*Proceedings of the IASS 2024 Symposium*
*Redefining the Art of Structural Design*
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

# Restoration and repair of Félix Candela's most celebrated shell: 'Los Manantiales' Restaurant

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## Abstract

'Los Manantiales' concrete shell, was built in 1958 by the Spanish born architect Felix Candela, to replace a previous timber restaurant built in 1938 and which was lost in a fire in 1957. The new project was entrusted to the young architect Joaquín Álvarez Ordóñez, who asked the already famous shell builder Félix Candela to develop the structural design of the roof. In 1958 'Los Manantiales' restaurant -"the structure that Candela considers his most significant work'- was opened to the public and has remained an iconic piece of architecture until today. The beautiful shell 'is perhaps the most delicate concrete membrane that has ever been built" Faber [1]. As the years progressed, the structure presented various structural problems caused mainly by differential subsidence of the site. The earthquake that shook Mexico City on the 19th of September, 2017, and which dramatically affected the borough of Xochimilco, caused serious damages to 'Los Mananatiales' shell which lost its original geometry and put at risk the structural integrity of the shell. This prompted researchers, academics and practitioners to consolidate a multidisciplinary group 'Rescate Manantiales' ('Manantiales Rescue') to explore strategies for the repair and restoration of the shell. In 2020, the team successfully secured governmental financial support from the National Reconstruction Plan to develop the first stages of the restoration plan agreed by the team. This paper presents an account of the damages that 'Los Manantiales' shell suffered, and the restoration works that have been carried out since 2021 to date. This is one of the most significant restoration and rehabilitation works carried out on a concrete shell in Mexico, and the authors of this paper would like to share and disseminate amongst the IASS community the lessons learnt during the restoration project.

**Keywords**: historic concrete shells, restoration, Felix Candela. Manantiales, Xochimilco.

## 1. Introduction

Born in Madrid in 1910, Felix Candela fled to Mexico as an exiled political refugee after concluding his architecture studies and enrolling as a volunteer in the Republican Army. Ten years after his arrival in Mexico he founded the construction company: Cubiertas Ala. During this period Candela mastered the design and construction of thin-shell concrete structures, in particular the hyperbolic paraboloid concrete shells or commonly known as 'hypars'. Although the use of the 'hyapr' geometry was not new in construction Candela's innovation in the construction process was key to develop unprecedent complex 'hypar' shells. Once the geometry of the shell was determined and the structural analysis verified, construction techniques and construction management required a sophisticated approach and a skillful team to place the formwork, layout the steel work, pour the concrete (by hand) and carefully remove the formwork to be reused and polish final details by hand.

In 1958, Commissioned by the Joaquín Álvarez Ordóñez, Candela built 'Los Manantiales' restaurant on the banks of one of Xochimilco's lake canals (Xochimilco has given UNESCO World Heritage recognition since 1987). The shell of the restaurant is one of the most iconic and famous thin-shell concrete structures that Candela built in Mexico. The shell is an eight-sided groined concrete vault formed by four intersecting hypars covering an area of 900 square meters, and it is the finest example of 'free edge' concrete shells built by Cubiertas Ala.

## 2. 'Los Manantiales' restaurant brief history.

Xochimilco Lake was one of the 5 pre-Hispanic lakes in the ancient valley of Mexcio City and was the core of the chinampa agriculture activity (man-made floating agricultural gardens built during the prehispanic period). Unfortunately, the decline of agriculture due to the destruction of dams and sluice gates after the Spanish conquest of Mexico as well as the rapid and dense urbanisation during the last century have gradually dried up the lake, thus having adverse impact on the soil mechanics. By the mid-twentieth Century smaller scale agriculture activities continued along the banks of the remaining canals and recreational and cultural activities started to grow, particularly 'trajineras' (gondola-like) weekend rides.

The canals and natural springs found in this region and the unique beauty of the chinampas provided a new picturesque scenery that supported a cohesive a vibrant social interaction and which became an important touristic hub, highly promoted in the 1930s by the city's government. The government's encouragement brought economic, cultural and social activity and the construction of commercial buildings increased including important restaurants such as: El Amapolas, El María Bonita (understood to have later changed its name to María Candelaria, inspired by the film by the extraordinary director Emilio Fernández), Las Flores, and 'Los Manantiales' restaurant. These restaurants were crucial to promote and facilitate economic activity and social and cultural interaction. The current shell of 'Los Manantiales' restaurant was preceded by a wood-built structure erected on the banks of Lake Xochimilco in 1938 "figure 1".

Figure 1. Los Manantiales Restaurant circa 1948, before lost in a fire in 1957

In 1957, the wood-built restaurant was destroyed in a fire and the owners asked the engineer Joaquín Álvarez Ordóñez to rebuild it using non-flammable materials. Considering the fire resistance properties of reinforced concrete, the young engineer (he was only 25 years old at the time) proposed a concrete roof for the restaurant. By that time Cubiertas Ala had already built up a high reputation as experts in the construction of thin-shell concrete structures in Mexico and Álvarez Ordoñez contacted Candela, CEO of Cubiertas Ala, to develop this project. This commission was very timely for Candela as he had already completed successfully the 'hypar' groined vaults of the Stock Exchange shell in 1953 and he had also built the first free-edge 'hypar' concrete shell for the church of San Antonio de las Huertas, 1956, in collaboration with the architects Enrique de la Mora and Fernando López Carmona. Another example of free-edge 'hypar' shells built by Candela in 1957 was La Jacaranda Cabaret at Hotel Presidente in Acapulco and in collaboration with the architect Juan Sordo Madaleno.

Candela's final drawing for 'Los Manantiales' illustrates the proposed octagonal groined shell composed of four intersecting hypars. Covering a span of 32.4 meters- the distance between supports is 32.4 meters, measured along the groins and which were stiffened using V-beams. These V-beams were well integrated and concealed within the thinness of the shell. The free edge form was achieved by cutting outward-tilting planes resulting in perimetral arches that have the shape of hyperbolas "figure 2".

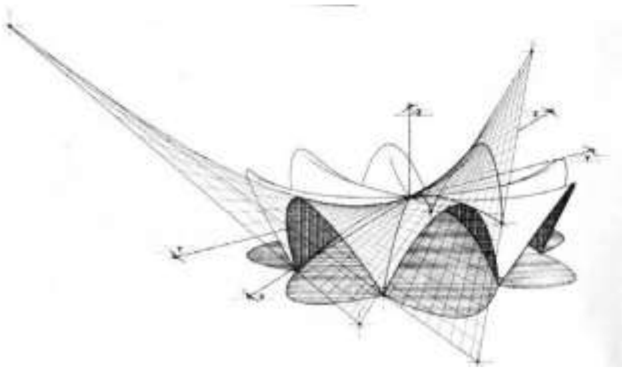

Figure 2. Felix Candela's architectural drawing for Los Manantiales restaurant. Source: Colin Faber, *Candela, The Shell Builder*.

## 3. 'Los Manantiales' shell site and its construction.

The site where the thin-shell concrete for 'Los Manantailes' restaurant was built sits on the Lake Zone of Mexico's City Seismic Hazard Maps.  The seismic hazard maps of Mexico City divide the basin in three zones: The Lake Zone (I), the Transition Zone (II) and the Hill Zone (III) of which the Lake Zone is at greatest risk due to the presence of lacustrine clays. Mexico City is well known for its high seismic activity, in particular those originated in the subduction zone of the Pacific Ocean, where the Cocos plate subducts the North America plate Flores-Estrella [2].  Some of these earthquakes have been disastrous causing building collapses and human casualties such as the 1985 and 2017 earthquakes.  The construction of the shell commenced with marking the layout of the foundations for which two squares of 22m were drawn on site, one of the squares was rotated 45 degrees off-the center of the first square to create a star-like shape.  The points at which the squares interested were used to mark the location where the foundations were to be erected. The shell's foundation consisted of square umbrella footings (4m X4m) as illustrated in "figure 3".

Figure 3. Los Manantiales shell umbrella footings.

Umbrella footings had been pioneered by Candela, first used in 1953 at Las Aduanas project. Furthermore, and to secure the continuous curvature, the original sharp v-shape of the supports (where the groins met) was modified to integrate into the curve of the shell Moreyra-Garlock[3]. The site's soil trapped under the umbrella footings also supported a stronger anchor to the site and the natural compression of the soil. To resist lateral thrust, these eight footings related by a perimetral tie-beam (with 1-inch reinforcement and few stirrups to work in tension). On top of each umbrella footing, a concrete cap was built from which the groin raised with a gradual thickness variation (95 centimeters at the base to 7 centimeters at the crown). As illustrated in "figure 4" the V-shape beams, concealed in the groins, included a considerable amount of steel reinforcement to receive the shell forces (in a groin vault the shell forces travel to the groins) and its positioning was arranged to meet the camber of the groins. The rest of the steel was a mesh of 5/16-in. bars spaced at 10 cm and its curvature was guided by the timber formwork. The 5-centimiters-thick free edge was reinforced with two 16 mm (5/8 in) bars following the sinuous perimeter of the shell. The groins span almost 33 meters from footing to footing.

Figure 4. Los Manantiales formwork and shell steel reinforcement.

The shell's formwork was made with 1.27cm in tongue-and-groove timber boards and placed according to one generating system. The concrete pouring was made by hand using buckets as illustrated in "figure 5".

Figure 5. 'Los Manantiales' shell – concrete pouring by hand.

It is worth mentioning that since concrete shells work in pure compression like an eggshell, the shell could have still standing even in the absence of steel reinforcement. However, steel reinforcement was needed to absorb the thermal expansion and contraction of concrete.

Decades of water extraction caused an imbalance in the Xochimilco ecosystem and particularly in the area of Zacapa island and many others which suffered endless ecological impact. This phenomenon began to generate problems in the soil where 'Los Manantiales' shell is located. At the bottom of this micro-basin, dozens of meters below, the basaltic layers of the soil have also been altered, fractured, and deformed by seismic movements over the past centuries. The most representative seismic events and relevant to the restoration of 'Los Manantiales' shell have been the earthquakes that took place on the 19th of September 1985, 15th of June 15, 1999, and 19th of September 2017.The survey conducted in April 2018 by a group of experts from Universidad Nacional Autonoma de Mexico also confirmed that the damages of the structure had not only been caused by the effects of the 2017 earthquake but also due to the progressive and differential subsidence of the site throughout the life of the shell, as in Mendoza and Cueto [4]. Investigations at that time showed that differential subsidence has affected the footings of the shell and at least one of the tie-beam connecting footings is believed to have been broken before the 2017 earthquake.

Also, it is important to mention that 'Los Manantiales' shell is practically at the foot of the hill where Nativitas borough is located, an area that is sinking due to the dehydration of the subsoil and which has caused a vast number of unpredictable cracks. The research and analysis carried out by 'Rescate Los Manantiales' also found that one of those cracks had already been present decades before the 2017 earthquake and exacerbated by it, thus causing damages to the shell (the crack crossed the interior of the shell axis "4" to axis "8" and branching to axis "1", forming a Y-shape).

Figure 6: Crack on the earth that damaged the shell.

Since 2018, the project 'Rescate los Manantiales', coordinated by Dr. Juan Ignacio del Cueto Ruiz-Funes and directed by the architect Andres López García has put together an interdisciplinary team of experts to assess the damages to the shell and develop an intervention plan to restore it. The expert team included: Faculty of Architecture and Engineering Institute, as well as the Federal Culture Secretary, Xochimilco's Borough Council, the National Institute of Arts and Literature, Ingeum, Colinas de Buen, Ruyiro and CAV (specialised in heritage preservation). The restoration plan of 'Los Manantiales' shell has been funded by the Federal Government of Mexico City under National Reconstruction Programme and comprises three different stages. The first stage included the analysis and pathologic study. In 2021 different studies were carried out to understand the geometry, structure, construction and architectural significance of the 'Los Manantiales' shell before and after the 2017 earthquake including the following points:

1.Current state of the building: Detailed inspection to determine the structural condition, construction material conditions, existing damages, and any other relevant aspect that may influence the feasibility of repair or rehabilitation.

2.Regulations: Analysis of local, regional, or national laws, regulations, and restrictions that needed to be considered for the intervention of the shell particularly because it sits in the UNESCO World Heritage Site of Xochimilco.

3.Technical study: The team developed a technical analysis to determine possible repair and rehabilitation solutions that could be applied to the building, considering its construction methods, historical and architectural value. This included: structural engineering analysis, soil mechanics, surveys (traditional and point cloud). The team also researched and considered other innovative techniques for repairing shells, such as the CRP (CarboCon) reinforcement technique used in the restoration of Urlich Müther's shell in Magdeburg as in Riegelman, et al. [5].

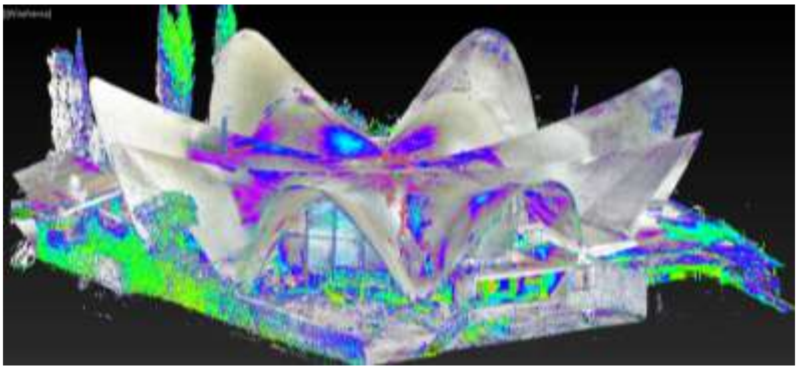

Figure 7: 'Los Manantiales' Point Cloud 3D Model.

4. Economic analysis: Evaluation of estimated costs for repair and rehabilitation, including labour costs, materials, equipment, permits, and any other related expenses. The team successfully secure funding from the Federal Government of Mexico City under National Reconstruction Programme. However, many adjustments to the budget had to be done as this funding was way below the initial estimated cost to repair and restore the shell.

5. Social, environmental, and cultural impact: The team carried out an assessment of how the rehabilitation of the building could affect the local community, tourism, cultural identity, and how the repair and restoration of the shell could support the United Nation Sustainable Development Goals. The successful completion of the first stage provided a strong platform for the restoration project proposal of a 20$^{th}$ Century masterpiece of structural art.

The second stage dealt with the repair and restoration of the shell. This stage started with the removal of all non-original elements (partition walls and blacksmith work added at the lower levels of the groins for security) that had gradually caused different damages to the shell. The successful repair of the shell needed careful consideration of the original strategies and methods applied during the construction of the shell. Reinforced concrete was relatively a new material in Mexico, and it was never used before for such innovative 'hypar' shells. Furthermore, soil conditions and the rapid urban expansion of the area were important aspects to be considered. The scarce construction and maintenance records of the shell were a challenge and the team had to rely on old photographs, chronicles, living accounts from the engineer Joaquín Álvarez Ordóñez, and other historical documents. This aided in grasping as much insight as possible into the construction of the shell. Simulations, mathematical models, and other calculations were also pivotal in gaining a comprehensive understanding of how the weight of the shell is supported by the footings. The total weight of the shell amounts to 350 tons (evenly distributed, each footing ought to bear 44 tons without factoring in incidental displacement or live loads).

In the investigations conducted to comprehend the material's characteristics, the team found notable discrepancies that played a crucial role in the decisions regarding the structural repair of the shell. Among these were the variations in the resistance coefficient of the concretes, ranging from 100 to 300 kg/cm2 of f'c. Additionally, the elastic behaviour analysis of the steel reinforcement proved to be highly unpredictable, with minimal elongation observed in some instances. This unpredictability can be attributed to their manufacturing process and the limited quality control measures, which were still in their infancy during the mid-20th century.

The computer simulations carried out to predict deformations showed that under seismic movements of $M_w$ 9 deformations at the highest crest of each 'hypar' of the shell could reach a horizontal displacement of up to 20 cm. Under the simulation conditions, once the earthquake had concluded the elastic behaviour of the shell allows it to return to its original shape. However, the poor quality of the soil and the 7.1 moment magnitude earthquake on September 19, 2017, excreted high stresses one of the of the shell causing plastic deformation and resulting in the structural failure of the footing. Moreover, the footing failure influenced the perimeter tie-beam which in turn pushed down the eastern footings displacing the soil outwards to the canal. The soil displacement was exacerbated by the gradual lake draught which had reached a 5-meter drop. The original masonry steps that worked as a retaining wall on the edge of the canal "figure 8" was removed in the 1990s and replaced by an unfinished concrete wall. The presence of a retaining wall on the edge of the canal would have been of vital relevance to avoid this soil displacing and the sinking of the footing in axis 6. The failure of the footings and the tie-beam deformed the 'hypar' edges in axis 7 and 8 losing its original geometry.

Figure 8: 'Los Manantiales' original masonry steps on the canal side.

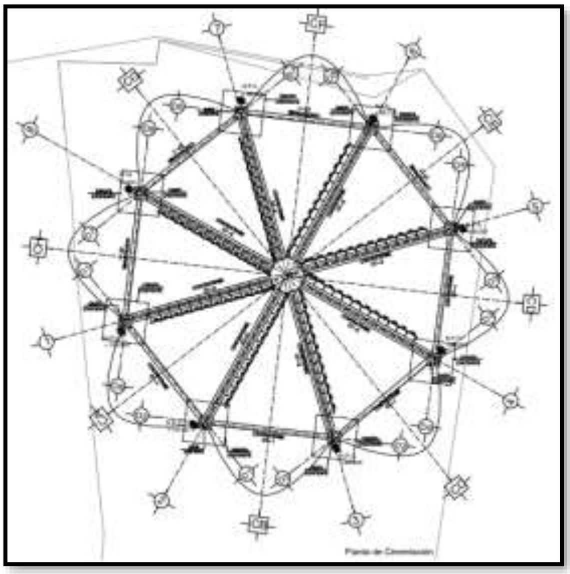

Figure 9: 'Los Manantiales' foundation plan showing existing repaired footings and new radial tie-beams.

The third stage of the project (almost competed) included the repair of all structural damages and the restoration of the shell's original architectural qualities. This stage included additional support to the current shell´s foundation with piles and radial tie-beams as illustrated in “figure 9”. It also dealt with the repair of all the interior floor concrete screed and slab as well as new electricity, gas, plumbing, and drainage works. The careful repair of finishes, landscape works, restoration of the mosaic-mural and the blacksmith work of the perimeter gates will also be accomplished after the structural repair has been done. It is important to note that throughout the first and second stages parts of the building have been kept in use. This uninterrupted, use of the building has been key to continue the sense of place and belonging of the community and to keep all stakeholders on board.

The most challenging part of this thrid stage of the project was the repair and reinforcement of the footings and tie-beams. The most pressing task was to repair the perimetral tie-beam to link back all footings and avoid further displacement towards the edge of the canal. Moreover, the removal of the metal fenestration of each ‘hypar’ was paramount as some of them had caused perforations on the shell during the 2017 earthquake. Removal of other elements which were gradually added for security, services and/or ornamental purposes were essential to free the shell of undesired and detrimental vertical loads.

During the earthquake shear forces caused a significant displacement between the concrete cap of the footings and the groins generating a 5 mm crack between them. To repair this a connection steel plate with cavities on both sides was built to receive and secure the connection of the cap and the groin “figure 10”.

Figure 10: Steel plate to strengthen the connection between the footing concrete cap and the shell’s groin.

These plates were epoxied into the heart of the concrete footing cap and along with this, the necessary shoring was placed in all the footings with metal beams that passed tangent to the faces of the concrete cap to form a strap around and creating an ‘H’ shape to assist in distributing loads from the damaged foundations “figure 11”. Two footings collapsed due to the weight of more than 300 tons of subsequent constructions that were built on them. These buildings were demolished. It is alarming to understand that the grand total of the deck has an approximate weight of 350 tons without considering any type of effort or extra live load and 300 tons were supported only on two supports. This was the fundamental reason for propping up the foundation with two metal arms that help the footings unload the weight of the restaurant onto two wooden beds that, in turn, transmit the weight and forces to the ground.

Figure 11: Existing footings connection with new radial tie-beams.

Considering the complex characteristics of the soil, it was paramount to provide a robust anchoring of the shell to the ground and a series of 16 meters long friction piles were included as well as eight radial tie-beams running from footing to footing following the groins axis in plan "figures 12a-12c". This strategy was developed to minimize the vertical movement of the shell produced by the trepidatory movement of an earthquake.

Figure 12a- 12c: New radial tie-beams connecting the shell's footings.

The section of the shell which had been severely damaged was partially demolished to repair and restore the original geometry of the shell "figure 13". Other minor cracks presented on the shell were also sealed.

Figure 13: Partial demolition and repair of one of the 'hypar' shells.

A new foundation embedded in the ground, a restored geometry and treatment to the shells cracks the team has rescued and prolonged the live of this extraordinary piece of structural art.

## 4. Conclusions

This paper has discussed the repair and restoration of ‘Los Manantiales’ restaurant shell. The IASS community was very concerned about the serious damages that the shell suffered by the 2017 earthquake ($M_w$ 7.1). This paper aimed to report and share the structural repair and other restoration works being done to the shell until today. Throughout its lifetime ‘Los Manantiales’ has hosted countless private and public social, cultural, and political events. After the 2017 earthquake ‘Los Manantiales’ shell was closed to the public. However, ‘Rescate Manantiales’ has worked diligently to provide a safe tour of the site for visitors interested to learn about the history of the shell and its restoration. In 2023, approximately two thousand visitors took this tour.

## Acknowledgements

The authors of this paper would like to thank the Federal Government of Mexico City under National Reconstruction Programme for funding this project. Also, we are thankful to all stakeholders involved in the planning and works of repair, restoration and safeguarding of the shell.

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