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Architecture

HISTORICAL DESIGN OF CANTILEVER SHELLS OF MODERNIST ARCHITECTURE

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Abstract

Introduction: Studying the historical design system of the pioneer concrete shells helps to reveal a relevant part of the History of Construction, which is also fundamental in acquiring the knowledge necessary to conserve and restore this iconic heritage. Cantilevered shells, like large domes, have been the most difficult to design and dimension when computers did not yet exist. **Methods:** The research included two phases: firstly, the selection and analysis of some of the most relevant pioneer cantilevered shells, and secondly, the comparative analysis of their design systems. **Result and discussion:** The analysis pointed out that the pioneer master engineers used different design systems. Pier Luigi Nervi and Eduardo Torroja mainly used scale model tests to check the structural behavior of their new continuous structural forms, Ildefonso Sánchez del Río always used ribbed shells and chose geometric forms that were easy to calculate manually, and Félix Candela used real size models for the tests. The result reveals the different paths that they used to design and build their relevant legacies, which nowadays belong to the international heritage of Modernist Architecture.

Keywords

Concrete shells, design system, cantilevered structures, Modernist Architecture.

Introduction

The formal and technological conquest of Modernist thin concrete shells is inseparable from the development of reinforced and prestressed concrete. The first vaults and concrete domes were built at the end of the 19th century using the pioneer patents, among others those of: J. Monier, F. Henebique, G. Schlüter and H. Habrich (Christophe, 1899). They were the precedents of thin concrete shells. Consequently, the thick concrete vaults and domes became shell structures, which were evolving, becoming bigger, thinner, and slender.

On the other hand, cantilevered structures made from wood and even such materials with low flexural strength as stone were used in buildings throughout the history. But what allowed building large cantilever structures was the discovery of new materials with high flexural strength and rigidity, such as iron and reinforced and prestressed concrete.

It is a fact that the appearance of the first shell structures of reinforced concrete in the second decade of the 20th century opened new possibilities of ˝flying˝. Undoubtedly, the thin and slender concrete shells that are “floating in the air” have not only a great complexity of design, but also special and disturbing attractiveness. We are going to analyze some selected pioneer cantilever concrete shells designed and built by several masters and reveal different design systems they followed to achieve their results.

Methods

The research included two phases. Firstly, the selection and analysis of some of the most relevant pioneer cantilevered concrete shells, which were designed using three different systems: the historical graphic statics method, the pioneer manual numerical dimension system by Franz Dischinger, and a physical reduced model.

Secondly, the comparative analysis of some pioneer types of cantilevered shell structures resulting in different resistant shapes and cantilever stiffening systems.

Results and Discussion

To understand the importance of the specific contributions to cantilevered concrete shells development, it is necessary to analyze them while simultaneously considering what was happening at that moment in the international context. How were the cantilevered shells designed during the *“Concrete Shells Adventure”?* It is well known that the cantilever structures are highly based on torque moment and rotational equilibrium. Loads, whether dead or live, must be balanced out on the cantilever section. They must be rigid, and the easiest way to get rigid shells is to use a set of rib-beams. This is the reason why most of the first cantilever concrete shells were designed with depth ribs.

In 1929, Pier Luigi Nervi (1871–1979), one of the most relevant protagonists of the pioneer *"Concrete Shells Adventure"*, designed his famous Florence football stadium — *Stadio Giovanni Berta* (Nervi, 1956), now known as *Stadio Artemio Franchi.* It was inaugurated in 1932. It is a cantilever concrete shell masterpiece, a pioneer building of Modernist Architecture, and an icon worldwide (Figure 1).

The structure of the grandstand and its cantilever roof form an ingenious resistant unity. It was made of reinforced concrete with a scenography image of resounding and nude modernity. Its roof is a pioneer cantilever ribbed shell. It consists of a set of 23 concrete modules formed by 8 pillars of different height supported by 2 inclined beams and 2 cantilever curved ribs. These cantilever ribs have an aerodynamic shape. Their total length is 22 m and their overhang is 17 m from the crossing point of two inclined supports. A light sheet of ceramic material is provided on them for support. The curved ribs have a shocking geometric shape that serves to balance the structural set by the large inclined foot, which crosses the inclined beam to the back pillar (Iori, 2009). In this respect, the grandstands act as a buttress resisting the overturning moment. The inclined beam starts from the head of the same pillar (Figure 2). The transverse bracing of the cantilever curved ribs is formed by a smaller curved ridge of reinforced concrete ribs between two main ribs (Figure 1, on the right). All the structural elements form an ingenious resistant unit, which demonstrates not only an

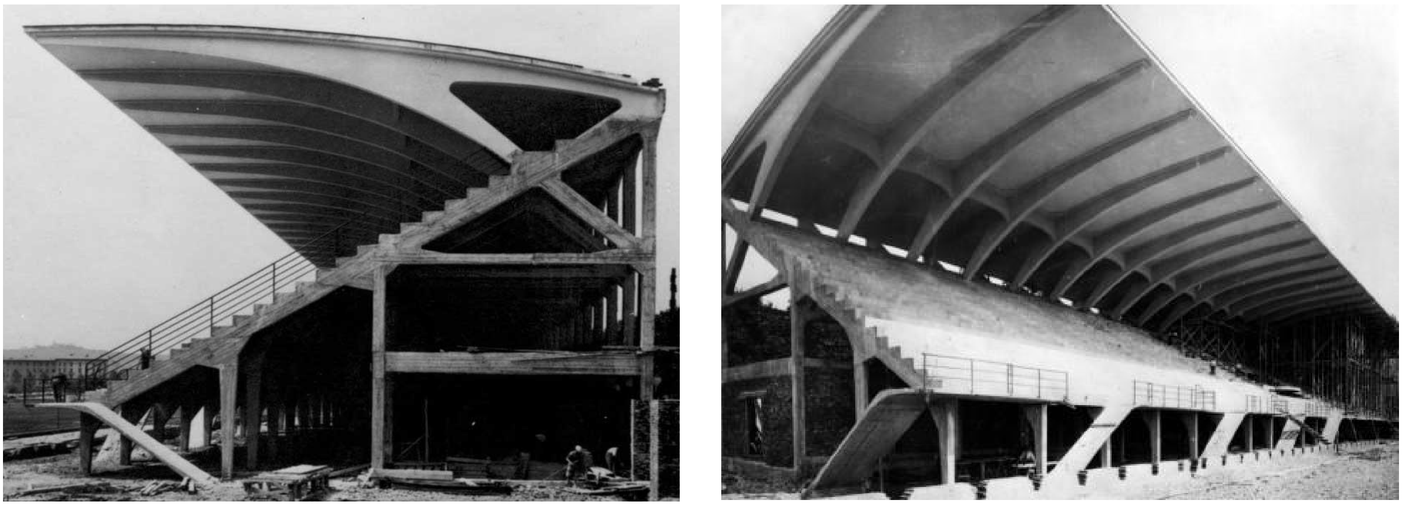

Figure 1. Florence football stadium (photographs) (archive: Fernando Cassinello)

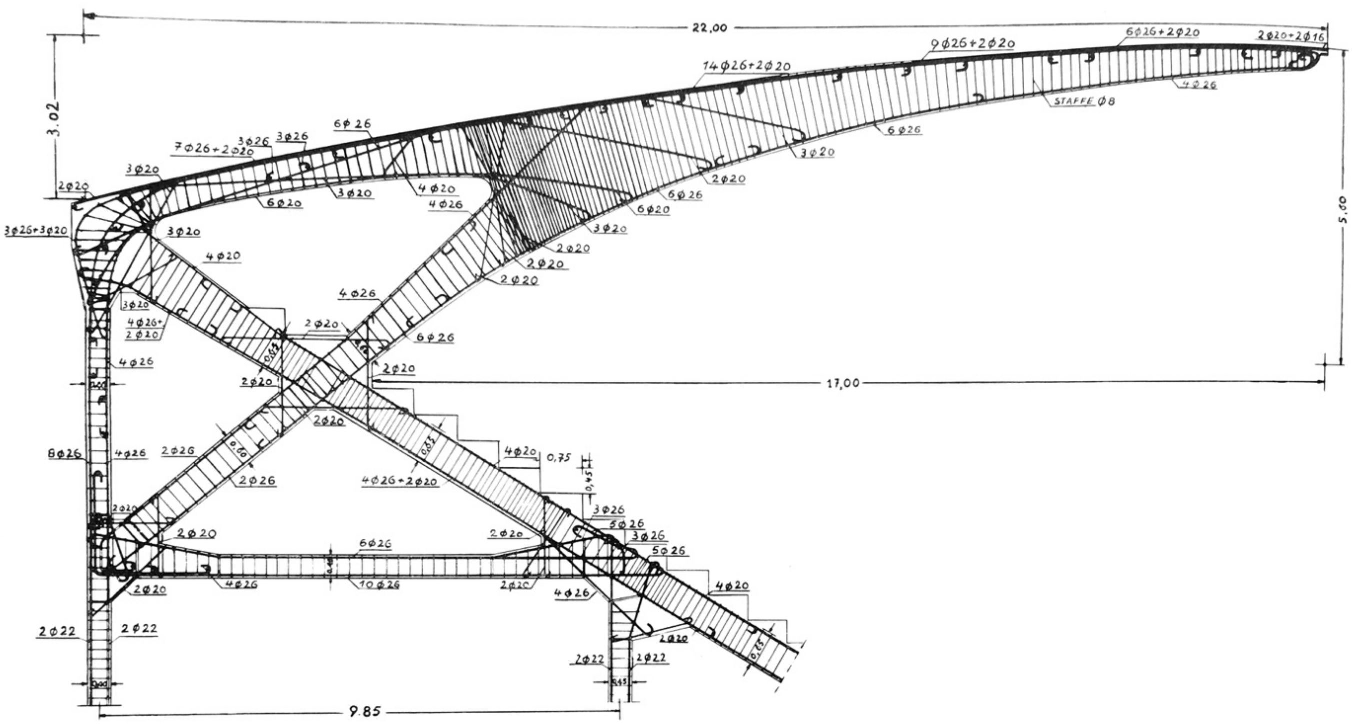

Figure 2. Florence football stadium (layout) (archive: Fernando Cassinello)

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optimal structural behavior, use of material and process of construction, but also the naked modernity image Pier Luigi Nervi managed to express.

At that time, Eduardo Torroja, another outstanding civil engineer of the 20th century, pointed out that it was impossible to design a new concrete shell with numerical calculations only. At that moment, they were using a complex and manual calculation system developed by Franz Dischinger (Dischinger, 1928). As Eduardo Torroja said, it was necessary to check the results by a physical model test. In the early 1930s, Torroja founded his company ICON. It was specializing in testing physical models as a method for analyzing structural behavior. The micro-concrete models for the *Algeciras Market* and *Recoletos Jai-alai Court*, both on a scale of 1:10, received particular acclaim (Cassinello, 2016). He earned international renown for his concrete shells: *Algeciras Market* (1935), *Madrid's Zarzuela Racecourse* (1935), and the *Recoletos Jai-alai Court*, also in Madrid (1936). *Zarzuela Racecourse* is the only one of his three famous concrete shells which is cantilevered.

In 1934, Torroja began the construction. The cantilever is a thin and continuous reinforced concrete shell without ribs or folds. It gives an impression of a fine wavy fabric that floats in the air above the bleachers (Figure 3). Its significantly Modern language and innovative structural form prompted the engineer's inclusion in the book *Art and Artist* (1956), along with relevant sculptors like Henry Moore, Ernst Mundt and Alberto Giacometti, photographers like W. Eugene Smith and painters like Paul Klee, among others (Torroja, 1956). This was only fair for Eduardo Torroja managed to achieve a remarkable feat of reinforced concrete architecture when this material was still in development.

The *Zarzuela Racecourse* has three bleachers, with the two outer 60 m long structures flanking a 30 m long central stand. Each unit consists of transverse portal frames spaced at 4.88 m, which in turn consist of a set of modules formed by a shell of double cantilever, one longitudinal (12.75 m) and one transversal (2.44 m), which is supported by a single pillar and not a shell on two pillars as some people wrongly assume. Eduardo Torroja chose the geometric shape of hyperboloid sectors for the design.

As he explains in his book *The Structures of Eduardo Torroja* (Torroja, 1958), he was looking for a double curvature surface to get the rigidity needed. He did not like to use ribs, he always thought on continuous shells resistant due to their geometrical structural shape. A threaded steel tie positioned at the rear provides the balance for these bold structural forms. It resembles an enormous Calder's sculpture. When the wind blows, you can see its slight movement in its articulated props on the pillars. The shell is 5 cm thick at the outer edge and 14 cm over the support.

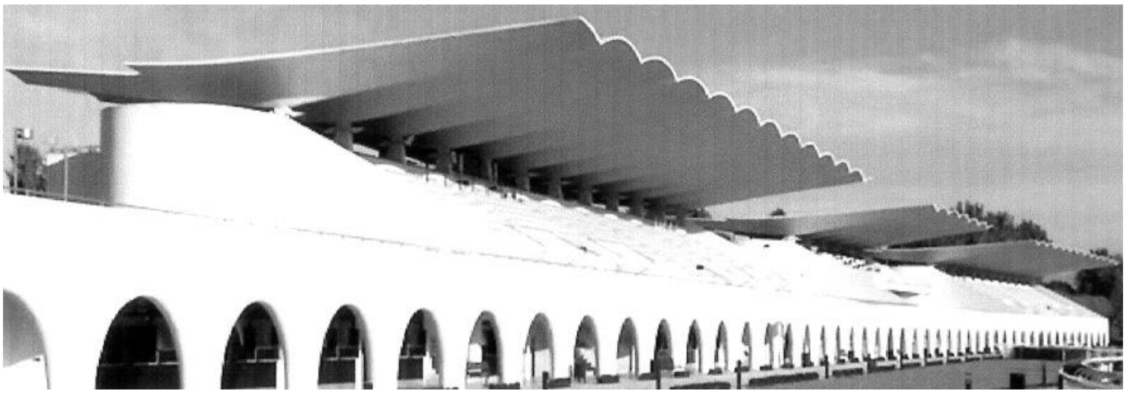

Figure 3. Cantilever concrete shell on the bleachers. *Hipódromo de la Zarzuela – Zarzuela Racecourse* (archive: Pepa Cassinello)

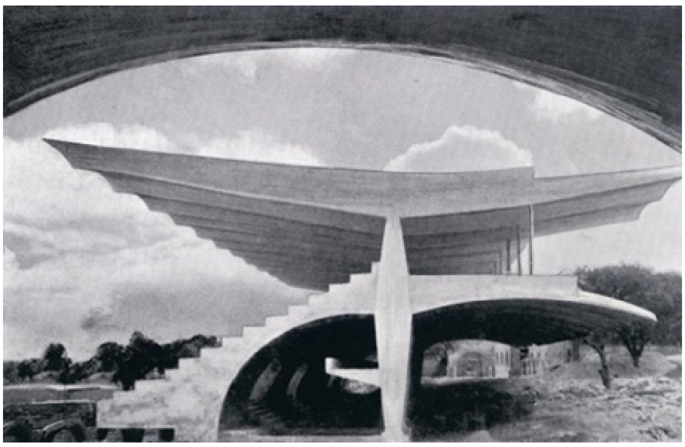

Figure 4. Zarzuela Racecourse. Photo by Sibily von Kassel (archive: Eduardo Torroja)

Figure 5. Alexander Calder's sculpture (archive: Fernando Cassinello)

Two decades before David P. Billington coined the term “Structural Art” at the University of Princeton (Billington, 1983), Eduardo Torroja had already built a gigantic reinforced concrete sculpture (Figure 4) like those mobiles made by Alexander Calder with steel bars and color plates (Figure 5). In fact, the concrete shells, that nowadays house the Eduardo Torroja Museum, are mobile sculptures. They are supported by Freyssinet-type joints that allow them to move on the pillars (Figure 6). On windy days, visitors may observe how they swing on them. Their balance is guaranteed by the metal braces located at the back of the large 12.80 m cantilever. Only Eduardo Torroja was able to create this innovative reinforced concrete structure, coining in his hands the birth of the inexhaustible *Era of the Structural Art* of reinforced and prestressed concrete, as Robert Maillart, Eugenne Freyssinet and Pier Luigi Nervidid. These four engineers were pioneers and titans of the reinforced concrete works during the new feeling that emerged in Modernity.

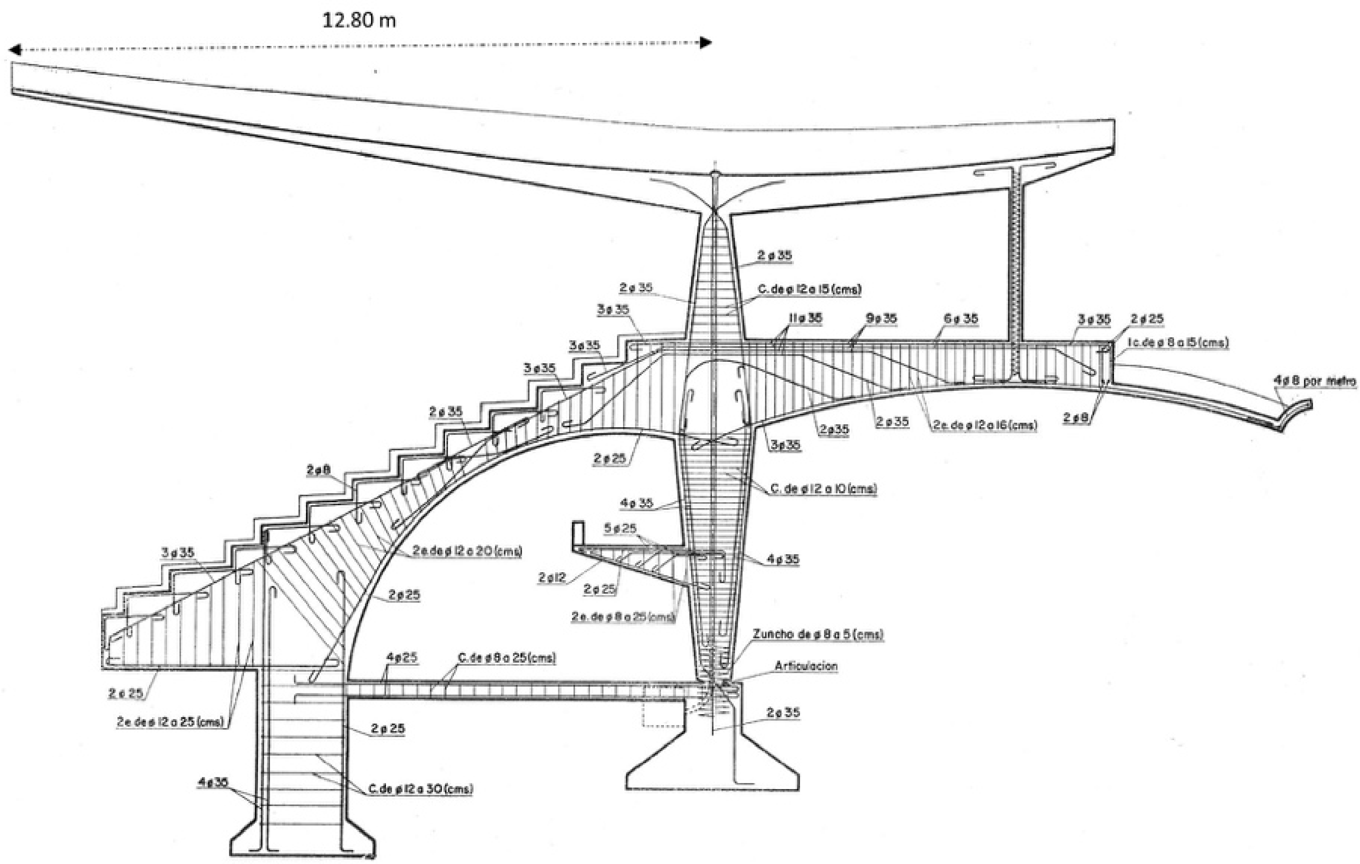

Figure 6. *Zarzuela Racecourse* (transversal section)
(archive: Eduardo Torroja)

In the case of the *Zarzuela Racecourse*, Eduardo Torroja conducted a test on a full-scale physical model (Figure 7). That approach verified not only structural behavior, but at the same time the complex construction process of this innovative structural cantilever form. In view of the complexity of building the junction between the two hyperboloid lobes, he decided to make a straight joint between them (Figure 8). In this way the final structural geometric shape is only similar, but not identical, to the intersection of two sectors of hyperboloids. These straight joints have a variable width, being wider over the pillar and more mats at the end of the cantilever. He checked the module’s structural behavior under loads (Figure 9). It was tested under deadweight and snow loads and the results demonstrated that it had three times the resistance necessary.

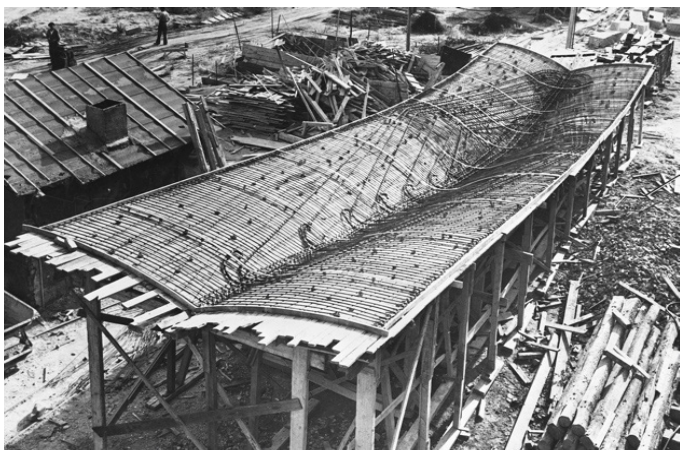

Figure 7. Full-scale model
(archive: Eduardo Torroja)

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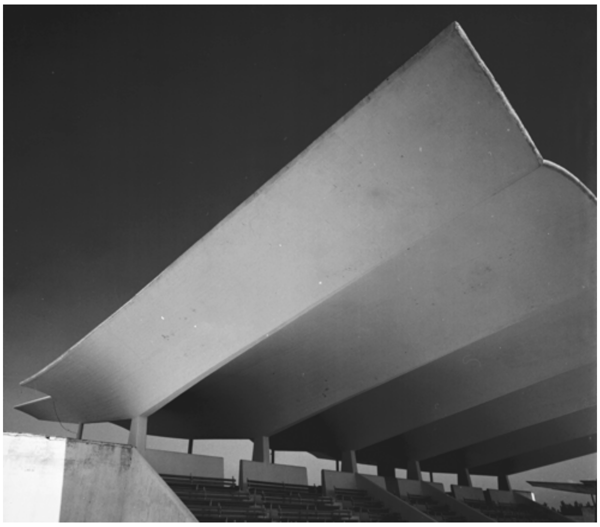

Figure 8. Cantilevered shells
(archive: Eduardo Torroja)

Figure 9. Load test of the cantilever module
(archive: Eduardo Torroja)

During the Second World War, the shortage of steel in Europe was one of the reasons why the use of prestressed concrete proliferated as it required less steel. In 1951, a cantilevered shell structure recalling the pioneering *Zarzuela Racecourse* was presented at the Hannover exhibition. It was built with prestressed concrete by German engineers Finsterwalder and Pistor, and architect Gütschow. Its geometrical shape corresponded to the spatial twist of three circular segments with an outer radius of 24 m (Figure 10) supported by ribs on the pillars. Its cantilever was 15.80 m, 3 m more than the Torroja's one, but with larger ribs.

In 1932, the Oviedo Stadium (Spain) was inaugurated (Figure 11). The structure of the bleachers and their cantilever reinforced concrete shell were designed by Spanish engineer Ildefonso Sánchez del Río (1898–1980). It was a cantilever concrete ribbed shell. Given the difficulty inherent in engineering these incipient thin shells, in the 1920s, he developed his own design system. It was based on the use of geometric shapes that could be designed, dimensioned and built in an easy way. For this reason, the concrete shells were formed by a set of identical ribs (beams or arches), with lightweight concrete elements built on top of them (Cassinello, 2011).

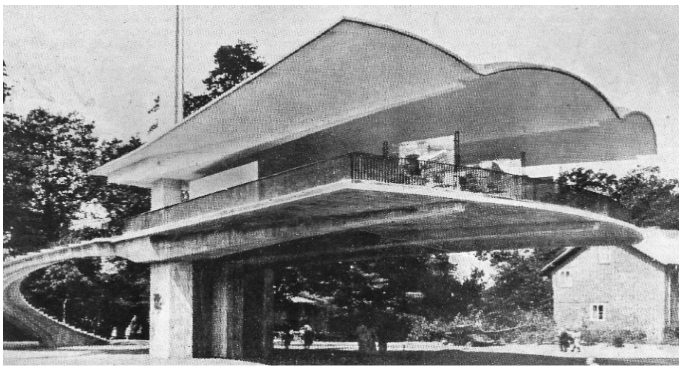

Figure 10. Hannover Exhibition. Coffee-restaurant. 1951 (archive: Fernando Cassinello)

Figure 11. Oviedo Stadium
(archive: Fundación Juanelo Turriano)

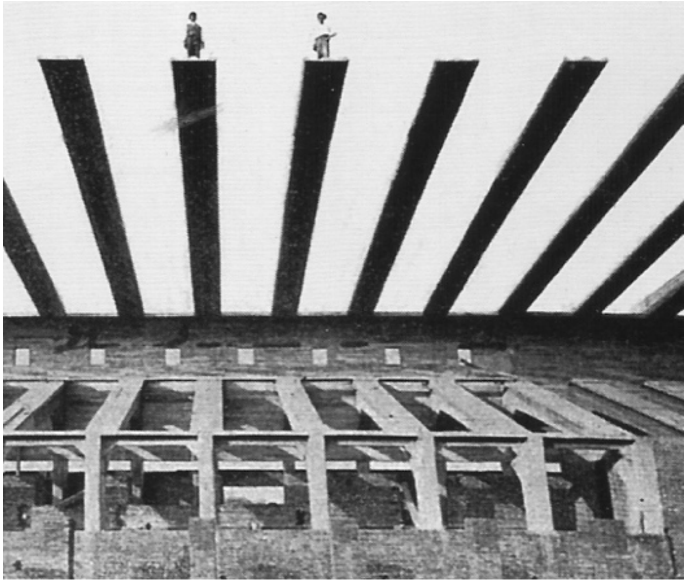

Figure 12. Flat ribs
(archive: Fundación Juanelo Turriano)

One of the most original aspects of this roof was that its cantilever was not curved, but consisted of a variable flat section with ribs 15 m long and 1 m wide (Figure 12). Similar to Pier Luigi Nervi's design, the structure of the inclined grandstand and its cantilever roof formed a resistant unity, which guaranteed the balance (Figure 13).

This concrete shell consisted of a set of concrete flat ribs with light domed prefabricated fibrocement plates (Uralita) bolted on them. This way, the weight and the cost of the roof were optimized.

From 1925, Sánchez del Río used this system to build many concrete umbrellas. In 1972, he inaugurated the livestock market at Pola de Siero – *El Paraguas.* It was an octagonal concrete shell umbrella 40 m in diameter, which means 20 m of cantilever only 3.5 cm thick. A dimension never exceeded by a reinforced concrete umbrella anywhere in the world. To know the structural behavior, an experimental test was made by the Institute founded by Eduardo Torroja. It has 8 radial ribs of square sections. The concrete ribbed shells are hanging from the middle-section of the ribs (Figure 14).

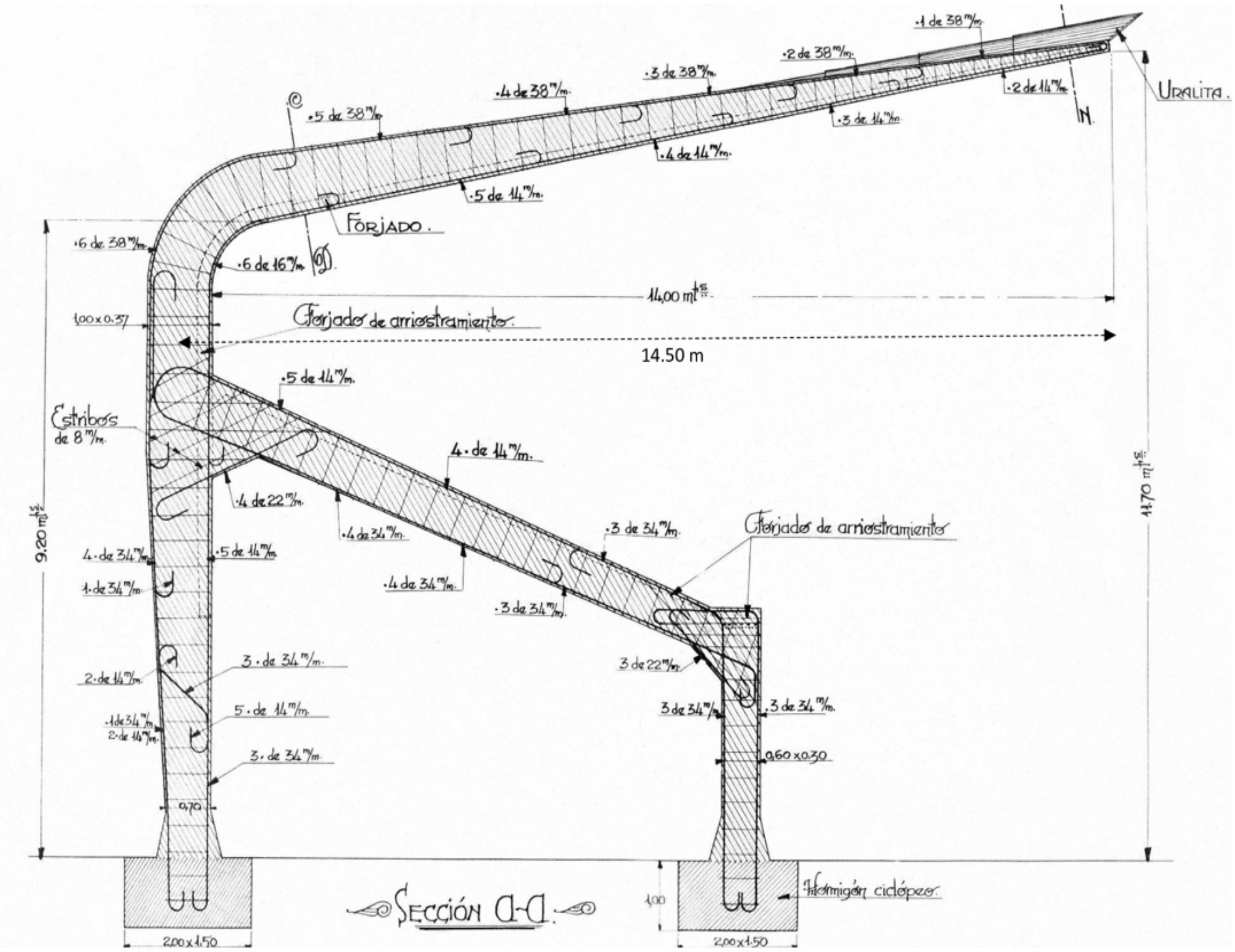

Figure 13. Oviedo Stadium under construction
(archive: Fundación Juanelo Turriano)

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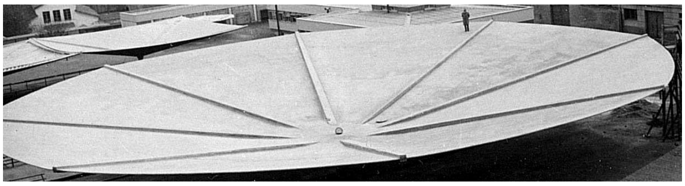

Figure 14. Livestock market at Pola de Siero
(archive: Fundación Juanelo Turriano)

In the 1950s, architect Félix Candela (1910–1997) founded his own company "Cubiertas Alas" in México. In two decades, he built the largest number of concrete shells ever built.

Félix Candela used full scale model to check his designs (Cassinello, 2010). He built experimental shells with different geometric shapes. He built the Ctesiphon Vault in 1949, the Fernández factory conoid in 1950, and the umbrella at Las Aduanas in 1953 (Figure 15). While at first he experimented with different geometries, most of his *oeuvre* was based on hyperbolic paraboloids, or ˝hypars˝, a form that enabled him to generate a wide variety of shells whose strength was derived from their double curvature geometry. Another considerable advantage of these structural forms was that they optimized construction costs because concrete could be cast to simple formwork built with a board arranged along the straight lines generated by the hypars. Candela created umbrellas by joining four straight-edged hypar surfaces (Figure 16).

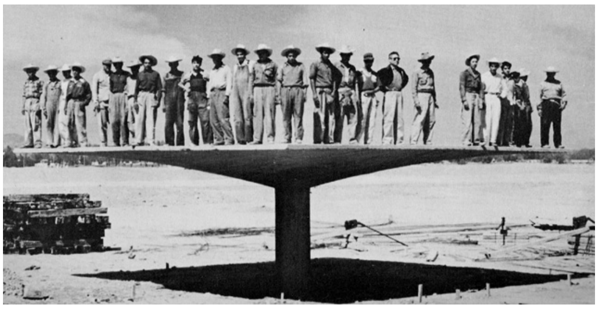

Figure 15. Las Aduanas. México
(archive: Fernando Cassinello)

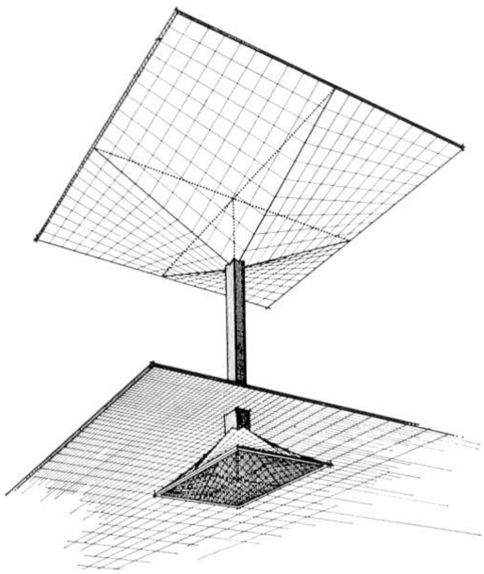

Figure 16. Umbrela hypar
(archive: Fernando Cassinello)

He analyzed thin reinforced concrete shells and developed simplified methods for their design. He concluded that if the shell support system could be regarded as isostatic, static equilibrium equations for membranes would suffice to solve the problem. Further to this reasoning, Candela devised a way to simplify thin concrete shell engineering, teaching himself to create new structural forms and contributing to revolutionize and disseminate an understanding of such structures. He authored a book titled "A new philosophy of structures" (Candela, 1962). Not only did Candela learn to design free edge shells with no ribs on his own, but as David P. Billington said, he also learned the discipline of thinness. His most famous works were able to save 30 m between supports with only 4 cm thickness, among them are the restaurant of the Manantiales in Xochimilco (1957) and the Bacardi bottling plant (1958) (Candela, 1985). With respect to the cantilever shells, the umbrellas reached 12 meters on the side resulting in a 6 m cantilever. In 1982, with Spanish architect Fernando Higueras, Candela designed the Murcia Airport (Spain), unfortunately not built. The hypar umbrellas had 24 m on side, cantilevers reaching 12 m with 5 cm thickness (Blanco García and García Ríos, 2018).

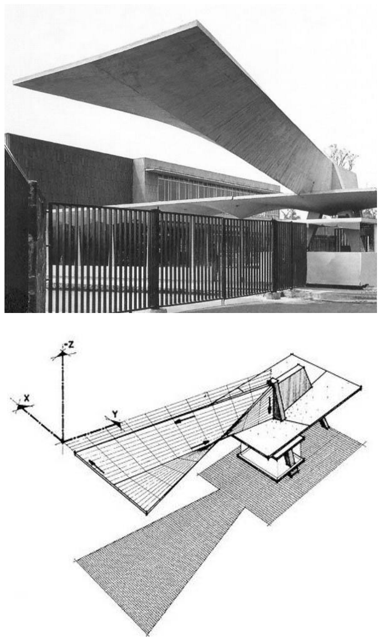

Figure 17. Lederle laboratories
(archive: Fernando Cassinello)

The cantilevered shell of the Lederle laboratories reached 12 m (Faber, 1963) (Figure 17). But it was in his sculptures that he achieved the longest cantilevers. This is the case of the Band at Social Security's in Santa Fe, Mexico City (1956) (Figure 18). It is a large overhang supported by a vertical element that is braced in two small concrete walls anchored to the ground to prevent overturning as can be seen in the model made for the exhibition commemorating his centenary (Cassinello, 2010) (Figure 19). The roof is formed by three equal folded pieces and each one covers a triangular area. Its cantilever is 12.5 m. Candela's cantilever sculptures are undoubtedly iconic pieces of Modernist Architecture.

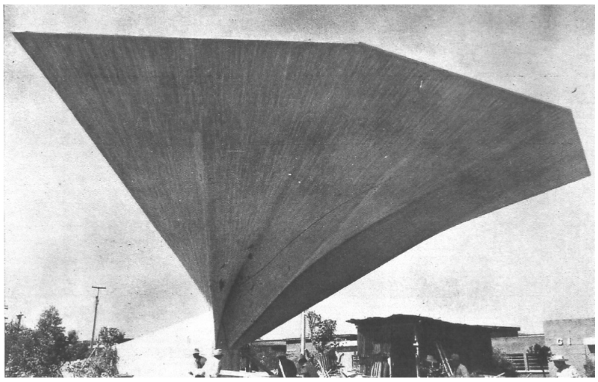

Figure 18. Band Shell
(archive: Fernando Cassinello)

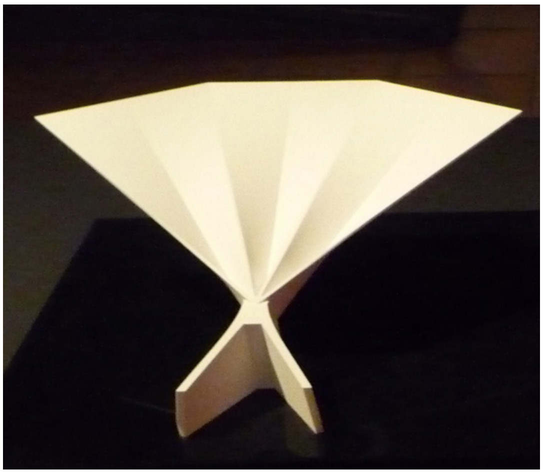

Figure 19. Exhibition model
(archive: Pepa Cassinello)

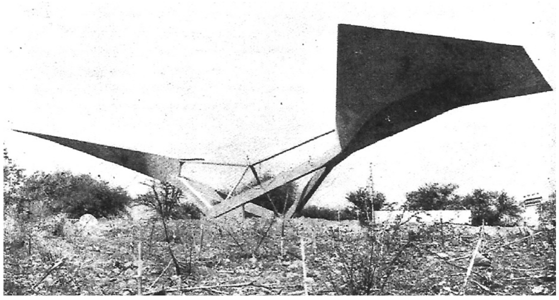

Figure 20. Tequesquitengo
(archive: Fernando Cassinello)

Figure 21. *Plaza de los Abanicos*
(archive: Fernando Cassinello)

During the 1950s, he designed other cantilevered concrete shells such as the one at the Lake Tequesquitengo (México, 1957). It was formed by two cantilever shells connected by reinforced concrete V-beams and tie rods that guarantee the balance. The fans were formed by 4 folded sectors 4 cm thick and a 10 m cantilever (Figure 20). Another is the one designed for the *Plaza de los Abanicos* in the Lomas de Cuernavaca (México). It is located on a sheet of water. It is formed by three shells that are in the vertices of a triangular plant with a side of 10 m. The shells are folded concrete plates 4 cm thick and a 6 m cantilever. In the upper part, there are cylindrical perforations that favor the decrease of the wind pressure. The whole structure is balanced by straps that connect the three fans. The tubes that shoot water jets and bathe the structure hang from these straps (Figure 21).

Candela used folded hypars as an alternative to his umbrella (hyperbolic paraboloid) since folded plates were one of the types of concrete shells that proliferated most in the 1950s and 1960s. The concrete cantilever shells were fundamentally built by using a folded surface because they are the easiest to build, for the formwork and reinforcement are planar. Structurally, as in corrugated shells, the amplitude of the fold increases the depth of the shell to absorb bending without thickening the shell, a cost-effective solution to stabilize and stiffen the element as a whole.

In 1958, the UNESCO building was inaugurated. It was designed by Marcel Breuer, Bernard Zehrfuss, Eeron Saarinen and Pier Luigi Nervi. At its entrance, an exempted canopy was built generated by two different cantilevered ruled surfaces (Figure 22). They are united by a segment of a parabolic dome, which holds the two cantilevers. This was the best solution to balance the big horizontal resultant force. The bigger one follows a parabola in a vertical plane, with the vertex downwards and is 10 m of cantilever. The other is a 5.30 m conoid cantilever.

In 1959, Spanish architect Julio Lafuente (1921–2013) built the *Tor Di Valle Hippdromein* in Rome, collaborating with engineers Gaetano Rebecchini and Calogero Benedetti. The cantilever concrete shells are formed by 17 umbrellas generated, as the Candelas's ones, by joining four straight-edged hypars (Lafuente, 1960). The fundamental differences consist in these umbrellas having large prestressed concrete ribs, although they are bigger and reach 19.50 m of cantilever (Figures 23 and 24).

Figure 22. UNESCO canopy, 1958
(archive: Fernando Cassinello)

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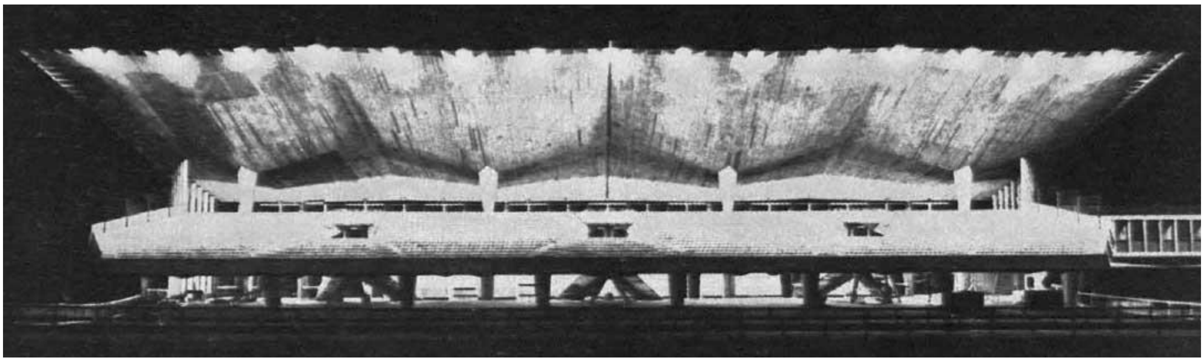

Figure 23. *Tor Di Valle Hippdromein*, 1959
(archive: Fernando Cassinello)

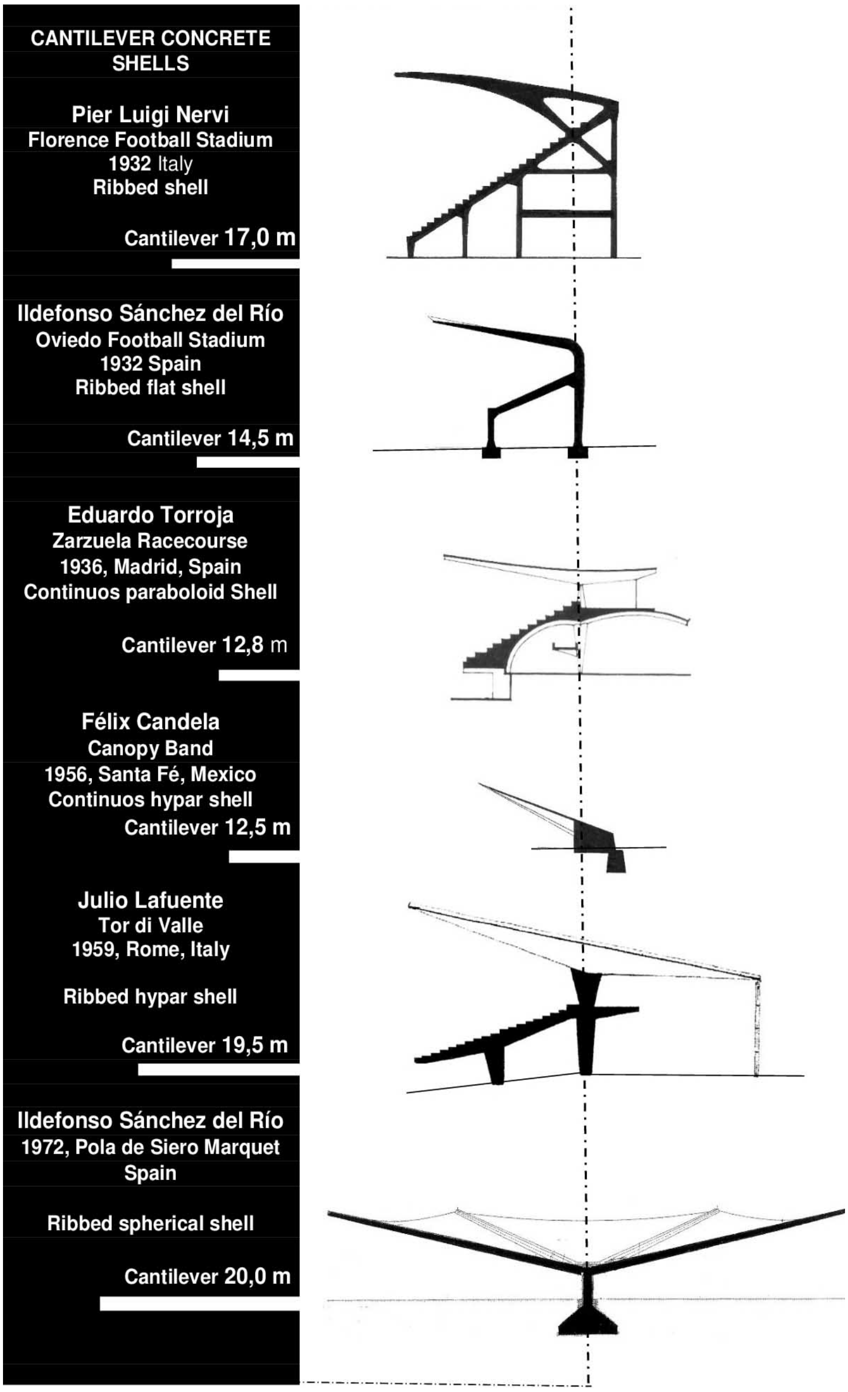

Figure 24. Comparison of cantilever length
(archive: Pepa Cassinello)

Conclusions

Of all the types of pioneer concrete shell structures, those with the largest and thinnest cantilevers were the most difficult to design. In this article, we analyzed only a small sample of the cantilevered structures built by some pioneer master shell builders, but it was enough to point out the structural design systems they used to build efficient and iconic concrete shells, as well as the structural forms they used, and what cantilever sizes they reached.

In the 1930s, they used a complex and manual calculation system developed by Franz Dischinger in 1928. For this reason, they checked the results by testing physical models and sharpened their wits to find simpler design systems. From 1930s to 1970s, to build cantilever concrete shells, designers first used ribbed shells, such as Nervi and Sánchez del Río from the end of the 1920s. In the 1930s, Torroja built a 12.80 m cantilever using hyperbolic continuous shells without ribs or folds. Candela fundamentally used the geometric form of the hyperboloid parabolic and folded plates to build concrete canopies and umbrellas in the 1950s, which reached up to 12 m of cantilever.

During the 1950s and 1960s, folded plates were usually used to build cantilever shells because they presented an easier solution. A bigger cantilever shell umbrella was built by Sánchez del Río in 1972. It was a hanging ribbed shell 40 m in diameter with 20 m of a cantilever shell 3.5 cm thick.

Nervi and Torroja usually checked their structural intuition by scientific scale model tests, while Sanchez del Río and Candela used full-scale models.

On the other hand, Nervi and Sánchez del Río designed ribbed concrete shells. Ribs were the protagonists of their works. In the case of Sánchez del Río, it was due to the fact that his design system was based on the use of geometric shapes that can be decomposed in a set of equal ribs, thus simplifying the design process of the shell. The Nervi’s ribs are quite different from the Sánchez del Río’s ones. They follow the direction of the main moments at each point of a slab that works in two directions, subjected to a uniformly distributed load, or in other cases, they form a rigid frame to lead the prefabricated shell elements. It means a different design-system philosophy. Torroja and Candela built continuous concrete shells on supports or with cantilevers, although in a different time and following different paths.

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