickness of the concrete. This approach not only reduces material consumption but also lowers the carbon footprint associated with the production of cement, a material that generates a significant amount of CO_2 emissions during its manufacture. Curved, geometrically optimized shapes, such as Candela's shells, distribute loads efficiently, eliminating the need for additional reinforcement or support. This reduces the amount of steel and concrete needed, optimizing both cost and resources used.

This structural efficiency allows buildings to be lighter and, consequently, use less energy and resources in their construction. Longevity is a fundamental principle of sustainability. Candela reinforced concrete shells are extremely durable, which extends the life of buildings and reduces the need for maintenance or reconstruction. This is a crucial factor in reducing the environmental impact of buildings, as it avoids additional consumption of materials and energy for frequent repairs or replacements. Hyperbolic paraboloid construction may offer advantages in terms of material and innovative design, while conventional construction is better known for its established methodology and wide applicability.

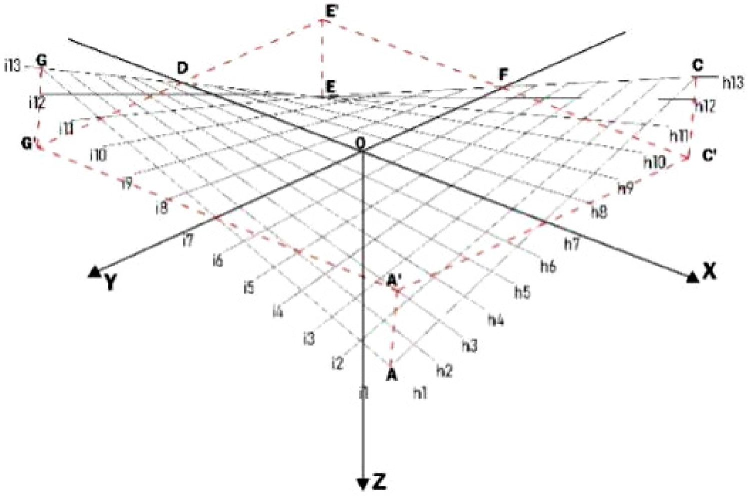

Figure 9. Diagram of the generation of a surface; the straight lines hn that intersect both guidelines, while being at the same time parallel to a plane X0z called the director plane, define the surface. They are called the first system of generatrixes

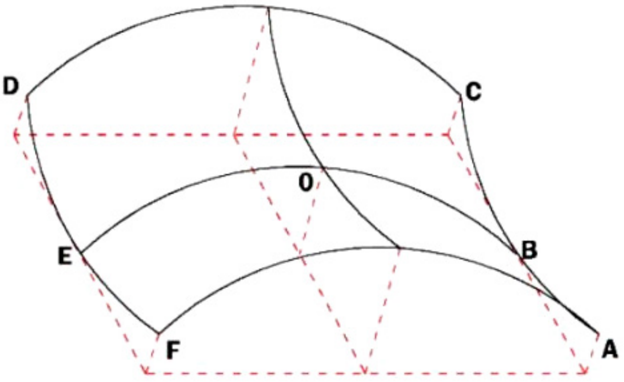

Figure 10. Spatial and topology analysis of hyperbolic paraboloid

6. Conclusions

The hyperbolic paraboloid has been used in modern architecture, in projects that seek balance between aesthetics and sustainability, as demonstrated by the work of architects such as Félix Candela, who popularized this shape in the construction of light and resistant roofs. The hyperbolic paraboloid is a geometric surface that has the shape of a saddle and belongs to the category of ruled surfaces, which means that it can be generated by straight lines. This characteristic allows it to be an interesting structural element in architecture, due to its curved shape but with a relatively simple construction. Hypar shells garnered increased attention when Félix Candela introduced this family of geometries into his structural repertoire. His innovative use of hyperbolic paraboloid shapes pushed the boundaries of architectural design and construction, inspiring architects and engineers alike to explore the potential of these unique structural forms.

Candela's contributions have left a lasting impact on the field of architecture, emphasizing the aesthetic and structural possibilities of hypar shells. The integration of computer technology into architectural design has brought renewed emphasis to the principles of continuity theory, particularly the differential calculus that underpins it. These concepts have been translated into mathematical functions and implemented in computer software, allowing for parametric manipulation of forms and the visualization of smooth, curvilinear shapes. This convergence of continuity theory and computer technology has sparked a discourse on new architectural forms in the digital age, enabling architects to explore unprecedented levels of creativity and innovation in their designs. In addition to his pioneering work with hypar shells, Félix Candela also conducted studies on two distinct boundary conditions: straight edge hypars and hypars with arbitrarily curved boundaries. In the case of straight edge hypars, Candela found that it was possible to leave two edges free of oblique stresses, resulting in the other two edges becoming determinate in their structural behavior. This exploration of boundary conditions further expanded our understanding of hypar shell structures and their potential applications in architectural design and engineering. Due to structural efficiency and reduced material usage, buildings with this shape can be more affordable. In areas with limited resources, this can be a viable solution for building durable, aesthetic, and efficient housing or public spaces.

The shape of the hyperbolic paraboloid allows for the creation of structures that optimize the use of materials. As it can be built from straight lines, less material is required compared to conventional curved surfaces. This reduces the carbon footprint associated with the production and transportation of building materials.

7. Future Work

After studying and making contributions to the hyperbolic paraboloid, this research promotes the creation of light structures by applying the principles used by Félix Candela in each of his structures. It is important to note that for the development of future structures, it is expected that technology, sustainability and geometry will be integrated as the ideals of construction, with the aim of being able to build while trying to mitigate the effects of climate change. Thus, at the conclusion of this research, it leaves a range of possibilities regarding light, technological and sustainable construction.

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