

Eduardo Torroja and «*Cerámica Armada*»

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The Spanish engineer Eduardo Torroja Miret (1889–1961) was one of the leading structural designers of the 20th century. Torroja's extraordinary work includes two of the most significant thin shells in reinforced concrete: the market hall of Algeciras (1933) and the roof of the Zarzuela Hippodrome in Madrid (1935). (Fernández and Navarro 1999; Billington 1985) Though Torroja is better known for his work in thin shells of reinforced concrete, he pioneered numerous ideas in construction during his long career. One of his most significant ideas, construction in reinforced brick, or *cerámica armada*, has not received significant attention from historians of construction.

This paper examines Torroja's use of reinforced brick as a construction system. Following on the long tradition of timber vault construction in Spain, Torroja developed a system of thin brick shells, lightly reinforced with steel bars to resist tension. The fundamental advantage of the proposed system was the possibility to build shell structures without any supporting formwork, except for lightweight guides for the placement of the masonry. Thus, Torroja's use of reinforced brick provided an inexpensive and efficient structural system, which reduced the formwork costs associated with complex forms in reinforced concrete. Torroja applied reinforced brick throughout his career, from his earliest work on bridge caissons in the 1920's to a series of mountain churches in the 1950's. This paper provides an overview of Torroja's work in reinforced brick and the construction process he developed.

HISTORICAL DEVELOPMENT OF «*CERÁMICA ARMADA*»

Torroja did not invent the concept of metal reinforcing in brick. In the late 19th century the French engineer Paul Cottancin patented a system of reinforced masonry and concrete, which he called *ciment armé*, in contrast to Hennebique's *béton armé*.¹ Most notably, the architect Anatole de Baudot applied Cottancin's system in the church of St.-Jean de Montmartre in Paris completed in 1904. (Frampton 1995) Around the same time, Rafael Guastavino, Jr., son of a Catalan master builder who immigrated to the United States, was granted a patent for reinforced brick shells as shown in Figure 1.² (Collins 1968; Huerta 2001) It is likely that Torroja was aware of these systems though they do not appear to have inspired his own work on reinforced brick.

The Uruguayan engineer Eladio Dieste was the most accomplished designer in reinforced brick of the 20th century and his work has been well documented in recent years. (Jiménez 2001; Pedreschi 2000) Dieste began his experimentation in 1946 and was responsible for hundreds of innovative long span buildings in South America over the next 50 years. It is clear that *cerámica armada* was an independent invention in South America. Dieste was not aware of the reinforced brick precedents in Europe and he distanced his system from timber vault construction. (Tomlow 2001; Ochsendorf 2003) Conversely, Dieste's work may have stimulated Torroja to revisit the concept of

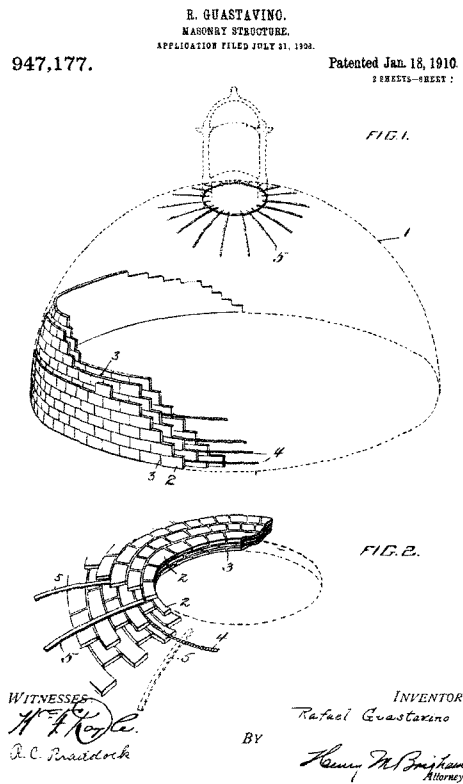


Figure 1
Patent for reinforced brick shells issued to Rafael Guastavino, Jr. in 1910. (Source: U.S. Patent Office)

reinforced brick construction in the 1950's. Although there is no proof of any correspondence between Torroja and Dieste, it is possible that Torroja learned of the early work by Dieste during a trip to South America in the summer of 1952. Torroja traveled widely in Argentina, Chile, Colombia and Peru, giving dozens of lectures and meeting with leading South American engineers. In his first application of *cerámica armada*, Dieste completed the thin brick roof of Casa Berlingieri in 1947. Dieste published this project in a South American engineering journal, so the work was known in the construction community and it is likely that Torroja would have learned of Dieste's work during his travels. Upon returning to Spain, Torroja completed a flurry of small church projects in the next several years and he dedicated himself to structural

design in reinforced brick during 1952 and 1953. (Antuña 2002) Torroja's design proposals were based on his earlier experience with reinforced brick shells, which began with the foundations for the Sancti Petri Bridge in 1926.

SANCTI PETRI BRIDGE CAISSONS (1926)

In 1923, Torroja began his career in the company Hidrocivil, working for his former professor, the leading engineer José Eugenio Ribera. Among other projects in his early career, Torroja designed various foundation systems for bridge piers and in 1925 he proposed a new system for the caissons of the Sancti Petri Bridge in Cádiz, Spain. This system was composed of two brick shells, circular in plan, with an interior space that could be filled with concrete. The exterior and the interior walls had the form of concentric hyperboloids of revolution with a common vertical axis. (Figure 2) The surface of the brick vaults was then covered with a steel mesh on both sides together with a layer of cement mortar to reinforce the caisson. The exterior dimensions were approximately 7 meters in diameter and 6 meters high and the thickness of the brick walls was about 8 cm. The interior cavity between the two walls was then filled with concrete to sink the caisson and provide a foundation for the bridge superstructure.

The brick vaults were constructed with a double layer of hollow tiles, called *rasillas* in Spain. This

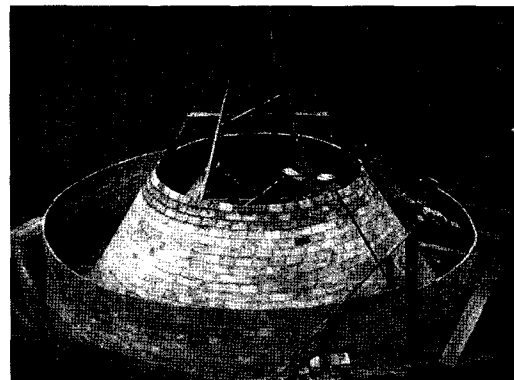


Figure 2
Foundations of Sancti Petri Bridge under construction. (Source: Torroja archive)

thin vault, known as a timbrel vault or *bóveda tabicada*, remains a common structural system in Spain and is valued for its ease of construction. With a fast-setting mortar, these vaults can be built without formwork or other temporary support.³ Torroja was a great admirer of traditional timbrel vaulting and he realized that it could serve as a permanent formwork

for reinforced concrete construction. (Fernández and Navarro 1999) By constructing a shell of brick and pouring concrete on the interior, the brick becomes the exposed surface of the concrete. Thus, in the bridge foundations of Sancti Petri, Torroja married a vernacular tradition with his civil engineering education in reinforced concrete.

Torroja seems to have refined the construction process for the Sancti Petri caissons as the project progressed. Figure 2 is clearly an unreinforced brick shell, suggesting that the vaulting was constructed first and the reinforcing was added afterwards. Figure 3 illustrates a completed reinforcing cage, which awaited the thin brick shells. Finally, in Figure 4 the vaulting is visible together with the reinforcing bars in a nearly completed caisson. It is not clear which system Torroja preferred and for what reasons, an issue which we will address in the discussion.

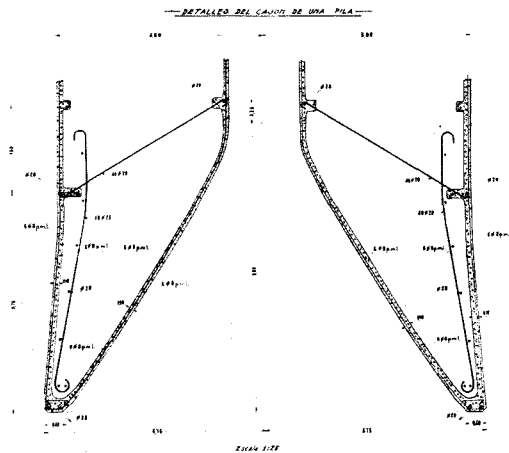


Figure 3
Sancti Petri bridge caissons under construction, with brick being assembled after the steel reinforcing cage is in place. (Source: Torroja archive)

THE ZARZUELA HIPPODROME RESERVOIR (1941)

The reservoir tower at the Zarzuela Hippodrome in Madrid is Torroja's second significant work in reinforced brick. For the original project in 1934, Torroja proposed a highly innovative reinforced concrete structure, which would have required a complex formwork system. (Figure 5) Due to its higher cost the original design was never built and Torroja complained that the Spanish civil war «frustrated this dream as it did so many others.»

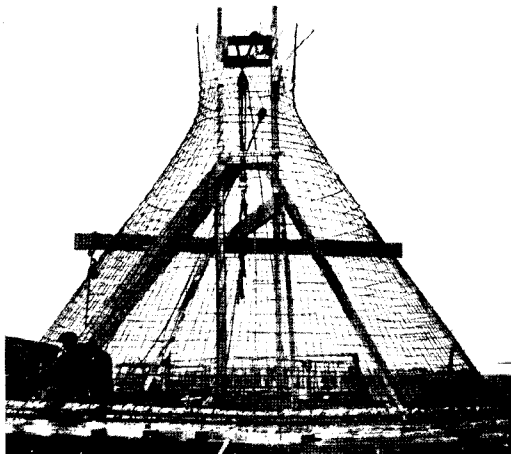


Figure 4
Brick shells together with steel reinforcing during construction of the Sancti Petri bridge caissons. (Source: Torroja archive)

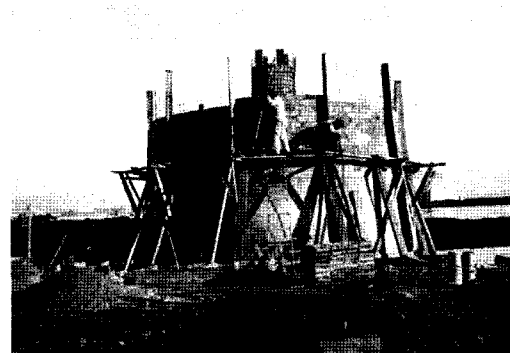


Figure 5
Torroja's original 1936 proposal for a reinforced concrete reservoir tower at the Zarzuela Hippodrome in Madrid. (Source: Torroja archive)

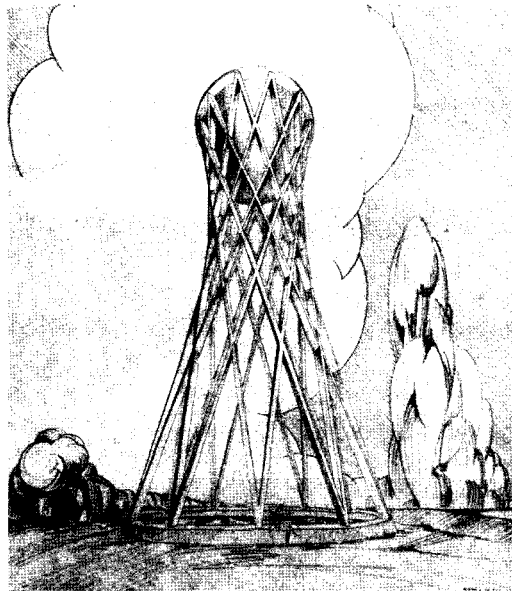


Figure 6
View of brick reservoir at the Zarzuela Hippodrome,
Madrid. (Source: Torroja archive)

(Torroja 2000) After the war Torroja constructed a reinforced brick tower which solved the same design problem at a substantially lower cost. (Figure 6)

Torroja's solution in brick is a hyperboloid of revolution, which in appearance is a precursor to the hyperbolic paraboloid cooling towers of reinforced concrete in later decades. The tower is elegant and simple, designed so that the lower region of unreinforced brick acts in compression. The upper region of the tower is subjected to internal water pressure and requires steel reinforcing to resist the resulting tensile hoop stresses. (Figures 7 and 8) The weight of the water is supported by a shallow concrete dome, which transfers the vertical load to the brick walls. The thrust of the shallow dome is redirected onto the walls with the aid of a tension ring at the base of the dome.

As with the foundations of the Sancti Petri Bridge, the method of construction for the reservoir is not clear. The key question in both cases is whether the steel reinforcing bars were placed prior to the brick, or after the brick was built. Because of the outward curvature at the top of the reservoir tower, the

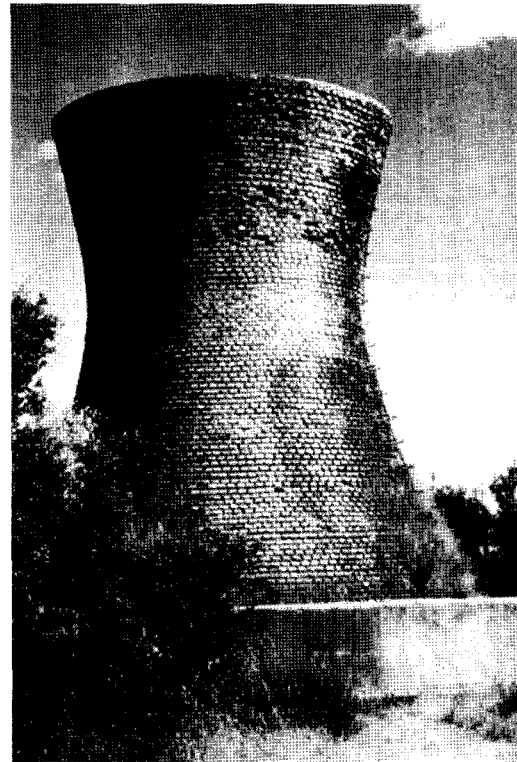


Figure 7
Cross-section of Zarzuela reservoir. (Source: Torroja
archive)

structure would experience tensile hoop stresses in this region during construction as well as in its final configuration. Figure 7 illustrates the extent of this curvature in the upper region and suggests that the exterior brick shell could stand under its own weight without steel reinforcing. The small tensile hoop stresses due to self-weight could be resisted by the cohesion of the brick and mortar assembly. Considering this possibility, it is likely that the brick shell was constructed initially and the steel reinforcing cage was installed afterwards. The concrete was then cast on the interior of the upper region of the tower. Though Figure 8 does not illustrate a masonry dome below the concrete shell, it is possible that this may have been constructed as a timber vault to serve as permanent formwork for the concrete dome. The shallow dome supporting the

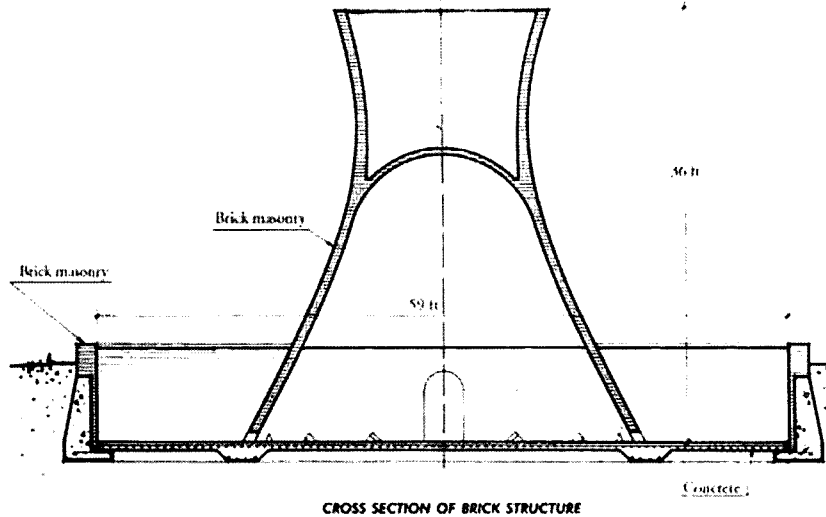


Figure 8
Drawing of reinforcing detail for the Zarzuela reservoir. (Source: Torroja archive)

water would act predominantly in compression under its own weight, and therefore could have been built as a brick or tile dome.

THE CHURCH OF PONT DU SUERT (1952)

By 1950, Torroja was known internationally and had recently designed various systems of reinforced concrete shells for long-span roofs, such as the central hall of ENASA of 1948 and the roof for the experimental laboratory for the Instituto Técnico de la Construcción. (Antuña 2002) Upon returning from South America in 1952, Eduardo Torroja started work on several church projects in the Pyrenees Mountains. These projects, the churches of Xerallo, Pont de Suert, and the mountain refuge of Sancti Spirit, have been ignored, if not discounted, by historians and critics unimpressed by their formal qualities.⁴ We will focus on the largest and most significant of these projects, the church of Pont du Suert in Llérida. (Figures 9–15)

The church of Pont de Suert has four parts: a long nave, terminating in an apse, with a small chapel and

another room connected on the side. The reinforced concrete floor structure spans between masonry walls of 1.38 m thickness. The low masonry walls support the roof structure, which is a curving shell of lightly reinforced brick. The roof shells were built with minimal formwork and are of greatest interest to the present discussion. Each shell is made of two to three layers of thin bricks (*rasillas*), covered on the exterior with 3 cm of mortar reinforced with a 4 mm steel mesh. In each one of the four parts the form of the roof is different, but the construction technique is the same throughout.

A study of the structure of the nave serves to illustrate the constructive system. The exterior of the nave is a rectangular plan 13 m wide and 20 m long, plus 8.5 m of the apse and 2.5 of the low entrance to the choir. The lateral walls are of stone masonry 2.75 m high, measured from the plane of the interior floor, and 1.35 m wide, including an exterior façade of one layer of cut stone. The top surface of the walls forms a continuous plane to support the roof. For the interior face, the mass of the wall is decreased by repeating ellipsoidal niches 3 m wide. The roof of the nave is divided into five independent sections, called «lobes»

series of transverse sections. During construction, a thin metal framework served as a guide for the placement of the first layer of the thin bricks. The surface can be generated by displacing a curve of a circular segment from another similar curve with a different radius C_c . (Figures 12 and 13). The interior surface of the resulting figure is an arc segment of circumference C_i . The curves generated are contained in a horizontal plane which rotates on an axis passing through the center of the curve C_i . The surface is defined by the coordinates of 26 transverse sections contained within the plane and supporting points of the exterior curve of the lobe, as indicated in the figure. The lines that define the edges of the shell are curves whose transverse projection is the curve C_i , and in the longitudinal plane it is a curve corresponding to the expression:

$$y = 0,59x^{1,249} \quad (1)$$

The curve is defined by the condition that its vertical asymptote is perpendicular to the ellipsoidal section of the lower niche. Figure 12 indicates the center of gravity of each curving section defined by the surface C_g , and the centroid of each of the arches, C_c .

To construct the roof, 26 guides were used following the form defined by the 26 arc segments indicated in Figures 13 and 14. The guides were placed on lightweight scaffolding, used to define the

form of the first layer of the bricks, which would become the lobe. The first layer was placed with a fast-setting gypsum mortar and subsequent layers were built with a cementitious mortar in the same manner as the timber vaulting constructed by Rafael Guastavino. (Huerta 2001) The metal guides also helped to support the weight of the roof until the two sides of the pointed arch met at the crown. After the two sides were joined, the structure was stable and worked in compression predominately. A longitudinal beam at the crown of the arches connects all of the lobes along the exterior surface, without being visible on the interior. This provides a point load at the crown of the arch which causes the internal line of thrust in the roof to more closely follow the center of gravity of the section, reducing the eccentricity and any associated bending stresses in the brick shell. (Figure 15)

To analyze the structure Torroja treated it as a fixed-end arch with a hinge at the crown, which is a structure with two degrees of static indeterminacy. Torroja carried out an elastic analysis, considering the material as isotropic, homogeneous and perfectly elastic. He determined the geometrical characteristics of the various sections, area and moment of inertia, and with these values he calculated the internal stresses in the brick roof. Finally, he applied the same procedure to the roofs of the apse and the baptistery. The thrust of the nave is resisted by the lightly reinforced concrete walls formed on each side of the niches in the walls. The shell works in compression

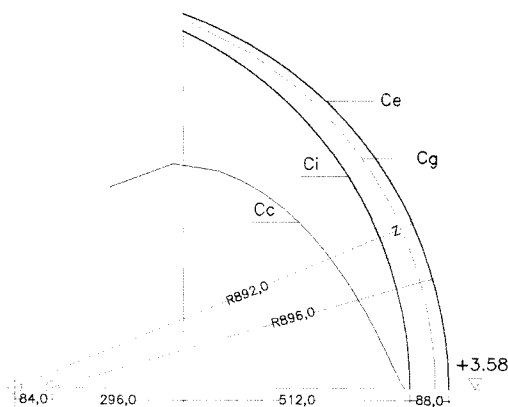


Figure 12
Geometry of the «lobe» for the church of Pont du Suert.
(Source: Antuña 2002)

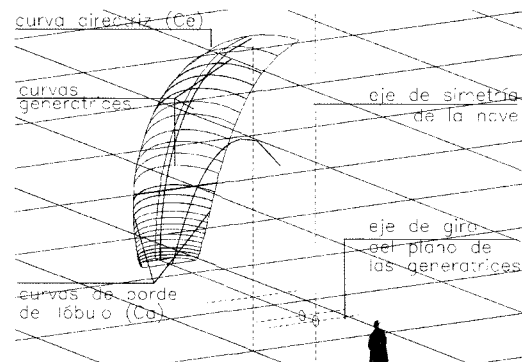


Figure 13
Three-dimensional drawing of an individual lobe. (Source: Antuña 2002)

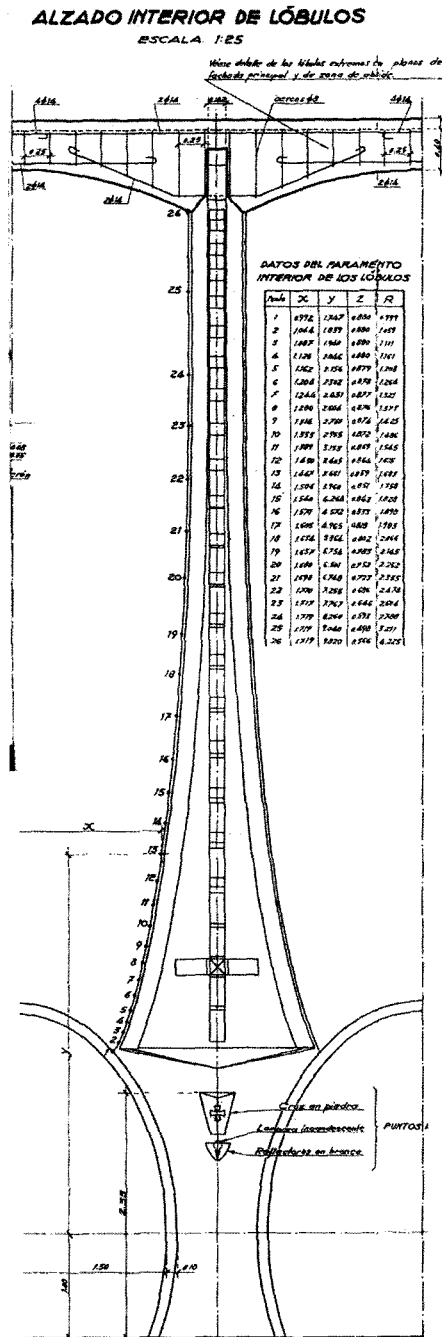


Figure 14
Elevation of the intersection between two lobes, including a table giving the geometry. (Source: Torroja archive)

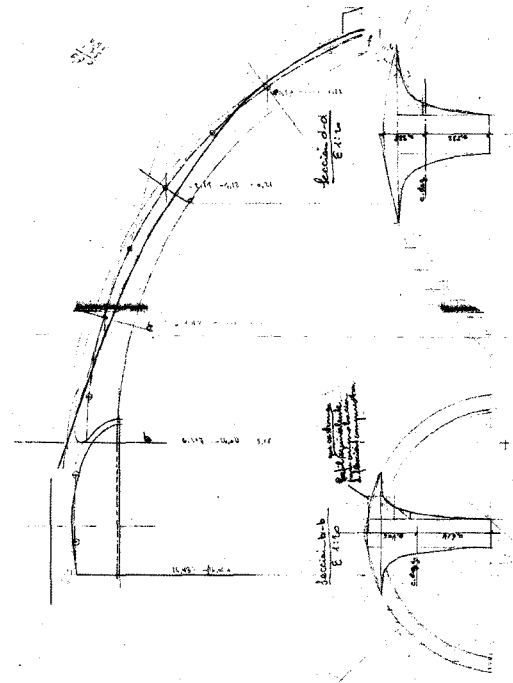


Figure 15
Graphic calculation of the internal line of compression acting in the arch of the church of Pont du Suert under self-weight. (Source: Torroja archive)

predominantly, using a thickness of 17 cm, so that the slenderness ratio is 70. The form of the structure is designed to be maintained in compression and the internal steel reinforcing is kept to a minimum.

In his earlier projects of reinforced concrete shells, Torroja used surfaces of a simple geometry: spherical domes, cylindrical shells, or ellipses. He imposed this limitation because it allowed him to make an elastic analysis of the structure by integrating the equilibrium equations, which had only been established for simple geometries. However, beginning with the church of Pont du Suert, he proposed more complex forms culminating with the roof of the club Tachira de Caracas of 1957. In the church designs, the small span and slenderness of the shell provided a stable surface of double curvature with very low stresses in the material. (At the shell support for the nave of the church of Pont du Suert, the compressive stresses in the concrete are

approximately 2.75 kg/cm².) The design for the church of Pont du Suert is the result of a detailed study of the adequate form for a brick vaulted structure which could be constructed with minimal formwork.

DISCUSSION

In each of these three projects, Torroja chose reinforced brick for its advantages during construction. By using thin bricks, Torroja achieved complex geometries which would have been difficult to build in reinforced concrete. In particular, the formwork costs associated with reinforced concrete would have been prohibitive. Thus, Torroja's method of construction in reinforced brick is distinguished by one important characteristic: formwork is not required to define the curving brick surface. In each project, Torroja demonstrated the formal possibilities of reinforced brick as a construction system.

During his career, Torroja experimented with methods for combining the brick with the steel reinforcing. In particular, it is clear that he used different methods of constructing the caissons for the Sancti Petri Bridge, in some cases installing the steel prior to the brickwork and in other cases installing the steel after the brick.

Significantly, the Sancti Petri caissons and the Zarzuela reservoir were not mentioned in the commemorative journal issue published by the Torroja Institute after his death. (*Informes* 1962) This suggests that contemporary engineers did not attach much importance to Torroja's system of reinforced brick construction. Most engineers of the period did not think of reinforced brick as a viable system for large-scale structural problems, perhaps because they viewed brick as an antiquated material when compared to «modern» reinforced concrete.⁵ Yet, these early projects in reinforced brick were clearly important to Torroja, for he included both projects in a book describing his best work. In the preface of the book (originally published in 1958) he wrote: «Many of my works are not mentioned here, but I feel that the few which are included best exemplify what I was searching for, and what I finally achieved.» (Torroja 2000)

Given the recent interest in reinforced brick structures designed by Eladio Dieste, it is worthwhile to compare and contrast the methods of *cerámica*

armada developed by each engineer. Torroja and Dieste proposed two different solutions in *cerámica armada*, at approximately the same point in history, with the aim of reducing the construction cost for long span roof systems. The system developed by each engineer had various aspects in common:

- a) In both cases, the structures have a form which is difficult to express analytically, but can be built easily due to the nature of brick construction.
- b) Both engineers considered the structures to be formed by homogeneous and isotropic materials and they both made elastic analyses of their structures.
- c) The shells are formed by modular elements, which can be repeated indefinitely, and can be built by reusing the same scaffolding and formwork.

However, the systems of reinforced brick designed by Torroja and Dieste are significantly different:

- a) In the architectural design of the church of Pont du Suert, Torroja chose to finish the brick on the interior and exterior with a layer of mortar and paint. Dieste left his brickwork exposed in most of his completed designs. Though Dieste's method was less expensive, Torroja was concerned about the long-term durability in the harsh environment of the Pyrenees and his protective layer of mortar and paint is justified.
- b) Though both Dieste and Torroja innovated in *cerámica armada*, their construction systems were completely different. Dieste proposed structures similar to thin shells of reinforced concrete that could only be built on a continuous formwork. In Dieste's structures, large tension forces are resisted by extensive steel reinforcing. Torroja's structures are closer to the tradition of timber vaulting, in which the brick is in a state of compression. Torroja explored forms which could be maintained in compression, with only small values of tension carried by minimal steel reinforcing.

Both Torroja and Dieste proposed solutions in *cerámica armada* as an alternative to the dominant system of reinforced concrete construction, though

few engineers have pursued this idea in recent years. Unlike Dieste, Torroja's proposals have not been further explored by engineers or historians of construction since his death in 1961.

CONCLUSION

By the 1950's, the construction of thin concrete shells was an expensive solution due to the increased costs of formwork and labor. Before steel construction became the most common structural solution for long spans, Torroja and others studied alternatives to reinforced concrete, which would not require expensive formwork systems. The construction aspects of these projects are of historical interest because they offer alternatives for an economical construction method using local materials.

Torroja's experimentation with reinforced brick was the result of his civil engineering education combined with his knowledge of the vernacular tradition of tile vault construction in Spain. The work of Torroja and Dieste suggests that brick is a useful material for structural design and construction, though these possibilities are largely unexplored in structural engineering today.

NOTES

1. Cottancin received a patent in France in 1890 and in Spain in 1891. His Spanish patent, No. 12301, was titled «objects of plastic material, with metallic reinforcing, composed of a wire or other mesh» (*Objetos de materia plástica con armazón metálica compuesta de tejidos de alambre u otros*). A Spanish competitor, Antonio Macia Llusá received a patent in 1894 (No. 15562) titled «A system of construction by means of reinforcing formed of steel wire mesh, combined with various layers of brick or hollow tiles, covered with mortar or a layer of concrete» (*un sistema de construcción por medio de armazones formados por mallas de alambres de acero, . . . , combinadas con varias capas de ladrillos o rasillas . . . , enluciendo o no la obra con mortero o una capa de hormigón*). Several water reservoirs were built in this system at the end of the 19th century in Spain.
2. It seems that Rafael Guastavino Jr. employed metallic reinforcing in some of his brick shell structures in the United States, though more research is required to document the extent of this practice.
3. This is the same construction system that the Guastavino father and son employed with wide success in the United States. (Huerta 2001)
4. One critic wrote that these mountain churches were «among the most ridiculous monstrosities in modern Spanish architecture.» (Fernández and Navarro 1999)
5. This situation is reminiscent of what historian Eric Schatzberg (1998) has termed the «progress ideology» of metal, when engineers neglected the advantages of wood as a structural material for airplanes during the 1930's and 1940's, choosing metal instead.

REFERENCES LIST

- Antuña Bernardo, Joaquín. 2002. *Las estructuras de edificación de Eduardo Torroja Miret*. Doctoral Thesis, Escuela Técnica Superior de Arquitectura de Madrid, Madrid.
- Billington, David. 1985. *The Tower and the Bridge: The New Art of Structural Engineering*. Princeton University Press, Princeton, NJ.
- Collins, George. 1968. «The Transfer of Thin Masonry Vaulting from Spain to America.» *Journal of the Society of Architectural Historians*, 27: 176–201.
- Fernández Ordóñez, José Antonio and Navarro Vera, José Ramón. 1999. *Eduardo Torroja Miret, Engineer*. Ediciones Pronaos S.A., Madrid.
- Frampton, Kenneth. 1995. *Studies in Tectonic Culture*. MIT Press, Cambridge, Massachusetts, pp. 54–56.
- Huerta Fernández, Santiago. 2001. *Las Bóvedas de Guastavino en América*. CEDEX, Madrid.
- Informes de la Construcción*. 1962. No. 137, Instituto Eduardo Torroja de la Construcción y del Cemento, Madrid.
- Jiménez Torrecillas, Antonio (Ed.). 2001. *Eladio Dieste 1943–1996*. 4th Edition, Junta de Andalucía, Seville.
- Ochsendorf, John. 2003. «Eladio Dieste as Structural Artist», in *Eladio Dieste: Innovations in Structural Art*. Stanford Anderson, Editor, Princeton Architectural Press, Princeton, NJ.
- Pedreschi, Remo. 2000. *Eladio Dieste*. Thomas Telford Publishing, London.
- Schatzberg, Eric. 1998. *Wings of Wood. Wings of Metal: Culture and Technical Choice in American Airplane Materials, 1914–1945*. Princeton University Press, Princeton.
- Tomlow, Jos. 2001. «La bóveda tabicada a la catalana y el nacimiento de la “cerámica armada” en Uruguay.» in *Las Bóvedas de Guastavino en América*, Santiago Huerta, Editor, CEHOPU, Madrid, pp. 241–253.
- Torroja, Eduardo. 2000. *The Structures of Eduardo Torroja*. 2nd Edition. (in English), CEDEX, Madrid. (First edition, 1958, F.W. Dodge Corp., New York.).