

The Shell Structure of the Frontón Recoletos: from Design to Construction

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Abstract

Shell structures, also known as laminar structures, profoundly influenced the design and construction mentality of the leading exponents of Constructive Rationalism in the first half of the 20th century. The structural art of designers like Eduardo Torroja, Pier Luigi Nervi and Félix Candela achieved its maximum aesthetic expression in this fascinating type of construction, which based static resistance on the shape of the structure itself.

This construction archetype –mainly influenced by the geometry and relationship of the structural elements– requires an accurate representation –both in the two-dimensional and three-dimensional spheres– of the spatial elements that compose the work. This is accompanied by the practical aspect of construction, characterised by the use of concrete with the support of articulated ribs and formwork.

This article addresses the main aspects of laminar structures, to which Torroja contributed through the creation of some of his most famous works. The most audacious –both from an architectural and geometric-structural point of view– was undoubtedly the Frontón Recoletos and its roof, whose geometric and constructional peculiarities made the building famous worldwide. Much of the credit for the construction of the shell and its skylights is attributed to the engineer himself, who was responsible for the design, structural calculations and actual construction.

Keywords: Shell structures, geometric-structural configuration, representation of the construction.

Introduction

This contribution highlights the importance of geometry for the configurative and structural genesis of architecture. In this regard, it is interesting the multifaceted nature of the study of geometry, including analytic, euclidean, descriptive, and projective geometry, as well as Topolgy. In this sense, we begin with the elementary shapes and their properties developed in the euclidean context, which studies the assets of objects (planes and solids) that remain unchanged despite their rotations, translations, and reflections [Ugo 2020]. These properties include the congruence of segments that have the same length, the congruence of angles that have the same measure, and parallelism. Logically, in topology, we move to a more critical dimension of shape, since we leave

aside measure and angles to include the concept of 'place' [Docci 2007].

These features are complemented by the theoretical aspects of descriptive and projective geometry, which are related to the representation and communication of architecture. For instance, projective geometry studies how objects are seen, also distinguishing between the real shape of the object and its appearance. In both cases, the study of surface genesis is fundamental [Carlevaris, De Carlo, Migliari 2012].

What I state since now highlights the role of Geometry in both creativity and visual communication: the first aspect is related to the creation of a surface, and the second is linked to the communication of this surface through its

representation. These topics constitute the educational foundation of geometry: underlying the configuration of space, knowledge of the geometric theory is essential for the creation of innovative architectural/engineering structures. Therefore, an understanding of shapes is also crucial, since it is closely linked, to a large extent, to observation, and since it has fundamental implications for the actual possibility of creating complex configurations so that can be clearly communicated and understood.

The geometric representation of surfaces

The study of architectural theory is closely related to its implementation, with a strong connection between a conscious creative intuition and the precise physical reality that connects shape and structure. For this reason, geometric/structural awareness is essential to invent and precisely proportion an architectural surface. Moreover, the effectiveness and productive power of creative intuition is widely demonstrated and attested by the grandiose works handed down to us from the past, when contemporary scientific theories were completely unknown. Indeed, today, the accuracy of modern digital systems, in continuous and progressive development, has allowed us to achieve outstanding results in the creation of ever more grandiose and audacious works.

But the geometric/structural idea –which allows us to efficiently decipher the current architectural surfaces, which are proposed every day by the unstoppable development of every aspect of construction activity– is the result of a harmonious fusion of personal inventive intuition and objective and realistic geometric genesis linked to the structure [Giordano 1999].

Fundamental, therefore, are the theoretical developments of geometry, with an intuitive response that enlivens them, diminishing their impersonal technical harshness, and making them more human and comprehensive. Meanwhile, theories based on formulas must offer methods of precise evaluation that are responsible for achieving maximum results with minimum means, that is the ultimate goal and fundamental direction of all human activity. In this sense, an architectural work becomes a synthesis of configurational and structural aspects, where in-depth study and examination will be particularly useful to future architects, who must know how to design and proportion it in its general lines, so that it is efficient,

significant, and, ideally, beautiful. This creates an opportunity to understand architecture in all its aspects (aesthetic, economic, social, and technical), especially in the field of the genesis of architectural shapes and therefore of load-bearing structures, which allow the construction of works of extraordinary scale [Colombo, Giordano 2022]. In architecture the geometric/structural component is essential. “Sia che l'uomo costruisce un semplice riparo per sé e la sua famiglia, sia che erigesse ampi locali dove centinaia di persone potessero esercitare il culto, commerciare, discutere di politica od assistere a spettacoli, egli ha dovuto foggare certi materiali ed impiegarli in determinate quantità perché le sue costruzioni potessero resistere alla forza di gravità od altri pericolosi carichi” [Salvadori, Heller 1963, p. 18]. In this sense, it is important to ensure a shape that can support and resist to internal and external forces, yet conceived according to aesthetic criteria, which often impose more stringent requirements on the construction of structures than those of strength and economy. Some architects and engineers of the XX century –such as Eduardo Torroja, Pier Luigi Nervi and Félix Candela– have created highly beautiful architecture in which the close connection between shape and structure is evident. It is equally obvious that, once the basic principles of geometric/structural genesis have been established, design and execution management are also straightforward, making it easy to draw on these experiences, systematize this knowledge, and come to understand how and why a modern structure functions/works.

The representation of surfaces, in its various expressive forms, therefore constitutes the necessary cultural and syntactic element of mediation and integration between reality and imagination, as well as a specific theoretical and technical production tool for architectural design.

Form-resistant structures

Form-resistant structures are unique geometric configurations in which specific curvatures allow for increased resistance without having to increase thickness. Solutions of this type have always been widely used throughout history. Examples of this innovation can be found in Antoni Gaudí's architecture, which repeatedly used the catenary arch and its harmonious geometries to support roofs. Evoking shapes already present in nature, the Catalan master's works

feature parabolic arches, whose shape blends perfectly with the structural solution [Benvenuto 1995].

From the 19th century, a revolutionary advance was made in the design and planning of vaults: the concept of graphic statics made it possible to obtain the cable-stayed shape of structures, working solely on compression and eliminating tensile and bending stresses. This solution was particularly favourable for constructions made with ceramic materials, such as brick and concrete. Regarding brick solutions, in Catalonia, the brick vault played a primary role in the construction of both industrial buildings and noble palaces, particularly those of Ildefonso Cerdá's Barcelona Plan [Ochsendorf, Freeman 2010].

Eduardo Torroja Miret, an engineer from Tarragona (Catalonia, Spain), was an undisputed master in the field of form-resistant structures, working in a fertile context of geometric and constructional innovations. During his early academic journey, Torroja developed a strong passion for the brick vault construction system. Thanks to his Catalan ancestry, he was deeply surprised by the great potential of this local construction technique, which he himself defined as "a typical product of this land, just like the carob beans of its fields" [Ochsendorf, Freeman 2010, p. 195] (fig. 1).

The secret of their stability lied precisely in their lightness, shape and softness [Maure 2004]. However, beyond purely aesthetic considerations, the practical aspect was and remains the greatest advantage of this type of construction. In his research inspired by vernacular architecture, Torroja used *bóvedas tabicadas* on several occasions

Fig. 1. Construction of Catalan vaults for the Sagrera Market in Barcelona [Torroja 1957, p. 280].



to build his structures, both to cover relatively long spans and as a substructure for upper floors. All this was done without the use of any type of formwork, resulting in significant savings in terms of both time and money. In some circumstances, he even used them as formwork for the construction of laminar structures, like in the case of the Fedala water reservoir (Morocco). Formwork for the entire structure would have involved a considerable cost, given the amount of material required and the particular geometry of the work. For this reason, Torroja decided to build the support structure for the concrete casting using his beloved Catalan vault, whose versatility allowed him to achieve the desired shape without using formwork. For the roof, which would not be subject to hydrostatic pressure, it was decided to leave the structure light with exposed triple-leaf bricks [Chías Navarro, Abad Balboa 2005] (fig. 2).

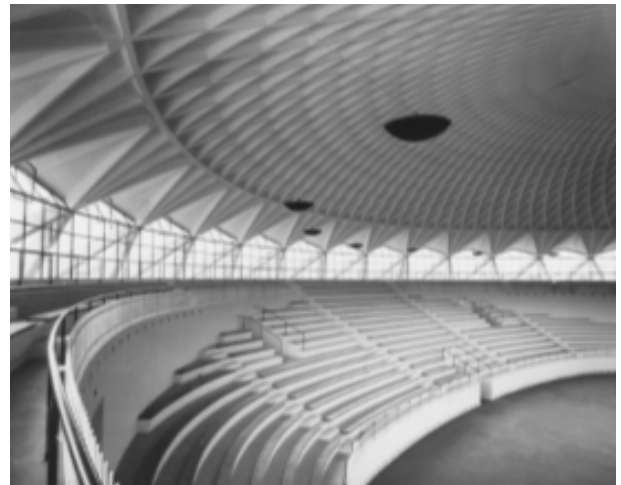
This example is just the latest demonstration of how brick vaulted ceilings are metaphorically (and in practice) the structural solution for support and transition—as well as the precursor—of reinforced concrete shell structures. For Torroja, the adaptability of reinforced concrete laminas in their structure, as well as their monolithic nature and spatial continuity, made this roof solution one of the most beautiful innovations in modern technology and architecture [Maure 2004]. Furthermore, the slenderness resulting from their derisory thickness ensured a perfect correspondence between the interior space and the volume visible from the outside, so much so that the functional expression of the building revealed itself [Colonnetti, 1957].

These were years—the ones in which he operated—when designers aimed to enhance the aesthetic value of a piece of work by expressing its resistance capacity [Torroja 1957]. However, the adoption of a particular structural type was not dictated exclusively by engineering considerations. It was also influenced by other fundamental functional reasons, primarily the construction process, which was closely linked to the economic feasibility of the project. This last consideration allows us to introduce another figure who was central to the development of this theme and who found himself interacting and discussing ideas with Torroja on more than one occasion: Pier Luigi Nervi, who, in the strictly constructive field, was able to fully orientate the formal conception of his structures. Nervi mastered reinforced concrete with great skill, which allowed him to optimise the cost of the

Fig. 2. Fedala water reservoir, Torroja, 1956: exterior view (up) and detail of the intrados with Catalan vault (down) [Torroja 1957].



Fig. 3. Comparison between the intrados of the roof of Mercado de Algeciras (up) by Torroja and the Palazzetto dello Sport of Nervi (down).



work and rationalise the construction process, so much so that in the years that followed he was recognised not only as a “great sculptor of architectural spaces”, but also as a “magician in the exhaustive control of the cost of the work” [Cassinello Plaza 2006, p. 28].

All this without ever ignoring the question of aesthetic expression, which had to be based essentially on the ‘truth’ of the architectural work. The structure had to comply perfectly with static requirements, allowing the forces involved to be visibly materialised. In this respect, Nervi probably proved to be more effective and consistent, as the ribs on the underside of his roofs perfectly reflected the transmission of loads to the ground. A comparison of two works by the authors clearly highlights this difference. Nervi’s Palazzetto dello Sport, built in 1955, 22 years after Torroja’s Algeciras Market, while still featuring a spherical dome roof, has a network of ribs on the underside that declare the Italian engineer’s firm intention to transfer the loads to the ground. Torroja, on the other hand, seems to want to hide the stress of his roof, concealing the lines of tension that run inside it (fig. 3).

Indeed, the Spanish engineer seems almost to take a step back from considering architectural truth as an absolute and exclusive dogma, declaring that “while it is true that lying is sinful, hiding the truth is not always a sin” [Torroja 1957, p. 248]. In several cases, Torroja prioritises the concept of functional truth over structural truth, according to which there must be a perfect correspondence between the internal space and the volume visible from the outside, so that the functional expression of the work can be easily understood [Colonnetti 1957]. According to him, this is the type of construction that best reveals the nature of the building to the exterior, as well as the architectural features that are evident inside it. In such structures, the boundary between interior and exterior is so thin that it is difficult to speak of the intrados and extrados of the surfaces.

Similarly, an artist capable of creating works whose slender projections were almost ‘negligible’ in thickness was certainly Félix Candela, who was firmly convinced that in a building, beyond mere numerical calculations, there was a strong connection between form and structure. Candela found Mexico as the ideal environment for developing his challenging shell structures. The extremely favourable climate allowed him to overcome problems related to thermal insulation and waterproofing, while the low cost of labour favoured reinforced concrete

solutions, given the complexity of the formwork. At the peak of his career as a builder, he took the ‘umbrella’ structures designed by Giorgio Baroni as reference and, with the geometry of the hyperbolic paraboloid, he improved their execution. The main characteristic of this surface –as well as the hyperboloid– is that it appears concave in one direction and convex in the orthogonal direction. This dual orientation gives them a high aesthetic value: their sections and shadow lines give rise to the formation of ellipses, circles, parabolas, hyperbolas or straight lines depending on their orientation, with a gradual transition from one to another as the light changes [Torroja 1957]. From a construction point of view, the advantages of these surfaces are that the formwork is easier to install, as the boards used to contain the concrete must be arranged along the straight lines that generate the shape (fig. 4).

In the works of Torroja, Nervi and Candela, geometric-configurative design and structural framework were in perfect symbiosis. The artistic form and structural layout merged into a single whole, eliminating purely ornamental elements and enhancing, in their simplicity, the grace of the lines, the proportion of the masses and the rhythm of the openings [Torroja 1957].

Despite their purely engineering education and background, their design philosophy was perfectly in line with the principles promoted by the Modern Movement. The engineer Torroja became the spokesperson for these concepts, expressing them repeatedly in his works through a style based on the absence of elements. According to his conception of structure as a piece of art, its beauty had to be based on the rationality of the structure. Such splendour had to be achievable without the need for additions or external ornamentation [Colonnetti 1957]. Torroja believed that aesthetic value lay in the functionality of its structure, endowed with a rich static expressiveness. All these principles were reflected in the nude intradoses of his laminar structures which, except in cases of functional necessity, remained pure and free of ribbing or cladding material.

The gesture

At the beginning of the 20th century, the ideology of purity of the Modern Movement went side by side with those of dynamism and movement promoted by avantgarde

Fig. 4. Preparation of the casting for the roof of the Los Manantiales Restaurant, Félix Candela, Xochimilco, Mexico [Casinello Plaza, 2006].



currents, like the Italian Futurism and Russian Constructivism. These styles were constantly searching for expressions of energy and dynamism through sketches, drawings and architectural configurations. In the early days, this gesture was translated into a variety of barely hinted signs: strong gestures and strokes in Futurism, forced perspectives and unbalanced compositions in Russian Constructivism, accompanied by violent diagonal movements [Frampton 1986].

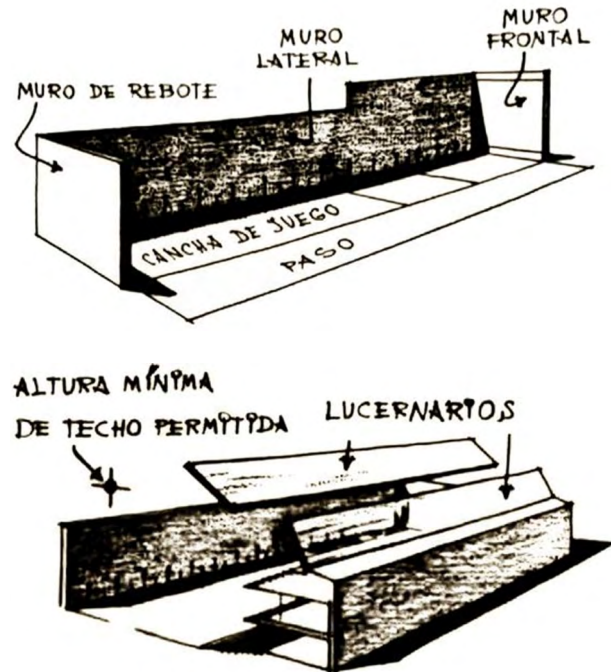
In Torroja, as in Candela, the gesture emerged spontaneously from an encounter between function and control of construction techniques. The functional solution activated the gesture, while the constructional mastery endowed it with security and firmness, as well as the desire for expression definitively guided the pencil. The gesture was integral because it was based on function and construction even before generating form. And once constructed, this form totally delineated the space, giving it a meaningful character.

Even the roof of the Frontón Recoletos sports hall – one of Eduardo Torroja's most recognisable works – was born from a clear and recognisable gesture. The structure and shape of this roof perfectly expressed the vaulting, physical violence and movement that athletes performed when hitting the ball. At the same time, it conveyed the energy and speed characteristic of the Modern Movement and the 'machine age' [1] [Salvadori, Heller 1963].

From the very first pages of the book *Razón y ser de los tipos estructurales*, it is clear that Torroja always associated the creative process through which he developed his buildings with an artistic process, linked to intuition and acquired experience. Theoretical study and technical-scientific education were limited to checking the forms and proportions that he had already assigned in advance. It is therefore clear that the creation of an artefact is not achieved deductively, through logical reasoning. To achieve the perfect form, Torroja worked by bringing together the starting conditions, from which he then conceived the geometry through intuition, imagination and pencil. It was an experimental approach in which calculation was relegated to a final tool to confirm the validity of the form obtained, where technical mastery was the support for the expression of the idea [Artieda, Machin 2013].

In the case of Frontón Recoletos, the initial constraints imposed on the roof were closely linked to the

Fig. 5. Frontón Recoletos: design constraints for the roof [Torroja 1962].



requirements of the sport, which also determined the geometry of the playing field. Modern *pelota vasca* is a discipline that was played in a *frontón* enclosed by front (*frontis*), side (*pared de izquierda*) and rear (*muro de rebote*) walls. Spectators occupied the fourth side, which was open and located opposite the side wall. In addition, local regulations imposed a minimum height for the roof, justified by the minimum heights that the *frontón* walls had to have. This requirement allowed the *pelota* to trace its harmonious curvilinear trajectories without encountering any kind of obstacle (fig. 5).

As a first solution, the possibility of incorporating the two skylights into a multifaceted glass and steel roof was evaluated. The design involved a series of trusses joined together by longitudinal joists. However, the solution was not satisfactory for both aesthetic and structural reasons (fig. 6).

The second proposal, on the other hand, consisted of placing two large truss beams, leaning on the gables at the edges, through which indirect light could filter. The beam was therefore composed of a pair of crossbeams connected to each other by a network of diagonals (fig. 7). However, this option was not ideal either, especially from an aesthetic point of view. During the creative process, however, something completely spontaneous and irrational happened that led to the final design of the shell. The lines of the roof were softened, and the profile took on a curved shape. Always taking into account the height and lighting requirements of the room, as well as the desire to convey a feeling of maximum spaciousness, the hand of imagination instinctively traced two arches whose asymmetry coincided with that of the room itself. The idea took shape with the adoption of a cylindrical reinforced concrete lamina with two lobes which, at the skylights, was converted into a triangular mesh of glass panels [Torroja 1999] (fig. 8).

The system defined by the final design was therefore characterised by a cylindrical reinforced concrete shell only 8 cm thick, which doubled (16 cm) at the orthogonal intersection of two cylindrical lobes, generating the so-called 'gull-wing' section. The new shape was thus born from a gesture: it expressed the movement of the athlete hitting the ball and at the same time conveyed the dynamism of the machine. The new concrete solution was the ultimate expression of the concepts of horizontality, speed, strength and nudity [Artieda, Machin 2013] (fig. 9).

Fig. 6. *Frontón Recoletos*. First project proposal: poly-gonal roof [Torroja 1962].

Fig. 7. *Frontón Recoletos*. Second project proposal: truss beams [Torroja 1962].

Fig. 8. *Frontón Recoletos*. Permanent solution with asymmetrical lobes and triangular mesh skylight [Torroja 1962].

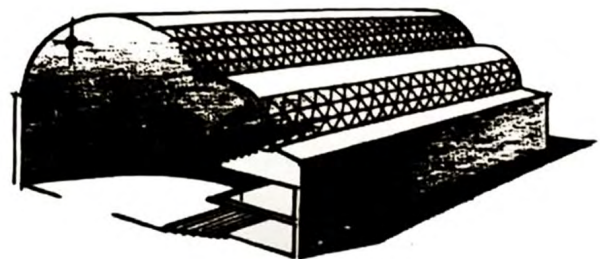
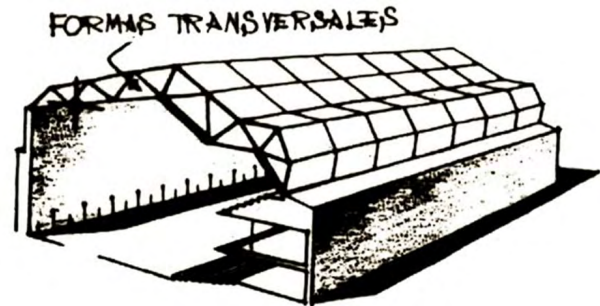
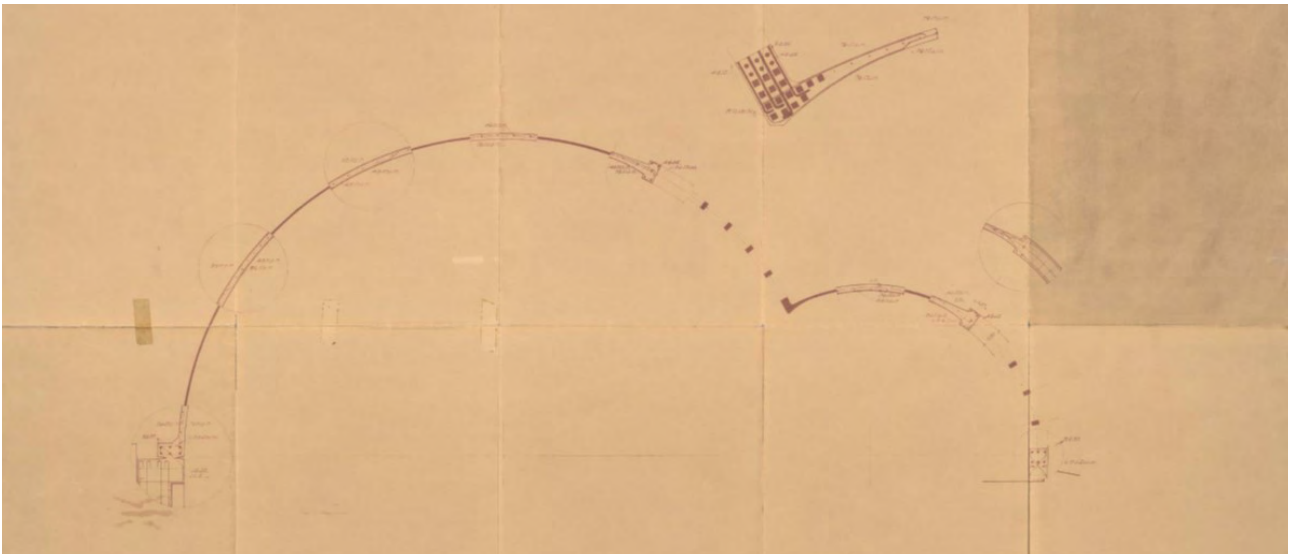
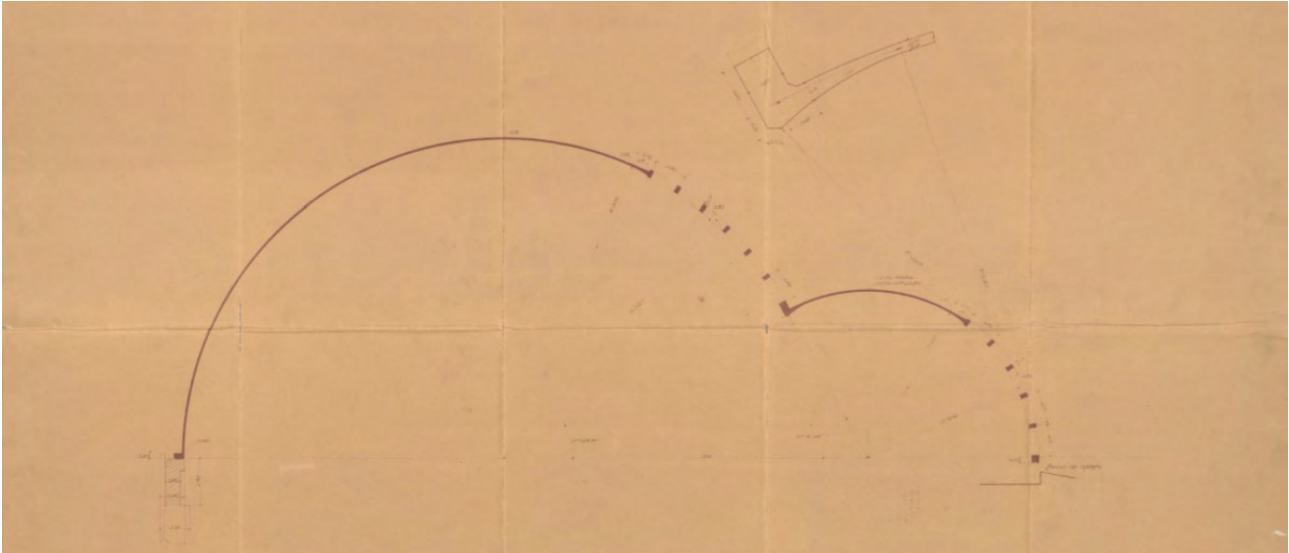


Fig. 9. Frontón Recoletos: cross-sections of the roof. Concrete and reinforcement drawings [Archivo Digital Torroja, CEHOPU-CEDEX].



From the paper to the construction site

Engineer José María Aguirre Gonzalo and professor Eugenio Ribera were called in as consultants to assess the structural feasibility of the audacious roof. The two structural experts produced a dozenpage report setting out their observations on the construction of the roof and the installation of the ribs for working at height [Ribera, Aguirre 1935]. Specifically, it was suggested that a horizontal ribbing be erected with the relevant support struts; that the formwork be removed carefully, together with monitoring of any deformations produced once this operation had been carried out; and finally, that an external layer of insulation be added to prevent excessive thermal fluctuations in the concrete.

From a construction point of view, for this type of roofing it was necessary for the lamina to behave as uniformly as possible. The casting of the concrete mixture therefore had to be simultaneous, without any repeated pouring. This inevitably led to a disproportionate consumption of timber, not only for the props, but also for the formwork. In fact, even though it was a series of repeated modules, it was not possible to take advantage of reusing the formwork from the previous casting. The choice was also dictated by the need to complete the work and start business as soon as possible, given that the income generated by the first sport events, according to the client's calculations, should have covered the excess costs. It was therefore decided to use quick-setting alumina cement in order to further speed up the construction time. The casting was then carried out in less than a week. Once hardened, the ribs were carefully removed under strict control of the deformations of the lamina, which were found to be in conformity with the calculations [Arredondo Verdu et al. 1977] (figs. 10, 11).

Conclusions

The essay clearly demonstrates how drawing and geometry are essential tools for the development of a design idea. In particular, drawing in the form of a sketch, or as a support for the elaboration of a drawing, represents the pivot around which the entire development of an architectural and structural concept revolves. In the circumstance of Frontón Recoletos of Eduardo Torroja, the engineer, translates his thoughts onto paper in the

Fig. 10. Frontón Recoletos: overview of the construction site layout [Liñán 2020].

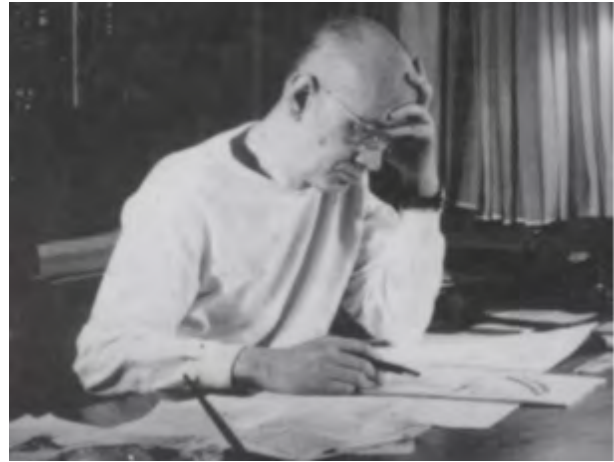
Fig. 11. Frontón Recoletos: the placement of formwork on the main vault. [Martínez Martínez, 2018].



form of diagrams, gathering his reasoning and sharing it with the observer. We talk about transparency of structure –provided by the monolithic solution of concrete shells– but we also and especially talk about transparency of thought.

Through paper and pencil, the author takes us into his imaginary world and allows us to participate in the creative process, offering us the key to access and understand the path that led to the final conception of the work. The sections of the project, on the other hand, offer an insight and appreciation of the engineering effort behind the curtain of the architectural envelope. In this case, the geometric design acquires graphic and technical value, representing the manual for the effective realisation of the work. The interesting aspect of laminar structures is the lack of distinction between structural consistency and geometric-architectural configuration. This is even more evident in the graphic production of the designs, in which the visual description of the load-bearing element takes on both aesthetic and constructive value (fig. 12).

Fig. 12. Eduardo Torroja, "solo et pensoso".



Notes

[1] The term 'machine age' refers to the aspects of energy and dynamism, key elements of the Modern Movement and related architectural

trends. In addition to these elements, there is the concept of the 'Machine for Living in', repeatedly proposed by the architect Le Corbusier.

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