



Article

A Ferrocement Patent for Emergency Housing: The Technological Hut

Jorge Roa-Fernández *, Carmen Galán-Marín  and Carlos Rivera-Gómez 

Departamento de Construcciones Arquitectónicas 1, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avda. Reina Mercedes, 2, 41012 Seville, Spain; cgalan@us.es (C.G.-M.); crivera@us.es (C.R.-G.)

* Correspondence: jroa@us.es; Tel.: +34-954558593

Received: 7 October 2019; Accepted: 4 December 2019; Published: 11 December 2019



Abstract: This article focuses on the comparison between the Spanish architects de La Hoz (Madrid, 1924) and José María García de Paredes (Seville, 1924) projects for ‘ultra-cheap’ housing in Cordoba, how it evolved from a British patent named Ctesiphon, and the study of some of existing buildings erected following this construction system. The aim of this article is to establish the evolution of the system from the original patent into a new possibility for low-income social housing. This system was used to erect new developments in the 1950s that would relocate people living in huts during the dictatorship era in Spain, thus new “technological huts” were proposed and erected. The research process includes an analysis of the documents and literature available of the patent and the projects themselves, and in situ tests (infrared thermography and samples extraction) will allow to establish the relation between its original inventor, the dissemination of his works in publications from that era, and the Spanish company that subsequently, as a concession of the original patent, introduced that system in Spanish architecture. Analysis of the original patent document allows to study the primitive system as it was invented and for what uses it was conceived. Thus, such a methodology supports an establishment of the technical innovations achieved in order to adapt the system to the Andalusian environment at that time and its use for housing.

Keywords: Ctesiphon; ferrocement; emergency housing; case study; construction system

1. Introduction

Innovation in the field of architecture arises when architects are required to give a response with construction solutions adapted to and focused on a time and location and taking advantage of the technology available to do so.

After the Second World War, the positive conditions that were present in the previous era of experimentation in modern housing were substituted by a massive need of housing and emergency reconstruction plans for a collapsed Europe.

Spain, in the first half of 20th century, isolated due to its political regime, did not take part in the Great War and thus had no consequent need of reconstruction. Although due to its own internal situation, there was a large rural exodus towards the cities and subsequently there were a large number of different social housing programs throughout the 1950s and 60s. The economic weakness produced by a lack of solutions from the business sector, coupled with the lack of vision on the part of politicians, as well as information and technological isolation dragged Spain far behind the European trends and high growth of the 1960s [1].

Rafael de La Hoz (Madrid, 1924) and José María García de Paredes (Seville, 1924), belong to a group of young architects who defended the modern movement and the need for a professional, technologically updated model. This was not without difficulties however, with the trends and industrialized construction solutions available overseas. Rafael de La Hoz was a relevant contributor

to the IET (Technical Institute of Construction and Cement founded by Eduardo Torroja). Along with García de Paredes, several of his works obtained an early national prize of architecture in 1949. After a long and prolific career in 1987, he was awarded the Prince of Asturias's prize of fine arts.

This generation of Spanish modern architects based their proposal on three fundamental pillars: the need to generate a new language with the resources available, curiosity about new technologies and patents translated from non-architectural mechanisms and the necessity for new ways of conceiving local architecture [2], and the substantial social responsibility which the modern architect stands committed. In Spain, these three concepts of modernity made it possible to produce interesting solutions for social and economic housing so innovative as the concept of “technology hut” being analyzed in the present research (Figure 1).



Figure 1. Ctesiphon houses in Palma del Río. Notice on the left side the old existing huts to be replaced by the new houses [3].

The Ctesiphon System. British Origin

The name “Ctesiphon” was adopted by its inventor, James H.G. Waller, [4] after a visit to the ruins in the city of Ctesifonte—one of the most important cities of the Mesopotamian civilisation located on the banks of the Tigris River [5].

The Ctesiphon system is based on an inverted catenary arch vault formed by a concrete sheet. Its simplicity, not only in design and calculation, but also in execution, requires only a small number of unskilled workers to complete the construction in a short space of time.

Some authors establish the origin and first development of the new Ctesiphon constructive system in England around 1941, associating its use with military construction as in soldiers lodginga [5,6]. A military barracks plan designed by Waller in 1942 is shown in Figure 2.

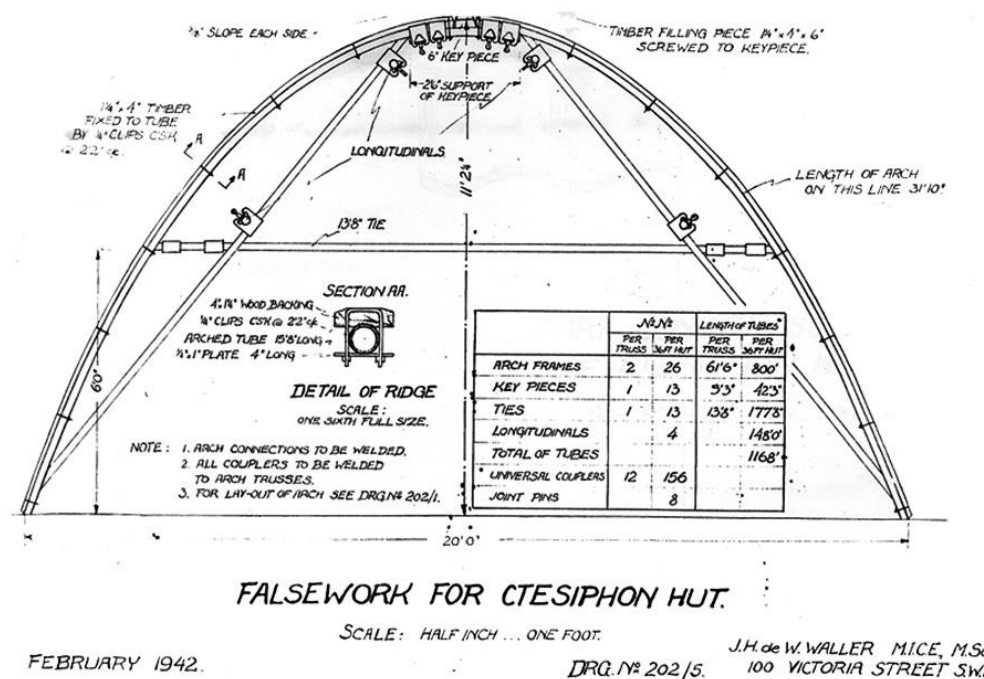


Figure 2. Cross section map of military barracks designed by Waller in 1942 [6].

For this research, the Ctesiphon in Spain has been analysed, as a patent recorded by the company Iberlar Edificios Patentados S.A [7]. The company's director, Francisco Moriones, repeatedly visited the architect De la Hoz in Cordoba in 1953, whereupon the architect intended to learn the origins of the system and began to apply it to isolated warehouses [8].

There is another link between the Ctesiphon system and De la Hoz: the publication in the Architectural Review journal [9] of "Christ the King" Church, erected between 1949 and 1950 in Bristol (Figure 3). The project was developed by the architectural office Burrough and Hannam and advised by engineer James H.W. Waller, as builder of the vaults. This work was published along with other works in a general article, "Current Architecture", in 1951. The Architectural Review was a British journal to which De la Hoz paid particular attention, one of the few publications which the study regularly endorsed.



Figure 3. Christ the King church in Bristol (1951) [9].

Some authors [5] have credited Kurt Billing with the invention of the patent, possibly for its appearance in his 1955 publication “Precast Concrete” [10], in which it is referred to as a “Ctesiphon Building”. As we will see however, there were previous references in the United Kingdom.

In recent investigations [11], the origin and conception of the system is credited to James Hardress de Warrenne Waller, born in 1884, engineer in the production of reinforced concrete, and specifically, in innovations in the construction of concrete shells.

During the Second World War, Waller developed various patents from an innovative method for the construction of concrete laminate roofing with a cross section of the catenary arch. This system would have the particular feature of working only on pure compression, a characteristic which eliminates the need for steel reinforcement.

This characteristic provided Waller with the means of providing a counterpart to the models of shelters for soldiers, which so far have been made in an arch-based metallic structure and corrugated steel plate envelopes.

J. Waller’s definitive patent [12] bases its nature on three fundamental aspects:

- A sheet of concrete with self-supporting textile sackcloth-based formwork, which avoids conventional shuttering and uncasting.
- Its form is an inverted catenary arch, where the forces generated by the weight of the concrete on the rest arches are purely compressive, thus avoiding the need for traction and flexion reinforcement. From both a structural and formal point of view, this system had already been used by Gaudí in his famous domes [13].
- The simplicity of the system, not only in design and calculation but in execution, requires only a small number of unskilled workers to complete the construction in a short space of time.

2. Materials and Methods

2.1. Methodology

For the constructive characterization of the Ctesiphon system for hangars by J. Waller the following methodology has been followed:

- Firstly, analysing references from the specific literature [4–6,10] it has been concluded that constructions made with the same system as it is described in the original patent [12] were built in different locations.
- Secondly, a collection of case studies has been preselected. From this initial group, two buildings constructed by De la Hoz and García Paredes with the Iberlar patent system adapted for housing purposes have been selected as case studies.
- Thirdly, for the analysis of this construction system used by De La Hoz and García Paredes, different material and performance tests have been carried out. For this purpose, in situ samples have been extracted from the case studies for subsequent laboratory characterization. Additionally, thermographic analysis of these constructions has also been conducted in order to analyze their structure and interior composition.
- Finally, a discussion was carried out based on the results obtained.

2.2. Waller and IBERLAR Patent

With the aim of establishing a comparison between the patent and its interpretation carried out by the architect De la Hoz, we will begin this study by analysing the original source: the Spanish patent signed by IBERLAR S.A. as a concession of J.H. Waller’s patent for its exclusive use over 10 years on Spanish territory and colonies, where it was widely used [14]. Afterwards, we will analyse, based on tests and samples carried out, the changes or adaptations made by the architects in their proposals.

The patent was recorded in the Spanish Patent and Trademark Office on the 13/02/1952 [12]. It consists of 18 pages of reports and an appendix with three plans identical to those in J.H.W. Waller's original patent.

Initially, this patent was focused on the demand for large-scale constructions (100–500 feet) for the use of hangars and warehouses with particular needs. “The aim of the current patent is to solve these problems and facilitate economic construction of large-scale structures, reducing to a minimum the use of steel and other expensive materials, and according to the current patent, the principles of corrugated, arched constructions.” [12].

The method in its initial basic conception is the one previously mentioned on on-site construction of an arched Ctesiphon-type structure, corrugated through the following method: “Fastening of the flexible shuttering by a light, steel rod framework, including pre-manufactured grooved linear, catenary piece, suspended from a temporary external arch or support framework, and perpendicular arched Ctesiphon pieces secured to said grooved pieces, in a way that the shuttering is adapted to the grooved catenary form” [12].

As we can see in the text above, the true complexity of this technique is the creation of form work for the arch and the removable wave trusses, which serve as exterior structural fastening while the concrete sets. So, Moriones probably saw an interesting potential business in providing the builders with the trusses with pre-determined modulations to facilitate the approval of the system.

The company advertisement and its innovative system in the *Revista Nacional de Arquitectura* (R.N.A.) journal [15] already presents supports and trusses for modulated dimensions with a span of 6, 8, 10, 14, 16, and 20 metres.

Unlike the traditional systems in which the use of concrete thickness of the elements is related almost proportionally to the covered spans, this system for building on the first moment a main paraboloid arch and, secondly, an intermediate catenary channel means that the structure only works on compression. Therefore, there is no requirement for traction and flexion reinforcements, and as a consequence, the thickness of the sheet does not need to be modified in proportion to the covered span, but only in relation to the dimensions of the grooved wave. Thus, the system of supports and trusses can be reused and industrialised, separately from the particular conditions of each building work.

With regard to what we call formwork-flexible woven shuttering that has been adapted to the form of the catenary by its own weight, this patent outlines the opportunity to use hessian (coarse fabric made from jute or jute and hemp) or to substitute it for low-thickness wire mesh or chicken wire—an opportunity to which Rafael De la Hoz and Garcia Paredes give preference in their projects, which would bring them closer to the technique known as ferrocement, already commonly used for the construction of ship hulls, and shortly before by Pier Luigi Nervi in Turin [16].

Concerning the materials, setting aside the supports, trusses, and mounting frame, the formation of the laminate is simple. As well as the non-recoverable flexible shuttering and the optional metallic mesh, only the concrete is provided, pumped or by hand, which should rather respond to the composition of a cement and sand mortar without coarse aggregate, as advised in the patent, due to occasional fragility of small thicknesses, just as used in ferrocement.

It is worth emphasising, as has been mentioned, the use of different types of steel framework, not as reinforcements in the concrete itself, but for the formation of a supporting cage, for the later flexible shuttering (mesh) and which in turn, prior to the projection of the mortar, hung from the exterior supports, as seen in Figure 4. It is important to remember that the patent is destined for large scale buildings like the example developed at the end of the document and which therefore requires these reinforcements to counteract the efforts derived from horizontal actions like wind action. These steel bars are grouped in the following types, depending on function and management. They are listed according to their installation order [12]:

1. Foundation framework: The framework of the concrete element on which the laminate is supported, which we could assimilate to the foundation of the building.

2. Sag rods: Steel framework that forms the convex curvatures of the trough of the waves between the crests are moulded “in a catenary curve”.
3. Crest rods. Frameworks similar to the sag rods, but with a concave form, and put in place after those used to form the normal curvature of the arch.
4. Arch rods: Reinforcements that follow the shape of the main arch and will absorb the effects of the wind in the same plan of the arch.
5. Flexible shuttering: As has been mentioned, the patent refers to the stretched mesh, low-thickness mesh, or natural fibre sackcloth as different possibilities.
6. Fastening support elements: Hooks, wires, bolts, and other support materials.

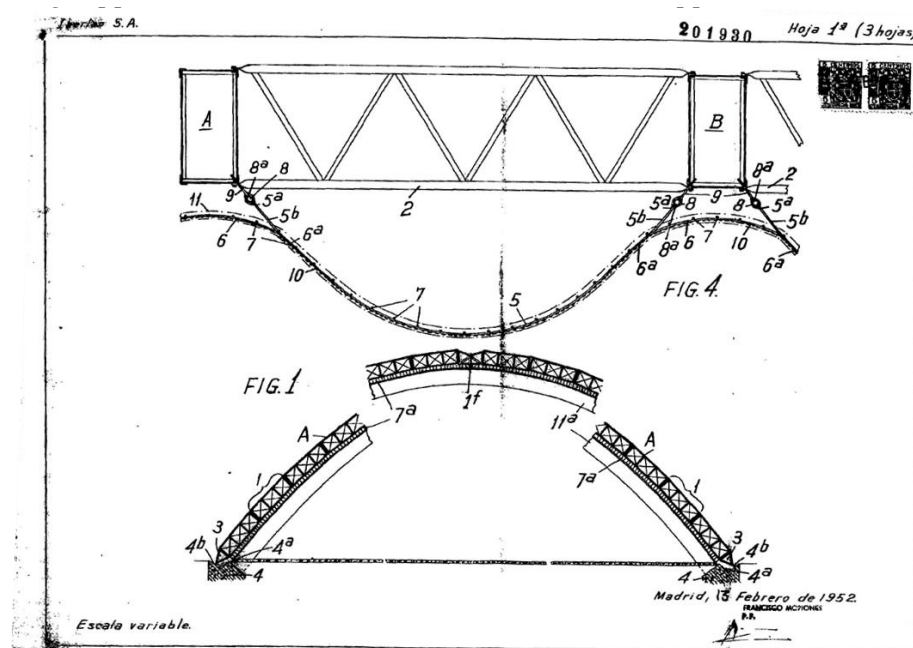


Figure 4. Illustration of the Iberlar SA Patent, (Spain Patent No. 20930, 1952). In Figure 1, the frontal elevation of the structure with the shape of the arch in fragments is observed. You can also see the curved formwork to be used in the construction of the arch. Figure 4 has a longitudinal fragmentary section of the arc structure, showing two wavy ridges and an interposed corrugated part suspended from the formwork [12].

Once the steel cage is positioned, the concrete is poured in several layers of no more than 1.5" (3.8 cm) always from the exterior of the dome and reaching a final thickness of no less than 2.5" (6.4 cm).

The patent does not provide a calculation method for the thickness of the laminate. This means that if they do fulfil the pre-dimensioning criteria of the geometry of the laminate, the thickness is standardised for all spans [17]. The criteria are as follows:

- Arch height: 1/3 of the arch span
- Crest width: 1/10 of the main arch span
- Width of crest: 1/4 of the crest span

Both the pre-dimensioning as well as the formalisation of the cage are much more permissive when the covered spans are considerably decreased.

2.3. Case Studies in Spain: Rafael De la Hoz works

Even before the system was used for housing and the concession of the patent to Iberlar S.A. in 1955, numerous buildings already were executed in Cordoba. These initial tests favoured by the

relationship between the architect and the company were modules initially used as support structures for livestock activities, construction warehouses or rural annexes.

The groups of buildings studied in this research are the following:

- Complex 1: Palma del Río (Cordoba), Calle Huertas
- Complex 2: Villaviciosa de Cordoba (Cordoba), CO-3075

The two cases selected were for different reasons: Complex 1: Palma del Río (Cordoba), calle Huertas, being on the eve of demolition, it allowed for destructive tests such as samples extraction. Complex 2: Villaviciosa de Cordoba (Cordoba), CO-3075 it is the one that has been preserved in better conditions of conservation, having been assigned a degree of heritage protection in regional regulations and therefore has allowed to complement the information with the non-destructive tests according to its original state [18].

2.3.1. Complex 1: Palma del Río Houses

In Palma del Río, two different sets were detected. A complex of four Viviendas Ultrabarratas in Palma del Río published in R.N.A. in 1953 [15] served as a documental source. Further, a complex of eight dwellings located on Huertas street in the village of Palma del Río was among those upon which our tests were performed.

Between the years of 1951 and 1953, Rafael De la Hoz, in collaboration with J.M. Garcia Paredes, carried out one of his first contributions to social housing. The housing in Palma del Río (Figure 5) is one of the few models which remain preserved through a series of actions for its use as housing and small entities. The housing is distributed across the provincial territory in Córdoba, being the biggest project executed under the promotion of the Provincial Board for the Improvement in Rural Housing (Patronatos Provinciales para la mejora de la Vivienda Rural) [15].

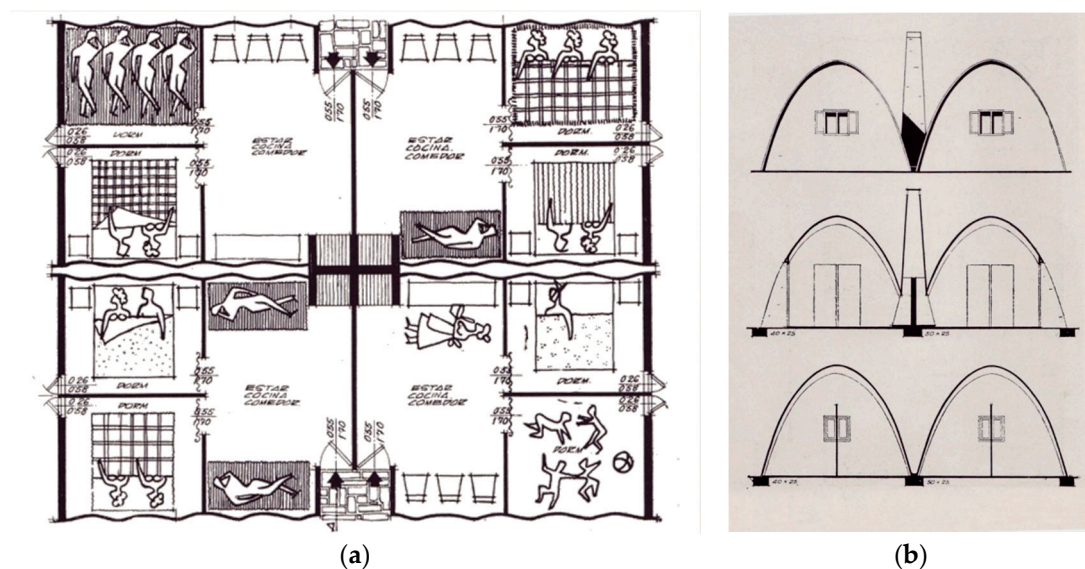


Figure 5. Houses in Palma del Río. Plans by the architects. (a) Floor Plan Distribution (b) Elevation plan and sections (La Hoz & García, 1953) [15].

From the measurements performed on the eight dwellings in Huertas street, the following data were obtained (Figure 6): the arch span is 5.15 metres (B) and the height of the keystone is 3.00 metres (A). The length of the building is 10.15 metres (C) and the width of the wave is approximately 100 cm (D).

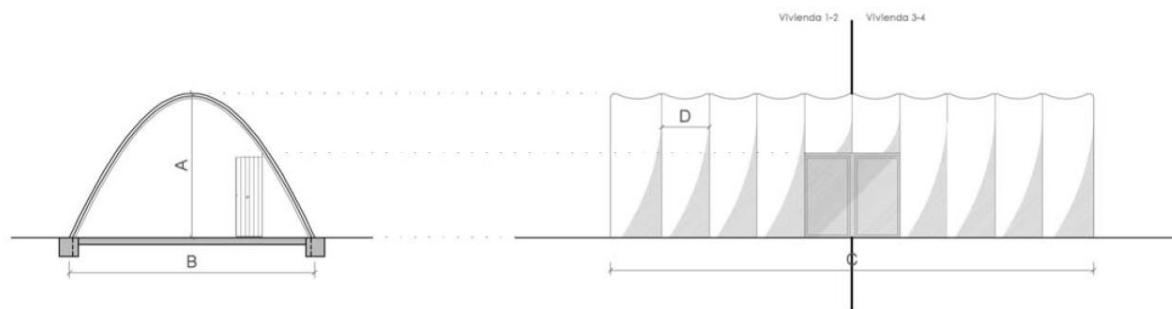


Figure 6. Section and elevation of the Palma del Río houses.

The essential starting point is that the proposal for the project is not social housing regulated by established minimum standards. The goal is to generate an alternative to the uncontrolled settlements that are beginning to locate themselves in the vicinity of the province's urban nuclei and to the proliferation of slums or huts, meaning uncontrolled movement of populations with little or zero purchasing power. These “ultra baratas” (ultra-cheap in Spanish) houses are intended to substitute the nucleus of inhabited huts in the ancient Alcazaba (citadel) of the city. In fact, in the original publication of this project in the R.N.A. [15], the architects begin their report by outlining the problems with “misery” below the poverty line, as an emergency situation that needed to be addressed.

From the aspects mentioned, we can deduce that both the customisation of the truss span and the fact that the published information does not coincide precisely with the building. It intends to be a prototype with a repetitive function, and therefore the project is fuelled by the basic principles of the proposals of the emerging pre-fabrication. Responsiveness should be rapid, effective, and controlled. In this case, however, it is conditioned by the technical circumstances and possibilities.

Although the project was proposed “without any concession to the art by the art” [15], as time passes, these buildings are not devoid of poetics. These poetics, however, perhaps consist of the formal materialisation of a technological paradox, produced by the singularity of a prototype of minimum housing conceived to be repeated, however detached from the need of mass production.

2.3.2. Complex 2: Villaviciosa Houses

This is the most recognised (Figure 7) and most widely spread in numerous publications. Although, paradoxically, it was never published at that time. It is the biggest original model and the one which still remains loyal to its original state (it currently keeps the same use and attribute). This has been fundamental for adding it to the Architectural Record of the Modern Movement Heritage as DOCOMOMO-type housing.

The architects' assignment came from the Guadalquivir Hydrography Confederation (Confederación Hidrográfica del Guadalquivir) who decided to build it for its workers close to a reservoir as temporary housing. This is the main reason for their current good condition, since there is still a relationship between the Confederation and the workers on the reservoir.

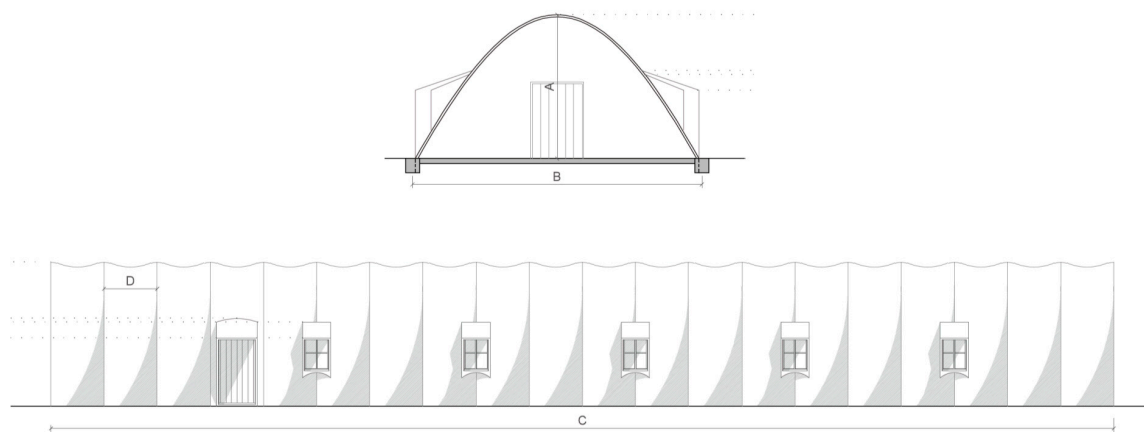
The distribution of the set is the most complex of those carried out. Not only do they deal with housing, but also large pavilions located in the back side, using truss spans, for communal uses.

The distribution of the “family” housing units is identical to the previously known Palma del Río dwellings. We also ought to highlight that, in relation to the openings or windows, when positioning the buildings in parallel, one after the other in long rows, the architect's original idea, represented in Palma del Río, of not drilling holes into the laminate, could not be followed. On this occasion, unlike in the other examples studied, the windows and doors are located at the axis of the main arches or ribs, possible for requirements arising from the internal distribution. This layout confirms that the system, once the concrete is set, behaves structurally as a compact membrane and not as discharging arches. The “ribs” can be interrupted without affecting the stability of the unit. According to the measurements, the following data were obtained (Figure 7): the arch span is 6.00 metres (B) and the

height of the keystone is 3.00 metres (A). The length of the building is 20.00 metres (C) and the width of the wave is approximately 95 cm (D).



(a)



(b)

Figure 7. (a) Picture (b) Section and elevation of the Villaviciosa houses.

3. Results

The work of De la Hoz and García Paredes in Cordoba incorporates certain variables with regard to those analysed in the Iberlar S.A. patent. Modifications were carried out in the search for a more simplified system than the previous, with a view of reducing costs, decreasing the labour force and input of steel materials, and its adaptation to the needs housing with minimum arch lengths.

3.1. Samples Analysis

The concrete sheet of the houses in Palma del Rio includes in its composition certain variables to discuss with regard to the theoretical variables of the patent. For studying it, samples of the sheet of one of the dwellings have been taken for this research, as shown in Figure 8. This building was about to be demolished by the local government so we were able to perform destructive tests for identification and characterisation. Three samples were taken in different locations.



Figure 8. Sample taking and characterization tests. The mortar layers in different phases are separated quite easily, as well as the interior layer of plaster with sacking reinforcement. Between the layers of mortar, each sample has the flexible chicken wire shuttering.

- Sample 1 was taken on the crest area. Formed by three layers of mortar ($2 + 2 + 2$ cm), corresponding to three concrete pouring carried out at different times, with chicken wire between two of them, the middle one and the exterior one. This chicken wire, with a hexagonal geometry and low thickness, appears in all three samples, thus we can therefore give it the function of flexible shuttering. On the inside there is a fourth layer of plaster with sackcloth reinforcement.
- Sample 2 was taken on the wave. The composition of the sample taken is the same as the previous one, but with lower thicknesses as a result of the execution and lower sectional requirement on the wave trough, since, at these points, they do not have to respond to the transmission of loads to the foundation to horizontal loads.
- Sample 3 was taken from a construction joint. There are construction joints every four arches, meaning every three waves. These joints are a matter of planning the execution and performance of the workers. To make these joints, a strip of bituminous material is used in contact with the two layers of concrete that joins the two arches and is reinforced outwardly with double chicken wiring. Within the concrete sheet, there are several strips of lead, approximately 6 cm wide, located on the axis of the constructive joint and deposited perpendicular to the joint.

3.2. Thermography Analysis

The function of the thermal enclosure and its hygrothermal behaviour was one of the architects' biggest concerns with regard to the suitability of these constructions for use as housing.

In particular, reference was made to the need for appropriate ventilation to avoid condensation on the surface of the laminate when a high moisture level and high temperatures inside overlapped with low temperatures outside. Conditions which could easily arise for example when cooking inside in cold seasons such as autumn and winter.

For this research we performed a study on the hygrothermal behaviour. For it, in situ thermal transmittance coefficient (U-value) tests were carried out on one of the pavilions to which access was granted. Test were done 25th July, previous day outdoor temperature ranged from 42 °C maximum and 23 °C minimum. Thermography images (Figures 9 and 10) were taken to graphically support certain hypotheses and calculations of condensation were performed using computer program eCondensa2 [19]. These tests have been performed on the complex in Villaviciosa, which are well-maintained and remain in use nowadays.

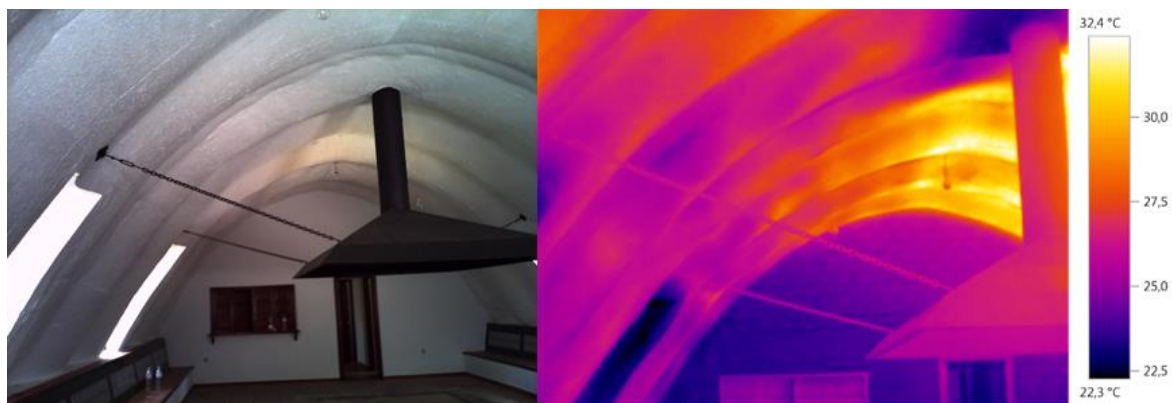


Figure 9. Thermographic image. Difference in temperature between the enclosure and the rest of the premises. The temperature of the enclosure is not transmitted to the inside, but it dispels through the laminate itself.

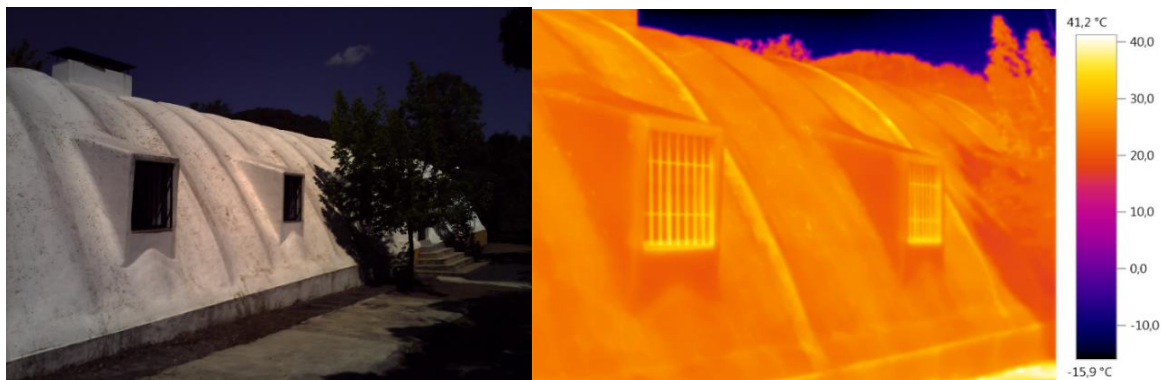


Figure 10. Thermographic images taken in Villaviciosa de Cordoba, 2015. Constructive joints are detected each 4 arches or 3 waves.

3.3. Thermal Tests, U-Values

The instrumentation used for the data gathering for these tests was a multi-function measuring instrument TESTO 435-2 with 3 thermal transmittance sounding lines (with removable adhesive putty) and radio module and wireless sounding line TESTO 868 MHz for taking outdoor temperature.

Test were conducted over 72 h. Data was recorded every 15 minutes. The data has been treated with software and subsequently processed. The results from transmittance tests are showed in Table 1.

Table 1. U-values Test Results.

	W/(m ² ·K)	[°C] T int	[°C] T wall	[°C] T ext	T ext—T int
AVERAGE	4.053	24.95	31.710	37.461	12.5

4. Discussion

As there are no photographs of the constructive process of these dwellings in the article published in 1953, these samples allow us to make a hypothesis on the constructive process. Based on the information collected through the interviews carried out, as well as bibliography and documentation from that time [15], a hypothesis is set out on the constructive process in order to gather the differences with the Iberlar S.A. patent (Figure 11).

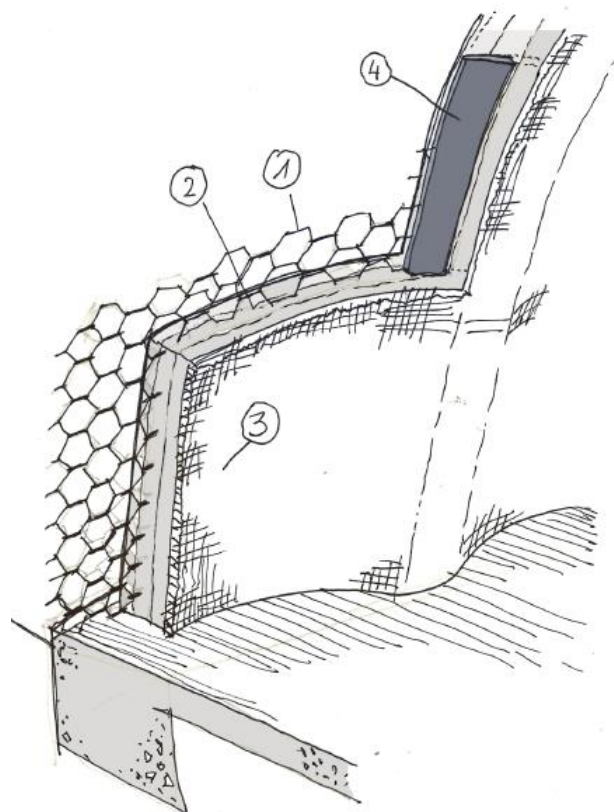


Figure 11. Hypothesis of Ctesiphon section in Palma del Río. (1) Chicken wire. (2) Triple mortar layer. (3) Inner layer of plaster and a sackcloth fabric. (4) Construction joint, strip of lead.

This building construction hypothesis is structured around the following on-site steps:

1. Laying the foundations: The system is based on top of a continuous foundation of unreinforced concrete ditch.
2. Supports and trusses: The prefabricated trusses are simplified enormously in their design by the fact that the cage of reinforcements, and the flexible shuttering in this case, are self-supporting. This implies that they do not require external trusses that would simply add complexity for large spans.
3. In terms of the strip of lead located on one of the crests appearing in the samples performed, we can see, thanks to the thermography images (Figure 10), that they are repeated every three waves, coinciding with the constructive joints. The choice of this material is very appropriate due to its malleability and ease of adaptation to the curvature of the catenary. Its main task is that of a sealing construction joint.

4. Positioning of the sackcloth: The sackcloth is positioned by means of attaching it to the lead strips and to the trusses. Its function is to act as support from the first layer of fresh mortar. Subsequently, the metal reinforcement mesh is positioned between the successive layers of concrete. The function of the mesh is to control the forces provoked by the shrinkage of the concrete and to avoid cracking provoked by possible flexion in the laminate.
5. Applying the mortar: The materials used are similar to any job using reinforced concrete, excluding steel and coarse aggregate. A controlled granulometry of no greater than 12mm is recommended, along with a ratio of gravel with a sand content between 40% and 80%. In countries without significant seismic risk, as is the case, these laminates can be applied without any metallic reinforcement. Although chicken wire is used in this case, it cannot be considered a metallic reinforcement, but simply as a woven support used when applying the mortar, and because it can “incur imperfections relatively easily in construction” [20].

The positioning of the material is done in three successive layers with a thickness of approximately 2cm. There are two reasons for splitting the execution into three different moments. First, for the self-supporting limit of the woven shuttering. And secondly because the system, once the first layer has set, turns into a support for the next layers.

For guidance on the performance of these constructions, we could build on the data published by J. Weller’s company in [15,21] which generate an “average of 0.278 m² per workman and hour”. This advice could allow us to estimate the construction time of each dwelling in Palma del Rio in approximately four days, using a group of four people.

6. Removal of formwork: Uncasing does not exist per se. The supports are simply taken away by dismounting them from the inside. The simplest way of removing the formwork involves taking away the central bar and loosening the spring at its highest point.
7. Curing should involve avoiding moisture loss from the concrete since there is a large amount of surface in contact with the air in relation to the volume of material. This can be achieved on one hand by protecting the surface with plastic or by using traditional methods like sprinkling fine sand on the surface and often water to create a protective layer that will isolate the mortar mass from outdoor conditions [19].
8. Finally, an inner layer of a material consisting of plaster and a sackcloth fabric made from hemp is applied to the structural system, once dried, to provide some thermal insulation (according to the authors in [15]).

In relation to transmittance (U-value) of the enclosure, the value obtained from the original enclosure, as conceived by the architects, is 3.885 W/(m²·K) according to software calculation, and according to the in situ tests 4.053 W/(m²·K). They are obviously very high values, far from those which we handle today using the current regulations, meaning they put up very little resistance to the passing of heat. Although we must keep in mind that these requirements are subsequent to construction, and thus, although they serve as a reference for putting us in relation to the values provided, they should not be taken as values for performing comparisons. At that point, there were no limits in Spanish Standards for U-values, whereas today the limit for such a building in its location according to Spanish Building codes is 0.65 W/(m²·K). [22]. So that we can have a more suitable comparative range, an envelope formed by one single layer of brick, half a foot long (11.5 cm) without insulation, a typical solution at that time, has an approximate transmittance of 2.60 W/(m²·K).

In the 1950s there was not as much concern among architects regarding the thermal behaviour against high temperatures as it is today. It seems to be that the architects were convinced that it was a very suitable system to be used in environments with extreme temperatures like it happened years after in the Spanish African colonies. This could seem contradictory with the U-values before expressed of 4.053 W/(m²·K). However, the thermal behaviour of the building will be more related to other system’s properties.

Specific data for the tests provides us with a lot of information is the difference between the interior air temperature and that of the wall. If between the exterior and interior of the wall there is a difference of 5 °C, between the wall and the interior atmosphere, (being only air between both sensors), there is a surprising difference of another 5 °C.

Probably the architects themselves deduced this quality of the system through both the material and formal characteristics of the inverted catenary:

- Form: Having a curved surface, the sun exposure is always minimal, so at no point is a direct incidence produced over a plane that heats up. This allows the majority of the surface to be in a position to dispel this heat in summer as it is exposed minimally or not at all; while just one part of the laminate is heated up by an incidence close to the normal surface or perpendicular surface.
- The use of traditional lime coating on the outside generates a reflection surface which improves the previous situation.
- The high thermal conductivity of the concrete, along with the large surface in contact with the outside, ensures that the dissipation of stored heat is as fast as possible, and in all cases, during the night, the building reverses the diurnal heating cycle due to this high dissipation capacity. Once again, in the thermographic images, we can observe the transition of temperatures from hot to cold produced on the laminate, depending on the sunny area.

To summarize, the thermal behaviour is in line with the requirements, not because of the insulation provided by the envelope, which is minimal, but because of other issues relating to the tectonic form as the formal result of the inverted catenary, the continuity of material side by side and the use of white on its outer layer in the warm climate of Córdoba.

5. Conclusions

James H.W. Weller produced the initial impulse in pursuit of this system proposing it as an alternative to the metal barracks used in the army. The relation between both ends of this investigation, Waller in England and De la Hoz in Cordoba, was done through the company Iberlar Edificios Patentados S.A., as well as through some publications at the time read by arch. Rafael De la Hoz that allow him to have first-hand information of buildings erected with this system like the Bristol chapel. Rafael De la Hoz's work in Cordoba includes certain differences related to those analysed in the patent. These modifications were favoured for a smaller scale, and aimed at the search for a simplified system with views of reducing costs, decreasing labour force, less input of ferrous materials and its adaptation to the needs of the uses of housing:

- Elimination of the exterior truss complexes that support the woven shuttering during concreting;
- Elimination of all types of fastening reinforcements except from chicken wire during the process of creating the laminate;
- Elimination of foundation framework, sag rods, crest rods, and arch rods defined in the patent;
- Involvement in the structural system of an inner layer of material composed of plaster and a sacking fabric made from hemp or something similar to provide thermal insulation and hygroscopic regulation;
- Involvement of innovative lead rods in the construction joints every three arches, which simplifies the construction with a double purpose: to substitute the so called foundation framework or starter framework, performing the work and configuration of the construction joint itself, as well as to provide continuity to solve the problem related to water infiltration.

The innovative project, both in the shape and construction system from De la Hoz and Garcia Paredes becomes clear, i.e., to transpose the meaning of the original existing hut and to solve, in the most economical way possible, and with the simplest construction technique, the total capable volume of the shelter, eliminating the overlapping of professions, as well as inconvenient solutions for compatibility among different materials.

This paper recognizes the innovative project, in both the shape and construction system for dwellings. The underlying idea seems to be to maintain the features of the existing huts where people lived at that moment, and to solve, in the most economical way possible and with the simplest construction technique, the technological shelter.

Author Contributions: J.R.-F. conceived, designed and performed the experiments; C.R.-G. analyzed the data and edited the paper; C.G.-M. did the supervision, reviewed, edited, and was in charge of funding acquisition.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cassinello, P. Razón Científica de la Modernidad Española en la Década de los 50. In *Los Años 50: La Arquitectura Española y su Compromiso Con La Historia*; UNAV Publisher: Pamplona, Spain, 2000.
2. Hurtado, M.; Salazar, M.; Muñoz, G. Construction features of the historical architecture in the sea port city of Valparaíso: Architect E.O.F. Harrington's brick masonry buildings. *Rev. Constr.* **2016**, *15*, 67–76.
3. Municipal Archive of Palma del Río, Córdoba, Spain. 1953. Available online: https://www.palmadelrio.es/atencion_al_ciudadano/serviciosculturalesdeportivosyocio/archivo_municipal (accessed on 30 October 2019).
4. Williams, J. An Irish Genius: De, J.H., Waller, W., 1884–1968. *Ir. Arts Rev.* **1996**, *12*, 143–146.
5. Rabasco, P. El sistema Ctesiphonte. Evolución de la estructura catenaria. *Inf. Constr.* **2011**, *63*, 43–52. [CrossRef]
6. Colon Ciarán, J. James Waller's contribution to the advancement of shell roof. In *Proceedings of the Second International Conference on Flexible*; University of Bath: Bath, UK, 2012.
7. Iberlar, S.A. Un Método de Construcción de Estructuras Arqueadas de Hormigón Armado. Spanish 20930, 16 March 1953.
8. Roa, J. La Arquitectura Prefabricada de Rafael de La Hoz en Córdoba. Entre el Detalle Constructivo y La Generación Del Proyecto. Ph.D. Thesis, University of Seville, Seville, Spain, 2016.
9. Kenneth, E. Current Architecture. *Arch. Rev.* **1951**, *109*, 182.
10. Billig, K. *Precast Concrete*; McMillan: London, UK, 1955; pp. 272–273.
11. Veenendaal, D.; West, M.; Block, G. History and overview of fabric formwork: Using fabrics for concrete casting. *Struct. Concr.* **2011**, *12*, 164–177. [CrossRef]
12. Waller, J.H.D.W. Method of Forming Reinforced Concrete Arched Structures. U.S. Patent US2705826A, 12 April 1955.
13. Bassegoda, J. La construcción tradicional en la arquitectura de Gaudí. *Inf. Constr.* **1990**, *42*, 9. [CrossRef]
14. Prats, R. *Proyecto de Construcción de un Barracón de Dos Viviendas Catenáricas Para Tropa, Villa Cisneros, Sahara Occidental*; AIMC (Archivo Intermedio Militar de Canarias), Proyectos de construcción militar: Canarias, Spain, 1967.
15. De La Hoz, R.; García, J.M. Viviendas Ultrabaratitas en Córdoba. *Rev. Nac. Arquít.* **1955**, *135*, 17–20.
16. Olmo, C.; Chiorino, C. *Pier Luigi Nervi: Architecture as Challenge*; PLN Project: Brussels, Belgium, 2010.
17. Davidovich, N. *Cubiertas Onduladas de Hormigón (Sistema Ctesiphon)*; Universidad de Chile: Santiago de Chile, Chile, 1960.
18. Rabasco, P. *Arquitectura Social en Palma Del Río Durante el Franquismo*; Saxoferreo: Seville, Spain, 2007.
19. eCondensa2. Aurea Consulting. Available online: www.ecoeficiente.es (accessed on 18 May 2016).
20. Waller, J.H.D.W. Execution of works in reinforced concrete. *TICEI* **1913**, *39*, 83–104.
21. Calavera, J. *Proyecto y Cálculo de Estructuras de Hormigón: En Masa, Armado y Pretensado*; Instituto Técnico de Materiales y Construcciones: Madrid, Spain, 2008.
22. Gobierno de España. C.T.E. Documento Básico HE Ahorro de Energía 1. 2006. Available online: <https://www.codigotecnico.org/> (accessed on 30 October 2019).



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).