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Estudio comparativo de estructuras Ligeras en la arquitectura moderna: Eladio Dieste vs Félix Candela
Comparative study of lightweight structures in modern architecture: Eladio Dieste vs. Félix Candela

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Resumen-- **El siguiente texto presenta el análisis comparativo de las estructuras ligeras del ingeniero uruguayo Eladio Dieste y el Arquitecto español Félix Candela. A través de 4 obras relevantes, como son el restaurante Los Manantiales, la Iglesia Ntra Sra de Guadalupe, La iglesia de San Juan de Ávila y el pabellón del colegio Don Bosco, se comparan aspectos clave en el desarrollo de la arquitectura de ambos y su funcionamiento. A través de las luces, como objetivo principal de las arquitecturas singulares, los soportes y el proceso de ejecución, se pretende extraer las ventajas e inconvenientes de las técnicas constructivas singulares de estos dos genios de la ingeniería del siglo XX, la cerámica estructural y las cáscaras de hormigón. Como principales resultados podemos obtener que el uso de soportes estructurales (pilares) hace que se puedan conseguir alturas mayores que con el uso de las cáscaras de hormigón. En cuanto a los procesos de ejecución, no hay una clara ventaja de uno con respecto a otro, ya que cada uno tiene sus particularidades a la hora de llevarlos a cabo. Las luces conseguidas con las cáscaras de hormigón llegan a ser de casi el doble que, con la cerámica armada, lo cual lo hace adecuado para aquellas edificaciones singulares con necesidad de espacialidad diáfana.**

Palabras clave— Estructuras ligeras; Espesor; Comportamiento mecánico; Estudio comparativo; mecánica de medios continuos.

Abstract— **The following text presents a comparative analysis of the light structures of the Uruguayan engineer Eladio Dieste and the Spanish architect Félix Candela. Through 4 relevant works, such as the restaurant Los Manantiales, the Church of Our Lady of Guadalupe, the church of San Juan de Ávila and the pavilion of the Don Bosco school, key aspects in the development of the architecture of both and their functioning are compared. By means of the spans, as the main objective of the singular architectures, the supports and the execution process, the aim is to extract the advantages and disadvantages of the singular construction techniques of these two geniuses of 20th century engineering, structural ceramics and concrete shells. The main results are that the use of structural supports (pillars) makes it possible to achieve greater heights than with the use of concrete shells. As for the execution processes, there is no clear advantage of one over the other, as each one has its own particularities when it comes to carrying them out. The spans achieved with concrete shells are almost twice as large as with reinforced ceramics, which makes it suitable for unique buildings with a need for diaphanous spatiality.**

Index Terms— Housing; energy efficiency; thermal loads; design builder; passive systems; design builder.

I. INTRODUCTION

FÉLIX Candela and Eladio Dieste took a leading role in the world of architecture in the mid-20th century. "When Le Corbuiser said 'here and now 1927, the new Architecture is born', he was not just talking about architecture, he was proclaiming the birth of a new model of thought that had been

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in the making since the end of the 19th century, and which from then on would spread without recognising borders because its reason was not based on an idea or a desire for change in itself, its reason was the necessary adaptation to the scientific and technical current situation that would unstoppably transform the world"(Cabeza Láinez et al., 2000).

This was the focus of these two authors, who brought to the world a new vision of spaces and a new way of building. They created new construction systems that were revolutionary for the time. Existing materials were rethought and applied in ways never seen before. Designing structures of considerable size with concrete and ceramics, with a minimum thickness, was a revolution in the way of understanding construction and materials.

The cosmic ray pavilion (UNAM, 1951) was the fourth shell built by Candela's company, although the first to use hyperbolic paraboloids. After having been experimenting for a long time, he switched from using cylindrical vaults to using double curvature (warped) vaults. He decided to use hyperbolic paraboloids as this shape gave him greater rigidity, strength and stability.(De Boister et al., 2008) Dieste also succeeded in making structures of double curvature (warped) vaults.

Dieste also managed to make structures with double curvature using ceramics, as is the case of the Citrícola Salteña, S.A. (Paraguay, 1976),(Galindo et al., 2018) where the roof is formed by 17 double curvature vaults, tensioned, built with hollow pieces of reinforced ceramic (bovedillas25x25x15cm) joined with sand and portland mortar and covered on top of the ceramic with a 2.5 cm layer of sand and portland mortar in addition to a metal mesh.[11] The roof is made of 17 double curvature vaults, tensioned, built with hollow pieces of reinforced ceramic (bovedillas25x25x15cm) joined with sand and portland mortar and covered on top of the ceramic with a 2.5 cm layer of sand and portland mortar in addition to a metallic mesh.[11

The work of these authors was oriented towards diaphanous constructions, places where spatiality was of great importance and where it was possible to make the most of their designs. For this reason, a large part of this work is devoted to industrial and religious buildings.

Some of these examples make clear the simplicity and majesty of the spaces achieved, as in the case of the churches of the medal of the Virgen de la Milagrosa and the Atlántida de cristo obrero and Ntra Sra de Lourdes (Fig. 2), where, while one creates contracted and cold spaces due to the use of the material, imposing and fearful, the other manages to generate an enormous diaphanous space that welcomes, illuminates and warms the spirit.

These authors dedicated a large part of their lives to reflecting on breaking with the concept of traditional structure, to giving it another, hitherto little-known value, which was aesthetic. They were young, with an avant-garde and groundbreaking vision of their time, they had the necessary knowledge of structures to go a step further, they were non-conformist and curious to investigate and try out new solutions and, most importantly, they had the support and backing of those who trusted them when it came to trying out their new designs.

II. Experimental process

The comparison of the structures was carried out in the following way:

Two representative works of each architect have been selected, namely a religious work and an industrial work. Dieste selected works selected were San Juan de Ávila church (Alcalá de Henares, 1998) and Don Bosco school gymnasium and pavilion (Montevideo, 1983) (Fig. 5). Candela selected works were the Los Manantiales restaurant (Mexico City, 1958) and the Church of Nuestra Señora de Guadalupe (Madrid, 1967) (Fig. 6),These works are also related to each other by architectural characteristics such as spatiality, lighting and size.

Once the works had been selected, each one was analysed:

- Spans: maximum spans. They are classified as >10 and <10.
- Supports: if they are pillars, their structure and operation.
- Execution process: formwork, and time taken to load the work, as well as the systems used, their advantages and disadvantages.

Once this analysis has been carried out, a table will be drawn up with the main results and the references to each of them. Finally, the works of the two architects are compared with each other, to see the suitability of the structure with respect to the type of architecture that it houses.

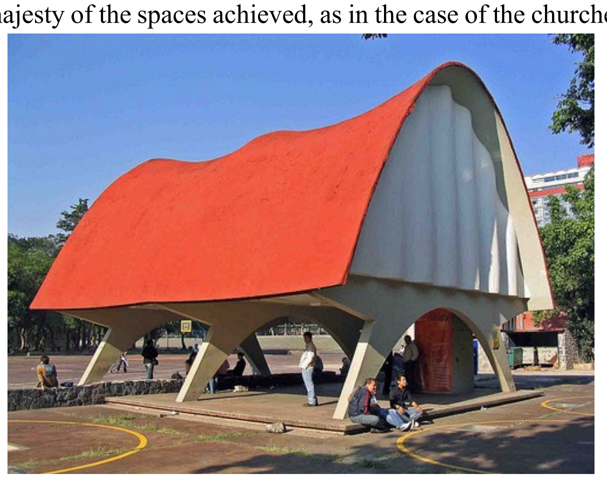

Fig. 1. Cosmic Rays pavilion. Félix Candela, 1951

Fig. 2. Cristo Obrero's Atlantic Church. Eladio Dieste, 1960

TABLE I
BUILDINGS ANALISED AND MAIN CHARACTERISTICS

Building	Architect	Constructive system	Spans	structure	Heigh	Máximum Heigh	Execution process
Don Bosco School	Eladio Dieste	Reinforced ceramics	24.4	Columns	14	15	Setting-out
San Juan de Ávila Church	Eladio Dieste	Reinforced ceramics	15	Columns	11,1	12,5	Setting-out
Los Manantiales Restaurant	Félix Candela	Concrete shell	35	Own structure		5,4	Formwork
Our Lady of Guadalupe church	Félix Candela	Concrete shell	30	Own structure		6	Formwork

III. RESULTS

Once the different points described above have been analysed, the following results have been obtained:

Table 1 shows collected data to be compared from the four selected works. Next, we will break down the results by sections.

At first glance, the most basic differences can already be seen. The spans of the Dieste projects are smaller than those of Candela, in some cases by almost half. The construction system, as well as the base material used in their projects, which we already knew previously, are also completely different.

There is also a difference in the free and maximum heights of the projects of both, where the difference is more than double, with the Uruguayan's projects reaching between 12 and 15 metres, compared to the 5-6m of Candela's designs.

Fig. 5. Don Bosco school gymnasium and pavilion.

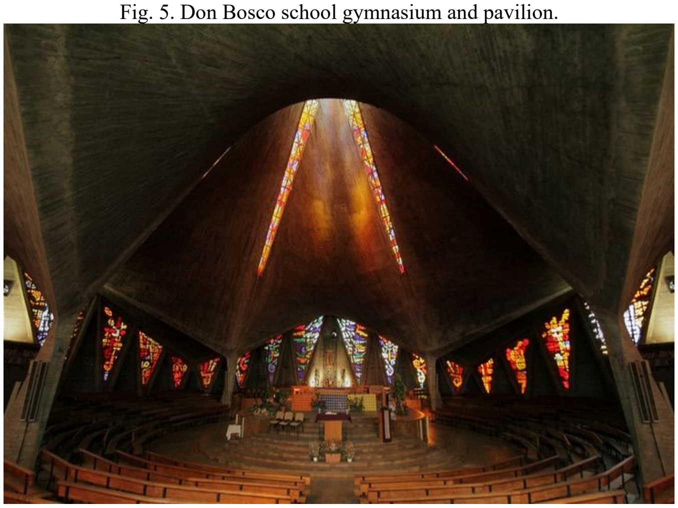

Fig. 6. Our Lady Guadalupe church, Madrid. Félix Candela.

A. Spans

Singular buildings, such as industrial and religious buildings, have specific spatial needs. They need to be large diaphanous spaces, with well-planned lighting and with the versatility to adapt to the different situations that may occur within them.

Therefore, most of these buildings must have large spans and unsupported spaces. In the case of religious buildings, the aim is to transmit spirituality, union and grandeur through space and lighting, while in the case of sports centres and restaurants, as in the case studies, these are basic characteristics required by the needs of the programmes they occupy.

Of the four buildings chosen here, the one with the lightest is the Los Manantiales restaurant, with 35 m of light. The concrete shell structures, in this case, have a greater span than the reinforced ceramic ones. This difference is due to the material or construction technique used, as well as the shape of the project.

In both cases, the roof is formed by a wing, with double curvature, so the stresses are distributed in a more balanced way. (Martínez et al., 2018)

In the case of the Don Bosco school pavilion, the roof is again of double curvature and with a span of 24.40 m, which is a little closer to the 30 m of the church of Ntra Sra de Guadalupe, also with a double curvature roof. The construction technique is completely different, although the functioning of the structure is the same. The double curvature allows the relief of the loads and distributes the stresses in a smooth way. (Cabeza Láinez et al., 2000).

In addition to the type of construction technique and the base material used, another factor by which the span is limited is the supports.

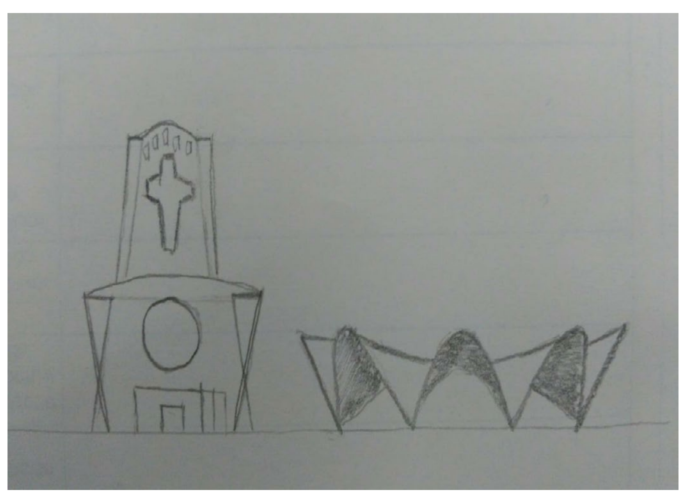

Fig. 7. Own comparative sketch of Rte Los Manantiales- Iglesia San Juan de Ávila.

B. Supports

Supports are one of the fundamental elements of any structure. They are responsible for transmitting the forces to the foundations and the configuration of the interior space, the height of the building and the load that a building can support depend on them.

In the case of Eladio Dieste's structures, the roof was supported by pillars embedded in the masonry walls that rose from the foundations and were crowned by an edge beam that braced the entire structure, as well as braces that absorbed the thrust of the vaults, which were placed from wall to wall, on the outside of the building so as not to detract from the majesty or alter the interior finish. This is the case in the great majority of the Uruguayan's works (Fig 8) (Martínez et al., 2018).

Fig. 8. San Juan de Ávila church construction process. (Lávila, 2018)

However, in the case of Félix Candela, the supports were part of the roof itself; it was the shells themselves that started from the ground as an enclosure and became the roof. We have as a study one of the exceptional cases of this author, the Church of Our Lady of Guadalupe, where the roof was still the union of 4 hyperbolic paraboloids, but they were supported on 4 central pillars that transmitted the loads. The case of the Los Manantiales restaurant does respond to the construction of a single envelope element. (Martín et al., 2018)

Figure 9 shows how the building is braced by the crowning beam, as well as the formation of the eaves and the start of the vault. This beam runs around the perimeter of the building, engaging with the heads of the columns. Therefore, the walls themselves have no load-bearing function other than that of their own weight.

In the case of the Church of Our Lady of Guadalupe, the concrete shell acts as a roof and there are no walls as such; this roof rests on the pillars and transmits the load directly to the foundations. (Martínez et al., 2018)

While the construction system chosen by Dieste is the traditional one of load-bearing structure + enclosure (heavy or light), Candela proposed a single skin, the shell, which performed all the functions, both enclosure and load-bearing structure. (Mas et al., 2005)

C. Implementation process

This section is one of the most interesting in terms of these authors. Once we know how their structures work and what advantages they have over each other, the next step is to describe the construction process, the systems used, their installation, speed of execution and loading, among other characteristics.

The first thing that can be highlighted is the system used for their construction. While the use of ruled shapes and their development with a material that is liquid when it is poured requires the use of wooden formwork, reinforced ceramics, being already a solid and resistant material, only requires the setting out, both on the ground and on the top floor or roof floor, of the shape to be developed and the launching of a series of ropes to generate the surface to which the ceramic tile installation will have to be adapted. For the layout on the top floor it is necessary to use scaffolding and a wooden base on which to make the drawing.

There are two peculiar situations regarding the formwork. On the one hand, the Los Manantiales restaurant might seem that to build it we would only need a formwork with the shape that is repeated 8 times. However, the structure is designed to

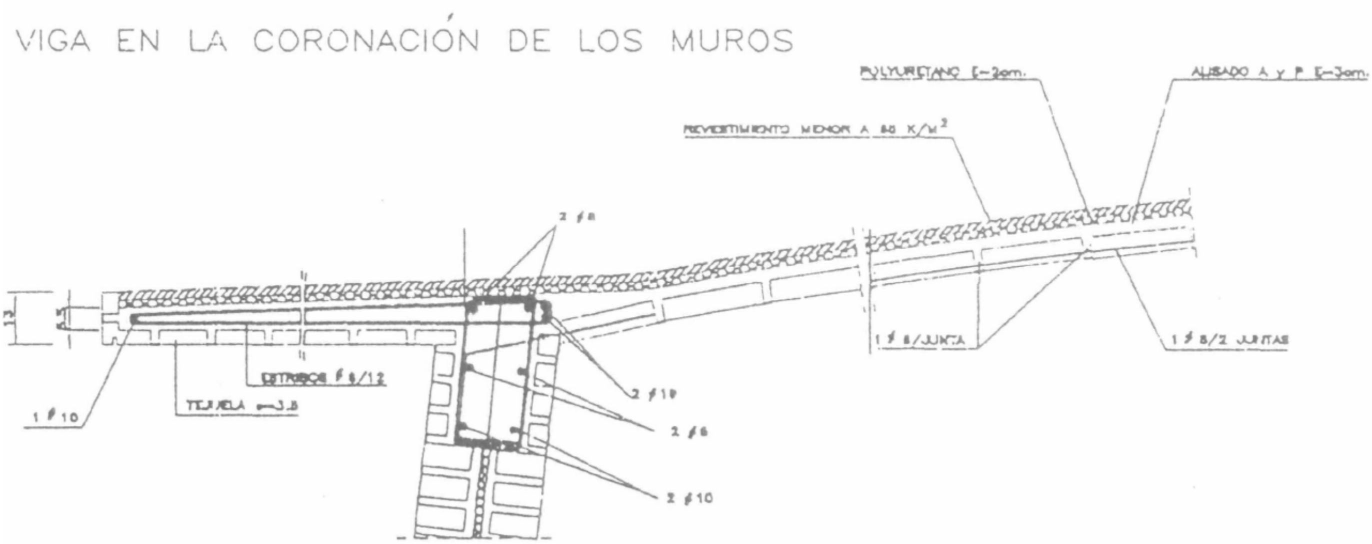

Fig. 9. San Juan de Ávila church construction process. (Lávila, 2018)

function homogeneously, so for its construction it was necessary to prepare the formwork for the entire restaurant before starting to pour the concrete. (García et al., 2016)

On the contrary, in the case of the reinforced ceramics, to build the vaults of both the church and the school pavilion, only a single mould was necessary, since, once it was stripped after 24h, it only had to be moved to where the next vault was to be built and start placing the pieces with the waiting pieces that had been left from the previous one.

The preparation of the reinforced factory is simpler due to the workmanship, the manual work, and the specificity of the concrete formwork (one formwork is only suitable for one project). This also applies to the labour required, both in terms of quantity and qualification. (Galindo et al., 2018)

Once the formwork/replants are in place, the next step would be to start construction. At this point the balance tips towards concrete, since, once the formwork is in place, all you must do is pour and vibrate the mix, which also comes already prepared or is prepared in situ, while, in the case of reinforced ceramics, starting with the setting out, a process of laying ceramic pieces begins, following the lines of the ropes pulled from floor to ceiling. Once this process has been completed, the gaps between pieces are filled up to halfway, and then the reinforcement is added and the joints are filled until they are flush. Once this was done, a 2.5cm compression layer was added, which included a metal mesh. The finish is white paint to reflect light (Galindo et al., 2018).

IV. Conclusions

After analysing the results, the following conclusions have been reached:

- The use of passive systems helps to improve the energy savings of dwellings in terms of cooling and electricity consumption.
- It is not necessary to make a large investment or significant modifications to install some of these passive systems, which start to generate benefits as soon as they are installed.
- In this case, the passive systems chosen do not serve to reduce electricity costs for lighting and DHW.
- In addition to being considerably lower, the consumption of the house is much more homogeneous throughout the year, which can be considered a great fact to consider when contracting the power of light of a house.
- Although they can be considered when designing a project, passive systems are rarely used.
- The implementation of these systems may involve a higher initial investment, but they will have a considerable impact on energy consumption and can be amortised.

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