ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTION

Master's Thesis

Nohema Cassandra Ruíz Gómez

Significance and Conservation of Thin-Shell Concrete Structures of the 20th Century

UNIVERSITAT POLITÈCNICA DE CATALUNYA

University of Minho

Spain | 2021

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DECLARATION

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Year:	2021

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University:	UPC Universitat Politècnica de Catalunya
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A mi familia,

Papá y Mamá, gracias por ser mi apoyo en todo momento.

Jesús y Samantha, gracias por creer en mí.

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ACKNOWLEDGEMENTS

I would like to thank to my supervisors Prof. Pere Roca and Dr. Juan Murcia for your guidance, support, and feedback throughout this thesis.

I would like to express my sincere gratitude to all my professors for sharing their invaluable knowledge.

Thanks to the SAHC Consortium for the awarded scholarship and for letting me be part of this great program.

Thanks to Dr. Mariana Esponda Cascajares and Dr. Marisela Mendoza Ramos for your valuable comments and for sharing with me the information needed to carry out this work.

Thank you, SAHC colleagues for all the love, laughter and support provided. My sisters Maria Laura, Jill, and Maria. The brothers Seyed, Ameer and Soon. Dhairya, Lucy, Demiana, Tatiana, Carla, and Caro.

Gabriel, thank you for the incredible support you have given me since the beginning to make this adventure possible.

Thank you Mtra. Gaby Vázquez for your support.

Thanks to the friends who accompanied me in the distance during these months.

Thanks to my family.

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ABSTRACT

The conservation problems related to the concrete-built heritage during the 20th century entail the technical difficulties inherent to material nature and the applicable theoretical criteria. Due to the lack of value significance, protection, legal gaps, and ignorance on technical procedures, these architectures have become vulnerable worldwide. The problem is particularly important for concrete shell structures because, concrete research has mainly focused on rigid frames buildings, which have a different structural behavior than shells

The conservation and intervention in concrete shells require a particular methodological approach that encompasses understanding of the structure and geometry, material behavior, construction systems, and deterioration mechanisms. From this knowledge, it is possible to come up with adequate solutions that help to safeguard shell heritage. These actions must be complemented with academic studies and dissemination among the population and users to publicize the heritage importance that it implies.

The work of Félix Candela is one of the worldwide examples that entail this type of structures. The meaning and cultural value his structures possess are due to the architectural and technical expression, but also from the economic, social, and political context in México that allowed the development and construction. Despite this, due to the lack of patrimonial declarations and gaps in the country's legislation, the works are at constant risk of degradation and loss.

This research will review and critically analyze the state of conservation of selected shell structures of Candela in Mexico and expose their value and heritage significance. Then, based on the conservation guidelines proposed by international and national organizations, a series of applicable recommendations will be presented to carry out appropriate interventions and actions that guarantee their preservation.

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RESUM

Significat i conservació de les estructures laminars de formigó del segle XX

La problemàtica que involucra la conservació del patrimoni construït amb formigó durant el segle XX, engloba no només les dificultats tècniques inherents a la naturalesa material, sinó també al desenvolupament de criteris teòrics aplicables. Aquestes arquitectures són vulnerables a escala mundial a causa de la falta de significat , protecció, buits legals i desconeixement de procediments tècnics. El problema és particularment greu per làmines de formigó perquè la major part de les investigacions referents al formigó estan enfocades a edificis amb estructures porticades, les quals tenen un comportament estructural diferent de les làmines. .

La conservació i intervenció en les **closques de concret** necessita una aproximació metodològica particular que abasti no sols la comprensió del funcionament estructural i geomètric, sinó també del comportament dels seus materials, sistemes constructius i mecanismes de deterioració. A partir d'aquest enteniment integral es pot arribar al plantejament de solucions adequades que ajudin a la seva conservació. Aquestes accions han de ser complementades amb estudis acadèmics i la difusió entre la població i els usuaris amb la finalitat de donar a conèixer la seva importància patrimonial.

L'obra de Félix Candela és un dels exemples en l'àmbit mundial que engloba aquest tipus d'estructures. El significat i valor cultural que les seves estructures posseeixen no només es deuen a l'expressió arquitectònica i tècnica, sinó també al context econòmic, social i polític que va permetre el seu desenvolupament i construcció a Mèxic. Malgrat això estan en un risc constant de degradació i pèrdua a causa de la falta de declaratòries patrimonials i buits en les legislacions del país.

L'estudi que es presenta elaborarà una revisió i anàlisi crítica de l'estat de conservació d'un grupo d'estructures laminars de Candela a Mèxic i també exposará el seu valor i significat patrimonial. També es presentaran una sèrie de recomanacions basades en les línies de conservació plantejades per organismes internacionals i nacionals amb la finalitat de realitzar intervencions apropiades i accions que garanteixin la seva preservació.

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RESUMEN

Significado y Conservación de los Cascarones de Concreto (Láminas de Hormigón) del Siglo 20

La problemática que involucra la conservación del patrimonio construido con concreto durante el siglo XX, engloba no solamente las dificultades técnicas inherentes a la naturaleza material sino también al desarrollo de criterios teóricos aplicables. Debido a la falta de valor, la protección, los vacíos legales y el desconocimiento de los procedimientos técnicos, estas arquitecturas se han vuelto vulnerables en todo el mundo. El problema es particularmente importante para los cascarones de hormigón debido a que la investigación este material se ha centrado principalmente en los edificios de marcos rígidos, los cuales tienen un comportamiento estructural diferente al de los cascarones.

La conservación e intervención en los cascarones de concreto necesita una aproximación metodológica particular que abarque no solo la comprensión del funcionamiento estructural y geométrico, sino también del comportamiento de sus materiales, sistemas constructivos y mecanismos de deterioro. A partir de este entendimiento integral se puede llegar al planteamiento de soluciones adecuadas que ayuden a la salvaguarda. Estas acciones deben ser complementadas con estudios académicos y la difusión entre la población y los usuarios con la finalidad de dar a conocer la importancia patrimonial que implica.

La obra de Félix Candela es uno de los ejemplos a nivel mundial que engloba este tipo de estructuras. El significado y valor cultural que poseen no solamente se deben a la expresión arquitectónica y técnica, sino también al contexto económico, social y político que permitió su desarrollo y construcción en México. A pesar de esto están en un riesgo constante de degradación y pérdida debido a la falta de declaratorias patrimoniales y vacíos en las legislaciones del país.

Esta investigación realizará un análisis crítico del estado de conservación de algunas obras de Candela en México con el objetivo de realizar una puesta en valor y exponer la significación patrimonial. Se expondrá una serie de recomendaciones aplicables basadas en los lineamientos de conservación planteados por organismos internacionales y nacionales con la finalidad de realizar intervenciones apropiadas y acciones que garanticen su preservación.

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1. INTRODUCTION

The construction of concrete structures during the 20th century occurred continuously and at a very fast pace. García Gutiérrez Mosteiro (2011) points that "the architectural production of the 20th century is excessive concerning the construction that humanity carried throughout its history, if not greater than this". Standardize criteria applicable to carry out specialized conservation actions become difficult due to the large number of existing typologies built with concrete. The attribution of heritage values is also a complicated task because of the lack of significance given to these structures. As a consequence, a large number of structures built in that century are at constant risk of loss.

Thin concrete shells are not an exception because a large number of this buildings were built all over the world. Tang (2015) mentions that the decline of these structures had various causes such as the passing of the great masters, complex analysis, building codes, changes in fashion, among others. What happens after the decline of these structures? The challenge to answer this question encompasses the understanding of the past conditions that allowed their development. Also, an analysis of the actual conservation conditions must be carried out.

The conservation problems of the shells are not only related to material aspects and significance gaps, they also entail a limited understanding of the structural performance and geometrical characteristics of concrete shells. The concrete repair techniques in the codes most of the time do not consider heritage values. The difficulty of applying these techniques increases because if non-professionals execute it can be neglected and generate losses.

1.1 Motivation

The latent risk of loss of concrete shell heritage due to problems related to conservation is an issue that must be analyzed and studied. These structures are vulnerable not only for the general difficulties involved in preserving the concrete heritage. Some problems include the lack of recognition of values, lack of qualified professionals involved in the conservation of concrete heritage field, and the lack of significant knowledge by users and community members.

The use of reduced quantities of material and characteristics such as its thinness are factors that must also be evaluated. The structure, geometry, and materials give particular characteristics to the shells. The double curvature and the membrane behavior, complemented by the concrete's material properties, allowed the shells' development. The challenges involved, for instance, are the investigation samples that can result in invasive procedures, the unknown long-term effects of repair methods, and the impact on the existing patina.

Therefore, the following questions arise:

i) The comparisons between the problems of shells and other concrete structures are valid?

ii) What are the specific conservation problems that encompass the shells?

iii) Which theoretical and technical criteria can apply to guarantee its conservation?

This work seeks to raise interest and call attention to developed studies that contribute to the understanding of these structures. The scope of the study has been limited to the works of Félix Candela due to the constant risk of loss. Therefore, the situation of vulnerability to be demolished and the causes that lead to this must be discussed and analyzed.

1.2 Aim and objectives of the thesis

The main objective of this thesis is to conduct a review and critical analysis of the significance and conservation conditions of Félix Candela's works in Mexico. Through the choice of seven case studies, the thesis analyzes the current conservation conditions. It starts by proposed a damage causes classification from which the most recurrent causes are identified. Also, the discussion of the heritage protection regulations in the country is carried out and the challenges of the 20th century heritage conservation. This problem provides the elements to generate a final discussion that intends to contribute to recognizing the values and significance of Candela's work and expose the importance and challenges of concrete thin shells conservation.

1.3 Thesis outline

The thesis structure consists of five chapters that compile the outstanding and necessary aspects to understand the conservation problem surrounding Félix Candela's work in Mexico. The first is a brief introductory section to this study and the pursued objectives.

The second chapter contextualizes the concrete-thin shells focusing on the historical, climatic, and seismic aspects. Subsequently, the description of the geometries and structural characteristics of the projects is made. The chapter also addresses the construction processes and challenges for the generation of surfaces. Finally, some work losses result from conservation problems, and collapsed structures are shown. This chapter highlights the construction of curved forms from ruled surfaces and the membrane behavior that the concrete allowed in these structures.

Chapter three expose the case studies based on the location and urban contexts. The information of the constructions is complemented by the description of the geometries and structure, as well as the materials and constructive processes. Finally, is made the identification of the existing damages and the previous interventions.

Chapter four focuses on exposing the conservation problems of the case studies. The proposal of a damage classification and the discussion regarding the legal framework in the country are made. Lastly, the analysis of the conservation problems of the 20th century is added to compile the factors involved and carry out a critical review of the existing challenges. The outstanding conclusion is the identification of the anthropic factor as the principal cause of damage in the shells. The legal gaps in the law and the lack of protection for the 20th century structures is another spot to highlighted.

Once the problem is identified, the chapter five analyzes the recommendations applicable to the case studies. It addresses the identification of values and significance of Candela's structures. The international guidelines are examined and applied to the case studies. It also encompasses the need to update the legal framework and the dissemination of the information. The chapter compiles the successful interventions and management plans applicable to the cases. In the same way, are appreciated the failures and contradictions against the international recommendation.

2. CONCRETE THIN SHELLS IN MEXICO: FÉLIX CANDELA

This chapter is structured around the main aspects required to understand in a global way the development of Félix Candela's work in Mexico. The chapter starts with a brief historical overview of the architect's life in order to visualize the chronology of important events that mark his professional career. Afterwards, a description of the climatic conditions and seismic risks of the country is provided because these factors conditioned the design of his projects. The main geometrical and structural characteristics of the thin shells are then review in order to have a global understanding of the surface generation and the structural performance. The final section is devoted to the most outstanding aspects and challenges related to the construction processes employed.

2.1 Historical overview

Félix Candela Outeriño was born in Madrid on January 27 of 1910. His undergraduate studies were completed in 1935 at Escuela Técnica Superior de Arquitectura de Madrid, where he developed interest and excelled in the subjects of descriptive geometry and structural analysis. The reinforced concrete shell structures built in Europe since the 1920s was a theme in which Candela was enthusiastic to deepen (Del Cueto Ruiz-Funez, 2009).

The motivation to continue his training in this research area in Germany led him to request in 1935 a scholarship to the Royal Academy of San Fernando. The Conde de Cartagena scholarship was granted to him in 1936. However, due to the political situation generated by the outbreak of the Spanish Civil War, Candela decided to remain in Spain and enlist in the Republican army. The civil war ended in 1939 with Franco’s victory so Candela went into exile to Mexico. (Casinello et al. 2010).

Candela's life as well as his work can be classified and studied according to the period and activities developed at his residence place (Del Blanco García, 2016). The origins are considered in Spain from 1910 to 1939, the builder consolidation interval in Mexico from 1939 to 1971, and the full-time professor and academic period in the USA from 1971 to 1997, the year he passed way. These countries and their particular circumstances contributed to the professional training, development, and consolidation not only of his works but also of an entire philosophical contribution to the shell structures universe. Nevertheless, the current study focuses only on the works Candela developed in Mexico.

Cubiertas Ala Company was founded in 1950 by Candela and his brothers Antonio and Julia, as well as the architects Fernando and Raul Fernández Rangel who left the company in 1953. The aim of the company was the development and construction of concrete thin shell structures intended for various uses. Félix Candela directed the company until 1969 and during this time around 900 built works were record, while his brother Antonio stayed on charge from 1969 to 1976, the year the company closed (Cassinello, 2020).

2.2 Climate and seismic hazard of Mexico

Mexico is located in the southern portion of North America bordering in the North by the United States of America and in the south by Guatemala, Belize, and the Caribbean Sea. The Gulf of Mexico and Caribbean Sea are located at the east, while the west is surrounded by the Pacific Ocean. The annual average of temperature largely the Mexican territory is shown in the Figure 1 where the range of 22°C to 28°C, followed by 18°C to 22 °C and 12°C to 18°C depending on the location are observed. (SEMARNAT, 2015). In the north, the predominant climate regions are arid and semi-arid, while in the center and south of the country are the tropical wet, tropical wet-and-dry, and temperate with dry winters.

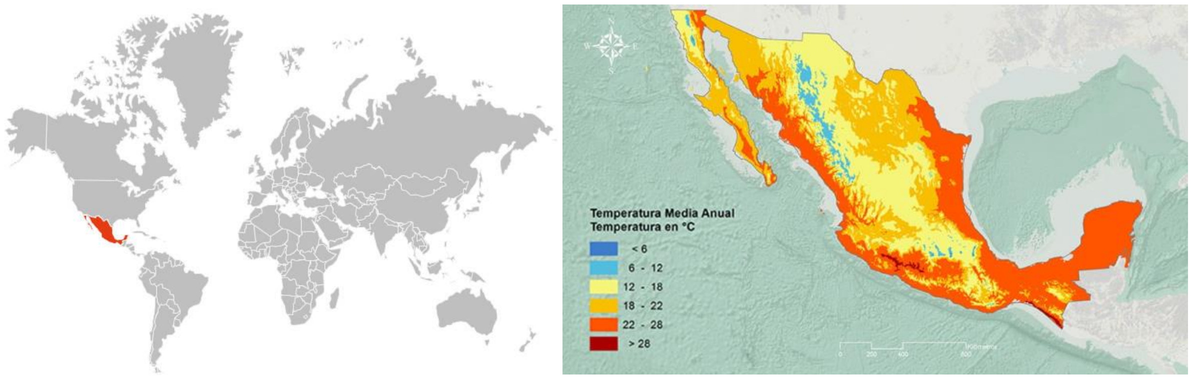


Figure 1. On the right image Mexico´s location and on the left the annual temperature average. Note: In (DANIELI PROCOME, n.d) and (SEMARNAT, 2015).

The climatic conditions of Mexico are favorable for the construction of concrete shells in comparison with other countries where this type of structures were also developed. Several authors indicated that this factor facilitated Candela's experimentation and calculations because there are no additional important loads such as snow (Laborda Yneva, 1998). The low insulation capacity due the reduced thickness of the shells represent a problem in cold weathers, so the mild temperatures of the locations of Candela´s shells helped to maintain a confortable indoor environment.

The Mexican territory is characterized by high seismic activity and, as a consequence, one of the main hazards that the shells continue facing. The country is located next to the Circum-Pacific Belt and between the Cocos, Rivera, Caribe, North American, and Pacific tectonic plates. The geological effects that occur more frequently are plate subduction and sliding. The most destructive earthquakes like the September 1985 and September 7 of 2017, were produced in the Cocos plate as observed in figure 2. The Puebla earthquake registered on September 19 of 2017 was an intraplate event but is also had destructive effects.

Figure 2. Strongest historical earthquakes since 1902.
Note: Modified from (BBC, 2017).

2.3 Geometrical characteristics of the shells

New materials and construction systems contribute to the development of geometries that determine the architectural morphologies and structural configurations. Regarding 20th century architecture, materials like steel and glass and the modern movement postulates triggered significant changes. For instance, Le Corbusier´s principles pose the free ground plan due to the replacement of supporting walls by pilotis offering experimental possibilities of the interior spatial arrangement and the facades.

Félix Candela's understanding of the influence of the geometrical shape on structural behavior using a new material like the reinforced concrete allowed him to optimize the design of the shell structures. The results are lightness and slenderness of the structural elements as well as movement and dynamism of the shapes. The development and construction of the hyperbolic paraboloids, also known as hypars, is considered an innovation in the historical architectural styles. Additionally, this surface became the most used by Candela, representing 90% of his built works (Casinello, 2010).

2.3.1 Shell surface

The characteristic of the thin shells is the considerably small thickness in relation to its other two dimensions. The geometrical developability is a parameter to explain the performance of the hypar. In this regard, shell surfaces can be classified as nondevelopable or developable as can be observed in Figure 3. The first ones apply to surfaces that need to be cut or stretched in order to obtain a planar form, like the synclastic and anticlastic. The second type can develop into a plane without the cut in the middle surface. The nondevelopable surfaces are stronger and more stable because the forces required to stretched them is higher compared to the developables (Farshad, 1992).

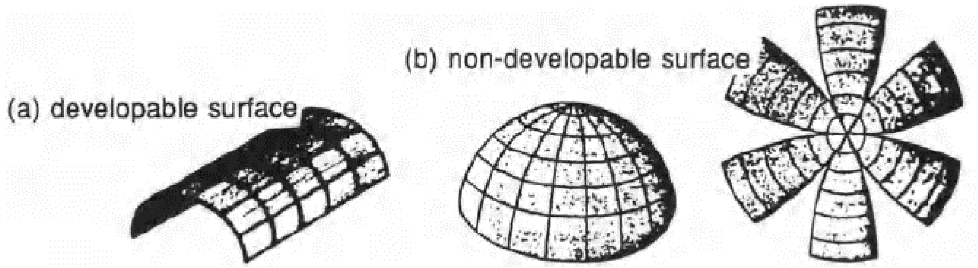


Figure 3. Developable and non-developable surface.
Note: In (Farshad, 1992).

To have a better understanding let us identify a point A located on a curved surface where an infinite number of planes can intersect this point. If the plane contains the normal, a series of curves called normal sections are obtained. One of these curves has the maximum curvature value (K1), and other the minimum value (K2). These sections are known as principal sections, meanwhile the K1 and K2 values are named principal curvatures of the surface (Farshad, 1992).

As spatially curved surfaces structures, the shells are classified according to the Gaussian curvature (K) that belong to the resultant product of the two principal curvatures $K = K_1.K_2.$ Therefore, depending on the result of this product it can be identified three cathegories (Farshad, 1992) that are explained below and ilustrated in Figure 4:

a) Synclastic: known as positive Gaussian curvature where both principal curvatures have positive sign($K > 0$). The dome exemplify these types of surfaces, "that carry their load by meridional and circumferential in-plane stresses" (Peerdeman, 2008) .

b) Monoclastic: If one of the principal curvatures is zero, the Gaussian curvature adquire this value too ($K = 0$). Examples of monoclastic curvature are the cilindrical shells used to cover air plane hangars and train stations.

c) Anticlastic: the principal curvatures present opposite signs, therefore the product is negative ($K < 0$). This condition of opposite curvatures in different directions permit "the shell act as a combination of a compression and tension arch when loaded perpendicular to its surface" (Peerdeman, 2008). The hypar is defined as a non-developable surface in double curvature with opposite directions (Kind-Barkauskas et al, 2002), so most of Candela's works are within this category.

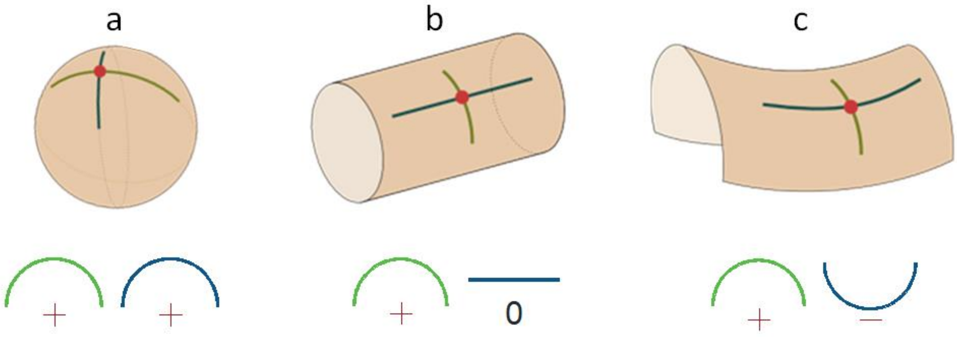


Figure 4. Gaussian curvatures.
Note: Modified from (Quora, n.d).

Few synclastic structures were developed by Candela, more specifically he experimented with this typology in four projects. Despite not being the main object of study of this research, these works are listed next. They include: the elliptical dome in Centro Gallego (1953) and the quarter sphere shaped Cabaret La Jacaranda (1954), both in Mexico City, the dome of the fermentation tanks at the Bacardi La Galarza plant in the state of Puebla, and the spheroidal dome for the auditorium of Ciudad Sahagun (1959). The higher costs and degree of difficulty to assemble the formwork in these structures discouraged Candela from using this typology in other projects (Faber, 1963).

2.3.2 Hypar surface generation

In this section, the generation of surfaces is explained to approach Candela's principles employed in the materialization process. It was previously mentioned that a large number of projects used anticlastic surfaces, highlighting the development and use of the hypar. For this reason, the present study is focused on this type of surface and the applicable variants. The aim is to understand the generation of the different typologies and link the surface shape to the structural performance.

Different theoretical solutions exist to generate anticlastic surfaces. Understanding them is very important to propose construction procedures that can improve execution, simplify workmanship procedures, and ultimately optimize project cost. It exists two main approaches to construct a hypar surface:

a) As a translational surface generated from the displacement of an upward parabola *EFG* sliding parallel to itself through a downward parabola *LOF*. The surface has two systems of parabolic generators as it can be observed in the Figure 5.

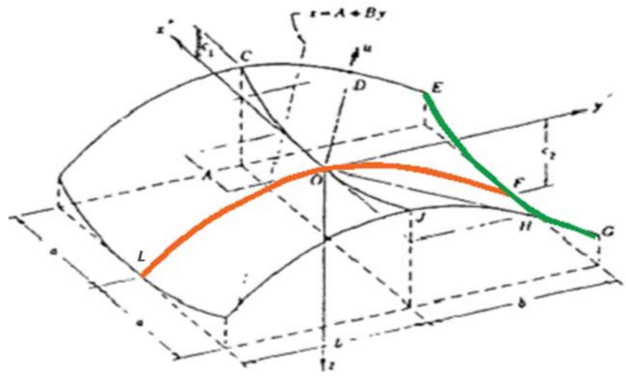


Figure 5. Hypar as translational surface.
Note: Modified from (Farshad, 1992).

b) As a ruled surface generated from the displacement of straight lines. These lines are named generatrices and are displaced over others that determine their direction and serve as a guide known as directrices.

In Figure 6, two non-parallel and non-intersecting lines segments HOD and ABC, provisionally called the directrices. The *xOz* is the first director plane and *yOz* is the second director plane. The intersecting straight lines *hn* parallel to the *xOz* plane are called as first system of generators, while the lines *in* that follow the other director plane correspond to the second generator system. (Oliva Quecedo, et.al, 2010). The intersection of the two systems h_n and i_n forms an angle ω, and every point in the surface contains this information. If the angle formed by the director planes is a straight one (ω= 90°), the hypar is equilateral or rectangular, and when the angle ω ≠ 90 the hypar is oblique.

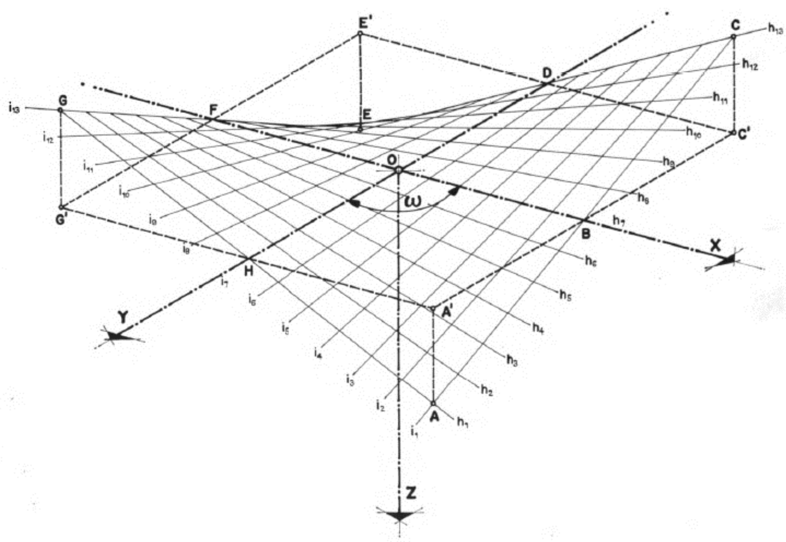
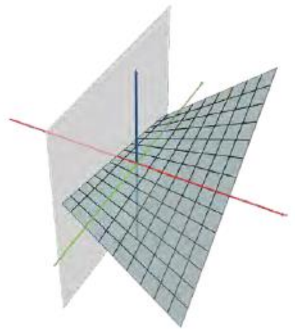
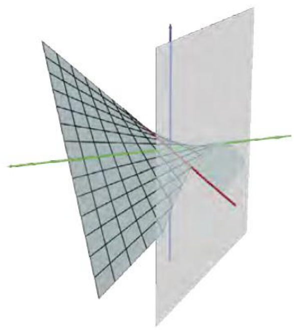
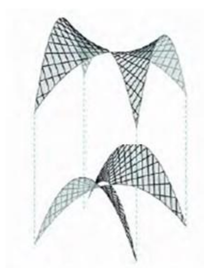


Figure 6. Two generator lines system that forms an hyperbolic paraboloid.
Note: In (Faber, 1963).

The hypars built by Candela correspond to different types, with the most representative compiled in Table 1. For each hyper variant, the table contains a brief description on how its surface is generated and an image to visualize the idea.

Table 1. Hyperbolic paraboloid variants

Note: Elaborated by Nohema Cassandra Ruiz Gómez

Hyperbolic paraboloid variants		
Variant	**Surface generation**	**Graphical representation**
Hyperbolic paraboloid with straight boundaries	This type of hypar is obtained when the cut plane is parallel to the coordinate axes.	 Image in: (Alarcón Azuela, 2018)
Hyperbolic paraboloid with curve boundaries	This variant is created if the cut is made in a transverse plane to the coordinate axes where a parabola is obtained. If the cut is inclined a hyperbolic arch is generated.	 Image in: (Alarcón Azuela, 2018)
Groined vault	This variation is generated by the intersection of two segments of a paraboloid. Candela went beyond the intersection of only two hypars. For instance, Los Manantiales is an octagonal groined vault.	 Image in: (Alarcón Azuela, 2018)

The umbrella, an additional hypar variation, is one of Candela's most relevant contributions concerning the concrete thin shells in Mexico. Despite the concept was taken from the annotations and sketches made by F. Aimond in 1936, the materialization as well as the aesthetic and functional improvement are results from Candela experiments. The experience gained during the construction of his works until 1952 allowed him to reinterpret the theoretical base and the construction procedures, including the foundations. (Garlock & Billington, 2009).

The Figure 7 shows the differences between Aimond's and Candela's umbrellas. Aimond's edge beam has a variable height because it decreases from the center to the corners. One can also observe that the central column is stubby and with a bigger cross section. However, Candela's work worried also about the aesthetic of the element, resulting in a more proportional and visually lightweight solution. These effects were obtained thanks to an increase of the column height.

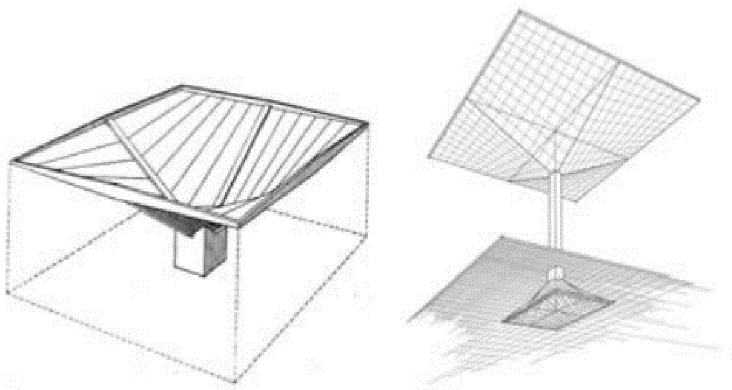


Figure 7. Aimond’s (left) and Candela’s (right) umbrella designs.

Note: In (Garlock & Billington, 2009).

The umbrella surface is obtained based on a horizontal rectangle which sides *2a* and *2b* and vertical distance *CC’* = *f* as shown in Figure 8. The *A* and *B* points are joined with *C* resulting in four hyperbolic paraboloids. The surface is created through the division of equal number of segments in each side and joining through straight lines. The paraboloids are equilateral because the director planes *ACA* and *BCB* are vertical and have right angles (Faber, 1963).

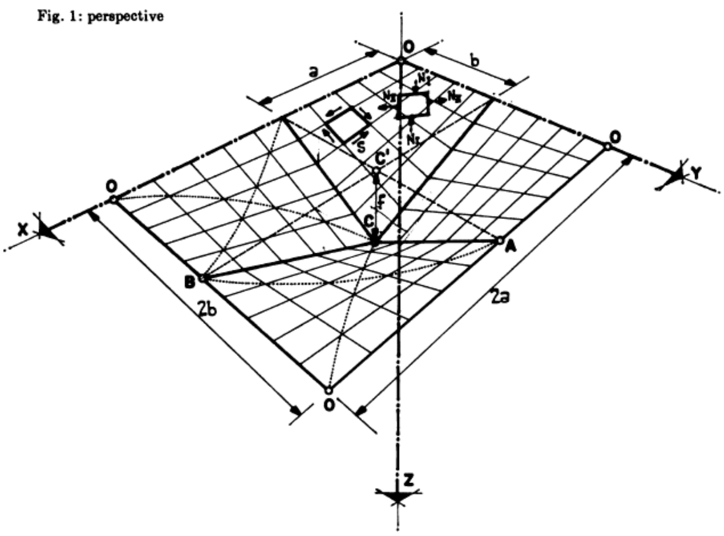


Figure 8. Surface generation of umbrella.

Note: In (Faber, 1963).

2.4 Structural characteristics of the shells

This section exposes a brief overview of the structural characteristics of the shells. These concepts will help to understand the concepts that influenced Candela to propose to simplify the calculation. Apart from the structural aspects, an additional reason was the reduction of the economic impact of the works because, at that time, the calculations through complex analytical methods were expensive and complicated.

2.4.1 Membrane behavior

The type of stresses identified on a surface element are observed in Figure 9 and are the following: i) membrane stresses acting on the plane of the element, distinguishing between normal and tangential stresses, ii) flexural stresses caused by bending and torsional moment, and iii) shear stresses perpendicular to the element plane (Sanz Balduz, 1999). Shell structures present a dominant membrane behavior which refers to the general state of stress that consists of in-plane normal and shear stress resultants which transfer loads to the supports (Peerdeman, 2008).

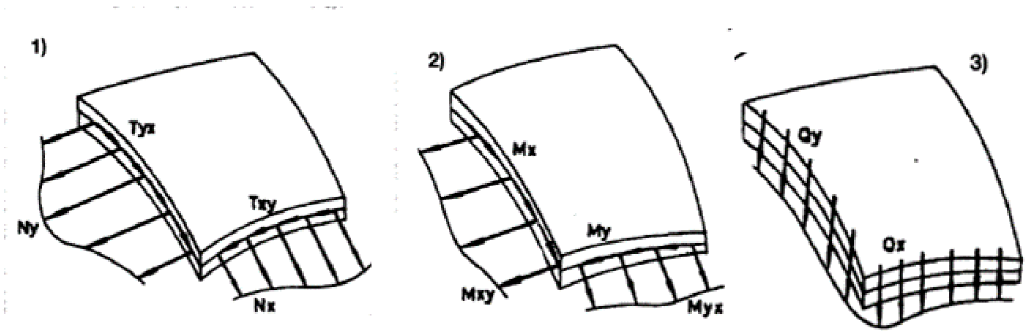


Figure 9. Stresses in a surface element.
Note: In (Sanz Balduz, 1999).

The double-curvature surfaces can be analyzed as members subjected to a pure membrane state under the following assumptions: i) reduced thickness of the shell, ii) absence of sudden changes in curvature, iii) absence of point loads and iv) lowered curvatures. Note that these conditions are not entirely met in reality. For instance, this is demonstrated by the results of the full-scale resistance test carried out by Heinz Isler during the demolition of an ellipsoidal roof. First, he added loads in specific points, increasing the load gradually; however, the shape did not register relevant changes. Therefore, he produced a hole in the roof using a wrecking ball. Despite this impact, the shell did not present important changes in the geometric configuration (Sanz Balduz, 1999).

The structural action of the hypar is described by the interaction of two main load-resisting mechanisms. The first is the arch action that is developed along the direction of maximum compressive stresses, and the second corresponds to the cable actions along the direction of principal tensile stresses, as shown in Figure 10. These two mechanisms act in different directions because the load is distributed inducing the compression in the arches and tension at the cables. The elastic stability is increase because the cables brace the arch subjected to compression as observed in Figure 10, where the structure is considered to be supported in two lateral points (Farshad, 1992).

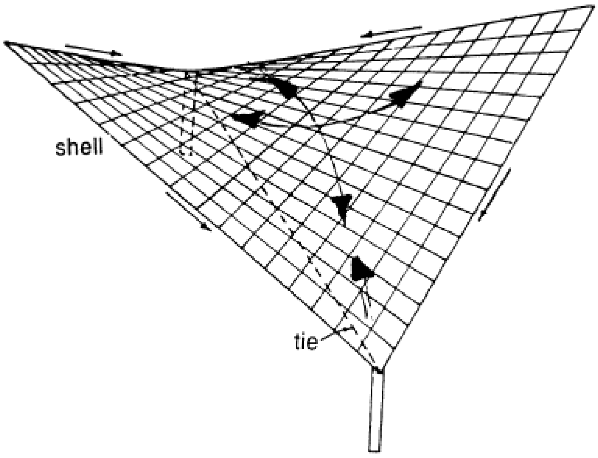


Figure 10. Internal forces from shell to edge members.
Note: In (Farshad, 1992).

The structural behavior of the hypar is defined not only by its specific geometry, but also by the existing boundary conditions. Figure 11 shows the straight edges cases, in the left image there is a direct flow of the internal forces from the shell body to the edges. The load is transferred through the ridge beams and edges beams to the supports in the central shells. Lastly, in the curved edge hypars, the shear forces are carried to the supports through the compression arches, as observed in the right image.

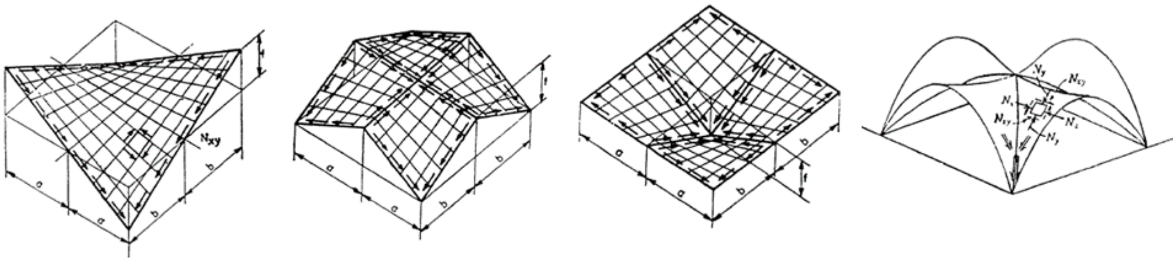


Figure 11. Internal forces at shells.
Note: In (Farshad, 1992).

2.4.2 Towards a new philosophy of structure Candela´s vision

Candela's expertise about the treatment and development of concrete thin shells, led him to write *Towards a new philosophy of structures* in 1951. The article was a critique to extend the application of simplified analytical methods and solutions for the calculation. The main criticism he points out is the insistence of some academics to apply existing theories, like the Theory of Elasticity, as a "recipe book" that do not adequately satisfy the premises and characteristics of the structural problem. (Candela, Hacia una filosofía, 1951).

Candela based his calculations on the membrane stress formulas developed by Pucher (Pucher, 1934) where the directions of tension and compression forces acted at 45° from the straight edges of the structure. The analysis is carried out on the basis of purely statics principles and does not consider the elastic properties of the materials, thus the complexity of the calculations is simplified to a certain degree (Faber, 1963).

2.5 Shell Construction

Candela highlights the construction profession claiming: "No one knew if I was an architect or an engineer, or if I was Mexican or Spanish. I liked it, and I still like to call me builder" (Candela, 1995). Following this remark, this section highlights the outstanding aspects and the challenges involved in constructing the shells. It begins by explaining the experimental models built to understand and prove the hypothesis. It continues with a description of the foundation’s design and its construction process. Next, the stakeout and the formwork are addressed and finally refer to the used materials.

2.5.1 Experimental models

The difficulties presented by thin shell structures can not only be reduced to the structural calculation and analytical methods because they extend to other areas. For instance, the experimentation with models, a methodology of study used by international exponents such as Eduardo Torroja. Candela solved the construction challenges of the projects in a straightforward way. His self-taught spirit led him to consider that the fastest and viable method of knowing the behavior of the structures was through direct experimentation with models to real scale. Thereby, the complex adjustments to the results and loads that scale models implied, were avoided (Casinello, 2010).

The first full-scale experimental model built by Candela was the Ctesiphon Vault in 1949, a funicular vault in San Bartolo Estado de Mexico. The shell had a constant thickness and only compressive stresses. This prototype was built without reinforcement steel and instead of formwork a guidelines wooden arches that support burlap sacks were assembled (Faber, 1963). The concrete was applied on the sacks being a complicated work because the mixture tends to fall off. However, this problem was effectively solved by the masons (Baldellou, Bonet, Sert, & Candela, 1995).

Based on the knowledge acquired through reading mainly French construction techniques, Candela ventures around 1950 in another experimental prototype. Again in San Bartolo but now for the Fernández Factory the prototype built was a 2.5 cm thick cone that according to the recommendations should use a "dry" and "very high quality” concrete. The result obtained was poor adherence between the aggregates and the cement as well as gaps in the lower part that later had to be filled. Another problem faced was the removal of the timber falsework due to the fact that it was attached to the shell and had to be removed through strong pulling (Baldellou, Bonet, Sert, & Candela, 1995).

One of the objectives raised with the prototype of the Fernández Factory was the possibility of reuse the formwork in a modular way. Thus, he was able to reduce the execution times, costs and therefore make the construction process more efficient even outside of Mexico (Del Blanco García, 2016). This achievement was higly exploited in the umbrellas that were used mainly in industrial buildings and that represent the 70% of the architectural typology executed throughout his career (Instituto Torroja TV, 2019).

In 1952 the first experimental umbrella was built based on 4 hypar tympans with dimensions of 10.06 m x 10.06 m, thickness of 0.38m and rise little bit of 0.91 m. The results of this prototype were deflections in the corners and flutter with the wind. In 1953 another umbrella was constructed considering smaller dimensions of 7.92 m x 7.92 m, rise of 0.60 m but a bigger thickenss of 0.83 m that recorded slight deflections in the corners. However, once the formwork was removed and the load test was carried, where 24 workers and Candela climbed to the upper part was stabilized. The experimental conclusion was that in order to reduce deflections the rise must increase (Faber, 1963).

Hide the reinforcements and ribs, and the design of the supports were elements which Candela focused special and particular attention. Despite the several satisfactory static solutions, the detail of structural design in these elements is an artistic activity more than a scientific one. He was convinced this details depict the key for success in his works (Maluenda, 2016). The continuity between foundations, supports and roofs become technical elements whose materialization and unity generates the visual and spatial sensation of lightness.

Figure 12. Experimental models: funicular vault in San Bartolo (left), Fernández factory (center) Inverted umbrella (right).

Note: In (Hernández Millán, 2020) (Faber, 1963) (Del Blanco García, 2016).

2.5.2 Foundations

The soil conditions in Mexico City generate important and particular challenges that are not only related with the seismic response of the structures. The construction of foundations became a challenge due to the low bearing capacity and the water table shallow depth. This natural condition motivated Candela to conceive another experimental proposal to solve the substructure that consisted on the design of an inverted umbrella-shaped footing. Figure 13 shows how the ground is contained within the footing to avoid sinking. The prototype was tested in Las Aduanas warehouse and subsequently used in large proportions.

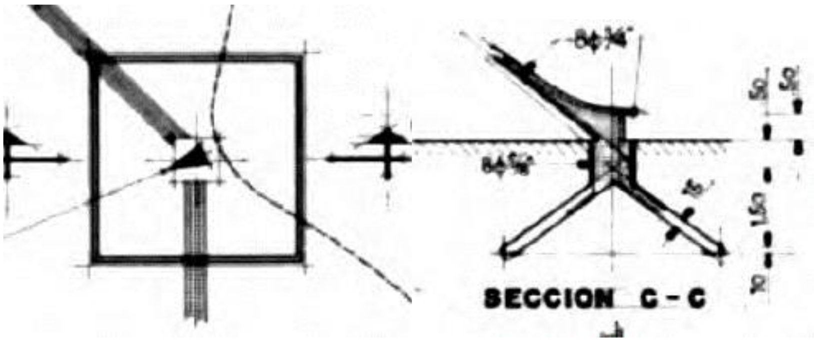


Figure 13. Plan and section of the inverted umbrella.
Note: In (Faber, 1963).

The construction of the footing was relatively simple because from a wood and wire mold the desired shape and curvature were carved directly using the soil material. Once defined, a grout was added in order to level the surface that would receive the reinforcing steel as well as the reinforcement elements of the superstructure. Finally, the concrete of the footing was poured with an approximate thickness of 6 in or 15 cm as it can be observed in the Figure 14 (Faber, 1963).The reduced amount of material and the fact that the mold can be reuse for its manufacture results in lower costs.

Figure 14. Inverted umbrella footing construction process.
Note: In (Faber, 1963).

2.5.3 Stakeout and formworks

The materialization of double curvature surfaces presents difficulties associated to the complex process of assembling the formwork. The construction process is simplified through the use of ruled surface and the straight lines. Frei Otto highlight this thought by mentioning that “Felix Candela's shells have complex shapes but are easy to build” (Seguí Buenaventura, 1994). The main formwork material that Candela used was timber, resulting in a crucial and outstanding intervention of carpenters who perfectly understood his ideas.

Despite the references in the literature to the great formwork execution and Candela’s knowledge on how to generate double curvature surfaces, it is also true that the research of the stakeout and constructive details are scarce. Therefore, in this section the proposals from some authors that try to explain these topics for specific projects are exposed with the aim of providing an overall idea of the process. Likewise, this is a topic with possibilities for future development.

For the groined vaults with square plans case, the initial stakeout considers the projection in plane of the paraboloid drawn through straight and parallel lines on the ground. These marks become the guide for the placement of the formwork. Subsequently, the generatrices that form the surface are also traced to obtain the intersections where are placed the vertical struts. Finally, due to the curvature of the shells, the strust should be cut with different measures ensuring the variable heights of the surface (Del Blanco García, 2016).

The struts must be fastened in the upper part through timber elements that supported the straight timber boards. A light grease layer must cover these boards before the concrete's poured to facilitate the formwork removal. The reinforcing steel is unfolded on the timber board, and after that, the concrete's poured (Alarcón Azuela, 2018). Once the formwork was removed, the final finish is applied as required by the project.

This study identifies two cases related to the use of the formwork in Candela´s works. The first is regarding the industrial buildings where the reuse, modulation, and displacement within a single project became the expression of efficiency use materials philosophy. In contrast, other projects requirements developed a higher degree of difficulty and uniqueness, resulting in formworks endowed with particularities, as observed in the figure below.

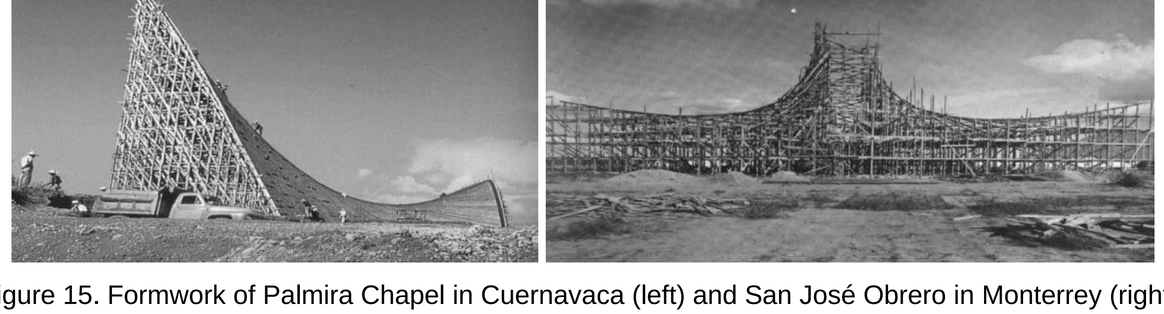


Figure 15. Formwork of Palmira Chapel in Cuernavaca (left) and San José Obrero in Monterrey (right). Note: In (Basterra Otero, 2001) and (Faber, 1963).

In 1964, President Gustavo Díaz Ordaz increased the minimum wage from 17.50 pesos to 32 pesos affecting a significant proportion of the labor costs in the construction of shells. It is important to note that the country's low salaries and the lack of regulation were among of the main triggers that allowed the construction of Candela's work in Mexico. Despite the reduced amount of material used in the shells, the number of workers compared with other concrete structures increased due to the formwork assembly. The overlap of these factors and the new regulations brought their unsustainability (Del Blanco García, 2016).

An alteration to the environmental regulation of the Forestry Law of 1960 affected the timber market in Mexico. Through this modification, the government began to ask for mandatory clearing of tree permissions to particular industries to avoid and control deforestation (Secretaría de Agricultura y Ganadería, 1960). The results of these new requirements were the scarce timber market and a higher acquisition cost. However, it is important to mention that despite the modification of the legal frameworks Mexico, the reduction and decline of shell construction was also occurring in other parts of the world (Del Blanco García 2016).

2.5.4 Materials

Towards the 1950's no specific rules existed to regulate the use or quality control of reinforced concrete in thin shells (Casinello, 2010). Also, very limited information has been found in the literature about properties of the materials used in Candela's shells. Dosages information for concrete mix used by Candela is scarce. As mentioned in the scale models section, the concrete composition was adapted depending on the properties and structural behavior that Candela sought to solve. However, specific records exist, such as for the Cosmic Rays Pavilion, where the mix had a proportion 1: 3: 2 with 1/4 maximum size of the aggregate (Faber, 1963). Regarding the reinforcing steel, the structural plans show in detail the grade and number of bars and the distances between stirrups, resulting in a more accurate approximation of the material.

The spatial requirements determined the use of elements like metal enclosures and gates that carried glass. The biggest challenge was the proper adjustments to the curvatures of the shells. If the architectural composition included walls, these could be made with a partition or reinforced concrete. The finishing surfaces of some shells were board-formed concrete. Meanwhile, the walls could have some stone coatings, as in the case of subway stations.

After the decline of the construction of concrete thin shells, Candela began to explore and created proposals for structures using other materials. The most representative example in Mexico that reflects the evolution of projects with new materials such as steel, aluminum, and copper is the Palacio De Los Deportes. This sports complex was inaugurated in 1968, and it is relevant because it also represents his last built work (Del Blanco García, 2016).

2.6 Lost works

The primary way of losing Felix Candela's works in Mexico has been demolitions with causes often related to owner and users' lack of interest and economic motivations. These demolitions have occurred from the 1970's to the present day.

Jacaranda nightclub

The first case is the Jacaranda nightclub, part of the Presidente Hotel project as shown in Figure 16, designed by the architect Juan Sordo Madaleno in Acapulco Guerrero. This beach has the particularity of being one of the most important tourist destinations in Mexico at that time. The structure was built in a short period that took only six weeks during October and November of 1957 (Del Cueto Ruiz-Funes, 2011).

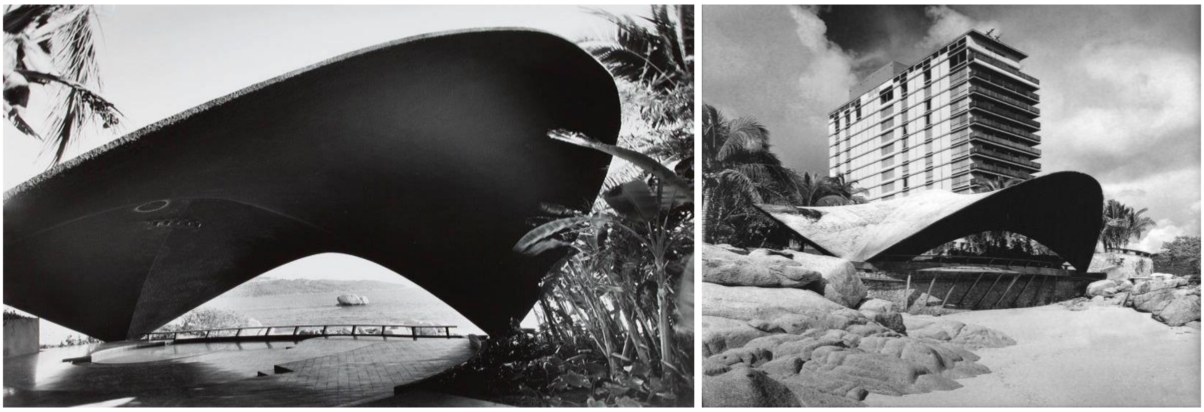


Figure 16. Internal view of the Jacaranda club (left) and exterior view where highlights the visual lightness of the shell as well as the integration into the context (right).

Note: In (Ochoa,2021).

The thin shell was composed by three hypars that intersected in the crown and distributed the thrusts to three support points linked by a lower floor tie ensemble with two steel bars of 1 inch of diameter each. The junctions between the three hypar produce crease marks that become rigid elements that transmit the thrusts to the supports. (Faber, 1963) The nightclub was demolished in the 70'sdecade to expand the hotel facilities.

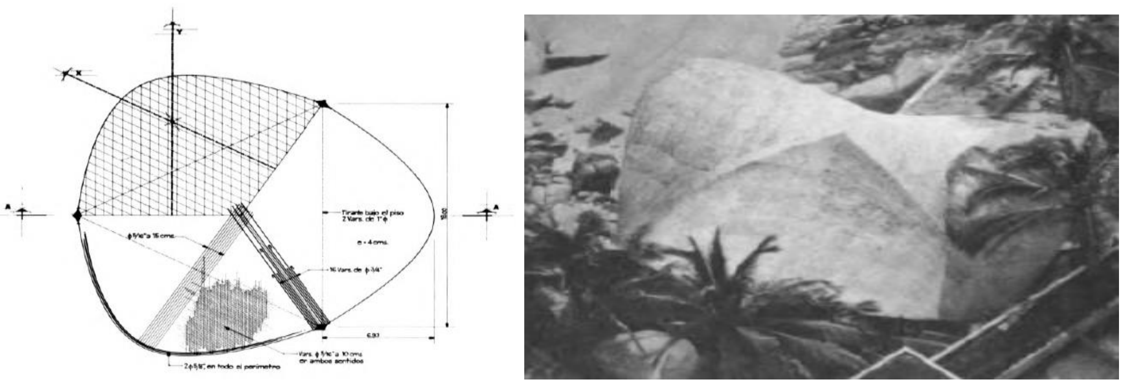


Figure 17. Plan with dimensions and materials of the thin-shell and top view of the nightclub.

In:(Faber, 1963, p.192).

Casino de la Selva Hotel

Located in Cuernavaca is one of the most unfortunate cases for the city's civil society because despite the efforts to save it was demolished. The shells do not correspond to the first constructive stage of the complex that dates back to 1931 and housed a casino, bedrooms, dance halls, and Olympic pool. In 1934 gambling was prohibited in the national territory, so the use was exclusively destined as a hotel. Around 1946 some extensions were made; however, it was until 1958 that Candela's hand designed the shells. The project included the bungalows shown in Figure 18, an auditorium - dining room known as Salón de Los Relojes, and the Mambo nightclub built around 1960-1961 by Juan Antonio Tonda (Alarcón Azuela, 2010).

Figure 18. In the left the original inverted umbrella roof can be observed, meanwhile in the right an opening can be noticed because the temperature was hot inside the bungalows of Casino de la Selva. In:(Faber, 1963, p.132) and (Album of Spatial Structures Isikawa Lab University, n.d).

Faber (1963) mentions that the dining room follows the same principle of groint vault than Los Manantiales. However, instead of the eight hyperbolic paraboloid segments, this is composed of five with similar dimensions where the biggest difference is the free edge span of 16.76 m. The auditorium was formed by an hyperbolic paraboloid with dimensions of 19.60 m in length and a maximum height point of 14.75 m as observed in Figure 19 (Alarcón Azuela, 2010).

Figure 19. Construction process and a final view of the dining room in Casino de la Selva. In:(Faber, 1963, p.200) and (Album of Spatial Structures Isikawa Lab University, n.d).

The information regarding the Mambo nightclub exposes that was built based on two hyperbolic paraboloids with a straight edge as shown in Figure 20. Alarcón (2010) provides approximate dimensions of the structure corresponding to 20 m at the base and 15 m in height. Such dimensions were estimated from photographs complemented by the advice of the architect Juan Antonio Tonda.

Figure 20. Construction of the hyperbolic paraboloid (left) and external view of the discoteques (right) in Hotel Casino de la Selva.
In: (Alarcón Azuela, 2011) and (south Clark, 2009).

After changes of ownership and the land value markets, the hotel business was not very profitable (Hesles Bernal, 2008). The 1994 crisis forced the Martínez Huitrón brothers to give to Secretaría de Hacienda y Crédito Público, government institution in charge of collecting taxes, the ensemble to settle the debts. The property belongs to the government until 2001, when it was sold to a corporation from the United States to establish a shopping center. Consequently, a group of activists emerged to avoid the demolition and recover the ensemble, while the social pressure began to be present. Until these reactions, the INAH and INBAL began to act in favor of its protection, however, was demolished (Alarcón Azuela, 2010).

Due to negligence and lack of response for protection towards cultural heritage of government institutions many criticisms arose. The request to the President of the Republic to expropriate and declare the property as an artistic, historical, and archaeological monument was presented in September 2001 (Poder Legislativo, 2001). However, the demolition works had begun on July 13 of that year (Rodríguez Araujo, 2001) and a replica of the dinning was later rebuilt in order to “preserve” the memory of the previous structure as observed in Figure 21.

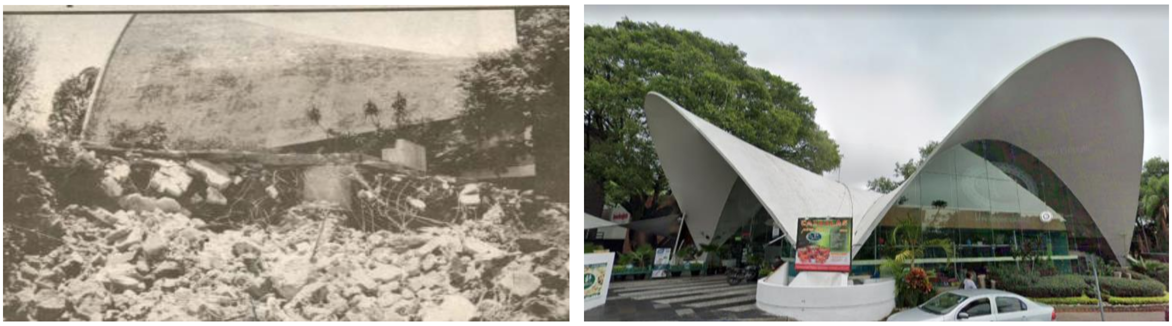


Figure 21. Demolition of the shell (left) and replica of the previous existing structures located in the commercial complex (right).
In:(Del Cueto Ruiz-Funes J., 2015) and (Google maps, 2019).

Lederle Laboratories

Five years later another one of Candela's works was lost. The control booth of Lederle Laboratories located in Mexico City, was demolished in 2006 in order to build a new one (Instituto Torroja TV, 2019). As is observed in Figure 22, this structure comprised a tripod that holds an umbrella covering the glass cabin, and a wing generated through two leaves that twisted from a vertical position in one end to horizontal position in the other end (Faber, 1963).

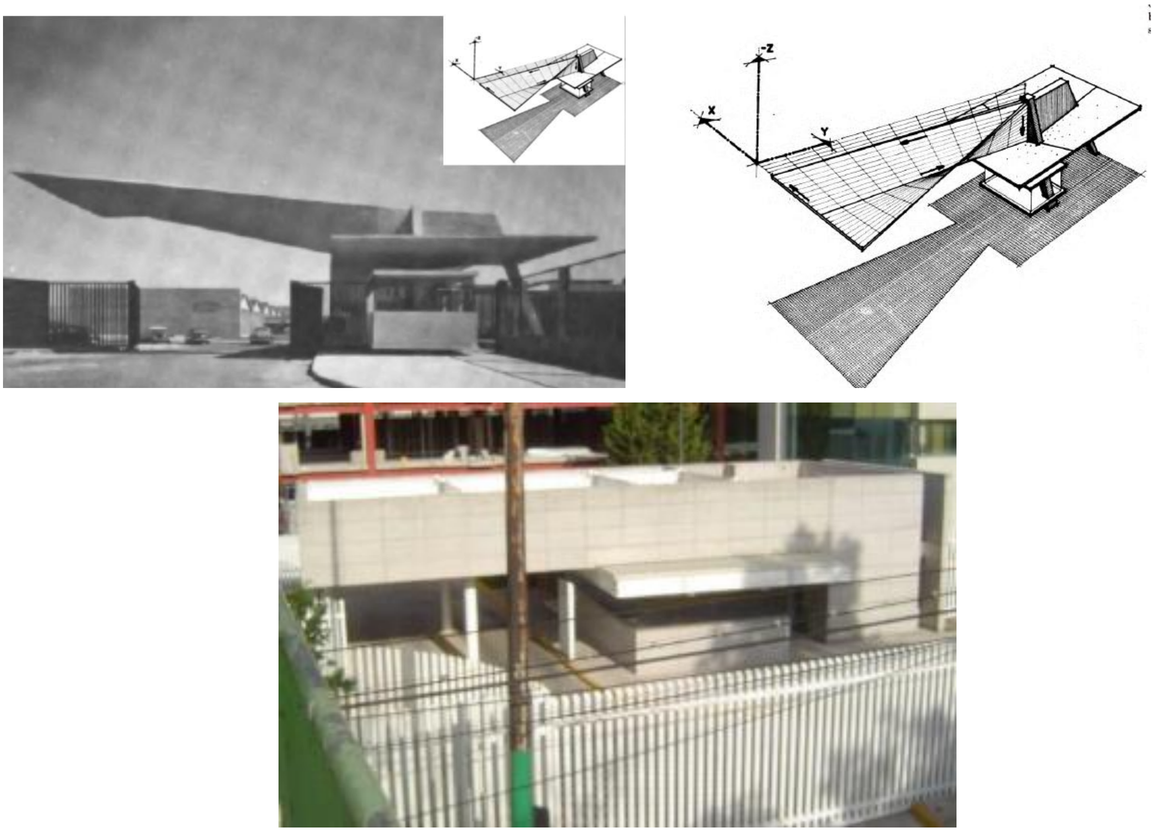


Figure 22. Original project of control booth of Lederle Laboratories (top) and control booth built after demolition(bottom).
In: (Faber, 1963) and (Del Cueto Ruiz-Funes J. , 2015).

2.7 Recorded collapses

The records of the collapse of shells structures throughout history are few. Regarding Candela's works, there is a record of a partial collapse that occurred during the execution of the construction of the Palmira Chapel and another generated by the earthquake of 1985 at Jamaica Market.

The structure designed for Palmira was based on a single hyperbolic paraboloid whose highest point registered a height of 24 m. When the formwork was removed, a section of the top part collapsed. According to subsequent studies, it is concluded that the problem was not related to the design but rather to a construction problem. The probable causes were the incomplete setting process of the concrete, local defects, or improper formwork removal. An interesting remark about the incident is made by Manuel Larrosa when he points out that Candela "charged double for his works because sometimes they fall off and have to be remade" (Basterra Otero, 2001).

The 1985 earthquake caused the collapse in Mexico City of the umbrellas that formed the Mercado de Jamaica as observed in Figure 23. The market was located in a zone of very soft clays soils. Due to the lack of structural damage reports, it is difficult to know the exact causes of the failure. The testimony of some market tenants indicates that "only a couple of the shell's columns had slightly toppled after the first earthquake and the rest seemed to be in good shape. These toppled columns finally hit the ground 36 hours later when an aftershock earthquake of 7.5 MW stroke again the city" (Mendoza et al. 2017).

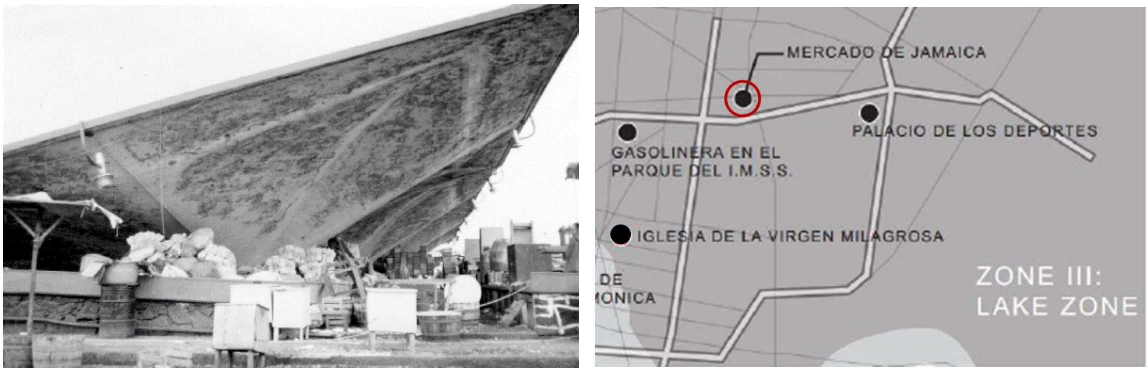


Figure 23. Collapse of umbrella columns, shells are seen without apparent noticeable damage (left) and location and soil types in Mexico City (right).
Note: In (Mendoza et al., 2017).

3. CASE STUDIES

In this section, seven shell structures built by Candela are described and analyzed regarding their design, construction, damages, and interventions. The methodology followed starts by identifying the typology, locations, and urban contexts to have an overview of the sample cases and their surrounding conditions. Next, the geometrical and structural characteristics and the material and construction process are briefly described to identify the similarities. Finally, the damages description and the previous interventions are carried out to expose the deterioration processes existing in the shells and possible solutions

The study sample comprises six cases located in Mexico City, while the remaining one is approximately 93 km far from it, in Cuernavaca. The following factors determined the selection criteria:

a) The importance of the hypar in Félix Candela's works. The cases are generated through hypars considering different chronologies and professional collaborations. Through this, the reader can appreciate the variations and evolution as well as the aesthetic and functional possibilities.

b) The different typologies and users. Service life and frequency of use of a building, determine the deterioration process and the maintenance programs significantly due to the constant flux of people. Besides, the subsequent interventions and additions are linked to new requirements most of the time.

c) The available information. The existence of relevant information obtained from previous studies and different disciplines that enables a critical analysis of the works

The creation process of the architectural object encompasses the research and project phase. During the research phase, the problem statement becomes the starting point and is synthesized in four questions: i) what is it? regarding the typology, ii) for whom? referring to the users, activities, and required spaces, iii) where? the terrain and environmental conditions are identified, and finally, iv) with what resources? Including the economics, humans, and materials (Turati Villarán & Pérez Rosas, 2010).

Direct the attention to the analysis developed at the work's origins is the objective of the preceding questions. Although the aspects to discuss the current conservation conditions are already defined, it is also necessary to understand the creation process from the origin to evaluate the interpret and analyze the value of the cases more deeply. Therefore, an attempt to answer each case's questions is carried out in the successive sections. The physical environment conditions are treated as one because the region is the same for most of them.

3.1 Geological conditions

The origins of the settlement and urban development of Mexico City are starting points to understand the particularities of the soil; therefore, a brief historical overview is provided to contextualize the outstanding events. In addition, the mention of the soil composition classification and the existing zones complement the knowledge of the geological conditions that determine the design requirements and behavior of the structures.

The Mexica culture settled around 1325 on an islet in the western part of Texcoco Lake. The sign that the god Huitzilopochtli gave for the city establishment was an eagle on a cactus devouring a snake. The natives developed constructive technologies and hydraulic engineering works like causeways to connect the islet with the mainland and allow life on the lake (Olmedo Vera, 2011). Floods were recurrent since pre-Hispanic times, therefore, the habitants carried out several works through different ages to dry it. In 1637 the viceroy settled in Nueva España proposed to build a drain which works finished in 1788 with poor results. During the XIX and XX centuries, hydraulic infrastructures were carried out to drain and increase the growing city area (González Evangelista, n.d).

The soil nature of the city and the seismic activity create a complex condition that becomes a determining factor regarding the design and structural calculation of a building. Therefore, the Building Code of Mexico City (Gobierno del Distrito Federal, 2017) divided the area into three main zones corresponding to the soil composition and geological characterization. The characteristics of these zones are explained below:

a) Zone I or Hills is formed by rocks or hard soils deposited outside the lake area. However, some sandy and soft clay deposits can exist. The presence of some cavities in rocks, sand mines, caves, tunnels, and uncontrolled landfills are common.

c) Zone II or Transition is formed by deep firm deposits that can be found at a depth of 20 m or less. Is composed predominantly of sand and silt layers interbedded with lacustrine clay layers. The thickness of clay layers is variable between a few tens of centimeters and meters.

c) Zone III or Lake is composed by deposits of highly compressible clay separated by sand layers with varying content of silt or clay. The layers can be firm to hard with variable thickness. These deposits are often covered by alluvial soils, dried materials, and artificial fill materials.

The Building Code of Cuernavaca considers only the soil types of Zone I and Zone II (Consejería Jurídica del Poder Ejecutivo del Estado de Morelos, 2017). It is essential to mention that the Building Code of Mexico City is the basis for regulations in other parts of the country due to the complexity of the mechanical properties of the soil. Therefore, local authorities carry out appropriate adaptations to satisfy the specific requirements of the states.

3.2 Architectural typologies

The buildings studied in the sample are collaborations of Candela with other architects where he mainly solves the structure. This is highlighted to avoid the belief that are creations of a single author. At this point, the design process questions previously mentioned will be retaken and analyzed. To answer the question, What is it? A typology classification is proposed in Table 1. It contains the seven cases pointing to the construction period, location, collaborators involved in the project, and architectural typologies. The sequence of appearance in the list responds to a chronological order to identify and understand the evolution of Candela's works properly.

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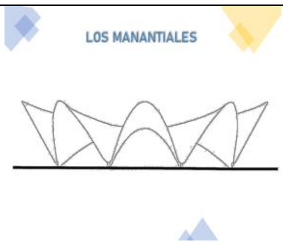
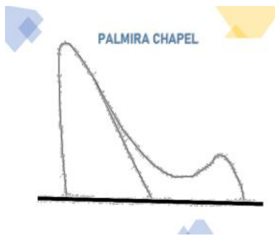
Table 1. Construction periods and typologies of study objects

Note: Elaborated by Nohema Cassandra Ruiz Gómez

Typology								
Building		Construction Period / Location	Collaboration	Laboratory	Church	Market	Restaurant	Transport Infrastructure
1		1951 Mexico city	Jorge González Reyna	X				
2		1953 – 55 Mexico city	José Luis Benlliure		X			
3		1955 – 56 Mexico city	Pedro Ramírez Vásquez			X		
4		1957 – 58 Mexico city	Joaquín Álvarez Ordóñez				X	

	Building	Construction Period / Location	Collaboratio n	Laboratory	Church	Market	Restaurant	Transport Infrastructure
5		1958 – 59 Cuernavaca	Guillermo Rossell and Manuel Larrosa		X			
6		1959 – 60 Mexico city	Enrique de la Mora and Fernando López Carmona					X
7		1967- 69 Mexico city	Julio Michel		X			

If the Table 1 is analyzed, it is observed that a wide variety of typologies are present in Candela's works, which denotes his ability as a designer and builder. Additionally, note the functionality and versatility of the shells to cover large spans and solve the needs and requirements of particular architectural programs. Candela himself already mentioned:

> "Although, there are many cases where the intended function for the building limits the free choice of the most logical structural system, there is a field where these limitations do not usually exist: the roofs. Specifically, those roofs covering large spans, in which lightness - and consequently economy - are usually decisive factors" (cited in Maluenda, 2016).

Typologies are linked to users and the activities that must be satisfied, so the design question for whom? is answered. According to the relationship with spaces, the study can classify the users into the permanents and the temporaries. These categories determine the spatial needs and frequency of use, helping to understand, for instance, the requirements to the finish material's resistance and durability. The user's profile is essential because the appropriation determines a large part of the preservation of a construction.

The sample contains three churches where the spaces are related to religious activities and reflect new forms and materials in this building typology. The importance of these innovations is due to the upgrades that the Vatican Council II carry out. The desire to modernize the Catholic Church raised new requirements and a series of spatial reforms to the eucharistic celebrations (Santa Ana, 2009). These reforms also tried to improve the interaction between the users, the priests, and the faithful, to generate a more direct relationship.

The cases corresponding to the market and metro station encompass peculiarities related to the materials' durability due to daily and continuous use. Large free areas are solved adequately by thin shells, making them an optimal possibility for spatial design in these typologies. However, these spaces are vulnerable heritage with constant risk due to their public and urban equipment nature. Therefore, the adaptations, new requirements, poorly planned interventions, and temporary solutions are persistent conservation problems.

The change of uses that the Cosmic Ray Pavilion recorded through the years defined new requirements and restrictions of access to a specific number of persons. For the restaurant, the users generate a constant flow that is also controlled. In this last case, the maintenance is in charge of the private owner; meanwhile, the University is responsible for the Pavilion.

The Catalogue of Projects and Works of Cubiertas Ala recorded the costs and provided an idea of the resources used. This catalog is available at the Architecture Faculty of UNAM through the Arquitectos Mexicanos Archive (Hernández Millán, 2020). Because a physical visit to the archive was not possible during the timeline of the present study, some cases' costs are not provided in this investigation. However, the following costs were obtained from the literature: the cost of the Cosmic Ray Pavillion was 72089 pesos (Hernández Millán, 2020) and the cost of Los Manantiales Restaurant was 384000 pesos (Del Cueto Ruiz-Funes, 2015).

3.3 Location

The terrain and the natural context where the buildings are placed are problems to be solved during the creative process. Section 3.1 exposed the three zones classification according to the soil type. The Figure 24 shows the locations of the buildings within Mexico City, creating an overlap with the soil types. The purpose is to identify, compare, and relate if the existing damages of the different cases are derived and directly related to these factors.

Observe and note the three cases located in Zone III where the most significant risk exists due to the unstable ground: i) Los Manantiales Restaurant, ii) the Medalla Milagrosa Parish, and iii) the Metro Station. Furthermore, the Chapel of San Vicente de Paul and the Market are place in the transition zone with a reduced distance. Lastly, only one case, corresponding to the Cosmic Ray Pavilion, is found at Zone I.

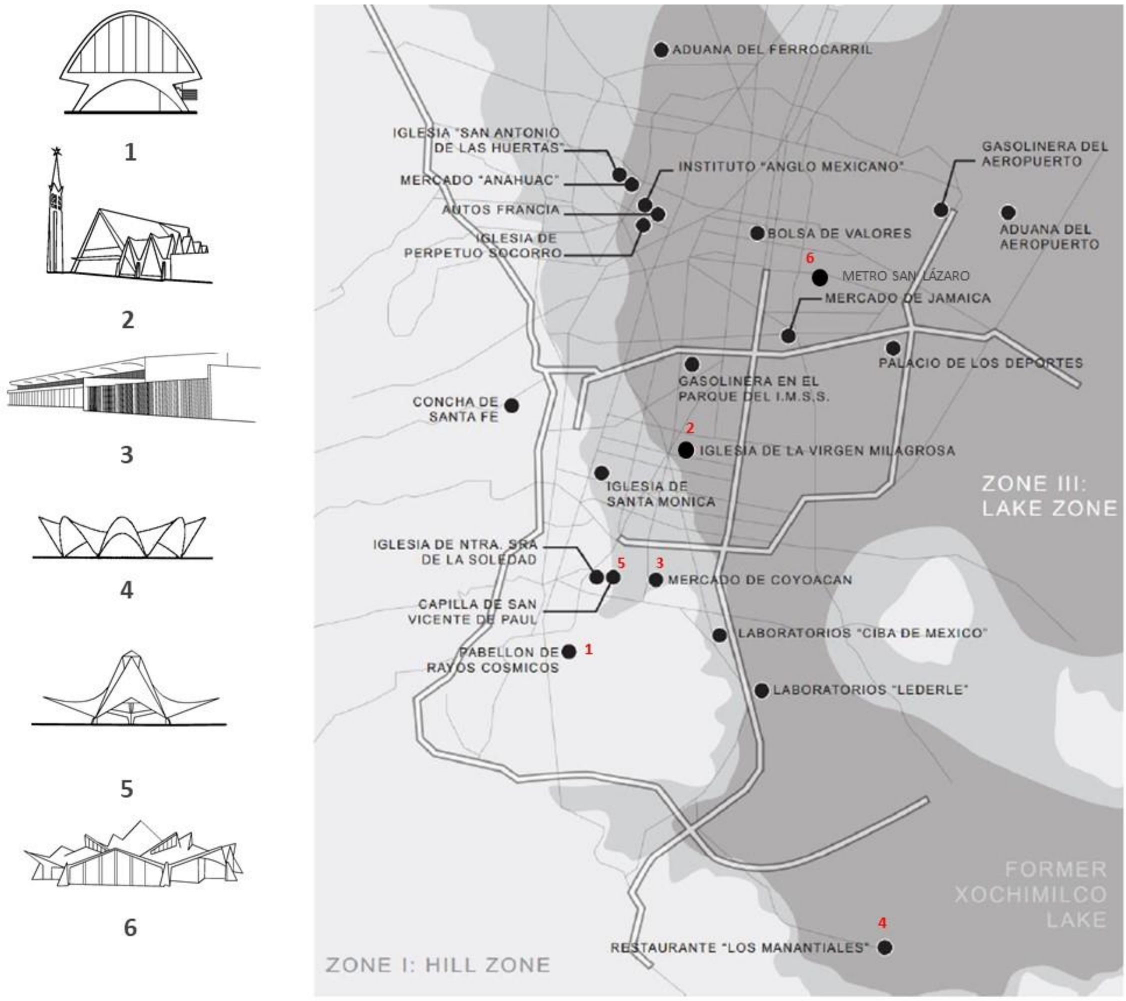


Figure 24. Location of the works and relationship with soil type.
Note: Modified from (Michiels,Garlock,& Adriaenssens, 2016).

3.4 Urban context description

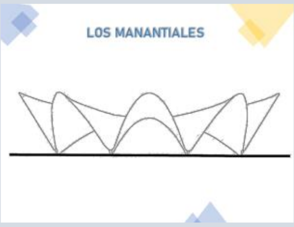
Analyze the context where the study objects are located is necessary to visualize the global state of conservation and carry out an evaluation at an urban level. Therefore, Table 2 compiles an urban description of the buildings. The modifications and alterations produce the loss of heritage value, especially if the building is within a monument zone or possesses a heritage declaration. The deterioration and loss of economic value of the terrains in the surrounding areas difficult the conservation because the population leaves, and users decrease. The opposite occurs when the value increase and monuments become at risk due to the market pressure. This battle, most of the time, is lost for the non-protected heritage.

Table 2. Urban context description.

Note: Elaborated by Nohema Cassandra Ruiz Gómez.

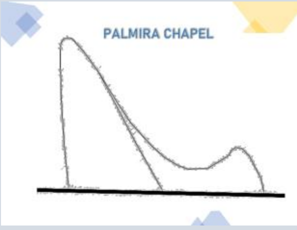
Urban context	
	**Location:** UNAM, Circuito Interior de Ciudad Universitaria, C.P. 04510, Alcaldía Coyoacán, CDMX     Images in: (Google Maps, 2019) Located at the University City Campus, the building is isolated and the scale is reduced compared to the surrounding constructions. Nevertheless, it is within the area declared by UNESCO as a world heritage site. Faculties such as Odontology and Medicine are nearby, stands out in this last mural made by the artist Francisco Eppens.
	**Location:** Matías Romero 78, Col. Vértiz Narvarte, C.P. 03600, Alcaldía Benito Juárez, Ciudad de Mexico, CDMX.    Images in: (Google Maps, 2019) The surrounding constructions have two or three storeys, so the building stands out in the area from an aerial and pedestrian view. The color, shapes, and especially the bell tower in the corner create an urban reference and street accent.

<table>
<tr><th colspan="2">Urban context</th></tr>
<tr>
<td>
</td>
<td>Location: Ignacio Allende s/n, Del Carmen, C.P. 04100, Alcaldía Coyoacán, Ciudad de Mexico, CDMX.

Images in: (Google Maps, 2019)
It is located in one of the traditional and most visited neighborhoods in the city from locals and foreigners. The market is a popular spot in the area because it specializes in the sales of handicrafts and food. The problems it presents are the urban infrastructure and the visual pollution that some elements such as electricity cables generate. It is essential to note the alterations to the original facades and the aesthetic of the project.</td>
</tr>
<tr>
<td>
</td>
<td>Location: Calzada Xochimilco Tulyehualco 60, Santa María Nativitas, C.P. 16450, Alcaldía Xochimilco Ciudad de Mexico, CDMX.

Images in: (Google Maps, 2019) and (Duque, 2011)
It is located in Xochimilco, a traditional neighborhood and one of the few places of the city that still preserve the water channels from pre-Hispanic times. The Partial Urban Development Program of Xochimilco incorporates it as a heritage building. The peculiarity of the restaurant is the nearby with one of the main waterways. The images show that the building stands out in the area for its shape, chromatics, and scale.</td>
</tr>
</table>

Urban context



Location: Plaza de La Parroquia, Lomas de Cuernavaca, C.P 62584, Morelos.

Images in: (Google Maps, 2019)

The absence of nearby high-rise buildings makes the Chapel the predominant construction in the context. The wide parking area and the visuals are preserved. The difference of the urban layout in comparison with the other objects of study can be noticed.

Location: Florida No.27, Santa Catarina, C.P. 04010, Alcaldía Coyoacán, Ciudad de Mexico, CDMX.

Images in: (Vazquez Ángeles, 2018) and (Ubertalli)

The restricted access to the property and the original typology keep the immediate surroundings in good condition. The original use of the building is still conserved.

<table>
<tr><th colspan="2">Urban context</th></tr>
<tr>
<td>
</td>
<td>Location: Calz. Ignacio Zaragoza, Col. 7 de Julio, C.P.15390, Alcaldía Venustiano Carranza Ciudad de Mexico, CDMX.
  
Images in: (Google Maps, 2019) and (Alarcón Azuela, 2018)

The Legislative Palace of San Lázaro, located few meters away, creating a crowded area. The current conditions are not optimal due to the establishment of informal commerce on the outskirts. The presence of bus stops restricts the visuals and makes almost null the appreciation of the structure from the street. Furthermore, informal wiring and the lack of planning of infrastructure elements affect the property.</td>
</tr>
</table>

3.5 Geometrical and structural characteristics

The versatile form and function of the three chapel buildings are visible in Figure 25, where different solutions are proposed for the same typology. This variety encompasses the orthogonal plan of the Medalla Milagrosa, the ground plan with curved edges of Palmira, and the geometric basic triangular shapes of San Vicente de Paul Chapel. In this last, the altar stands at a centric point with the presence of the faithful around it.

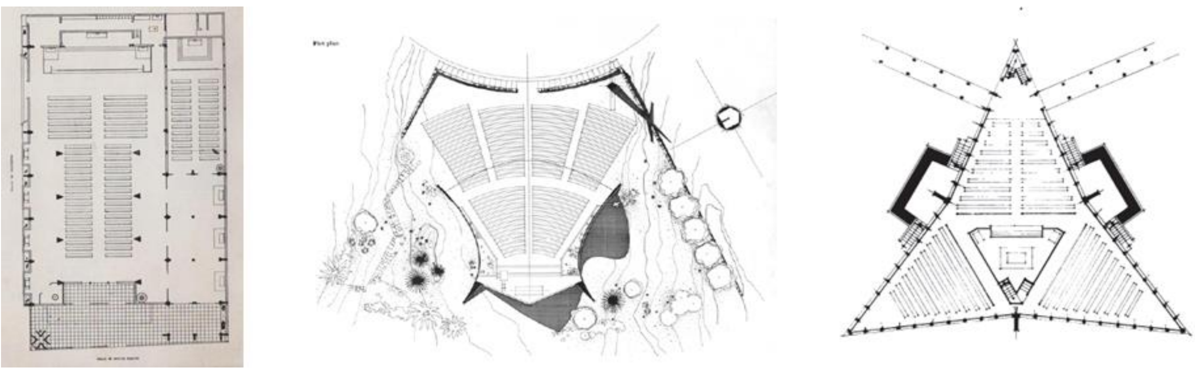


Figure 25. Geometries used in church plans.

Note: In (Taller AVB, 2015) and (Granell Santamaría, 2017).

The typologies of the other four buildings present regular and orthogonal ground plans with square and rectangular shapes as is observed in Figure 26. The use of these geometries is on the main floor and at the internal partitions. In the case of Los Manantiales, the figure plan is octagonal, with the orthogonal borders prevailing.

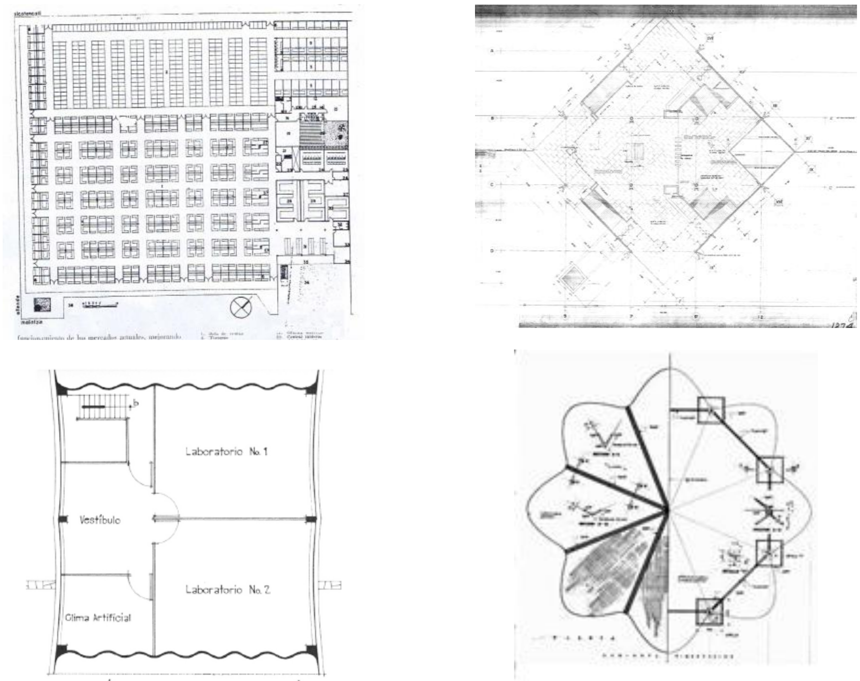


Figure 26. Ground floor geometries. Coyoacán Market and the Metro Station on the top, and Cosmic Ray Pavilion and Los Manantiales on the bottom.
Note: In (Cruz), (Alarcón, 2018), (Mendoza, et.al, 2020), and (Del Cueto & García Lopez, 2020).

Regarding comfort inside the shells, depending on the use and destination, the thermal and acoustic conditions might not be optimal due to the thinness. For instance, Los Manantiales presents relatively poor acoustic conditions because there is a high degree of reverberation. Equally, the churches require installing loudspeakers to improve the acoustics in the places furthest from the altar (Instituto Torroja TV, 2019).

Cosmic Ray Pavilion

The specific design requirement of the Cosmic Ray Pavilion was the cover thickness of 1.5 cm to carry out the measurement radiation. The solution of this specification results in two hyperbolic paraboloids coupled along a principal parabola and the surface built from the two director planes that formed a 60° angle. The membrane stresses are transferred to three hidden stiffen arches that conduct it to the supports and finally to the foundations, as observed in Figure 27. This small construction is significant because it is the first hypar built by Candela (Mendoza, et.al 2020).

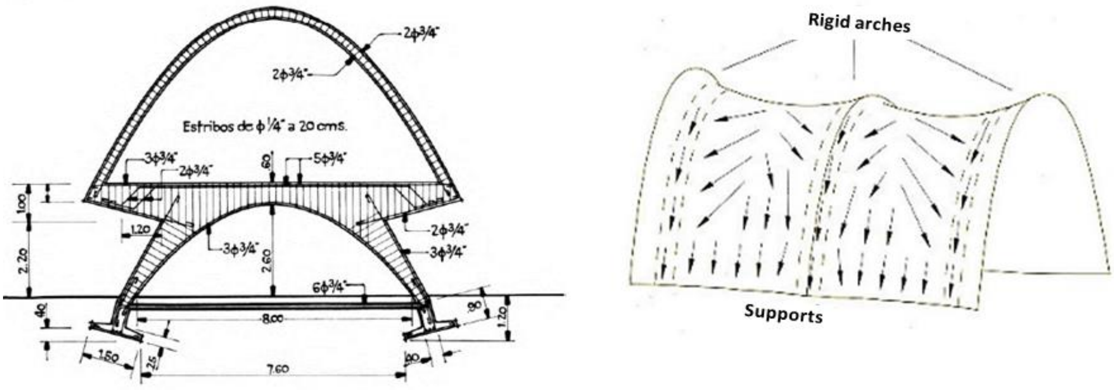


Figure 27. Section of the Cosmic Ray Pavilion (left), and membrane stresses (right).
Note: In (Mendoza et.al, 2020) and modified from (Cordero Toral, 2014).

Virgen de la Medalla Milagrosa Parish

The Virgen de la Medalla Milagrosa's nave is formed from four tilting asymmetrical umbrellas that mirror to obtain the roof of the nave, as explained in Figure 28. The addition of an interior thickened scalloped edge, emphasizes the design and helps to counteract the upward vertical force at the joint. Once together, the middle area of the edge that touches the ground extends to form a triangle. The thickness of the shell is 4cm, and hypars also form the apse. The interior columns are warping to have a most impressive visual effect of the roof (Michiels, Garlock, & Adriaenssens, 2016).

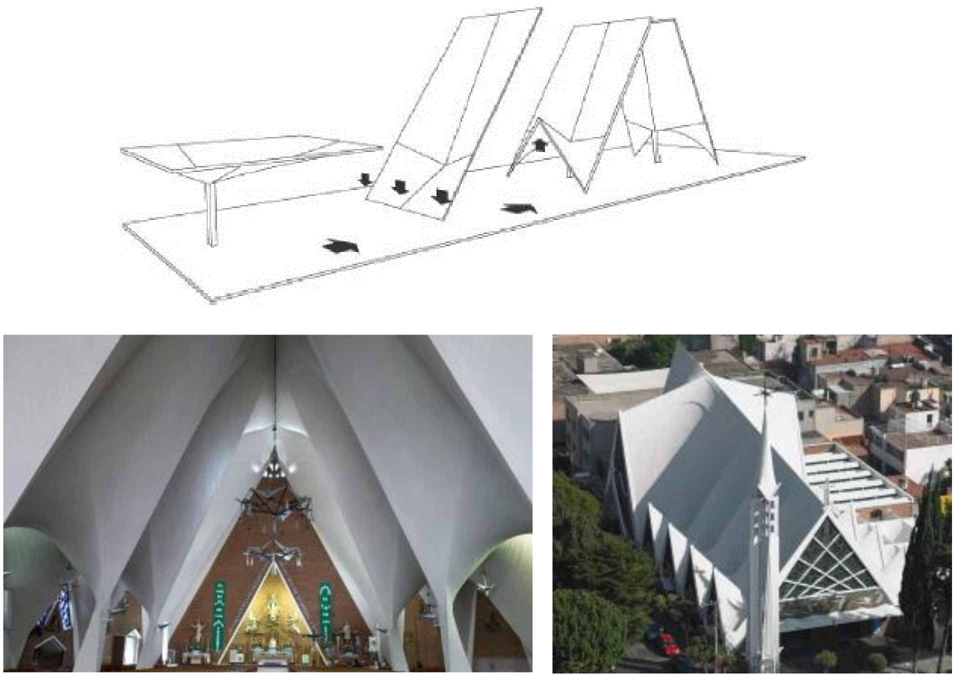


Figure 28. Sequence to obtain the surface (top), interior view where the design of the columns can be notice (left) and exterior facade (right) of the Virgen de la Medalla Milagrosa Parish.
Note: In (Michiels , Garlock, & Adriaenssens, 2016.)

Coyoacan Market

Coyoacan market was built based on asymmetric umbrellas where a comfort adaptation is achieved. The Figure 29 shows the openings produced due to the change of levels, which gives a solution to the ventilation and lighting requirements. This solution was extended to other markets, such as Arriaga in Chiapas, a project that Candela advised, where different levels provide an ingenious design to the property located in a hot climate. Unfortunately, this last was demolished in 2013 (Instituto Torroja TV, 2019).

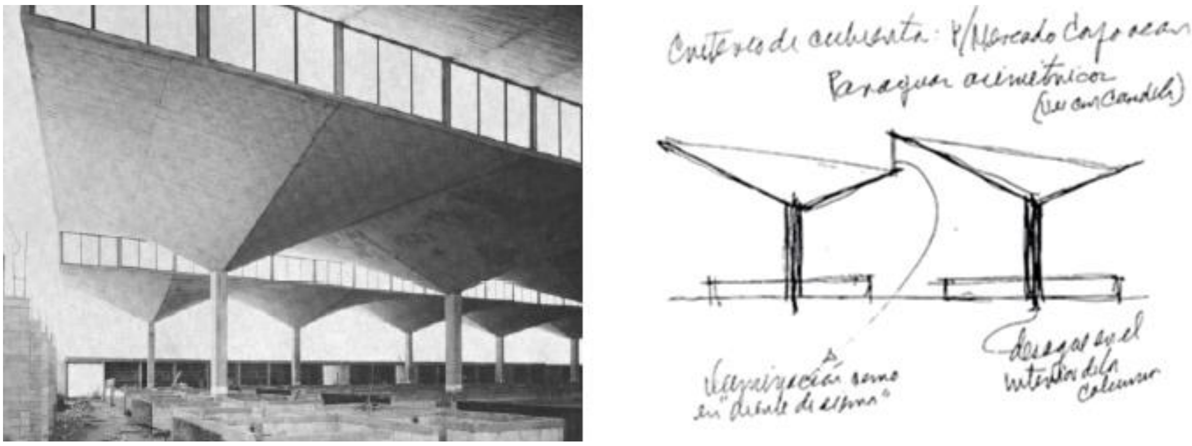


Figure 29. Internal views of the market (left) and sketch of the openings in the top (right)
Note: In (Carrión Fuentes, 2013).

Los Manantiales

The origin of Los Manantiales project was the substitution of a timber restaurant that suffered a fire and got lost. A reinforced concrete structure was considered to use the new fire-resistance materials (Del Cueto Ruiz-Funes J. I., Candela en Xochimilco, 2015). The roof is solved through four paraboloids with curved edges that rotate on an axis giving rise to the groin vault of eight segments. The thickness varies from 4 cm and growth towards the valleys until 12 cm. Eight footings joined by a perimeter tie that form the octagon support the roof, as Figure 30 shows (Oliva Quecedo et al.2010).

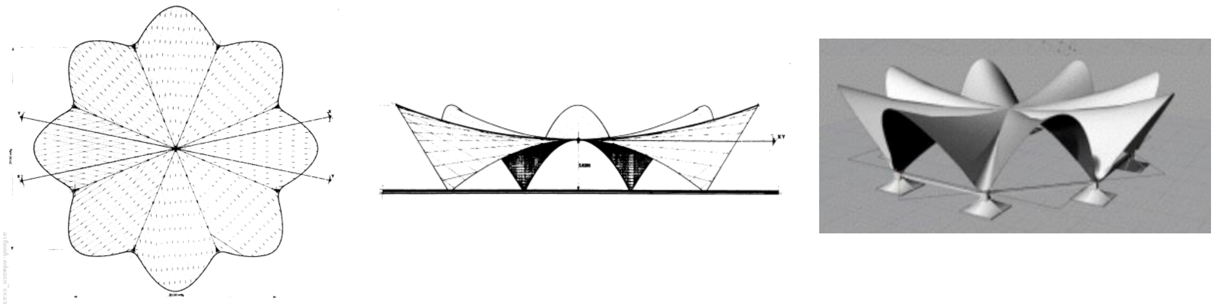


Figure 30. Los Manantiales Roof plan (left), elevation (center), and 3D model where the foundations and ties are appreciated (right).
Note: In (Del Cueto Ruiz-Funes & García Lopez, 2020)

Palmira Chapel

The design of Palmira's Chapel is one of the works that reflect Candela's constructive expertise. The surface is generated from a single paraboloid with a thickness of 4 cm that increases along the sides and has a maximum height of 21.90 m as Figure 31 exposes (Draper, Garlock, Billington, & Gordon, 2008). The structure presents three supported clamped edges with double reinforced sections and increasing thickness. A design factor considered was the wind, so Candela incorporated a compressive rib along the lip (Faber, 1963).

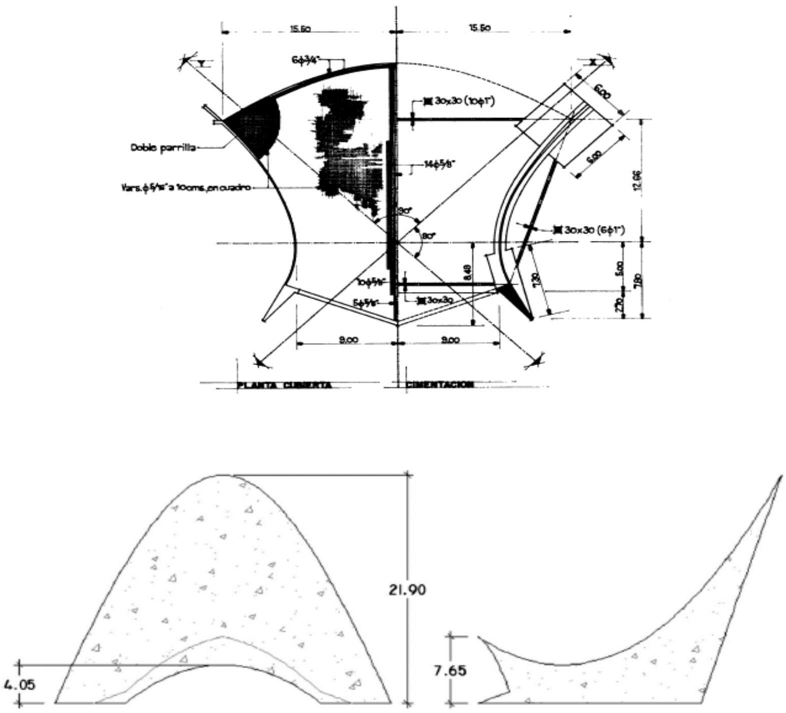


Figure 31. Palmira Chapel Ground - Roof plan (left), front elevation (center) and lateral elevation (right).
Note: In (Faber, 1963) and (Draper, Garlock, Billington, & Gordon, 2008).

San Vicente de Paul Chapel

The project was conceived to expand the convent of the St. Paul's sisters. An elderly retirement home already existed, so the few terrain area and visual restrictions were the challenges involved. The roof is based on three straight edge shells with a constant thickness of 4 cm that resembles the nuns' headdress. The flux and location of the users inside the building were projected to house the nuns in one wing, the elderly living at the retirement house in the other, and in the third one, the faithful (Granell Santamaría, 2017).

The inclination of the roof axes surface creates an opening between the three shells. A metallic structure joins them, gives rigidity, and supports the stained-glass windows. The edge beams on the long sides decrease in cross section when they get closer to the edge, as shown the Figure 32. The shells are held at two vertices by inverted triangular supports and a slope that complements them to act as a buttress. The edge beams rest on this support, and the cantilever is supported by steel posts that reduce vibrations and movements (Granell Santamaría, 2017).

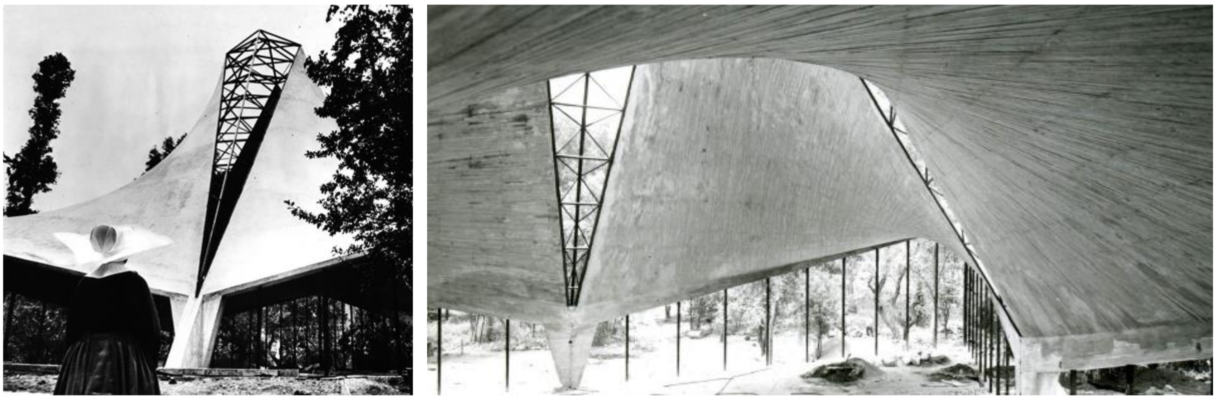


Figure 32. Headdress of nuns as concept of design (top), and supports and edge beams of St. Paul Chapel after the formwork removal (bottom).
Note: In (Tiovivo, n.d) and (Faber, 1963).

San Lázaro Metro Station

The design base are the hyperbolic paraboloids that lean outwards, forming the roof's perimeter and carried by the edge beam. These elements rest on two lateral supports located on each side of the rectangular plan. Towards the central part, another set of hypars with different heights is supported by columns with a cruciform section located inside the station as is observed in Figure 33. One of the achievements generated by this level change is the natural lighting through the openings generated by the hypars, so the light requirement is solved from a clever and simple solution (Alarcón Azuela,2018).

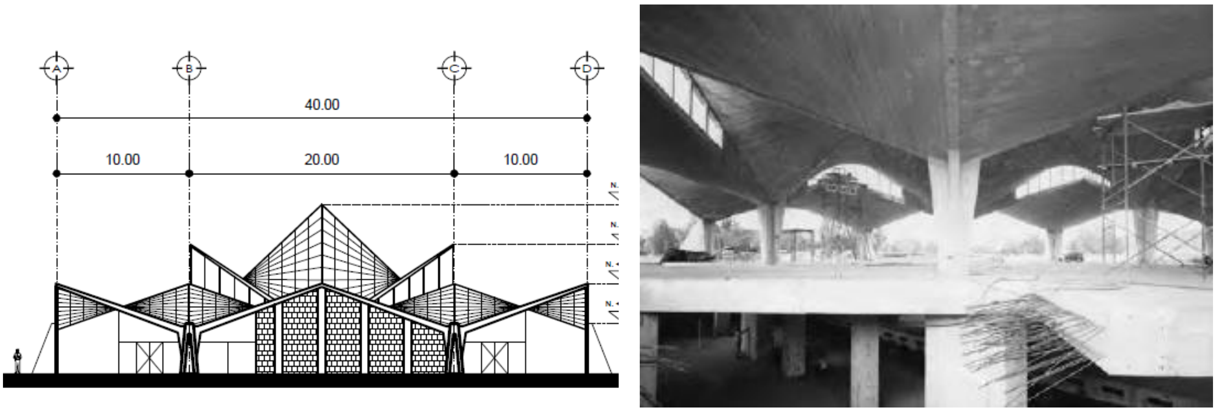


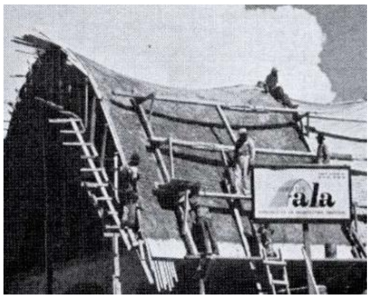
Figure 33. San Lázaro Metro Station west facade (left), and view of the interior of the station during the construction works (right).
Note: In (Alarcón Azuela, 2018)

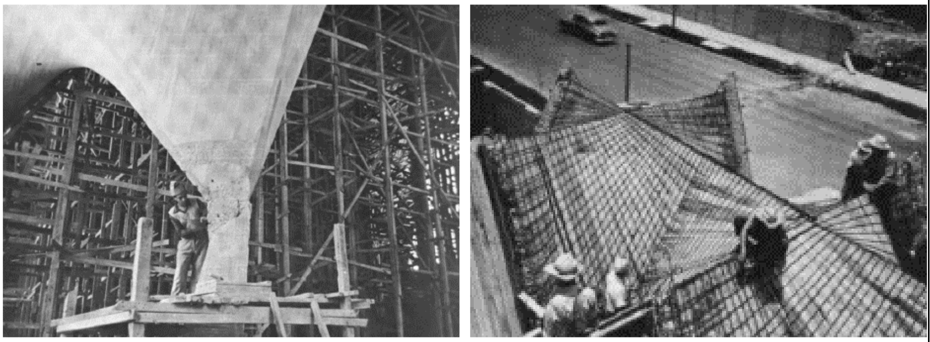
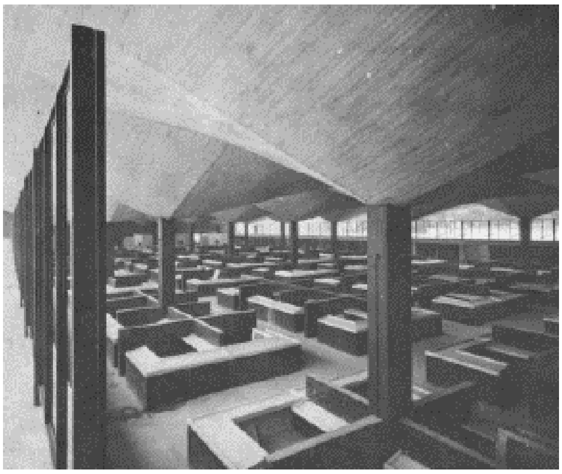
3.6 Description of materials and constructive procedures

Despite the reinforced concrete and the timber are the main materials used, the particularities of each case and the belonging to a different stage of Candela's experimentation process brought some specific challenges to design and constructive procedures. This section through the Table 3 will briefly expose and describe some of the challenges and the materials used.

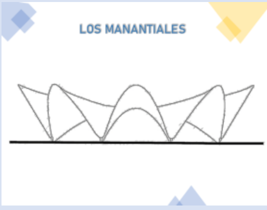
Table 3. Material and constructive process description

Note: Elaborated by Nohema Cassandra Ruiz Gómez

Materials and constructive procedures	
 	 Images in: (Faber, 1963) and (Hernández Millán, 2020). The formwork used for the shell was a tongue and groove flooring board over wooden joists disposed along the other system. Regarding the formwork of the stiffening arches “was designed to protect them after they had cured and also to support and create a continuous shell formwork” (Mendoza, et.al, 2020). This case is one of the few records about the concrete proportions used by Candela, being 1:3:2 with ¼” maximum size coarse aggregate. The reinforcement is a mesh 1/8” mild steel wire of 4” placed along the parabolas. The hand pouring process took about 8 hours (Faber, 1963). The works about final coatings include the waterproofing treatment of the shell, while the installations encompass lighting and air conditioning (Mendoza, et.al, 2020).

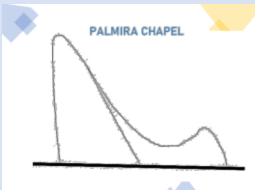
Materials and constructive procedures	
 	 Images in: (Faber, 1963) The materials used were timber formwork, reinforcing steel, and concrete. Some formwork problems arose at the junction of the upper edge, and due to the great slopes of the surface, constructive challenges like the poured of the concrete existed (Faber, 1963).
 	 Image in: (Carrión Fuentes, 2013). Specific information regarding the constructive process and materials of this case was not found. Thus, an analogy with the umbrella's structure is assumed. In these structures, the materials used were reinforcing steel and concrete. Regarding the finishing, the original project specified a black mosaic for a section of the walls.

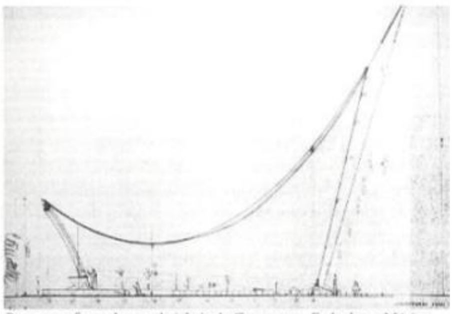
Materials and constructive procedures



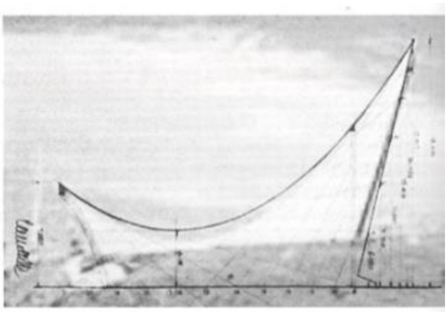
Images in: (Del Cueto Ruiz-Funes J. I., Candela en Xochimilco, 2015).

Timber was used for the formwork and the reinforcing steel is based on a square mesh formed by 5/16" rods. The poured of the concrete was done by hand and the proportions of the mixture are unknown. The windows casements were manufactured in metal and support large glass windows (Del Cueto Ruiz-Funes J. I., Candela en Xochimilco, 2015).





Proyecto reformado para la iglesia de Cuernavaca. Fechado en México D.F., febrero de 1958. Archivo Candela, Avery Library, Universidad de Columbia, Nueva York.



Superposición de los dibujos originales y la estructura construida.

Images in: (Basterra Otero, 2001).

Timber-based formwork was used, a steel double mesh of 5/16” @10cm was assembled and the concrete was poured. During the construction, a partial collapse was recorded thus the original project was modified. For more details consulted section 2.7.

<table>
<tr><th colspan="2">Materials and constructive procedures</th></tr>
<tr><td>
</td><td> 
Images in: (Alarcón Azuela, 2018) and (Faber, 1963).
The main materials used to create the surface of the hypars were timber formwork, a square steel mesh of 3/8” @10cm, and concrete. The metal lattice that joins the hypars is sealed with stained glass (Faber, 1963).</td></tr>
<tr><td>
</td><td> 
Images in: (Alarcón Azuela, 2018)
The case formwork was made of timber. The supports were cast before the hypar roof; note that both are made of reinforced concrete. After removing the formwork, the partition walls were incorporated. The finish of these walls is a quarry of golden color (Alarcón Azuela, 2018). The proportions of the concrete mixture are unknown.</td></tr>
</table>

3.7 Damages and previous interventions

In this section, a mention of the existing damages and previous interventions in the case studies are carried out. It is important to note that the information of only five cases are described due to the lack of records regarding the other two.

Cosmic Ray Pavilion

The Cosmic Ray Pavilion has been recently reported to exhibit signs of deterioration. While the structure did not suffer significant damage due to the 2017 earthquakes; it has not been exempt from other source of deterioration. In communication with Dr. Mariana Esponda (2021), she commented that during the visit to the building in 2019, the damages recorded were mainly related to maintenance. In addition, she remarked on the waterproofing system where the number of existing layers is unknown. The reason is the incorrect procedures and applications where the previous layers are not removed.

The procedure maintenance records made by the University are scarce, so the detailed analysis of the interventions becomes complex. The archival research carried out by Cordero and Esponda shows that the waterproofing was secure through the application of synthetic rubber paint inside and outside the shell. A photographic analysis revealed the application of an asphalt treatment to the shell (Mendoza et.al, 2020). It is essential to mention that this was a standard procedure in Mexico for flat roofs. At Figure 34 is observed the impact of the different waterproof finishes on the aesthetic of the original project.

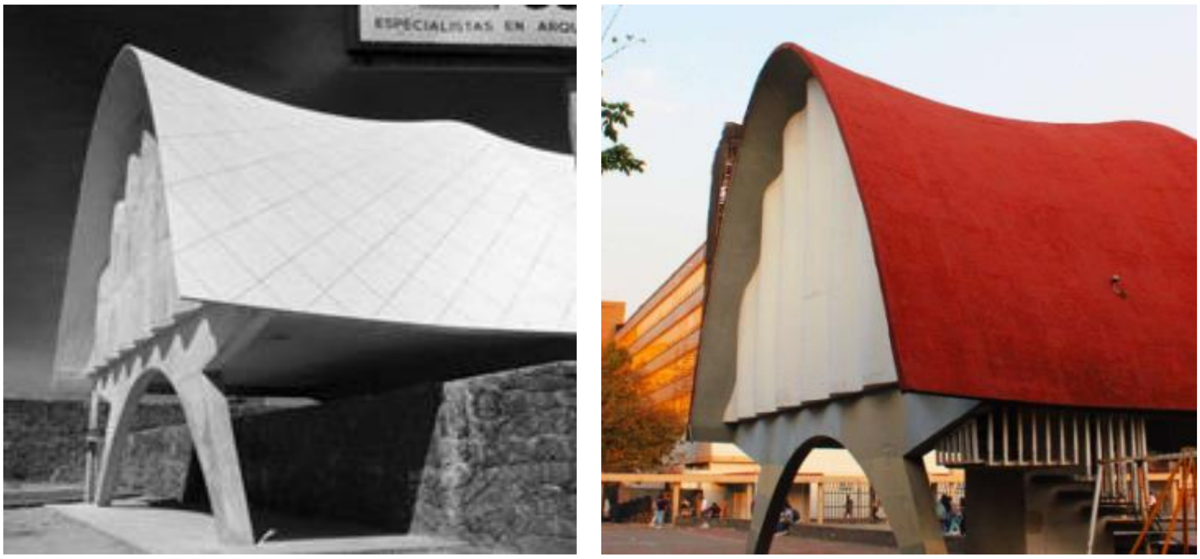


Figure 34. Cosmic Ray Pavilion hypar view in 1952 (left) and current state (right).
Note: Courtesy by (De la Torre Mejía, 2021). In (Hernández Millán, 2020).

During the decade of 1970, the building suffered alterations and changes of use. The first was in 1977 when a new Science Faculty was built and the institutes moved to it. In 1978 the Pavilion was adapted as a professional exams room for a period of 10 years. Due to this, the partition walls were removed, while the external stair was demolished and rebuilt with a new design as observed in Figure 35. A timber panel was added at the internal south façade to improve the acoustic isolation and comfort, new floors and lightings were also including. From 1987 to 2004, the building was used as the university's chess center, leaving it abandoned until 2007. Finally, the Sports Direction of UNAM adapted the building as a playroom and storage of recreative sports material, keeping it as its current use (Hernández Millán, 2020).

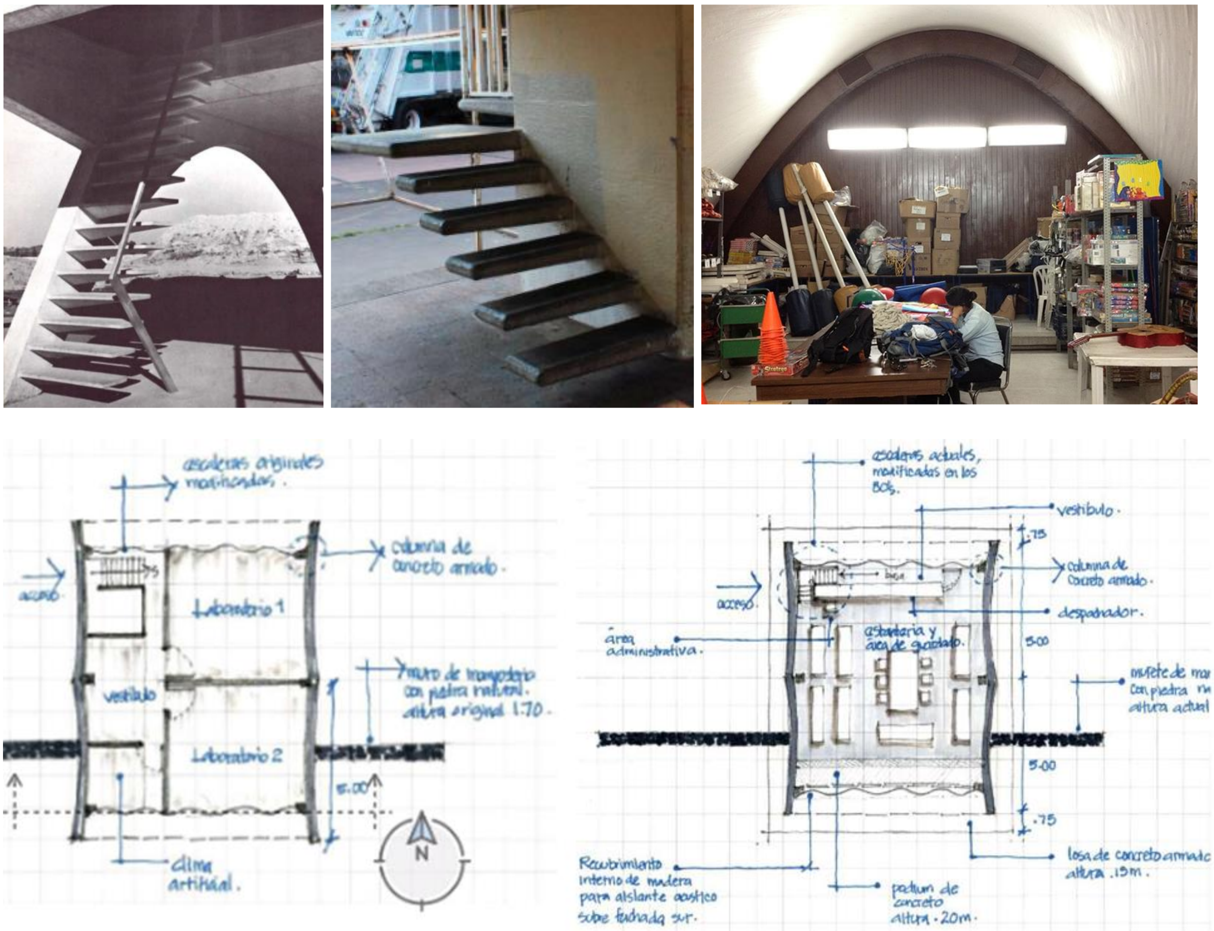


Figure 35. The images show the changes in the stairs and the acoustic timber panel.The sketches show the alterations to the original project (left) and the current state (right) of the Cosmic Ray Pavilion.

Note: Sketches and photos in (Hernández Millán, 2020) and (Redacción LOCAL, 2017).

In 2020, the General Directorate of Works and Conservation of UNAM focused on creating a general maintenance program of the Central Campus. The restoration project of the Pavilion was commissioned to the conservation architect Gabriel De la Torre, who elaborated a damage survey. The conclusions obtained through the mapping coincide with Dr. Esponda's pointed factors. The loss of waterproofing, thin cracks, and cavities in the finishes due to the lack of maintenance are the main damages recorded at the shell as is observed in Figure 36. At the same time, the external walls and supports present cavities and some corrosion problems.

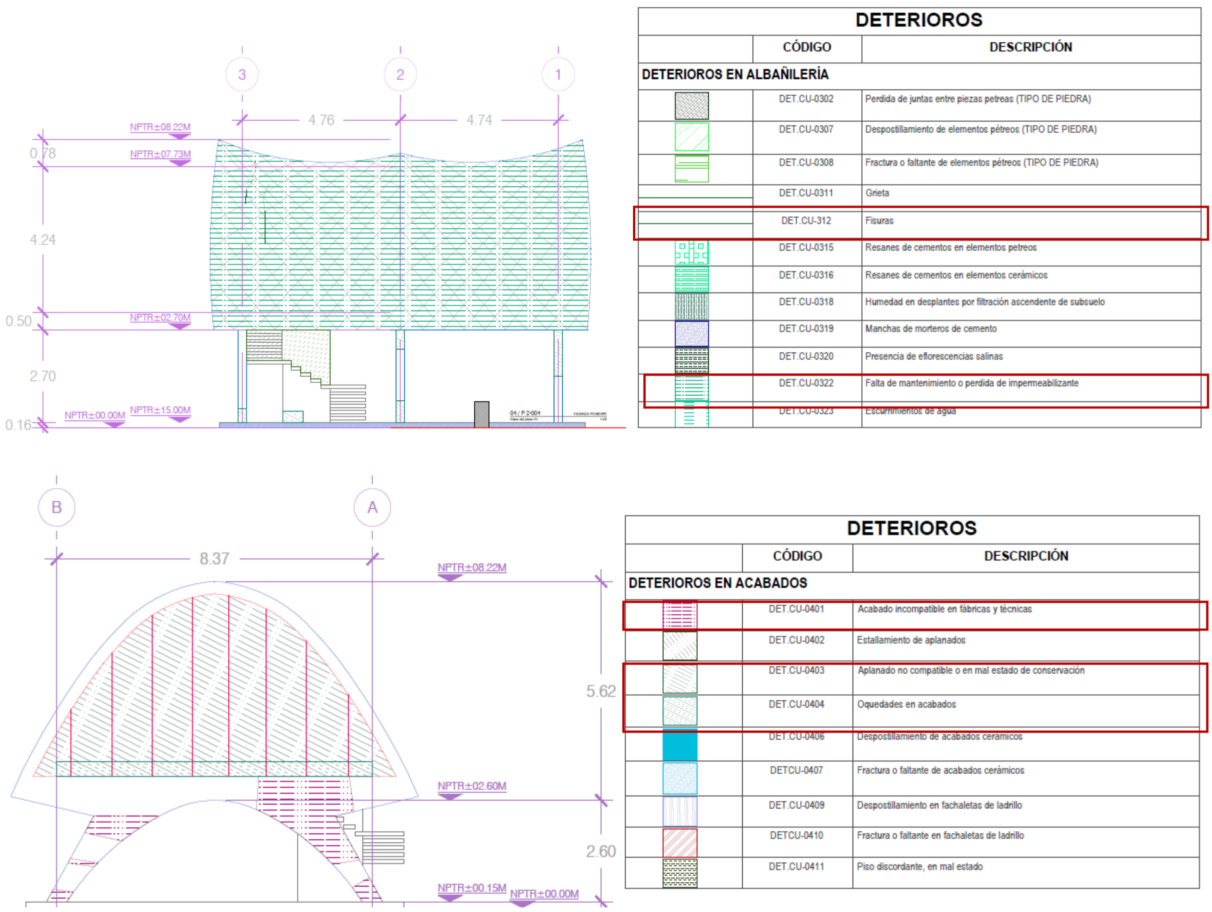


Figure 36. Damage survey elaborated for the maintenance program. West facade (top) and North façade (bottom) of Cosmic Ray Pavilion.
Note: Survey courtesy of (De la Torre Mejía, 2020).

Coyoacán Market

Coyoacán Market presents alterations regarding the original aesthetic, outstanding the facades as is observed in Figure 37. The addition of a body that grows outwards supported by four columns at the different entrances is noticed. The upper part has a central arch and a circular opening, while the roof is gabled at different levels. It is important to note that the market is painted with yellow at the outside and inside, while Faber (1963) mentions that "Its theme is black and white —black columns for the white shells and black mosaic walls half-enclosing the structure" (p. 116).

A relevant aspect of the maintenance is that the tenants tend to take care of this most of the time. Additionally, adaptations of the new requirements and needs are also carried out by them, allowing the additions and modifications that do not follow a general project. These alterations are reflected in later problems related often to electrical, hydraulic, gas, and drainage installations. The interventions in markets by the government are scarce and not constant, so the regulation, planning, and management in these immovables are complicated.

Figure 37. Façade alterations in Coyoacán market.
Note: In (Structurae, n.d.) and (Google Maps, 2019).

Los Manantiales

Los Manantiales gains importance because it is the case of the sample that suffered the most damage due to the 2017 earthquake. Although the soil composition is important, the professionals must discuss and analyze the previous conditions and interventions to create a most accurate approach to the causes and origins of the final damages.

The record of the conditions compiles through a research in 2006 indicates the existence of sealed cracks due to possible shrinkage. The study found patched leaks and drip stains on the underside of the shell at that time. However, the final diagnosis was "that the cracks have in no way compromised the structural integrity or safety of the shell, and that any deformations in the shell's present state are so small as to be invisible to the eye" (Burger & Billington, 2006).

Figure 38. Shrinkage cracks pattern after construction (left) and patched leaks (right) in Los Manantiales.
Note: In (Burger & Billington, 2006).

The original project posed the interaction of the waterways with the visitors who arrived in trajineras to the restaurant. However, the soil problems and loss of water level led the addition of platforms and retaining walls generating a significant rupture between users and the building as is observed in the Figure 39. In addition, the invasion of agricultural terrains that surrounded the building also affected the urban image.

Figure 39. Water level changes and additions at the exterior of the restaurant.
Note: In (González Pacheco & Nuñez Alfaro, 2013).

Non-appropriated intervention actions in the property are related to applying a red waterproofing coat as is observed in the Figure 40. In addition, to restrict the access to the roof, forges elements and water collectors in the base that hides the supports, were added to the shell. However, in 1996 the intervention works executed by Architect Elisa Valero Ramos are recognized as suitable by authors as Del Cueto. (Del Cueto Ruiz-Funes J. I., Candela en Xochimilco, 2015).

Figure 40. Red waterproofing in 1996 (left) and protections and addition of water collector (center and right).
Note: In (González Pacheco & Nuñez Alfaro, 2013) and (Del Cueto Ruiz-Funes J. I. Candela en Xochimilco2015)

The earthquake caused the foundations fracture in one section of the perimetral ties that joins the footings, as is observed in Figure 41 resulting in the outward displacement of these. The continuity between foundations-support-roof is broken by this punctual displacement, allowing the deformations in the geometry of the superstructure. In addition, the thinness of the roof favors some vulnerable spots regarding the interaction with non-structural elements, for instance, the perforations caused by the casement in the shell.

Figure 41. Lost of geometry at the hypar of Los Manantiales (top), Broke tie (left), and ground fracture (right).

Note: In (Martínez Burgos, 2021) and (Del Cueto Ruiz-Funes & García Lopez, 2020).

The lack of resources and immediate attention to the buildings damaged by the earthquake generated further deterioration. The time-consuming process to obtain reconstruction funds led to several buildings being abandoned for consecutive years, as in the case of Los Manantiales. The damages in the surrounding context are also visible; for instance, it can be noticed in Figure 42 the graffiti at the intrados of the paraboloid and the perimetral wall.

Figure 42. Urban context and vandalism.

Note: In (Alarcón Azuela, 2018) and (Google Maps, 2019)

Lastly, the damage mapping comparison between the record in 2006 and 2017 is shown in Figure 43. The intention of displaying them is suggest studying the evolution of the deterioration process in that period to know the actual incidence of the earthquake in the current damages. Furthermore, from this analysis, important data could be obtained regarding the relevance of maintaining and monitoring thin-shells in Mexico.

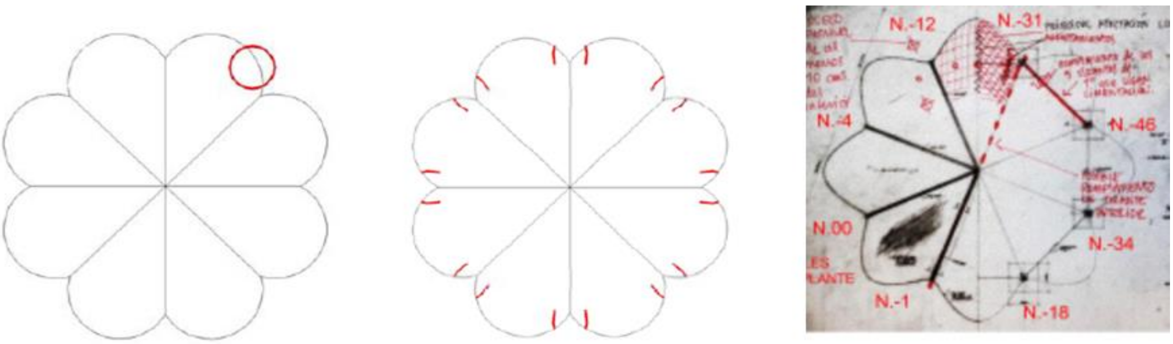


Figure 43. Los Manantiales damages in 2006 (left and center) and damages after the earthquake (right).

Note: In (Burger & Billington, 2006) and (Del Cueto Ruiz-Funes & García Lopez, 2020)

San Vicente de Paul Chapel

Alarcón (2018) point the damages registered in 2009 at San Vincente de Paul Chapel, which includes: i) the presence of corrosion on the metallic structure that join the hypars, ii) excess layers of waterproofing with an incorrect application, iii) cracks in the shell, and iv) thick layers of sealant on the glass windows. The alterations made by the users encompass modifications in the casement, the removal of original lights, and the incorporation of a ramp.

The 2011 restoration of the Chapel was carried out by the architect Andrés López. The intervention works to highlight at the shells are removing waterproofing layers, injection of cracks, and the application of a waterproofing layer as shown in Figure 44. This last is based on shredded tire waste and includes a final paint coat. Regarding the lattice, the project consists of removing the rusted metal elements and replacing the most damaged. The stained glasses were removed, restored, and placed again in the lattice (Alarcón Azuela,2018).

Figure 44. Crack injections (left), waterproof and paint coating application (right), and corrosion cleaning (bottom) at San Vicente de Paul.
Note: In (Alarcón Azuela, 2018).

San Lázaro Metro Station

San Lázaro Metro station presents damages in the shells that are mainly related to moisture from the improper roof water draining conditions. The moisture marks are visible from the inside of the station, while outside, the growth of biological colonization can be observed, these damages are shown in the Figure 45 (Alarcón Azuela, 2018). Furthermore, the water can also develop nonvisible damages under the concrete layer, like corrosion in the reinforcements or other chemical reactions. Hence, monitoring and tests are mandatory to prevent deterioration.

The addition of spaces to solve new requirements is another of the modifications that the station has undergone, for instance, a Health Unit of the Government of Mexico City. This affects the original conception not only in the internal space but also in the external views. Furthermore, the damages created by non-planned additions of hydrants and electrical installations and informal commerce increase the problem.

Figure 45. Moisture (left), roof water draining (top) and space additions (bottom) of Metro Station. Note: In (Alarcón Azuela, 2018).

Modifications to the esplanade have been made over time, encompassing pedestrian corridors and flower beds as is observed in the Figure 46. In 1997 the metro system enlarged and connected with another new line (Alarcón Azuela, 2018). Hence, the number of users increases, and as consequence, a structure is added to the station. The demolition of the corridors to increase the esplanade area is another alteration to the original project.

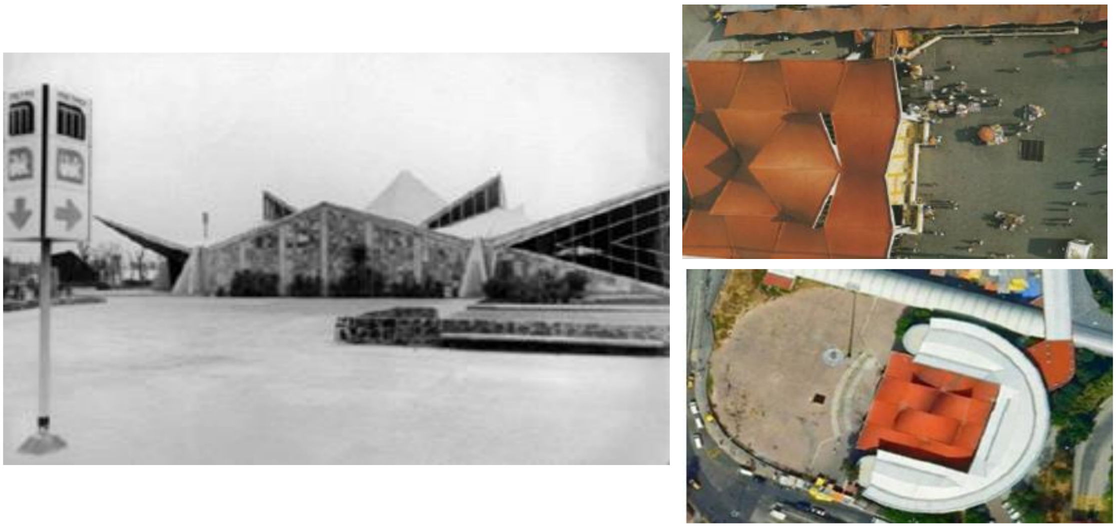


Figure 46. Esplanade with gardens and without corridors (left), Station with cover corridors at 90’s (top) and esplanade after 1997 (bottom).

Note: In (Alarcón Azuela, 2018).

4. OVERVIEW OF THE CONSERVATION CHALLENGES IN CANDELA'S WORKS

This chapter intends to expose the problems of the state of conservation of Candela's works based on the collected information. The first section focuses on the methodology and classification of the types of damages affecting the structures studied according to the causes that originate them. Subsequently, the legal framework that protect heritage in Mexico and regulate intervention actions in the historical monuments are analyzed. Finally, a critical review of the current state of conservation of the cases presented in Chapter 3 is provided.

An important note to consider throughout this chapter is the cultural significance and heritage values that the seven cases studied here possess, despite the absence of a formal declaration as a monument. Given their lack of legal protection, this study follows the approach, recommendations, and guidelines established by the institutions and organizations specialized in conserving heritage buildings.

4.1 Damage classification for Candela's shells

Identify the causes of the damages is essential for the evaluation, study, and intervention process of any work. These phases must be carefully and thoroughly analyzed when the structure has heritage values. The evaluation of damages in the concrete thin shells often focuses on material aspects. However, the alterations due to other sources can also entail important and major challenges for the building.

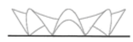
The damages in five out of the seven buildings studied here were already described in Chapter 3 (damage survey information was not obtained for two buildings: Virgen de la Medalla Milagrosa Parish and Palmira Chapel). A comprehensive and detailed methodology that considers the causes for damage is applied here to these five structures. Table 4 summarizes the types of damage present in these buildings, with the intent of identifying the most recurrent causes of damage. It is relevant to mention that future gathered data can be added to complement this table.

The Table 4 classification is based on the Guide for the methodical study of monuments and the causes of their deterioration by Gugliemo de Angelis D'Ossat (1982). His proposal is flexible to monumental variations; therefore, this study made some adaptations and modifications to apply it to the shells. The damages are divided into two main groups and the sections below show the explanation of the items and the table.

The particular objective of organizing the information through this table is to create an initial proposal to study damages in concrete thin shells. Generating a methodology for studying these structures is a topic which can be further developed and researched. In this case, only factors that affect Candela's work, in particular, are taken into consideration. If one wants to apply it to another author or shells with other characteristics, the classification may need to be reviewed and adapted.

Table 4. Classification of damages causes for Candela´s buildings

Note: Elaborated by Nohema Cassandra Ruiz Gómez

DAMAGES CAUSES			Buildings				
			 COSMIC RAY PAVILION	 COYOACÁN MARKET	 LOS MANANTIALES	 SAN VICENTE DE PAUL	 SAN LAZARO STATION
Intrinsic to the building	**Related to the building's position**	Geo-topographical climate and orientation			x		
		Ground carrying the foundations			x		
	Inherent in the structure	Building materials	x		x	x	
		Building systems (project and execution)					
Extrinsic to the building	Natural agents: prolonged actions	Chemical actions	x			x	
		Biological actions			x		x
	Ocassional actions	Earthquakes			x		
		Volcanic eruptions					
		Hurricanes/wind					
	Anthropic	Non appropiated interventions	x	x	x	x	x
		Constructive/material systems alteration	x		x		
		Context transformations		x	x		x
		Obsolescence	x				
		Lack of maintenance	x	x	x		x

4.1.1 Causes intrinsic to the building

The intrinsic causes are related to the origin and nature of the building. It encompasses two subgroups: the first is linked to the building position and the second to the inherent nature of the structure. Related to the building position are the damages originated by the topography, climate, orientation, as well as soil and ground conditions. This type of damage can be found for example in Los Manantiales, where the soil type and the water level reduction at the waterways affect the foundation's stability. Note that within the sample of buildings considered, these causes were only identified in Los Manantiales case.

The study of climatic and environmental context, to which the building is subjected for a long time, must be considered because it affects the conservation state. Therefore, it is relevant to emphasize the climate change and the modifications of the original conditions because the continuity of these can increase the structure's damage risk.

In this study the inherent causes are related to problems associated to the materials and the design and execution of the structure. Regarding the materials, the damages are related to the quality control and/or origins. The origin of the raw materials of the concrete, a mix composed of cement, aggregates, water, and sometimes chemical admixtures (Sena Cruz, n.d) must be documentary investigated and lab-tested because the performance can be affected by the mineral composition (Harrer & Gaudette, 2017).

Research studies or information on registers that point to the origins of the raw material of Candela's concrete mixtures as the cause and factor development of decay were not found. However, the presence of shrinkage in some cases was recorded. The shrinkage appears due to the water evaporation process at the surface that occurs before the setting. The symptoms are surface cracks generated by tensile stresses when the evaporation is faster than the water supplied (Gebregziabhier, 2008). Burger and Billington (2006) make the below observation for Los Manantiales case:

> That the cracks became more prominent from the initial pouring to the finishing of construction indicates they developed as the concrete dried. Los Manantiales was poured by hand, one section at a time, and as workmen moved over the formwork, finished areas were left to dry uncovered. The shell's exterior surfaces thus dried faster than its interior, creating "mud-cracks" as shrinkage pulled the outer surface into tension (p.6).

The sources consulted neither provide enough information regarding the constructive and structural details to relate them with damages. Therefore, this problem is not considered in Table 4. Finally, the partial collapse during the construction of Palmira Chapel is not included because it was immediately corrected.

4.1.2 Causes extrinsic to the building

The extrinsic causes that affect the concrete thin shells encompass natural long-term agents, occasional actions, and anthropic agents. D' Angelis (1982) mentions that the prolonged actions due to natural effects involved the chemical and electrochemistry, physical, botanic, and biological mechanisms for masonry. The natural agent classification used for this research to adapt the materials is proposed by Sena Cruz (2020), which groups the concrete degradation mechanisms. The degradation result of chemical reactions corresponds to the chemical mechanism, while the biological refers to the degradation resulting from reactions of biological nature.

The main chemical mechanism identified in the buildings studied is corrosion of steel reinforcement. Corrosion occurs when the ingress of chloride ions or the concrete carbonation cause the oxidation of the reinforcing steel. The consequences of the corrosion are the concrete cracking and spalling and the reduction of load carrying capacity (Gebregziabhier, 2008), so the monitoring of this mechanism in the shells is essential.

The table contains two cases with this mechanism. The first is the Cosmic Ray Pavilion, where the damage survey provided by De la Torre shows corrosion at the area of the access stair. The second is San Vicente de Paul Chapel, where the lattice that joined the three hypars presented rusting elements prior to the restoration.

Some of the buildings present also biological mechanisms of damage. The living activity refers to the organisms like algae, fungi, lichens, and mosses found at the concrete structures (Sena Cruz, 2020). Los Manantiales and Metro San Lázaro registered this biological activity mainly in the areas connected with water collectors or water drainage, respectively.

The extreme events considered for the Mexican territory are mainly earthquakes; however, other recurrent phenomenal as volcanic eruptions and hurricanes are added to the list. The earthquake box is checked only for Los Manantiales structure because, as it was previously exposed, it is the only building that reported damages.

The anthropic factors are principally related to modifications carried out by the owners or users, being not accurate most of the time. The classification is established to encompass the specific problematics at Candela's works like non-appropriated interventions, alterations of materials and constructive systems, obsolescence, context transformations, and lack of maintenance.

The non-appropriate interventions refer to those additions, modifications, and removals of architectonic, structural, or installations that affect and change the perception of the original concept in the project. These alterations are typically non-planned and without the approval of the authorities. Therefore, the minimal intervention principle recommended by international conservation charters, like the Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage is not applied.

Coyoacán Market, San Lázaro, and Los Manantiales are the cases with the most aggressive alterations caused by additions of volumes, elements, and areas that were not part of the original project. For the market, the design concept of the façade is entirely different, as well as the colors. The intention to camouflage the modernist facade within a traditional colorful neighborhood could be a reason to apply these alterations through the years. The health center addition to the San Lazaro station is another non-accurate intervention because of the absence of a transition link that properly integrated it into the original structure.

In Los Manantiales, this problem relates to the new spaces, forging elements, and water collectors that affect the aesthetic and generated additional damages like the biological activity at these specific locations. Regarding San Vicente de Paul, alterations like the ramp or casement modifications are the reason to check this box in Table 4. Although the Cosmic Ray Pavilion has gone through different adaptations for new uses, it can be pointed as accurate that interventions at the façade and the shell do not record significant modifications due to the spatial requirements. However, the box is marked due to the interventions inside.

It is relevant to mention that the damage analysis of the non-proper interventions is not based on a purist or pristine point of view. Alterations and modifications are part of the history of the structures, and these layers sometimes are the key to keep them alive through the years with new uses or adaptions. However, the relevant points that are trying to be discussed are previous analysis and the quality of the intervention compared with the conservation principles. The objective of a good intervention must enhance the actual conditions, ensures building conservation, and promote the appropriation by the community.

The damage category related to the constructive system and material alteration refers to incompatibility with the existing ones, which generates long-term damages. The used materials must guarantee compatibility, while the new technologies must be analyzed before the application (UNESCO, 2000). Table 4 identifies this type of damage for the Cosmic Ray Pavillion and Los Manantiales cases due to the waterproofing layer's records and the incorrect application.

Coyoacán Market encompasses changes due to the addition of urban infrastructure highlighting the electrical wiring, while the invasion of agricultural terrains at Los Manantiales is a fundamental reason for the transformation. San Lázaro context modifications are mainly at the esplanade where the existing corridors and flower beds were taken away due to the expansion requirements. Informal commerce affects the perception of the structure, so the first and especially the third case register this problem.

Functional obsolescence refers to the continuous changes at the architectonic programs leading to the non-satisfactory cover of the previous ones (Cirvini, 2019). It also includes the uses and activities that stop being productive or radically leading to their disappearance. The Cosmic Ray Pavilion is the case that presented a problem of this nature; however, it was solved through the new current use.

Finally, the lack of maintenance is related to the scarcity of financial resources or the few interest. Most damages in the cases are a product of gradual deterioration; that is why most of the boxes in Table 4 are checked in this category. At St. Paul's Chapel, the problem is linked to improper maintenance procedures, thus, it is not considered the same problem.

4.2 Legal and regulatory framework

It is not enough to describe and identify the damages in the Candela´s works to evaluate their state of conservation. Therefore, this section will refer to the legal framework of protection to have a complete and global vision of the conditions in which the shells are. The starting point is to understands the principles of the *Federal law over Archaeological, Artistic, and Historical Zones and Monuments* (1972), which is the legal and regulatory framework that governs the heritage in México. This law classifies the movable and immovable monument property of the country into three main categories:

a) Article 28 defines as archaeological monuments the properties that are the product of cultures previous the Hispanic.

b) The article 36 defines as historical monuments the property production during XVI to XIX centuries, including temples, seminaries, and convents. Also, buildings related to practice, teaching, administration, and disclosure. The ones destined for education, healthcare purposes, public service, military, and civil authorities, but also relevant civil works of private character are also included.

c) Article 33 states that the artistic monuments are those containing a relevant aesthetic value that will be determined by representativeness, insertion in a certain stylistic trend, innovative materials, and techniques.

According to the previous description, it is noticed that the buildings constructed after the XIX century are classified as artistic monuments. The significance of the context in immovable properties is another applicable consideration to the buildings. Furthermore, the works of foreign artists in the national territory can also obtain the monument declaration. Through this law, the Instituto Nacional de Bellas Artes y Literatura (INBAL) is empowered and declared as the competent authority in charge of the care, cataloging, and management of artistic properties. At the same time, the Instituto Nacional de Antropología e Historia (INAH) will manage the archaeological and historic.

The declaration may include all or only some elements of the buildings. The works located within an artistic monument zone whose authors' identity is unknown can also obtain a declaration. According to the law, a monument zone should be understood as one that contains several interrelated artistic monuments with open spaces or topographic elements. These areas form a monumental ensemble of outstanding aesthetic value (Cámara de Diputados del H. Congreso de la Unión, 1972, p. 10).

Article 34 bis explains that in case of risk of irreversible damage to the artistic properties, INBAL has the faculty to dictate a provisional declaration of a monument to avoid losses. Note the legal existing gaps in the laws that this emergency faculty entails and the vulnerability of the 20th century heritage in the country. Therefore, why is it necessary to reach those instances to begin the protection? Only when the 20th Century heritage faced the risk of possible demolitions will it be protected by the law? are the provisional declaration the correct way to preserve and avoid monument losses?

The cataloging of the constructions performed by the INBAL is an essential work regarding the documentation and record of the existing structures. Figure 47 shows a section of the cataloging sheet of Metro San Lázaro where twelve aspects are considered: location, identification, information, property regime, land use, current state, typology, cataloging justification, interventions, materials, and constructive techniques, style, and observations. However, it is important to mention that the existence of these sheets, under a strict legal framework, do not ensure protection.

CULTURA
SECRETARÍA DE CULTURA

INBA
DIRECCIÓN DE ARQUITECTURA Y CONSERVACIÓN DEL PATRIMONIO ARTISTICO INMUEBLE
SUBDIRECCIÓN DE CONSERVACIÓN E INVESTIGACIÓN
DEPARTAMENTO DE CONSERVACIÓN, REGISTRO E INSPECCIÓN DE LA ARQUITECTURA

FICHA DE CATÁLOGO NACIONAL DE INMUEBLES CON VALOR ARTÍSTICO — CLAVE: DF-VC-41-11907

NOMBRE/OTROS NOMBRES DADOS AL INMUEBLE
ESTACIÓN DEL METRO SAN LÁZARO

1.- LOCALIZACIÓN

Entidad Federativa:	Distrito Federal	Región:	018
Municipio/Delegación:	Venustiano Carranza	Manzana:	345
Localidad:	Venustiano Carranza	Lote:	02
Colonia:	7 De Julio	Calle:	Zaragoza Ignacio, Calz.
Codigo Postal:	15390	Núm.:	s/n
		Entre Calle:	
		y calle:	
		Esquina:	Molina, Eduardo. Eje 3 Oriente
		y esquina:	

2.- IDENTIFICACIÓN

Año de construcción/Década: ca. 1968/7
Arquitecto/Constructor: Candela Félix. Ingeniería del Sistema de Transporte Metropolitano (ISTME), Candela Félix.
Niveles de construcción: 2

3.- INFORMACIÓN
Fotos

4.- RÉGIMEN DE PROPIEDAD
Federal

5.- USO DE SUELO
Original: Servicios
Actual: Servicios

6.- GÉNERO
Servicios

7.- ESTADO ACTUAL
Bueno

8.- JUSTIFICACIÓN DE CATALOGACIÓN
Arquitectura Relevante

9.- INTERVENCIONES
Mantenimiento,

10.- MATERIALES Y TÉCNICAS CONSTRUCTIVAS
Fachada: Aplanado, Pintura
Muros: Tabique
Entrepisos: Concreto
Cubierta: Tridimensional
Vanos: Trapezoidales, rectangulares.
Otros:

11.- ESTILO
Moderno

12.- OBSERVACIONES
El trazo inicial se elaboro con el criterio de que una obra de esta naturaleza debia proyectarse y construirse para sus condiciones optimas de operación: una capacidad de 60 mi pasajeros por hora en cada sentido./Destacado por escala y volumen/Innovación de propuesta/Autor Destacado

Elaboró la ficha: DMO/JMOH   Fecha de Catalogación: 02/06/2001

Figure 47. Metro San Lázaro catalogue sheet

Note: In (Alarcón Azuela, 2018).

At the moment, 52 immovables and areas all over the country had a declaration as artistic monuments (INBAL, 2021). Felix Candela's constructions are not listed as individual works. However, the Cosmic Ray Pavillion is included as part of the ensemble of Ciudad Universitaria, one example of the 20th century architecture enrolled by UNESCO in the World Heritage list. Los Manantiales restaurant is within the monument zone limit marked by the Partial Urban Development Program of Xochimilco.

The shells do not count with a declaration and protection, so despite the location within the perimeters of heritage protection, there is no guarantees for adequate interventions and actions of conservation. Based on the preceding considerations, it can be concluded that most of Candela's works and 20th century architecture in México are at latent risk. The deterioration and possible disappearance of this heritage due to the existence of legal gaps is a danger to highlight.

The urban level and context are other problem sources related to the safeguarding of heritage and regulations. For instance, the urban development plans, the excessive growth, and interventions in the surrounding areas of the monument disrupt the values and significance. These affectations are generally observed in the placement of infrastructures that become invasive to the visuals and context, modifying the original meaning and perception for which was conceived.

The *Code of Federal law over Archaeological, Artistic, and Historical Zones and Monuments* explains the guidelines and the information that the declaration request must contain. First, a documentary background to justify and exposed the archaeological, artistic, or historical value. Second, the technical information of the building and finally, if is the case, a plan containing the area to be declared. Based on these guidelines, the importance of carrying out a complete documentation process of Candela's shells is highlighted. Furthermore, the analysis of the values of his work and the technical details obtained through the testing methods, laboratory studies, and monitoring can help with the future integration of this file (Cámara de Diputados del H. Congreso de la Unión, 1975).

4.3 Critical review of conservation problems

This section will expose the relationship between the damage causes, the legal framework, and the 20th century heritage conservation problems. The objective is to examine Candela´s works conservation problems in México considering the interaction of those three factors. In addition, this will guide the conservation proposals in the next chapter.

Figure 48 exposes the more frequent causes of damage recorded in the seven buildings studied. The objective of the graph is to visualize and identify the number of works affected by each cause to have a general overview that allows to analyze and subsequently give pertinent recommendations. The graph does not show the following damages because there were not recorded cases within the study sample: geo-topographical climate and orientation, building materials, building systems, volcanic eruptions, and hurricanes.

Figure 48 exposes the more frequent causes of damage recorded in the buildings studied. The objective of the graph is to visualize and identify the number of works affected by each cause to have a general overview that allows to analyze and subsequently give pertinent recommendations. The graph does not show the following damages because there were recorded cases within the study sample: building systems, volcanic eruptions, and hurricanes.

The most recurrent damages are related to anthropic causes and inherence in the structure. Within the first category, non-appropriate interventions are present in five cases, lack of maintenance in four, and context transformations in three. Three structures recorded damages due to the materials as well. Following a descending order, the presence of biological mechanisms, the alteration of materials and constructive systems, and the chemical actions record two cases each. Finally, causes due to obsolescence, earthquakes, ground carrying the foundations, and geo topographical, recorded one structure each.

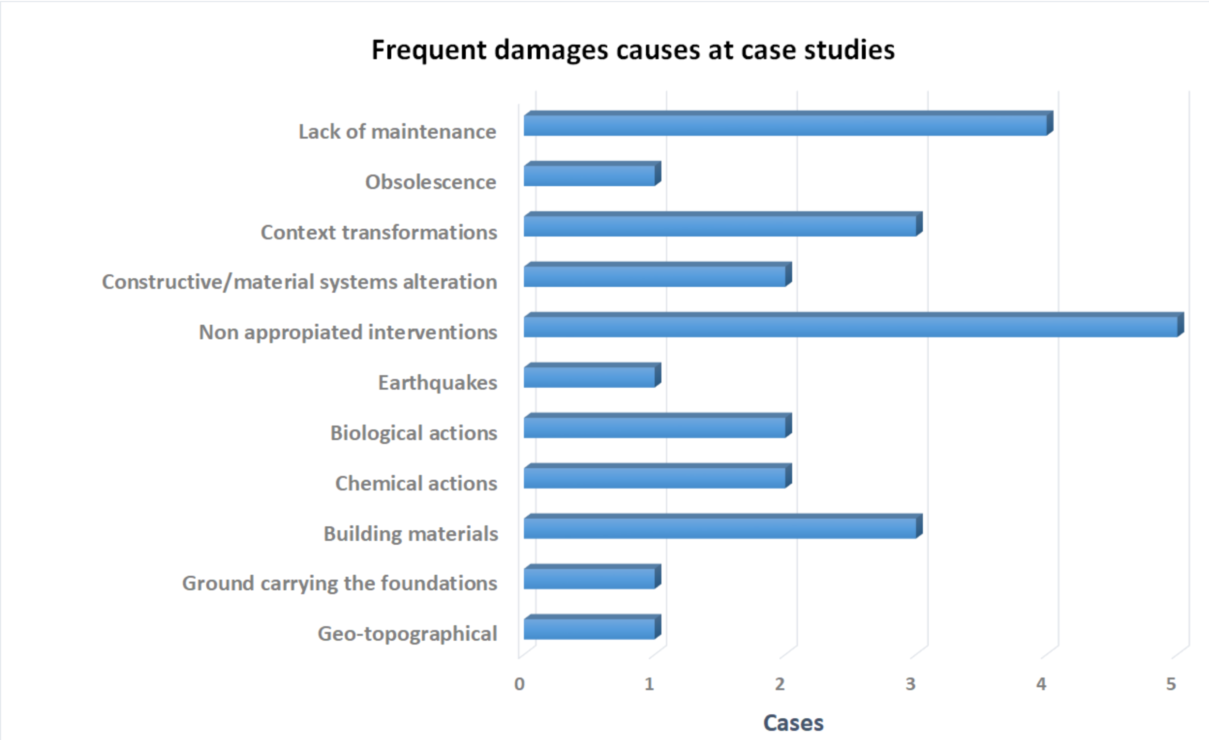


Figure 48. Frequently damage's causes

Note: Elaborated by Nohema Cassandra Ruiz Gómez

The anthropic damages cannot be considered an isolated case because they are directly related to the legal regulations and the heritage conservation principles. The complex situation that Candela's works face, and in general the 20th century heritage, remains in a constant state of vulnerability due to the lack of protection declarations, action criteria, and management regulations. García – Gutiérrez (2011) states the following related to the architectures of the 20th century: "In this condition of "vulnerability" it is convenient to point out, that much more frequent than demolitions –and no less lethal– are the alterations" (p.149).

The age value is part of the problem that surrounds these architectures. The materiality, in this case, the reinforced concrete does not allow to analyze the actions of time in the same way as for old masonry buildings (García Gutiérrez Mosteiro, 2011). Hence, the perception and trend of people to associate concrete with new constructions generate confusion and generalizations. Consequently, the owners and users can assume that concrete restorations do not require specialized studies and qualified professionals.

Regarding the architectural function, few existing studies on concrete thin shells have an approximation to the problem. However, the industrial heritage of the 20th century theme has been researched more extensively. Dr. Mendoza's (2015) research about shells in the United Kingdom is relevant due to the case of John Lewis Warehouse. Candela collaborated in this project and can be classified within the industrial typology. It also influences the design and construction of The Queensgate Market Hall.

The industrial typologies produced by Candela can be studied consider this approachment, and the umbrella structure-based projects, like the case of Coyoacán Market, can be included. The typologies of San Lázaro Metro Station, Los Manantiales, and the Cosmic Ray Pavilion are not within the industrial heritage; however, due to the amplitude of area that the shell covers, an analogy can be made to apply the same considerations.

The main problem of a new use for industrial building heritage is linked to the large areas involved because this type of buildings can be considered “big empty containers,” where the maintenance and internal spaces adaptations can affect the original design, perception, and concept (García Gutiérrez Mosteiro, 2011). Similarly, the concrete thin shells have generated this discussion, for instance, the case of the TWA Terminal at Kennedy Airport in New York, in which the new use proposal is a hotel reception (Cassinello & Poveda Coto, 2011) or the Commonwealth Institute, now the Design Museum in London (Mendoza & Chilton, 2019). The Cosmic Ray Pavilion has this type of modifications on a smaller scale, while San Lázaro and Los Manantiales are related with additions.

Regarding the obsolescence, even if the percentage at the study cases is minimum, it is relevant to mention that a new well-posed use proposals can avoid losses in future circumstances. The proposals must be planned carefully where the use justified the conservation. At the same time, the technological and formal legacy should not be destroyed or eliminated (Cassinello & Poveda Coto, 2011).

Despite the concrete thin shells show good performance during earthquakes, the horizontal forces created by these can generate issues (Michiels, Garlock, & Adriaenssens, 2016). If the soil condition is added to this premise, Candela´s works increase the risk for major failures when the event occurs. The low incidence of damages at the cases are in concordance with the expected performance. However, the failures in Los Manantiales and the collapse of Jamaica’s Market need deeper studies to understand the causes.

Context inclusion criteria for Los Manantiales and the Cosmic Ray Pavillion is evident due to the locations within the monument perimeter. However, Coyoacán Market acquires particular attention and care that entails the small distance to the center of this very traditional and popular neighborhood. Therefore, it is important to mention the participation and involvement of the residents actively to ensure the success of the conservation projects (ICOMOS, 1987).

The importance of the relation between the building and the context for 20th century heritage is mentioned at Cadiz Charter. The intervention criteria must not consider only the architectural qualities of the building because the projects used to include urban environments and landscapes that contribute to the complete understanding of the work (DOCOMOMO Ibérico, 2007).

Although concrete repair is not a recent knowledge due to the constant update of experiments, development of innovative products, research techniques, and professional training, concrete conservation is a relatively new field. The lack of recognition of the significance of historic concrete and the presence of a reduced group of specialists in this specific area can result in applying the methodologies and principles used at the new buildings (Macdonald & Arato Gonçalves, 2020).

Until now, the damage causes and some of the principal 20th century problems have been exposed; therefore, an analysis that involves the legal framework for heritage protection will be made. An analogy is used to illustrate and expose the conservation problems and risks that legal gaps involve. The Libertad Market located in the state of Guadalajara was projected by Alejandro Zonh Rosenthal, an Austrian architect who migrated to Mexico as a child running away from the Nazis. The project was built in 1959 and had a central rectangular space of 18 m x 18 m covered with thin concrete shells, as shown in Figure 49. The reinforced concrete is the main material in this building, and some glazed clay block walls are also used (López García, 2013). The market is one of the 52 immovables with artistic monument declaration.

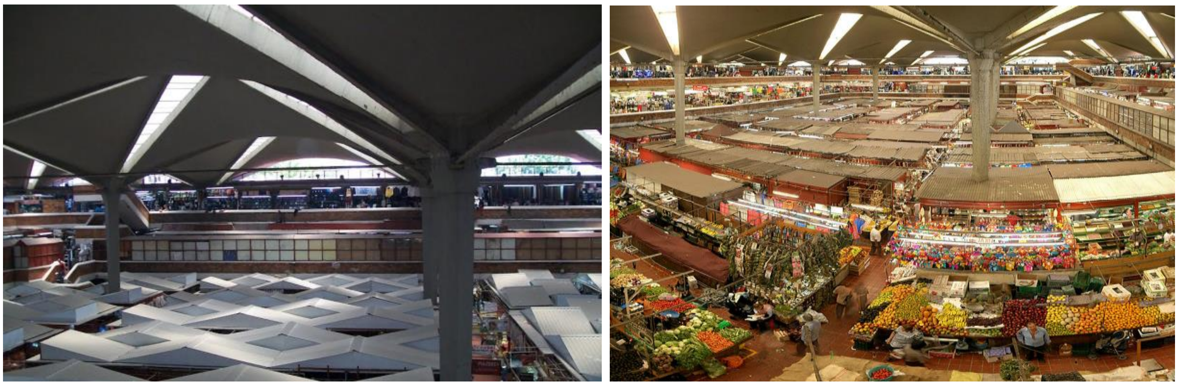


Figure 49. Interior views of the Libertad Market.
Note: In (INBAL, 2021).

The declaration order published at the Diario Oficial de la Federación highlighted the creative design and technology, the use of hyperbolic paraboloids, reinforced concrete, and glazed clay used at the Market. It is also supported by the following points:

> "That presents a high degree of innovation, considering the time it was built, in the one that the author used a unique architectural language in the use of the interior and exterior spaces, combined with the management of the structural design, as well as the modules of the shops, highlighting the idea of the Mexican *tianguis* with a contemporary language;
>
> That the materials and construction techniques used in this work, including finishes, use of color, interior and exterior design show sensitivity to conditions climate, economy in cost, use and adaptation of Mexican resources and materials" (Secretaría de Gobernación, 2005).

Reading carefully the particularities attributed to Libertad Market, wide similarities are identified and could apply to the work of Candela. López García (2013) remarks the influence of the Coyoacán Market and the Johnson Wax Building of Frank Lloyd Wright on Zonh's project. In 2001 the Libertad Market had some problems with the structure; therefore, three intervention options were presented by the president of the Engineering College, where the demolition was the last one (López García, 2013). This proposal was possibly one of the reasons to promote the protection of the building.

As a final remark, several are the architectural typologies with this type of declaration, being residential buildings the predominant type. If one reads the document declaration of other cases, one can identify common attributed values. The aesthetic, the belonging or expression of a particular artistic movement, the design concepts, and the values represent the aspects considered. So, is it necessary to do a deeper analysis and explanation of the heritage value of each case? Or, are the institutions relegating and leaving a large number of buildings with heritage value unprotected that already possess those particularities?

5. ANALYSIS OF THE SIGNIFICANCE AND RECOMMENDATIONS FOR CONSERVATION OF CANDELA'S SHELLS

This section analyzes the significance and values of Félix Candela's work, including tangible and intangible aspects. Once the values are established, a series of applicable recommendations provided by international heritage institutions are listed. The following sections mention some guidelines to be considered in the design and intervention projects and discuss a possible update of the legal framework. Finally, recommendations for education and dissemination to improve the preservation of the works are presented.

5.1 Identification of significance and heritage values

The heritage values result from the interpretation of the materials, buildings, and objects; therefore, the evaluation must involve the cultural context. Furthermore, due to continuous changes in the building and its context, the values can also suffer modifications regarding the analysis perspective and conditions. The evaluation is not a simple task in modern heritage due to the complexity of the discussions and analysis of industrialization, materials, and construction techniques that implies (Heinemann, 2013).

The cultural significance of 20th century heritage works entails tangible and intangible values. The tangible attributes encompass the location, design, colors, constructive techniques, materials, aesthetics, and technical equipment. The intangible values are related to the scientific, social, historic, and spiritual, but also include the creative genius (ICOMOS International Scientific Committee for the 20th Century Heritage, 2011). The key tangible attributes of significance identified in this study for Candela's cases are the aesthetics, the structural design, the constructive techniques, and materials. The intangible encompasses the creative genius of Candela and the workmanship.

Aesthetics and structural design go hand in hand in Candela's works because unconventional shapes were possible to build due to these factors. The stylization of the umbrella and the supports are details that polish the significance of the structure. Additionally, these forms and concepts are still valid and serve as inspiration for planning new current spaces and structural experiments.

The concrete heritage describes a building, structure, or other typology made of concrete and deemed to be of cultural significance (Macdonald & Arato Gonçalves, 2020). So, the significance is related not only to the use advantage of the mechanical properties that allowed the development of the shapes and surface. But also, the raw materials give particular aesthetics to the building. The finishing applied like the smooth surfaces, the exposed aggregates, or the texture of the formworks determine a cultural value. For instance, the perception of the shells without the color waterproof is entirely different from the image of the building without it.

It is hard to imagine a work by Candela made in another material at that time. Today the construction of double curvature surfaces in concrete continues, although with more limited production than in the past. Architectures with sustainable materials such as bamboo are emerging and being used quickly and extensively. Despite this, the perception of shape from other materials, colors and comfort conditions is different. Ghent University carried out a project for designing a temporary structure based on fiber-reinforced ice inspired by Los Manantiales in Finland in 2016. The Figure 50 helps to visualize the perceptions of materials and environments of the same surface.

Figure 50. Restaurant Los Manantiales (top), view of the ice Pavilion in Finland (left), and Luum Temple built with bamboo in Tulum (right)
Note: In (Uribe, 2017), (Duque, 2011), (Belis, et.al, 2016) and (Mortice, 2019).

The role that concrete plays in Candela's shells is transcendental; thus, the researchers should highlight the inclusion and assessment of the meaning of the material in the studies. The formwork marks at the concrete's finishing are part of the footprint of the work. It is not enough to limit the studies only to the technical aspect, and it will be necessary to expand the value considerations to this material that is the object of study with cultural approaches on restricted occasions.

The creative genius of Félix Candela is not limited to the understanding of the structures; it is also related to the entire constructive philosophy that he developed during his career. Candela's philosophy and his structures reflect the economic, political, and historical context of Mexico. He constantly mentions the social mission of the architect and the need to stop the messianic aspirations of the new constructions. This vision is not only a speech because it is embodied in the objective of reducing materials, money, and human efforts of his works. The critic of the large budgets destined to build constructions with low social benefits is recurrent; even in 1995, he mentioned it in the acceptance award speech granted by the Colegios de Arquitectos e Ingenieros de Madrid.

The curiosity and full-scale experimentation that Candela developed for his works carry intangible values. Understanding the scientific basis combined with the empiricism of the constructive knowledge of the workers is another key element. On-site work requires a proper direction and a correct execution. The workmanship in Mexico was of good quality, cheap and audacious; emphasizing that a large part of the workers emigrated from rural areas and their knowledge was acquired through practice.

Don Goyo and Don Lupe were the carpenters with whom Candela worked because they were the ones who understood his ideas (Instituto Torroja TV, 2019). It would be interesting to know the employment histories of these people. How did they start working with Candela? What were the most critical challenges on-site to solve? Regarding the apprenticeships, a before and after existed when they built these works? These are just few questions that hopefully will be solved in the future.

5.2 Evaluation of the applicable conservation principles

The challenges of intervention in heritage concrete structures encompass a global problem that is constantly analyzed and studied. Despite the buildings and their locations determine specific conditions that need to be solved, applied standards and conservation principles must be a priority to consider in the intervention project. This section mentions the institutions, organizations, charters, and recommendations that can be consulted and applied to Felix Candela's work in Mexico.

Despite the fact that charters and conventions for heritage protection were originated as a response to ensure the preservation of the heritage existing before the 20th century, several precepts are applicable to 20th century heritage and can be even considered a priority for its interventions. The following documents encompass principles that are useful to generate theoretical support for interventions in Candela's works:

a) International Charter for the Conservation and Restoration of Monuments and Sites, or Venice Charter of 1964.

b) Charter for the Conservation of Historic Towns and Urban Areas, or Washington Charter of 1987.

c) Nara Document on Authenticity of 1994.

d) Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage of 2003.

Regarding international organizations, ICOMOS International Scientific Committee on Twentieth-Century Heritage (ISC20C) developed the Approaches for The Conservation of Twentieth-Century Cultural Heritage, including landscapes, industrial sites, and urban areas. DOCOMOMO is a non-profit organization which efforts are focused on the documentation of the modern movement heritage. The TICCIH Principles for the Conservation of Industrial Heritage Sites, Structures, Areas, and Landscapes document can be consulted for industrial typologies.

The required approach to the problem is multidisciplinary, where the different sciences can contribute to the study and safeguarding of the heritage (ICOMOS, 1964). This approach is relevant because will optimally support Candela's works' significance and values, through the exposition, gathered information, and assemble a file that allows obtaining declarations of protection. Due to the complexity of values and the technical knowledge that the reinforced concrete heritage involves, the participation of specialized professionals is mandatory.

The context recommendations include the respect of the spatial layout in terms of scale and lot size when the new constructions or the adaptations are necessary. For this, the proposals and analysis must consider the urban patterns and the relationship between buildings and open spaces. In the case of new activities and functions, these must be compatible with the essence of the community and the activities developed within it (ICOMOS, 1987).

In the case of the Manantiales, the architects and engineers must complement the intervention project consulting anthropological, sociological, and economic studies of the area. The native neighborhoods and the deeply rooted identity are part of UNESCO's protection aspects in the zone. Furthermore, the "chinampas" that are the traditional floating gardens of Xochimilco, the water channels, the flora, and fauna are the key of the landscape and natural protected area. Therefore, reviewing studies of disciplines that cover ecological and environmental aspects is required.

Due to the proximity to ecological reserves, as is observed in Figure 51, the Cosmic Ray Pavillion major interventions could require landscape studies. Furthermore, concerning the population and users, the majority who carry out the activities within the campus are students, professors, and administrative personnel, so the designers must take their perception of the buildings into account. Finally, the interrelation with the other buildings and the open spaces must be evaluated to avoid ruptures in the ensemble.

Figure 51. UNAM’s boundaries.
Note: Modified from (UNAM, 2017).

An exercise of urban context and visual improvement is proposed to the Metro San Lázaro’s case. Despite regulations, informal commerce is hard to eliminate, so it can include spaces to relocate it with more order. The project should consider the location and design of the bus stops. Based on the information provided by Azuela (2018), the esplanade is hardly used by people, thus is creating a situation opposite to the international recommendations. A transition between the esplanade and the station is suggested to recover the use of this wide space.

The information gathered from the materiality of the building, traditions, techniques, historical sources, and the meaning within the cultural context will serve to understand, interpret, and assess the aspects of authenticity (ICOMOS, 1994). Therefore, the correct materials intervention, compatibilities, and registers play an essential role in the data collecting for the authenticity identification task, which is crucial to qualifying the heritage values.

In Coyoacán's Market, a proposal to recover elements in the façade and colors of the original design could be considered. For this purpose, a study of the tenants and neighborhood people's cultural appropriation and image perception must be carried out first. The obtained results need to be complemented by the evaluation of the current requirements and functionality. Regarding the technical aspects, an analysis of the elements to remove, materials, and the techniques to apply is required.

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This study will discuss the importance of following the elements additions through the example of the forge elements and the water collectors at the basis in Los Manatiales. As explained in the preceding sections, these alterations brought more deterioration than benefits to the structure; therefore, it is proposed to remove them. It is clarifying that previous studies of the current conditions on-site must be carried out to evaluate if removal is feasible and according to the minor destructive principles. Otherwise, adaptations that provide solutions to the generated problems, such as biological colonization, must be considered.

The new use of the Cosmic Rays Pavilion is a wise strategy because it saved the construction from abandonment, despite being completely different from the original. In addition, the almost null adaptations in the exterior façades and roof are appropriate; however, the opposite case is the staircase, where part of the current damages are registered. Due to the lack of information regarding the interior, the evaluation of that part will not be discussed in the study.

The aesthetic also represents a challenge for concrete's interventions because repairs of patches, decorative finishes, and textures can alter the original aspect. Patina is the age evidence of changes and interventions over time; thus, the recommendation is to apply techniques and materials that have a less possible impact on it and the concrete's cultural significance (ICOMOS International Scientific Committee for the 20th Century Heritage, 2011).

The previous recommendations are also found in the Madrid-New Delhi document, which exposes the importance of sensible management of the modern heritage. If the use contributes to the significance of a place, the new proposals must include it. Furthermore, regarding sustainability, if the project requires incorporating comfort conditions, the experts must evaluate the efficiency of the systems and materials. Finally, the renewable energy systems in cultural landscapes must be reduced and avoiding (ISC20C, 2017). These last recommendations are attractive due to the shells' thermal and acoustic conditions, so future interventions at Felix Candela's works can consider the guidelines.

For the Saint Vincent de Paul Chapel, the stage of intervention corresponding to the electrical installation is mentioned by Azuela. However, it was not possible to obtain information regarding the materials and final results; therefore, a final evaluation is not made. Nevertheless, two questions are exposed: what were the criteria considered for the proposal? And, the recommendations regarding sustainability were evaluated?

For the case of Coyoacán Market, it is necessary to mention the risk of fires in Mexico City markets due to irregular connections, lack of maintenance, and failures in the electrical network. So, it is recommended to inspect, relocate, and change damaged wiring if necessary. Finally, the proposals should evaluate the incorporation of sustainable systems or energy-saving lamps that do not affect the perception of the original project.

The need to incorporate principles related to universal design, focusing mainly on accessibility to guarantee equal opportunities for people with disabilities, is an increasing requirement for heritage buildings and their context (Ministerio de Sanidad, Política Social e Igualdad, 2011). A detailed study of the projects, the locations, and solutions might generate a less invasive intervention. Most of the selected Candela's projects have a favorable aspect: the existence of a single storey. The accesses and changes of levels based on stairs are present; however, a solution for this problem is the portable ramps that do not affect the structure and original design.

To conclude, the project cannot reduce the interventions related to materials and constructive systems to an aesthetic aspect where the main objective is to ensure the cultural significance of the structure. Furthermore, guarantee the safety of the users and durability are other aims that must be considered, mainly due to the risks that occasional actions entail (ICOMOS, 2003). Focusing on this last note, the proposal of Dr. Peña to change the intervention projects paradigm in Mexico is highlighted. According to Peña, the main objective nowadays is the conservation of authenticity to bring the building to the original conditions; hence the new paradigm must be the safeguard of human life (Peña Mondragón, 2021).

5.3 Recommended guidelines for interventions of concrete thin shells

In this section, some methodological considerations required to approach the intervention project of Candela's works are proposed. First, general remarks regarding historical research and aspects to consider for 20th century works are made. Then, the recommended approaches to materials, construction systems, and previous interventions are explained. Once this is covered, the importance of field and experimental research through non-destructive tests and possible laboratory tests are exposed. Finally, the benefits of having adequate monitoring before, during, and after any intervention in the shells is mentioned.

The objective of these guidelines is to complement the conservation principles to cover the international recommendations that indicate: "Intervention should be the result of an overall integrated plan that gives due weight to the different aspects of architecture, structure, installations, and functionality" (ICOMOS, 2003). The diversity of aspects and challenges to consider for interventions is evident in this expression, which addresses technical aspects and functionality.

5.3.1 Research and history

The historical survey aims to collect information from the building's past. The data should also provide information on the context, for example, economic, social, political, and cultural conditions that promoted its emergence. Based on this global understanding, proposals for intervention, techniques, and even new uses may be more feasible. The principal sources of information are the historical archives, books, photos, plans, reports, interviews, and drawings (Ramos, Masciotta, & Lourenco, Historical Survey, 2021).

For the 20th century heritage, an important source is the professional office's documents and the personal archives of the architects and engineers that developed the works. The original ideas, drafts, and processes can offer clues to have a better approach to the building. The type of information that constitutes these archives are sketches, mockups, budgets, plans, and textual documentation of the different phases of the work (Rivas Quinzaños & Suárez Menéndez, 2011). In the case of Félix Candela, the Mexican Architects Archive in UNAM has already been mentioned, but also some notes and personal production information are under the protection of the Avery Architectural and Fine Arts Library of Columbia University (Giral, 2011).

The study of local contexts and conditions, especially applicable to 20th century architecture, must be detailed. For example, understanding regional requirements and the interpretations and adaptations of models from Europe to Latin American realities (Hernández, 2011), and consequently focusing on the Mexican case. The information obtained from the documentary investigation must be verified on site from visual inspections and testing methods.

5.3.2 Recommended on-site inspections techniques

A complete understanding of the damages, materials and construction techniques of the structures is mandatory before any intervention. The information gathered from the visual inspection is the basis to propose complementary tests. Due to the restricted data obtained through this superficial evaluation, other tests must confirm the results. In addition, experienced professionals in the area must carry out the visual inspections.

Inspection techniques are divided into traditional and advanced. The selection will depend on the information required by the investigation, the time available, and the financial resources. The traditional techniques that can apply to the concrete shells are photographic survey using traditional cameras, architectural survey obtained through measuring tapes and laser distance meters, theodolites, and total station for topographic surveys, among others (Ramos, Masciotta, & Lourenco, Traditional Visual Inspection Techniques, 2020-2021).

Due to the curved shapes, and the performance of the structure and the concrete through time, traditional techniques will hardly register minimal variations between the project and reality. Therefore, the recommendation is the use of advanced techniques such as laser scanning and aerial photogrammetry. The precision of the data obtained will improve not only the data of the academic research because also the quantifications of materials and intervention budgets will have more accurate amounts.

The recent research carried out by Rajabzadeh, Esponda and Cordero (Rajabzadeh et.al, 2021) show an interesting exercise by comparing traditional and advanced techniques applied to the Cosmic Ray Pavilion. The study uses photogrammetry and computer software to record the architectural surface. In this case, the variations between the methods were negligible. However, through the results, some variations regarding the original project and damages in the current state were found.

One-site inspections are also intended to assess the concrete by identifying cracking, spalling, and crack patterns. In exposed reinforced steel, the information to evaluate is not limited to corrosion damages; also, data regarding the grading of the rebars and the production historical period is obtained (Sena Cruz, 2021). When conducting inspections, another objective will be to obtain data from previous interventions or repairs.

5.3.3 Testing methods and laboratory studies

The Madrid document pointed that to study modern heritage the material tests recommended are the non-destructive and non-invasive methods. If the test required involves a destructive analysis, this must be limited and carefully carried out (ICOMOS International Scientific Committee for the 20th Century Heritage, 2011). In this section, some testing methods are proposed to apply to Felix Candela´s work to incorporate these recommendations.

The verification of the data obtained from the field investigations is carried out through tests and laboratory studies. These studies are required for Candela's work not only for practical purposes intended to get a feasible design of the interventions project. Also, for academic reasons because information gaps regarding these topics exist. Furthermore, through the information gathered, the researchers can build a database to provide accurate details of the mechanical properties of the reinforced concrete in the shells for future studies.

The selection of the test will be based on the information the research is looking at. The objectives and the information scopes to be obtained through the test should be clear before carrying out to optimize resources and be less invasive. The experts must do the type and location elections carefully due to the thinness of the shells and the conditions of the materials.

The test for concrete embraces those that are entirely non-destructive, known as non-destructive testing or NDT, and the partially destructive named minor destructive testing or MDT. Furthermore, depending on the age of the concrete, the objective of the test changes. For instance, for new concrete it is intended for quality control, while for old concrete it is assessing structural integrity (Sena Cruz, 2021). Some of the NDT and MDT that can be applied to Candela´s works are mentioned below:

a) Rebound Schmidt hammer to measure the uniformity, quality, and compressive strength values of the concrete. The advantages of the test are the extensive areas to cover in minimum time, it is not expensive, simple, and quick. However, the results can be affected by moisture content, smoothness of the surface, and carbonation (Gebregziabhier, 2008).

b) Ground Penetration Radar to detect steel reinforcement and voids in the concrete. The advantages are that tests are quick to perform, but trained personnel must interpret the results and handle the equipment. Consequently, interpretation of results may take longer than other tests (Sena Cruz, 2021).

c) Penetration resistance to assess the quality and uniformity of the concrete, and it can also estimate the compressive strength. However, some disadvantages of the method are the holes that the probes leave at the surface (Gebregziabhier, 2008).

d) Pull of test to estimate the nominal tensile strength and to evaluate the bonding of repair patches. The results cannot be precise if the concrete surface is deteriorated. The area of the surface where the test is performed can record some damages.

The laboratory studies are necessary because they provide concrete characteristics information like chloride content and specific constituents, but also some causes of deterioration can be identified (Harrer & Gaudette, 2017). The analysis carried out are i) petrography that provides data about the original concrete composition, ii) chemical analysis to determine the presence and amounts of chlorides, and iii) physical analysis to determine densities, modulus of elasticity, and Poisson´s ratio (Gebregziabhier, 2008).

Additionally, it is important to mention that to confirm the results of the NDTs, some exploratory openings can be done (Harrer & Gaudette, 2017). As a final remark, due to the particularities of the soil conditions in Mexico City, the NDT, MDT, and laboratory studies should be complemented with updated geotechnical reports and tests.

5.3.4 Monitoring

According to the requirements, the monitoring procedures will develop particularities. For instance, the type of information collected through the first approach to the building will be different from the data required during and after an intervention (Vidovszky, 2016). Structural monitoring is: “a systematic process of observing, tracking and sampling data over a period of time, in order to assess the fitness for purpose of structural systems under inevitable ageing and damage accumulation resulting from operational and environmental conditions” (Ramos & Masciotta, 2020-2021). Therefore, the structural monitoring is recommended to be considered in Félix Candela cases exposed in the current study.

The monitoring procedure is subjected to a cost-benefit analysis, so the most relevant aspects should be selected and constantly checked. The periodicity is intermittent or continuous with removable or permanent testing equipment. In addition, periodic visual inspections should accompany these systems to detect sources of future problems and prevent degradation and damages. Degradation processes, mechanical response, external influences, environmental characteristics, and natural threats are aspects that can be monitored (Ramos & Masciotta, 2020-2021). The monitoring results should be check after and before the interventions. These results must be compiled and documented clearly into a file that will become part of the building's history (ICOMOS, 2003).

A concept to introduce is preventive conservation which refers to the inspection and monitoring routines that can identify the causes and minimized deterioration processes. This approach avoids expensive interventions that most of the time do not remove the causative factors, temporarily covering the problem (Maschiotta et al, 2019). Mexico needs to implement this paradigm change in the conservation field and apply it to Candela's works. In addition, the proposal of structural analysis can be carried if the building requires it and also if financial resources exist; the objective is to complement the monitoring.

The cases in which monitoring can be applied to those located in Zone III, for instance Los Manantiales and La Medalla Milagrosa. The continuous settlements due to the soil compaction in the city each year, an average of 50 cm (Chaussard et.al , 2021), and the previously exposed seismic conditions would be the criteria for this proposal. Furthermore, due to the current intervention, it is double recommended the monitoring during the execution and future actions to compile results and information in Los Manantiales.

5.3.5 Maintenance planning

Maintenance of the structures is the accurate way to avoid future invasive interventions due to the long-term damages. This is a recurrent recommendation through the different charters and institutions. For instance, since 1931, the Athens Charter exposes the creation of regular and permanent maintenance plans to ensure the preservation of heritage buildings (Congress of Architects and Technicians of Historic Monuments, 1931).

The lack of maintenance severely affects the archaeological, historic, and artistic heritage buildings in Mexico. The scarcity of financial resources and the poor maintenance culture in the country are some of the factors that lead to the gradual degradation. Therefore, it is important to highlight again the importance of incorporating steady maintenance plans and resources at the intervention projects to preserve the historical materials in a higher degree and, consequently, the original conditions (Vidovszky, 2016). Note the recommendation of ICOMOS (2003) that refers to "the best therapy is preventive maintenance"

Through preventive conservation, 40% to 70% of the maintenance cost due to major interventions can be saved (Sánchez-Aparicio et al, 2020). So, the benefits are not only perceived at a cultural level but also at the economic. The maintenance strategy and the preventive conservation plan must be carefully studied identifying priorities and the critical aspects. The financial resources problems can be partially solved because through the planned actions the limited resources will be used in the most accurate way.

Due to the Central Campus's inclusion at the World Heritage List, a management plan exists and considers six strategic lines: conservation, interpretation, research, inclusive site, sustainable site, and safety site (UNAM, 2017). As it can be observed, these lines cover part of the previous recommendations and also includes the factor of the safety associated with the insecurity, one of the most significant issues in the city. The management plan and the six lines of action adequately incorporate the principles and recommendations analyzed so far, including the maintenance.

Therefore, this study proposes to make a detailed evaluation of the achievements obtained and the existing difficulties in applying the strategies.

5.3.6 Repair and strengthening

The proposals for concrete's interventions can be divided into three actions: protection, repair, and strengthening. Protection includes the increase of the barriers to aggressive agents and the reduction of degradation conditions. The repair objective is to recover the initial conditions and characteristic. (Vasconcelos, 2020). The strengthening increases the resistance capacity due to the change of use, construction or design defects, update of codes, and seismic actions (Sena Cruz, Repairing and strengthening techniques, 2021).

The constructive systems and materials alteration resulting from the lack of analysis and studies previous to the interventions go against the recommendations proposed by the International Charters. For instance, the Principle for Analysis, Conservation and Structural Restoration of Architectural Heritage points that: “Information is essential on the structure in its original and earlier states, on the techniques that were used in the construction, on the alterations and their effects, on the phenomena that have occurred, and, finally, on its present state” (ICOMOS, 2003).

Related to the structure, the recommendations pointed that the safety level must be considered before carrying out any structural intervention. Special considerations are necessary when the safety level is evaluated because the current regulations and safety factors applied to new buildings cannot be comparable with the old structures. Therefore, a complementary report must include the values and explanations used for the evaluation (ICOMOS, 2003).

In addition, one of the objectives of diagnosis and safety evaluation is the minimum intervention. Furthermore, due to the correct interpretation of damage causes and decay, the design of the solution can also achieve the reduction of cost and minimal impact at the heritage building. The demonstration of the necessity to apply actions in Candela's shells before the intervention helps to reduce the effects. Finally, whenever possible, the priority should be repair rather than replace (ICOMOS, 2003).

Compatibility is one of the issues that must be solved and study in detail before any intervention. The repair mortars need to cover some requirements like the bonding between the existing and the new material, avoid different behaviors and similar chemical composition to guarantee the monolithic behavior of the structure. For the repair mortars, the modulus of elasticity must be evaluated to avoid different stiffness. In addition, the bond strength needs to be considered for the possible failures at the interface and the substrate. Finally, the chemical composition is important because future damages can be developed when low Ph mortars are located near the reinforcement, but also when contains high alkali contains (Heinemann, 2013).

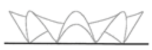
The durability of repair techniques is less studied than the durability of new concrete, which implies a problem for the conservation of heritage concrete. Durability is the serviceability over a specified time and is related to service life, which refers to the time frame to performed repairs (Heinemann, 2013). The selection of the technique depends on the purpose of the intervention since it can be short or long term. It should note that the interventions will also require maintenance actions (Gebregziabhier, 2008).

Heinemman (2013) points the importance of not trying to "translate" the methods and techniques presented in the code to the field of conservation. The reason is that the repair principles do not consider the criteria for conservation, preservation, and respect for the historic concrete. This is important to understand by the professionals who must complement the technical recommendations in the code with the values of the concrete when the intervention is carried out.

Table 5 is based on the Principles and Methods for protection and repair of concrete structures of EN 1504-9. These principles are taken as a starting point to propose some applicable repair techniques to the case studies. The buildings of Table 4 structure the new one; however, San Vicente de Paul is omitted because the intervention project has already been executed. Azuela (2018) partially explains the intervention; therefore, an analysis of the actions will be presented.

Table 5. Principles for repair and protection of Candela´s buildings

Note: Elaborated by Nohema Cassandra Ruiz Gómez

Principles for repair and protection for damages to the concrete		**Buildings**			
		 COSMIC RAY PAVILION	 COYOACÁN MARKET	 LOS MANANTIALES	 SAN LAZARO STATION
PRINCIPLE 1 [PI]	**Protection against ingress**	X	X	X	X
PRINCIPLE 3 [CR]	**Concrete Restoration**	X		X	
PRINCIPLE 4 [SS]	**Structural Strengthening**			X	
PRINCIPLE 5 [PR]	**Physical Resistance**	X	X	X	X

Principle 1 refers to reduce or prevent ingress of aggressive agents like water, vapor, or gases. This is feasible for all cases as a preventive action, including the Palmira Chapel and the Medalla Milagrosa Parish. The implementation of protection against water ingress is recommended to avoid damage to the concrete and the reinforcing steel. Concrete repair is recommended for the Cosmic Ray Pavilion and Los Manantiales cases, where some cracks and corrosion are recorded. The analysis considered applicable the Principle 4 to Los Manantiales due to the existing structural damage. Principle 5 is marked for all cases because actions to increase the resistance to physical or mechanical attacks are applicable for all structures.

This study recommends impregnation as a protection technique to apply in the cases. Impregnation is a treatment to reduce the surface porosity and strengthen the surface of concrete. Can be obtained by the partial or total filled of the pores and capillaries as observed in Figure 52. Is an easy technique to apply by using rollers or brushes. Before the process, the surface should be clean and with open porosity. (Vasconcelos, 2020).

Impregnation can be applied to buildings with a box marked in Table 5 corresponding to Principle 1 and 5. The advantage of impregnation is the almost null aesthetic alteration of the surface, coherent with the conservation recommendations. However, if the conditions are not adequately evaluated, the blocking of the pores can trap the water vapor in the concrete.

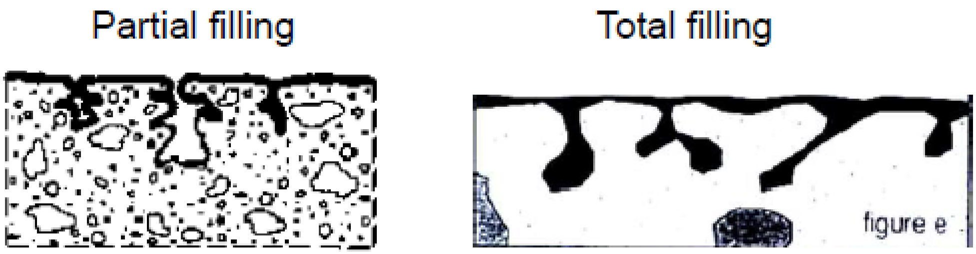


Figure 52. Full and partial filling of pores.
Note: In (Vasconcelos, 2020).

For nonstructural and dormant cracks, routing and sealing are recommended. The procedure consists of enlarging the crack to form a V-shaped as observed in Figure 53. Then, the groove is filled and sealed with a suitable material. The benefits are the execution simplicity and the accessible cost.

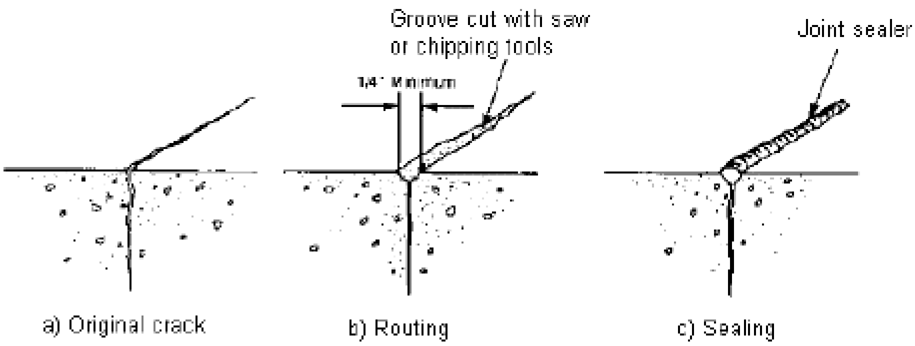


Figure 53. Routing and sealing procedure.
Note: In (Vasconcelos, 2020).

In the case of structural cracks in Los Manantiales, injections are a possible solution. If it is correctly executed, the advantage is that the monolithic behavior of the structure is obtained. However, the disadvantages are the irreversibility and the final finish matching with the surface. The procedure consists of removing the damaged concrete in the injection zone. First, the extension of the superficial opening must be done treating not to damage, adjacent areas. Next, cleaning the cracks to place plastic or metallic tubes is carried out. A surface sealing is applied to avoid leakages during the procedure. Finally, after the injections, the cosmetic repair must be done (Vasconcelos, 2020).

Los Manantiales' strengthening project considers the foundation's repair and the addition of a retaining wall to avoid sliding of the terrain. Regarding the works in the roof, these will consist of consolidations, injections, waterproofing, and paint. In addition, repairing of the electricity, hydraulic, and drainage systems will be improved as well as the floor finishing in the restaurant (Del Cueto Ruiz-Funes & García Lopez, 2020). Implementing a damping casement for the windows is considered due to the damage caused by this in the shell during the earthquake.

The actions of this proposal are correct and compatible with the recommended principles. Both, the repair of foundations and consider the improvements of the installations are following the guidelines. Even adding a damping system to the existing casements instead of removing them is accurate. Restoration works are currently executed, thus, the final results will be analyzed in the future. During the development of this study, it was not possible to establish communication with the authors of this intervention to obtain more information regarding the restoration processes and projects. Therefore, the information was obtained through UNAM's online publications.

Another repair case to analyze is San Vicente de Paul Chapel. In this case, the international guidelines of conservation are followed. For instance, in the lattice, recovery is the first suitable action, where the corrosion is removed, and then, if necessary, the pieces were replaced. Unfortunately, it is not possible to give a concise evaluation of the procedures and materials used because the information is limited. Therefore, a future study of the compatibility of the applied materials and the structural performance is recommended.

A special mention of the casements must be done. An increasing trend in Mexico City of replacing the old casement with new materials in buildings, is a risk to the 20th century buildings. For instance, in neighborhoods as Cuauhtémoc and Roma, these alterations are more frequently observed. The thin-shells are not the exception because alterations in San Vicente de Paul are recorded.

The change of use is interesting for the shells because concrete strengthening projects are generally focused on new uses in multi-storey buildings, which require the increase of the load-carrying capacity of beams, columns, and slabs. Meanwhile, in Candela's shells, a change of use that involves a drastic load change is unusual. Dead loads due to installations or comfort conditioning equipment could be considered; however, an analogy with multi-storey building requirements cannot be made. For the cases studied, only the Cosmic Rays Pavilion had this type of change; however, no record of structural repair or strengthening actions were found.

It is observed that not all concrete repair techniques can be used for shells, especially if they have a heritage value. For example, surfacing requires applying a uniform and a relatively thick layer of mortar or concrete. This would generate a change in thickness in the thinness characteristics of the shell affecting its value. In addition, the weight that this layer can represent for the structure must be considered. Techniques that consider increasing considerable thicknesses should be avoided in the case of thin shells. The almost null reversibility of these additions puts the heritage value at risk.

5.4 Update of the legal protection

The study exposed some cases affected due to the limitations resulting from the gaps in the legal framework and the Institutions in charge of protecting the artistic heritage in Mexico. Also, the case of the artistic monument declaration of Libertad Market, which presents a significant number of similarities with the shells built by Candela, is a clear example of the selection criteria for protection. Hence, why do Candela's works lack the artistic declaration? The adaptation of new technologies, workmanship, and material economization were present in his projects, so what aspects are still missing to obtain legal protection? Are the tangible and intangible values of these works not important enough to include some of them in the list?

Certainly, the proposals and modifications of the law are lengthy and complicated processes; however, the review and participation of experts in the update are necessary. Heritage conditions in the 60s and 70s are very different from the current situation. The laws must raise the requirements, problems, and solutions from a point closer to reality. The state must enforce law compliance and justice for heritage damage because, in many cases, the sanctions for the responsible of destruction are not applied or omitted.

UNESCO Declaration Concerning the Intentional Destruction of Cultural Heritage point that: “states should adopt the appropriate legislative, administrative, educational and technical measures, within the framework of their economic resources, to protect cultural heritage and should revise them periodically with a view to adapting them to the evolution of national and international cultural heritage protection standards” (UNESCO, 2003). Therefore, revisions and updates of the law are recommended from an internal politic to solve the problems and requirements. However, these needs are also highlighted and pointed by international institutions and organizations, reinforcing the argument presented.

Figure 52 exposes the importance of protecting monuments through Federal laws. In the case of UNAM's Central Campus, it is observed that three entities participate in the laws and regulations framework: the Federal Government, the University, and UNESCO. Despite this, the conservation conditions of the Cosmic Ray Pavillion are not optimal. So, for the cases where only the government is in charge, the risks and dangers increase. If the lack of updates and gaps in the law are added, the research can assume a relevant problem. Furthermore, many existing archaeological, historical, and artistic heritage without a declaration can complicate the situation because the institutions can be overpassed.

Figure 52. Applicable regulations to Campus central of UNAM.
Note: Modified from (UNAM, 2017).

5.5 Education and dissemination of the information

Conservation and preservation actions are not limited to the materiality of a heritage building but also to people who interact in it. With this understanding, the international recommendations indicate "publish and distribute twentieth-century cultural heritage, research and conservation/management plans, and promote events and projects wherever possible among the appropriate professions and broader community" (ISC20C, 2017).

Professionals consider the engineers and architects at the academy and industry and those professions involved in heritage protection as well. The participation in courses regarding technical problems of concrete interventions and the development of training programs and certifications courses that update the knowledge of cultural concrete is a task that requires more work (Macdonald & Custance-Baker, 2014). Likewise, participation in colloquium and academic discussions where professionals can discuss research or intervention projects results with the national and international scientific community is proposed for the cases shown in this study.

The general public encompasses the users and owners who must know the importance of the spaces they inhabit. The heritage cannot be preserved if there is ignorance about it, so the significance and value of the cultural heritage are given by the knowledge about them (Cottom, 2008). On the other hand, if the values are unknown, the protection and appropriation through the community become complex. The cases where the community gets involved in the defense, opposing demolitions, and active participation through manifestations of disagreement are not new in Mexico. The authorities have taken emerging and protective actions when registering these movements, therefore, disclosure is an important point.

The work of professionals at this point acquires didactic touches and requires developing communication skills. Due to the diversity of cultural backgrounds, the expositor must analyze the selection of information and the best way to transmit it to the community. The transmission challenge is not limited to a school and universities scope because it must also encompass the community practice. The establish of dialogue with key audiences and stakeholders can promote the appreciation, understanding, and conservation of 20th century heritage places, including the shells built by Candela (ISC20C, 2017).

Lastly, a recognition of the labor done by professors, students, and educational institutions such as the Faculty of Architecture of UNAM that, through proposals for integrating Candela's existing works to new projects and requirements, seeks to safeguard this heritage. However, despite these efforts, the decisions based on political, economic, or simply ignorance lead to their destruction most of the time.

6. CONCLUSION

This section presents the main outcomes and conclusions of this study on the significance and conservation of Candela´s concrete shell structures, along with some recommendations for future research.

6.1 Summary and Conclusions

A bibliographic investigation and critical analysis of the significance and conservation of Candela´s shells has been presented in this thesis. Chapter 2 provides the context and the most relevant aspects that allowed the development and construction of these structures. In Chapter 3, a sample of seven shell constructions by Candela is studied. Chapter 4 propose a methodology to identify and classify damages for this type of structure and evaluate the legal framework. A critical review of the conservations problems is also exposed. Chapter 5 recognize the values and the cultural significance of the buildings. Also, a review of the international conservation guidelines is carried out to identify the successes and failures in the seven structures studied here. Finally, a series of recommendations are made for improving the conservation and future interventions for the constructed work of Félix Candela.

The findings and insight gained in this study provide a number of conclusions and recommendations for action regarding the significance and state of conservation of the thin shell concrete built by Félix Candela in Mexico. The main conclusions are as follows:

a) Prompt action is required to guarantee the protection and conservation of the works of Félix Candela in Mexico. Buildings similar to Candela´s have a declaration as artistic monuments, demonstrating the lack of clarity of the criteria applied to heritage declarations. In this regard, legislation updates is a priority task.

b) There is a need to expand research and delve into the study of conservation of 20th century heritage. In México, a large part of this heritage, including thin shells, lacks protection. In addition, studies regarding the challenges of concrete's heritage interventions are topics that need constant remark by researchers and schools.

c) The main cause of damage at Felix Candela shells is related to anthropic factors. Inappropriate interventions and lack of maintenance top the list. Emphasis on the need of professionals, government, and society commitments to implementing actions that change the incidence of problems related to these causes is made.

d) Thin shells, despite being built with reinforced concrete, have a different behavior than conventional frame structures. Therefore, intervention projects and study approaches cannot homogenize structural criteria and materials application. The project's designers must understand the structural characteristics of the shells to carry out tasks that guarantee minimal interventions.

e) Material studies on existing shells need to be conducted through NDTs and MDTs, as well as laboratory tests on the different works. In addition, highlight the proposal to create a registry that compiles the materials' current mechanical properties to identify risks and sources of future damage. These studies can help to calibrate models that allow the analytical research of thin concrete shells.

f) The structural damages in Candela's shells are related to the earthquake and the soil type. Only one of the seven buildings recorded structural damage. For most cases, the intervention needs are linked to protection and repair rather than strengthening.

g) Including and develop maintenance plans. Experts on heritage concrete structures must carry this out. The proposal of steady maintenance plans with clear priorities to attend and defining the continuous actions is necessary for longer-term preservation. In addition, the creation of a manual explaining the correct criteria and activities must be included as part of the deliverable project. It is also recommended to share the manual with the owners.

h) Defining the significance of the 20th century concrete heritage is one of the most demanding challenges due to the age and values that this involves. In this framework, studies and proposals focused on Felix Candela's works, including the tangible and intangible values and encompassing most of the buildings, are relevant for the conservation. Furthermore, disclosing the information to owners and users can result in the awareness and knowledge of the background that the building entails not only for a community but also for the worldwide shell studies.

6.2 Recommendations for further research

This section indicates topics on which the researchers can develop new studies and future investigations. This aims to complement, update, and fill the existing information gaps that currently hinder a comprehensive knowledge of the work of Félix Candela in Mexico. The research topics are the following:

a) The study of the mechanical properties of concrete and reinforcing steel in existing shell structures. The constant lack of information records and proportions regarding the concrete mixes, could be solved from these studies. Through the use of this data, the structural performance and safety evaluations and can be more accurate and consistent with actual material properties.

b) Develop studies that compile and expose monitoring results and performance of materials used for the repairs and strengthening. These studies can also contribute to discussing the challenges related to concrete thin shells and create discussions and comparisons with the techniques used in other cases worldwide.

c) More in-depth studies on the formwork used in the shell structures. The investigations must consider design requirements, quantities of material, assembly times of the formwork, among others, to obtain complementary information. For the non-modular formworks, the next questions are presented: Does the hypar surface typology directly impact the cost? In what proportion? What percentage of the total cost corresponds to the supports and foundations? These factors had a direct influence on the choice of surfaces and design proposals?.

d) Complementary studies regarding the workforce can contribute to reinforcing the intangible values of Candela's work. The research can focus on searching records of the workers involved, places of origin, and previous jobs. In case of being possible, if some workers are still alive, data could be gathered from a direct interview or with relatives. The worker's vision and perception can be an interesting information source to generate a new approach between Candela's ideas and their materialization.

e) Studies on user comfort relating to acoustics and thermal conditions of thin shells. The elaboration of quantitative analyzes can provide information that can be useful to overlap with the newly developed technologies, materials, and future adaptations to comfort.

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