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Industrialization and prefabrication of thin vaults and shells in Latin America during the second half of the 20th century

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Abstract
After World War II, the socio-economic difficulties in some Latin American countries often led to political instability conditions. In this complex context, solutions were adopted by some designers to meet looming needs: housing for populations reduced to poverty and the construction of strategic infrastructures.
In these countries, starting from the 1940s, the introduction of new techniques and materials - such as concrete and steel - enabled the industrialization of building processes. This also allowed the experimentation of standardized models of thin vaults and shells using the traditional thin vaults, whose technique was imported from the Iberian Peninsula as a reference.
The solution of "thin" vaults is one of the most interesting, given the peculiarities that distinguish it from other systems. The small thickness of such vaults derives from the consideration that their strength is determined by their shape and cohesive behavior, following the theories of R. Guastavino Moreno.
Based on these assumptions, this paper aims to review some solutions developed for the prefabrication of thin vaults and the construction of some remarkable buildings. Based on the principles of prefabrication and reinterpretation of the traditional construction technique, the solutions adopted in some emblematic buildings can be useful for suggesting the development of new technical solutions to put in place shells and thin vaults in the second millennium.

Keywords: Thin vaults, Thin shells, Latin America, Prefabrication, Industrialization

1. Introduction

This paper shows the solutions adopted after World War II in several Latin American countries for prefabricated elements for constructing shells and thin vaults. In these countries, the use of brick elements was predominant over other building materials due to the high import cost of the latter. Prefabrication techniques for such thin-layered structures led to a reduction in construction time, and even today, they can be used as a model for the construction of modern prefabricated thin vaults/shells, where ribbing can be reduced or eliminated.

Uruguay, Mexico, Argentina, and Colombia are the Latin American countries where the work of designers such as Eladio Dieste, Carlos González Lobo, or Mario Kalemkerian took shape, significantly contributing to the development of the thin-shell technique. The circumstances in which these designers worked were marked by political instability and unfavorable economic conditions. This prompted them to think of vaulted systems in which they could combine their knowledge of building history with the possibilities obtained from the use of techniques and materials that were becoming preferred in those years (steel and reinforced concrete, among all).

The thin-tile vaulting technique has been altered throughout history. Designers/builders have been able to adapt them more and more effectively to the varying dimensions of the spaces as well as to the types of buildings in which they were being built.

On the origin of the construction technique related to thin vaults, many debates still take place and there are many hypotheses suggested to identify where it would derive from: from the timbrel vault found in the Campbell chamber inside the Great Pyramid of Giza (ca. 2550 BC) [1] to the *bipedales* brick vaults (sized 60x60x7 cm) of Roman times

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[2], to the hypothesis of an Arab architectural inspiration [3]. The oldest written evidence of the brick-and-gypsum mortar setting system dates from an early 15th-century document concerning the construction of a vault for a votive chapel in Valencia, Spain [4]. In the Spanish regions of Catalonia and Extremadura, some excellent examples of the so-called *bóvedas tabicadas* (bricked-up vaults) are still visible [5]. More examples, in addition to the Iberian area, can be found in Portugal in the Alentejo region (hence the name *abobadilhas alentejanas*, Alentejo vaults) [6], and in France, in Languedoc-Roussillon, where *combles briquetes* (bricked roofs) can be observed [7]. In Italy, they are known as *in folio* vaults [8] or, in relation to the areas where they are built, as *volterrana* vaults (in central Italy) [3] or *realine* vaults (in Sicily) [9] (Fig. 1, left).

The traditional construction technique for thin vaults consists of thin clay masonry tiles (no greater than 3 cm thick and weighing 1.6 kg) joined with gypsum mortar (in many cases combined with various materials or, more recently, substituted by cement mortar) [10]. The lightness of the tiles and the rapid setting of the mortar used to bind them offer several advantages, such as the ease and rapidity of installation and the absence of any ribbing systems. These features remained nearly unchanged until the end of the nineteenth century. Afterward, the advent of materials that were no longer associated with local culture, such as concrete and steel, enabled the testing of new geometries distinguished by their "free" shapes. As a result, an increase in the plan size of the elements (vaults or shells) corresponds proportionally to an increase in their thickness, albeit in a considerably smaller percentage when compared to typical vaults. In general, the capacity of shells to resist loads is dependent on their resistance by shape, namely the structural form (a unity of function, material, and statical principles) [11]. In this sense, Rafael Guastavino Moreno (1842–1908) is considered a pioneer in designing and constructing thin vaults. Thus, between the 19th and 20th centuries, he was able to rethink and readapt the *tabicada* technique, even registering several patents [1], exporting it to the United States of America, and carrying it to a level of excellence and audacity until then unexplored. He is also the first theorist of the structural behavior of thin vaults, defined as "cohesive structures", that is, structures in which the composing materials cannot be separated without destroying the entire element [12].

There is one distinction to be made between "carrying shells" and "carried shells". While these two varieties may appear to be similar from an architectural point of view, the distinction is primarily structural. In fact, in a carrying shell, subtracting a portion leads to a redistribution of internal tensile states. On the other hand, in a carried shell, the stress states remain unchanged. This is because, while stresses are distributed in a continuous pattern in the carrying shell, they are distributed linearly along the shell's surface in the carried shell, which behaves similarly to grid-shells. Otherwise, carrying shells must be modeled for planar continuous elements, whereas carried shells can be modeled for linear elements. Therefore, because of their conformation and structural behavior, shells and vaults shown in this paper can be considered carrying shells.

The earliest example of a proper thin shell is Robert Maillart's Cement Hall, built for the 1939 Swiss National Exhibition in Zurich and later demolished (Fig. 1, right) [13]. It was built using reinforced concrete, consisting of a parabolic shell connected to two large central arches. One of its remarkable characteristics was the lack of gaps between the roof and the vertical walls (a common characteristic of all thin shells).

Fig. 1. Left: *View of the extrados of a* realina *vault in Partinico, Sicily. Image by C. Di Maggio, 2019.* Right: *Cement Hall by Robert Maillart. Image by Billington, 2003.*

2. Evolution of the construction technique in Latin America

In Latin American countries, the earliest examples of thin vaults can be dated back to the work of the Valencian missionary Fray Domingo de Petres. Between 1759 and 1811, the missionary employed the traditional technique of

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tabicade vaults in Colombia in the buildings he built [14]. This technique, which soon spread to other countries [15], remained almost unchanged until the second half of the 20th century. During those years, each state's complex and unique socio-economic context provided fertile ground for experimenting with various vault and thin shell construction methods. In particular, these solutions were related to the specific area and used for the roofing of social housing as well as large strategic and public buildings. In this sense, the limited availability of economic resources and the consequent reduced import of cement and steel from abroad led designers to adopt building solutions using the raw materials available, including bricks largely used in traditional construction.

Since the second part of the 20th century, different types of shells and thin vaults have been tested in Latin America: reinforced ceramic shells, reinforced brick prefabricated vaults, and precast reinforced concrete vaults (see Tab. 1). Several variations exist for each designer who designed them, and in each country where they were built, not only in accordance with the various dimensions of the space to cover but also to specific circumstances. As a result, shell thicknesses vary, ranging from approximately 4 cm for vacuum concrete shells to 12 cm for Dieste's *cerámica armada* shells [16]. Another distinguishing feature includes the different types of ribs, formworks, or molds used to build or precast the various shells designed. The primary material used is wood due to its economy. Moreover, molds made of ceramic material have been used to shape the elements of on-site prefabricated vaults and shells and to shape the elements in reinforced brick or reinforced concrete.

Tab. 1. *Overview of the different types of shells/vaults designed and built in Latin America in the second half of the 20th century.*

Types of shells	***Designer***	***Country***	***Typology***	***Thickness***	***Type of application***	***Ribs/formworks/ molds***
Reinforced ceramic shells	*Eladio Dieste*	*Uruguay*	*Gaussian vaults and self-carrying shells*	*<12 cm*	*Community buildings – Industrial buildings*	*Wooden movable ribs*
Reinforced brick prefabricated vaults	*Eduardo Sacriste*	*Argentina*	*Vaults made of bricks set with cement mortar*	*[illegible]7 cm*	*Middle-class housing*	*Wooden formworks*
			Vaults made with prefabricated modules			*Light wooden formworks*
	Carlos González Lobo	*Mexico*	*Vaults made with modular prefabricated vaulted elements*	*<[illegible]0 cm*	*Poor class buildings*	*Vault mold built on-site made of ceramic material*
	Mario Kalemkerian	*Argentina*	*Self-supporting, prefabricated, brick vaults*	*5 cm*	*Strategic buildings*	*Vault mold built on-site made of ceramic material*
			Dome made of brick elements	*12 cm*		*Cover of a water tank used as a formwork*
Precast reinforced concrete vaults	*Álvaro Ortega*	*Colombia*	*Vacuum concrete shells*	*3.8 cm*	*Social housing*	*Wooden formwork built on-site*
	Teodoro González De León	*Mexico*	*Structurally independent prefabricated modular vaults*	*N/A*	*Social housing*	*N/A*

2.1 The reinforced ceramic shells

In the thin shell construction process, the improvements made by Uruguayan Eladio Dieste (1917-2000) deserve special attention. He is considered the initiator of the large-scale use of a new construction technique involving the use of local materials (brick for construction and timber for ribs), limiting the consumption of other imported materials, effective because of the simplicity of assembling the elements. It is referring to the so-called *cerámica armada*, consisting of «...shells formed by a single layer of tiles laid flat and with continuous joints in both directions so that both in the catenary directrix of the vault and along its rectilinear generatrix can be placed a small metal reinforcement that allows the complex to act as an elastic membrane. Once the ceramic part of the vaults is finished, a top layer of sand and Portland cement is added, in which a thin steel reinforced mesh is embedded to control shrinkage actions...» [17].

The layer of brick placed on the intrados, which in most cases remained exposed even after the work was completed, served as a formwork for the reinforced concrete cast in the following phase. The choice of this material - a high-quality product in countries such as Uruguay, Argentina, and Brazil - is related to its high mechanical compressive strength,

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which can reach up to 1,500 kg/cm^2. Moreover, as Dieste himself states, «...for the same strength, brick has a lower modulus of elasticity than concrete, which is an advantage and not a drawback, because it gives the structure greater adaptability to deformation...» [18]. Other benefits of using brick include better resistance to thermal shock and aging, as well as better acoustic and environmental qualities [19]. This construction system, which makes it possible to obtain structures whose maximum thickness -in realized cases- is 12 cm [20], has been applied for the construction of different shells and vaults belonging to two different categories based on the catenary principle: *bóvedas gausas* and *cascaras autoportantes*.

Among the former - literally "Gaussian vaults" (from the mathematician Karl Gauss, who described the geometry of curved surfaces) - belong those structures in which the double curvature of the geometries used allows structural resistance to loads otherwise not possible with single planar surfaces [21]. These vaults were made by varying the width of the shell's rise from a maximum value at the key to zero at the side walls. The geometric shape was achieved by moving a catenary with a fixed span and variable rise contained in a movable vertical plane that moved while remaining parallel to another fixed vertical plane [20]. In *bóvedas gausas*, the typical span-to-rise ratio is 10. From a structural point of view, the undulating geometry is designed to withstand deformation, providing, at the same time, maximum efficiency in the use of materials. Furthermore, the axial compression of the brickwork by its own weight is ensured by the catenary geometry of the vaults [22]. Examples of such shells are found in the Church of Christ the Worker in Atlántida (1958-1960), the TEM Factory in Montevideo (1960-1962), the Cítricos Caputto Fruit Packing Plant in Salto (1971-87) (fig. 2, top left), and the Cadyl Horizontal Sylo in Young (1976-1978) (fig. 2, top right).

The second category -constituting self-supporting shells- includes cylindrical barrel shells that, given their shape, resist bending as well as compression. Dieste developed an effective pre-stressing method to resist tensile stresses due to bending. This method consisted of placing steel cables in a ring shape on the top of the shells, anchoring them at each end of the shells. Pre-stressing was produced by pinching the cables together at the center point of the rings and conforming them into an "eight" shape (Fig. 2, bottom left). Once the required extension was reached, the wires were held in place by metal clamps. Finally, a concrete screed was cast to cover the wires [23]. The Lanas Trinidad Wool Industrial Complex in Trinidad (1965-1989) and the Municipal Bus Terminal in Salto (1973-1974) (Fig. 2, bottom right) were built using this method, which allowed cantilevers of up to 15 m.

In setting up these systems, particularly the bóvedas gausas, Dieste used the so-called *encofrados* (formwork/scaffolding), which provided a double advantage. In fact, on the one hand, since they could be used repeatedly, it was possible to make considerable savings in terms of materials. On the other hand, equally important was the time savings in both the construction of the ribs themselves and the shells (in fact, it was possible to strike the formwork 24 hours after completing the vault [22]). Each *encofrado* consisted of a rigid steel tube frame supporting a steel truss. Above this, a wooden truss had the task of defining the shape of the vault. The vertical sliding of the two trusses on the frame allowed them to be quickly moved after the construction of each vault and positioned for the installation of the adjacent vault [21].

In the entire production of Eladio Dieste, the load-bearing capacity of shells and vaulted structures depends essentially on their shape and is determined not empirically but through the use of calculation methods usually adopted for reinforced concrete shells [illegible].

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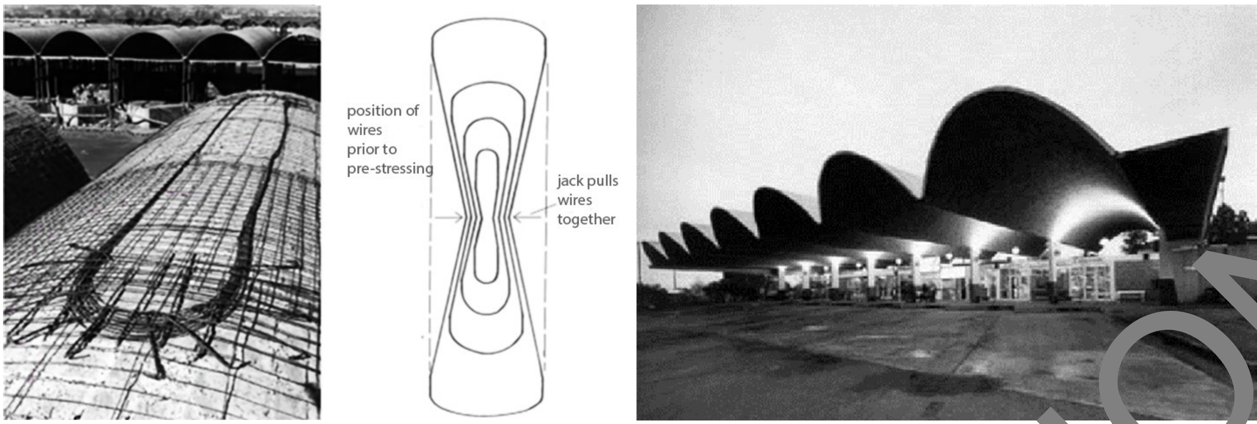

Fig. 2. Bóvedas gausas. Top left: *Cítricos Caputto Fruit Packing Plant. Image by Anderson et al., 2004* Top right: *Cadyssa Horizontal Sylo. Image by Anderson et al., 2004* Cascaras autoportantes. Bottom left: *Looped pre-stressing steel. Image by Pedreschi, 2006.* Bottom right: *Municipal Bus Terminal in Salto. Image by Anderson et al., 2004.*

2.2 The reinforced brick prefabricated vaults

Following the innovative capacity of Eladio Dieste's constructions in Uruguay, in Argentina, an innovative impetus for industrialization and, especially, prefabrication of thin-shell vaulted systems was Eduardo Sacriste (1905-1999) [24].

Sacriste's ability to combine aspects related to local building traditions (*tabicade* vaults were typical in the province of Córdoba) with the innovations he found in some examples of modern architecture (Casas del Garraf by Sert and Torres Clavé, Casa Berlingieri by Bonet and Dieste, Jaoul and Sarabhai houses by Le Corbusier) was useful in arriving at the definition of new techniques for setting up shells and thin vaults in Argentina.

His production focused on the design and construction of small-scale buildings: these were often single-story isolated houses, organized according to several adjacent spans, with heavy masonry walls on top of which the beams to support the vaults were built (Fig. 3, top left). The bricks for the vaults, produced in factories, were set in place with cement mortar to form two or more overlapping layers or a single layer to which a functional layer of concrete was superimposed, varying in thickness from 5 to 7 cm. In the case of House B of the Clérico Hermanos (Fig. 3, top right), built in 1948 in Salta province, the vaulted ceilings are made with a first layer of thin tiles measuring 20x20 cm (*tijuelas*), while the successive two staggered layers are of ordinary bricks. The mortar used is cement mortar. The spandrels of the vaults are filled with concrete (strong concrete up to 30 degrees from the springing line and, above this, concrete lightened with rice husk ash), on top of which there is a waterproofing layer (Fig. 3, bottom left). A layer of soil was finally placed at the extrados. The sides of each series of vaults terminate with a one-meter-wide flat slab, which acts as a buttress, thus countering the thrusts of the extreme vaults [2]. Another example of a vaulted roofing solution is one in which a single layer of ordinary bricks was laid on top of a lightweight metal formwork with the overlay of a 3-cm functional layer of concrete. In adhesion to this, a layer of about 10 cm of lightened concrete was placed. The extrados was completed using bituminous sheets and tiles for rainwater drainage. Sacriste's acumen is expressed in his ability to design buildings that are easy to build and low-cost (Casa Experimental Clérico Hermanos, Casa Experimental de San Miguel de Tucumán), in which the use of steel, as well as concrete, is kept to a minimum. Another remarkable example is the creation of vaulted buildings for the upper classes (Casa Clérico, Casa Wright), in which the principles of *cerámica armada* learned from the lesson of Eladio Dieste were applied.

Following the growing interest in prefabrication between the 1960s and 1970s, Sacriste and his group also tested various prefabricated thin vault solutions. The main objective was to overcome the scarcity of materials throughout the country and, above all, the lack of skilled labor. An example of an application in this sense is the Casa Carrieri (1961): here, spaces are subdivided according to the prefabricated modules of the vaults (called *costillas*), having dimensions of 3 m by 50 cm and a weight of about 200 kg. These modular elements, when placed together and joined according to their largest side, form the vaults of the different rooms of the dwelling.

On-site prefabrication was done with wooden formworks (as for the vaults of Casa Robert, Fig. 5, bottom right) or in brickwork (as for the vaults of Casa Carrieri) completed with mortar on top of which bricks were placed and joined. The use of a light scaffolding -useful also to allow transport- was provided for connection to the other *costillas* or to the perimeter walls, without the need, therefore, for supporting ribs at the time of installation.

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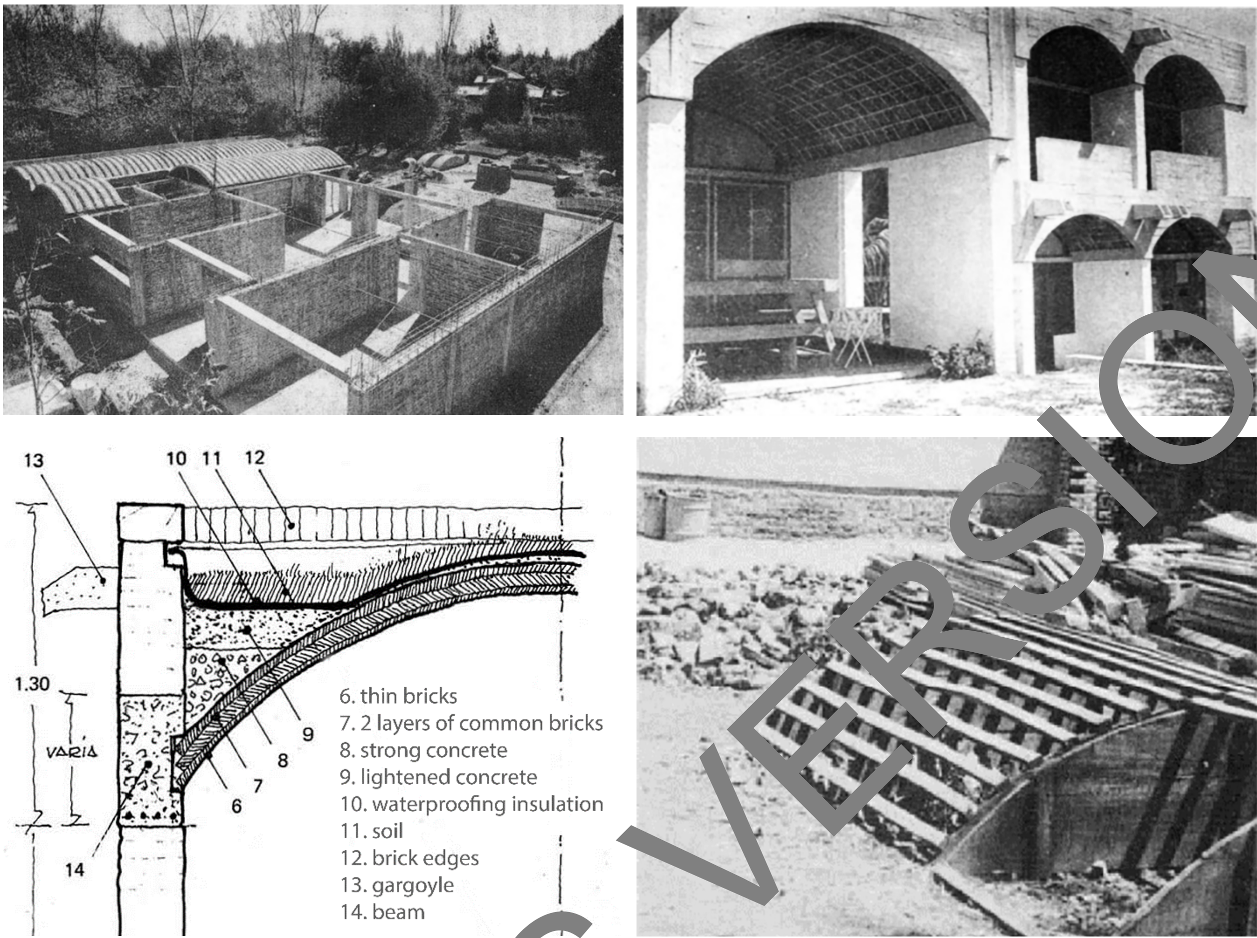

Fig. 3. Top left: *Reinforcement of the support beams of the vaults of Casa Carrieri.* Top right: *Gallery of Casa B of the Clérico Hermanos.* Bottom left: *Structural section of the vaults of Casa B of the Clérico Hermanos.* Bottom right: *Wooden formwork used for the vaults of Casa Robert. Images by Sacriste et al., 1977.*

In Mexico, the architect Carlos González Lobo (1939-2021), similarly to what Sacriste developed in Argentina, spent his time, until his recent death, experimenting with and building housing systems intended especially for the poorer classes [25].

Gonzalez Lobo's starting concept was the *gran galpón* (large shed), a large transformable open space covered by a thin vaulted roof that allows for greater volumetry.

González Lobo experienced the so-called "CGL-2 system", taking Dieste's *cerámica armada* as a reference, which he modified according to emerging needs and renamed *ladrillo armado*. An evolution of the earlier "CGL-1 system", CGL-2 consisted of modular vaulted elements made of clay bricks held together by steel and concrete reinforcement. The modular elements to be built, also called *costillas*, were conformed as smaller portions of barrel vaults, making them easier to transport and put in place. Each *costilla* was realized on top of a curved mold previously built on site (Fig. 4, left), filled with stones and spoil, and covered with a layer of lean concrete. Each unit involved the combination of a series of bricks placed in the plane, in a double row and single layer. In the joints between the bricks, of about 10 cm, ϕ6 steel bars, and iron wires were placed to form the reinforcement for the subsequent concrete filling (cement and sand in a ratio of 1:4). For the vaulting, the various *costillas* were assembled. The reinforced concrete edge beams were placed on the perimeter walls, while in the key, the reinforcement for a triangular section beam (*cadena triangular*) was installed. Once the concrete was placed, this beam was supposed to reinforce and join the various modules (Fig. 4, right). The vault was completed by a functional concrete layer where the steel-reinforced mesh was placed [26].

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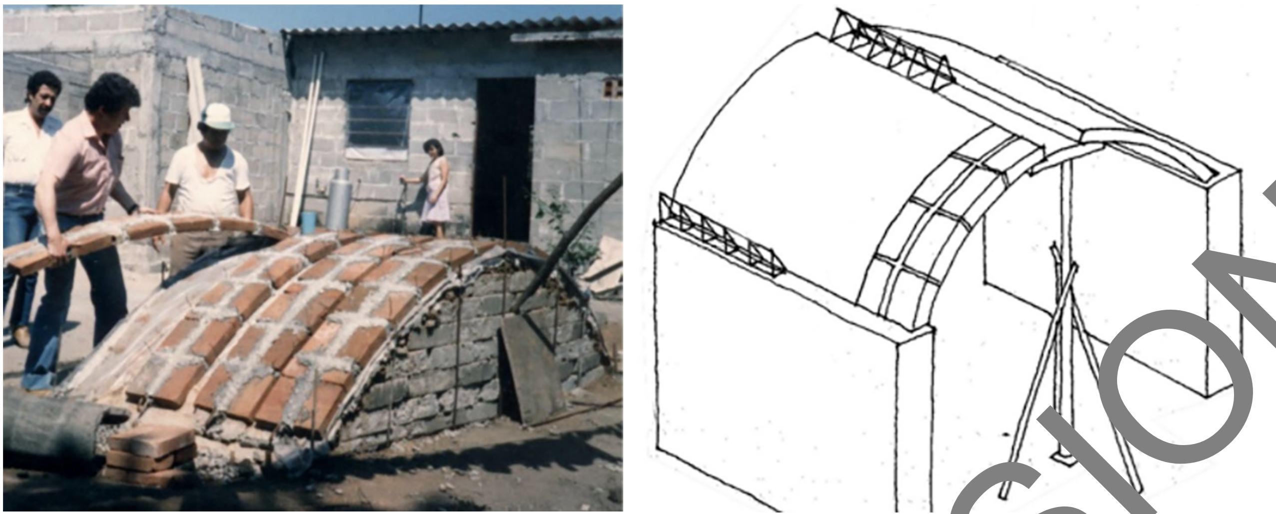

Fig. 4. Left: *Carlos González Lobo raises a* costilla *from the mold.* Right: *Connections of the costillas with the main structure. Images by Gonzalez Ortiz, 2001.*

An example of the use of precast thin reinforced brick shells made for roofing large buildings is due to Uruguayan architect Mario Kalemkerian. In this case, the system was used to rearrange the arsenal of the Argentine National Army. Kalemkerian's input included design for both the modernization of existing structures and the construction of new structures for use by civil staff [27].

The planned works included installing a series of prefabricated elements, from new roofs for existing buildings to floors and vaults. The latter are self-supporting, prefabricated brick vaults with a span of 13 m, rise of 1 m, and weight of about 6 t, while their thickness is 5 cm, corresponding to the thickness of the bricks with which they were made [15].

The vaults were executed on-site in the close surroundings of the building site (Fig 5, top left). To simplify the prefabrication work of these building elements, a vault mold (*boveda-molde*) was made of ceramic material, thus obtaining a shape conformed with sand and Portland cement, avoiding edged points to ease detachment during the removal of the formwork. This same vault mold was also helpful in forming the front gables of the vaults. The inner faces of the gables were separated by 5 cm from the formwork, covering them so that, during the lifting procedure, the inner formwork would detach without difficulty.

Once all the vaults were placed in their final position, the anchor bars of the piers and the bars of the edge beams were bent to give continuity to the adjacent panels. Similarly, a steel-reinforced mesh was placed later covered with a mortar layer of cement, sand and gravel, looking after its subsequent curing (Fig. 5, top right). Finally, the vaulted elements were finished with a white cement layer.

In addition to the main buildings, another planned space within the arsenal was a building to house the Oficina de Relaciones Laborales. The roof of this building is a dome -equipped with a skylight- made of brick elements with a diameter of 8 m and a 40 cm rise, weighing about 200 kg/m on the structure below. The formwork with which this was made is the cover of a water tank near the building (Fig. 5, bottom left).

Bricks used for the construction of the dome were placed following the direction of its construction. For every two rows, a d6 rod was inserted as a bracket. To overcome the dome thrust problem, a reinforced concrete beam with a height of 7.5 cm, coinciding with the thickness of the bricks, was placed along the entire circumference. Another beam, 5 cm thick and 25 cm high, was placed to delimit the skylight. Once the beams were completed, a 2-cm layer of reinforced concrete and an isolating layer of expanded polystyrene sheets were placed on the extrados of the dome. Finally, everything was covered with 3 cm-thick tiles (*tejuelas de campo*) (Fig. 5, bottom right).

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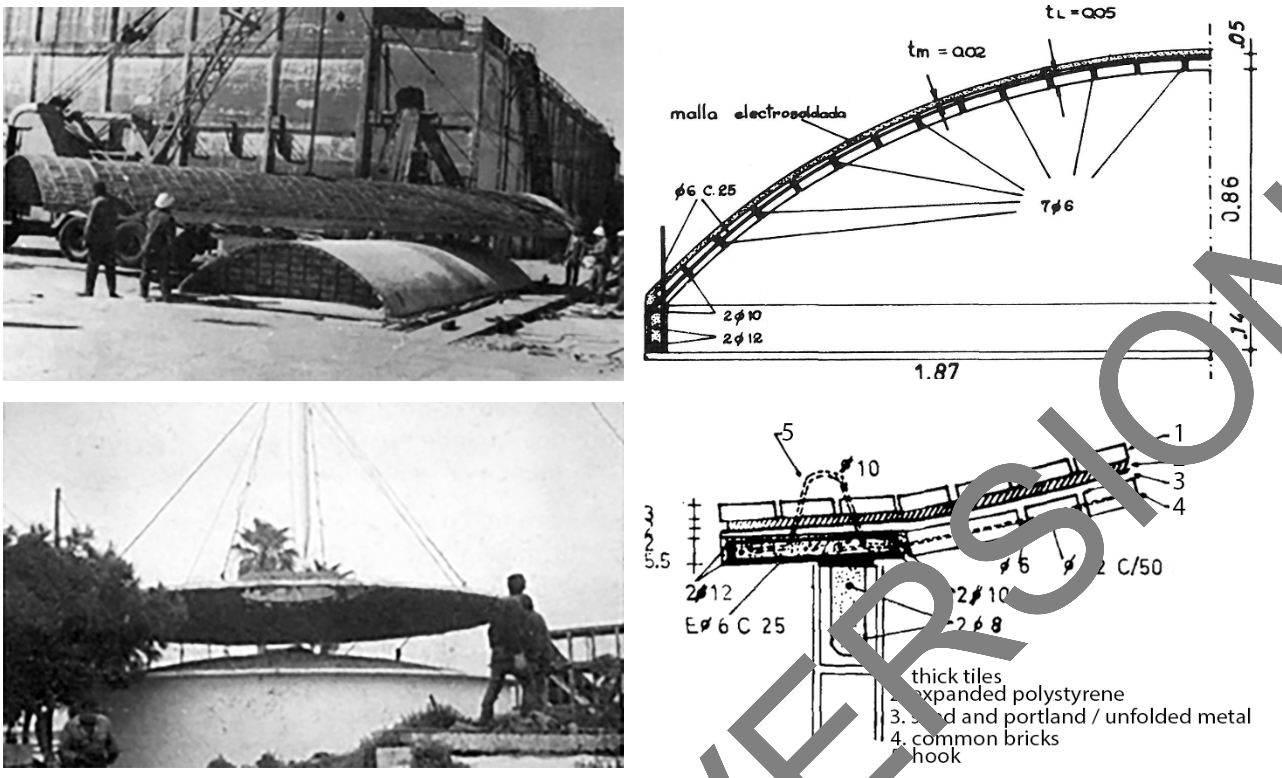

Fig. 5. Top left: *Transportation of two of the arsenal vaults.* Top right: *Structural section showing vault reinforcing bars and steel reinforced mesh.* Bottom left: *Lifting the dome from the tank used as formwork.* Bottom right: *Structural section of the dome. Images by Kalemkerian et al., 1976.*

2.3 The precast reinforced concrete vaults

In Colombia, the construction technique of Spanish *bóvedas tabicadas* was imported in the late eighteenth century. This remained almost unchanged until the 1950s. The spread of more modern materials and techniques, in fact, allowed the use of thin shells not only for social housing settlements but also for the roofing of large industrial sheds or factories. Among the most significant innovations in this regard is the use, by Álvaro Ortega, of the patented vacuum concrete system (*hormigón al vacío*) [28].

The patent titled "Method of and apparatus for treating concrete", registered by Karl Pauli Billner in 1936 and followed by other patents, requires the use of a vacuum pump to remove exceeding water from the wet concrete mix, improving its strength and reducing setting time. The advantages of this system are «…increased resistance, economy, elimination of formwork and nails, with quick construction, all concrete processed with vacuum can be used 24 hours after casting, an increase of resistance against time, maximum compactness and impermeability…» [29]. Furthermore, there is no need for skilled labor.

Starting in the 1950s, after obtaining the franchise for the Vacuum Concrete de Columbia company, Ortega used the system for residential and industrial buildings. The construction of 102 residential units in the *barrio* (neighborhood) Quiroga in Bogotá from 1951 to 1953 allowed for the large-scale application of the system, which was used to make the external walls and roofing shells. The dimensions of the shells were 5.08x5.18 m, for a thickness of about 4 cm. Each shell was internally reinforced with wire mesh. Construction began with the shaping of the first shell on a wooden formwork, thus making sure that the thickness was kept constant. After that, above this, the other shells were shaped, using layers of paper to divide them from each other. Thereby, each shell formed the mold for the next shell, and this allowed up to eight shells to be made per day (Fig. 6, left). The shells, as well as the panels constituting the walls, were moved by the so-called "Vacuum Lifter method", consisting of suction cups attached to girders hooked to a crane (Fig. 6, right).

During and after construction, several critical issues emerged due to inaccuracy in the formation of the different components on site: the non-perfect adherence of the joints between walls and shells, the presence of humidity in the canals formed between the shells, as well as the cracks that appeared due to stresses on the edges of the prefabricated elements.

The solution adopted by Ortega was improved in subsequent commissions concerning the construction of some industrial buildings in Bogotá (Clark's Chewing Gum factory and a warehouse owned by Banco de Bogotá). However,

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a growing general disinterest in precasting and, at the same time, the availability of more affordable steel quickly led Vacuum Concrete de Columbia to cease operations.

The use of precast systems, industrialized construction processes, and adherence to the principles of modular coordination can be found in other Latin American buildings constructed after World War II. Such is the case of González de Léon's José Clemente Orozco residential complex in Guadalajara, Mexico.

Fig. 6. Left: *Construction of the shells above a wooden formwork with vacuum concrete.* Right: *Setting a shell as a roofing for a residential unit through the Vacuum Lifter method. Images by Galindo-Diaz et al. (2022).*

In Guadalajara, central Mexico, another case of the application of thin prefabricated vaults based on a design by Teodoro González de León can be found: the José Clemente Orozco residential complex, built in the late 1950s (1957-1959) [28]. This is a unique example of prefabrication of structurally independent modular vaults to roof 488 single-story housing units.

The module-type consisted of a precast concrete paving-type vault to which a perimeter drainage gutter was attached for rainwater collection and disposal. The shells and the panels to form the outer walls were prefabricated on-site and later moved with the aid of cranes (Fig. 7, left).

Given its conformation and small size, such a system allowed a great deal of freedom in the spatial arrangement within the urban fabric of the prefabricated modular units while also allowing free aggregation. Modules were distributed and combined to create free spaces of varied sizes and achieve different housing configurations (Fig. 7, right).

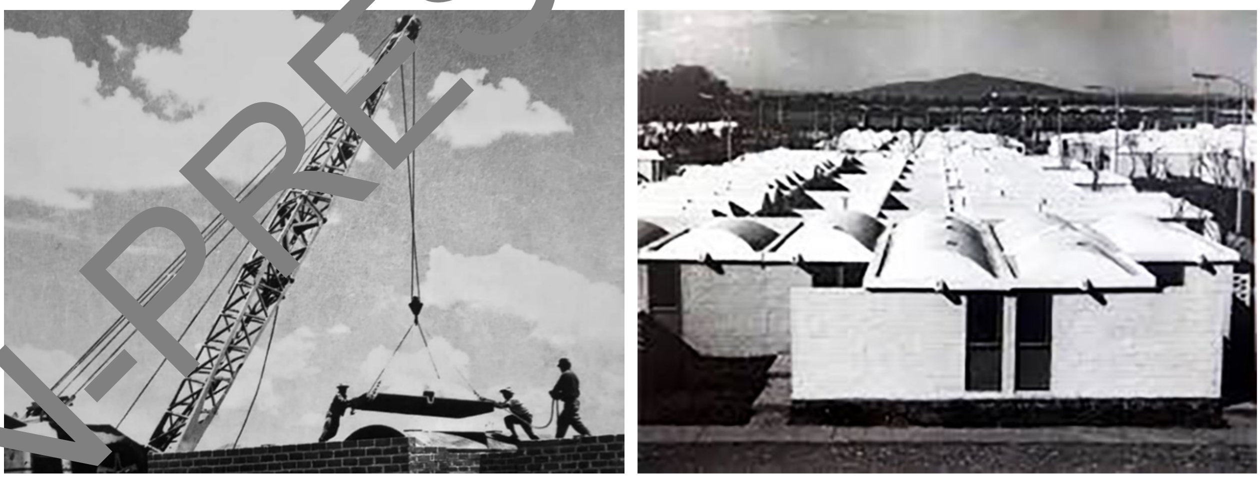

Fig. 7. Left: *Setting, by crane, of one of the concrete shells.* Right: *General view of the residential complex. Images by* https://momogdl.com/listing/unidad-habitacional-jose-clemente-orozco/

3. Conclusions

In the 20th century, Latin America became a center for developing and testing shell construction techniques and thin vault architecture.

Observation of the illustrated cases, particularly the various building approaches used to build them, allows for a

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description of some considerations. First, using vault molds for prefabrication on-site reduced the need for formwork and the need to move the parts to the construction site, leading to substantial savings in both time and money. Better scheduling and planning, together with increased oversight during the execution phase, usually allowed for the achievement of incredibly precise concrete proportions, thus resulting in material savings.

Another distinguishing factor in the prefabrication of these vaulted structures was the rapid training and education of the workers who materially constructed the various pieces to be assembled since it was possible to reduce the various stages to repeated and elementary movements.

The use of traditionally derived materials -such as clay bricks- and the availability of plants for their production in the proximity of construction sites has contributed to the overall economy of the system. Also remarkable is the ability to combine these materials with others unrelated to local culture (concrete and steel) so as to overcome their scarcity.

Finally, it is emphasized that the cases investigated refer mainly to the prefabrication of modular vaulted structures functional for use in the building, or reconfiguration, of houses or entire working-class neighborhoods. In addition, the design and configuration of such elements have been useful for the conformation of buildings and industrial warehouses of smaller sizes.

The importance of prefabrication in plants or on-site, the lack or reduced use of ribs, the skillful use and juxtaposition of different materials according to specific needs, the modularity of the built elements and the possibility of using even unskilled labor are some of the lessons that can be drawn from the case studies and from which it is possible to start designing and installing vaults and thin shells that can be used and reproduced both on a small (for civil buildings) and large scale (for industrial buildings or public infrastructure).

4. References

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