

Eladio Dieste and Félix Candela: a comparative analysis

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Abstract

Eladio Dieste and Félix Candela are both internationally known for their elegant designs of vaulted structures built in the mid 20th century. Dieste built his with reinforced brick masonry in his homeland of Uruguay. Candela built his most renowned structures with reinforced concrete in Mexico, which was his adopted county after being exiled from Spain. The choice of materials was partly based on the social context of the country at the time and in both cases it led to economical solutions. This paper examines that social context and the influence that it had on Dieste's and Candela's designs. It also compares the construction process of each designer and their sensitivity to aesthetics in arriving at the forms. The research shows that while both Dieste and Candela built with a different material and geometric form, both had similar design values and talents that made their structures efficient, economical, and elegant. These values and talents are: discipline of form, a builder's approach, an aesthetic intent, sensitivity to the social context, and a strong knowledge of engineering analysis.

Keywords: Candela, Dieste, sustainability, thin shells, roofs.

1. Introduction

'*Structural art*', as defined by David Billington (Billington [2]), arises out of correct technical form, careful construction practice, and a conscious aesthetic intention. Structural art illustrates three ideas which are essential to anyone with an appreciation for the built environment: the first is the true ethos of engineering, namely, the drive to conserve natural resources; the second is the ethic of engineering, to resist wasting money; and third, the aesthetic of engineering, to avoid the ugly. An engineer that is disciplined by these goals of efficiency, economy, and elegance are called structural artists. A work of structural art "is always the product of one person's imagination, an individual who conceives a new form, visualizes its final appearance, defines it by calculations, and develops a means of building it" (Garlock and Billington [12]). Such people were Eladio Dieste and Félix Candela.

Often Dieste and Candela are referred to as architects. However, based on their early career, their role as a builder and designer, and their own words, we posit that Dieste

and Candela practiced as two of the greatest structural engineers of the twentieth century, and hardly at all as architects. For example, when Dieste was asked whether he was an engineer or an architect, Dieste responded by emphasizing that he was first and foremost an engineer and that he did not study for architecture (Larrambebere [15]). However, the forms that he chose for his designs were not only appropriate for efficiency and economy, but they were also ideal for creating a pleasant spatial experience inside the building. Dieste believed that the “spatial conception and the form in which these spaces are built should be one and the same thing.”[Dieste, 9]

While Dieste and Candela have collaborated with other architects on their projects, it was Dieste and Candela’s innovative ideas and values that conceived of the design, and they served as their own contractor as well. While some of their buildings may appear to be more architectural, they were, indeed, born from a structural and functional viewpoint. For example, the undulating walls of the Montevideo Shopping Center (Figure 1) are not merely for show; they help resist the horizontal thrusts of the Gaussian vaults and add stability (Dieste [8]). Similarly, the thickened ridge at the top of the shell of Candela’s Our Lady of the Miraculous Medal Church (Figure 2), was there for a structural purpose: to eliminate large tensile forces that would have been detrimental to the concrete shell if the added weight of the thickened concrete were not there (Garlock and Billington [12]). Candela’s aesthetic created a visually appealing scalloped pattern on the ridge for this purpose.

This paper begins by briefly examining Dieste and Candela’s early careers and the experiences and education that prepared them to become shell builders. Then Dieste’s and Candela’s works are discussed and compared in the context of efficiency, economy, and elegance.



(a) Outside view



(b) inside view

Figure 1: Dieste’s Montevideo shopping center Gaussian vaults.



Figure 2: Our Lady of the Miraculous Medal Church by Candela

2. Early Development as Structural Artist

2.1. Dieste

Dieste's family immigrated to Uruguay years before Eladio Dieste's birth in Artigas, Uruguay on December 10, 1917. During his childhood, Dieste formed a close relationship with his uncle, Rafael Dieste, a writer who shared his interests in poetry, philosophy, and mathematics. Dieste studied at the University of

Montevideo's Engineering School after high school. Two years after graduating from the University in 1943, Dieste served as an assistant professor of mechanics at the University for twenty years. (Pedreschi [16], Irizarry [13], Dieste [9])

In addition to academia, Dieste became involved in various other projects. Dieste helped design bridges for three years with the Highway Administration of the Uruguayan Ministry of Public Works in 1944 and managed its engineering department from 1945 to 1948 (Anderson [1]). Dieste's most pivotal assignment in his career was perhaps his role as a structural engineer in the design projects with Antonio Bonet, a well-known Spanish architect at the time (1947). For their first project, the Berlinghieri House in Punta Ballena, Dieste advised the use of brick for the vaults instead of the commonly used concrete, a suggestion Bonet initially rejected due to brick's reputation of massiveness. However, Dieste was able to convince Bonet by attaining remarkable thinness in his brick designs and the project became a huge success. (Pedreschi [16])

It was not until 1955 that Dieste formed his own firm with friend and former classmate from the University of Montevideo, Eugenio Montañez. Named after its founders, the firm was called Dieste y Montañez, SA. Because the firm specialized in both the design and construction of projects, clients quickly realized the numerous advantages the firm offered. Dieste y Montañez's responsibility of building stimulated Dieste's creativity. He was able to continue his explorations with reinforced brick masonry with the firm and devised an "economic form of construction...that suited Uruguay, having an appropriate architectural language and using inexpensive, indigenous materials." Dieste's innovations in reinforced brick masonry developed extensively through the firm's projects. (Pedreschi [16]).

2.2. Candela

In his lifetime, Dieste had never met Candela yet their careers developed around the same time and with similar experiences. Félix Candela was born in Madrid, Spain, on January 27, 1910. Unlike Dieste, Candela was trained as an architect; he attended the Escuela Superior de Arquitectura in Madrid. Although he had chosen architecture as his discipline

rather arbitrarily, he possessed a strong talent and interest in geometry and, like Dieste, mathematics. (Garlock and Billington [12])

A year after graduating, Candela won a scholarship to study thin shells with Franz Dischinger and Ulrich Finsterwalder in Germany, but this trip was canceled due to the Spanish Civil War. He ended up in a concentration camp and in 1939 he was exiled to Mexico. When Candela arrived at Mexico he embarked on several projects and gained valuable experience in design and construction of traditional beam-column type structures. It was not until 1949 that he built his first experimental shell (a funicular vault), but not without extensive study of the analysis of such shells that he learned from published papers. Excited at the success of this experimental shell, in 1950 Candela formed a company, Cubiertas Ala, with his friend, Fernando Fernandez. Like Dieste, this was a construction company that also performed the engineering calculations and one that specialized in shells.

Candela's first significant shell structure was the Cosmic Rays Laboratory in 1951 built on Mexico City's university campus (UNAM) in 1951. The university required that the shell be no more than 1.5 centimeters thick at the top so that cosmic ray measurements can be made inside the laboratory. Candela – the engineer – gave the shell double curvature for the required stiffness and stability. Candela – the builder – used straight boards to create that double curvature and economy of construction by using the hyperbolic paraboloid form, which is a double curved surface that is generated with straight lines. And finally Candela – the artist – took a design given to him by an architect and modified it to create his own work of art. The Laboratory was a huge success and elevated Candela to international fame. (Garlock and Billington [12])

2.3. Precedents and Influences

Eladio Dieste claimed that he did not keep any specific examples in mind during the invention of his designs and focused on finding new forms and solutions (Larrambebere [15]). He was concerned with his own ideas and innovations. However, there are some precedents that have resemblance to his designs of masonry shells. For example Rafael Guastavino in the late 19th century and Antonio Gaudí, a Spanish architect born ten years after Rafael Guastavino, designed extraordinary structures in reinforced masonry.

By noticing the “fibrous materials, such as wood, bone, muscle, or tendon,” Gaudí became interested in the idea of straight lines generating curved forms, as Candela employed in his construction process. In fact, like Candela, Gaudí was preoccupied with the hyperbolic paraboloid, which he called the “father of geometry” (Burry [4]). Although Gaudí was well-educated in mechanics, he did not believe that complex mathematical calculations were necessary for design. Instead, he relied more heavily on creating models, which was common among future shell builders, such as Eduardo Torroja and Heinz Isler.

Torroja had experience in building with both reinforced masonry and reinforced concrete. Torroja asserted that both “logical reasoning” and “technical training” were requirements for innovation (Torroja [18]). Dieste shared a similar view. When asked about Dieste's approach toward design, Gonzalo Larrambebere, the chief engineer of his firm, explained that Dieste believed that both practice and theory came hand in hand and

were of equal importance (Larrambebere [15]). Larrambebere explained that each construction project was like an experiment that contributed to the progressive improvement of his designs. Although he had developed a deep interest for mathematical analysis, he recognized that complex calculations only served as confirmations of the stability of his structures.

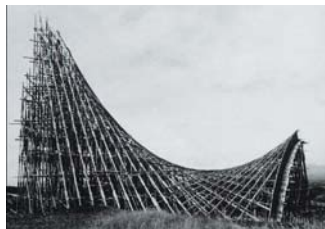
Candela also placed limits on the value of complex calculations for thin shell design and favored simpler ones. Such an approach was also embraced by Robert Maillart, who, in Candela's words "may have been one of the strongest influences at the critical moment in my career when I was trying to become a builder of shells" (Candela [6]). Maillart had constructed many slender elegant bridges in reinforced concrete and a few shells. Maillart's Cement Hall shell, in particular, stimulated Candela.

3. Efficiency

Efficiency means the search for forms that use a minimum of materials consistent with sound performance and assured safety. Dieste and Candela believed in strength through form and the forms were the basis for efficiency, economy, and elegance. Each favored a geometric shape in their works: Candela favored the hyperbolic paraboloid and Dieste the barrel or the Gaussian vault. While Candela used reinforced concrete in his designs and Dieste used reinforced brick masonry, both designed light thin shell structures without wasting materials since the form was efficient and proper. This section describes the geometric forms that were favored by Candela and Dieste, provides a brief discussion of the materials used for construction, and then illustrates the structure's performance and safety.



(a) aerial view



(b) falsework for construction



(c) inside view

Figure 3: Candela's Chapel Lomas de Cuernavaca (image (c) photo by Bruce White)

3.1. Form

Candela posited that "of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid." (Candela [5]) This shape is best understood as a saddle in which there are a set of arches in one direction and a set of cables, or inverted

arches, in the other. The shape also has the property of being defined by straight lines. The boundaries, or edges, of the hyperbolic paraboloid (also referred to as a hypar) can be straight or curved. The edges in the second case are developed by planes “cutting through” the hypar surface. Chapel Lomas de Cuernavaca (Figure 3) is an example of a curved edge hypar, while Milagrosa (Figure 2) and his many umbrella shells (Figure 4) are examples of straight edged hypars. Candela devised the umbrella form by combining four straight-edge hypar surfaces. By placing umbrellas side-by-side, large roof spaces were generated, as shown in Figure 4 and by tilting the umbrellas a saw tooth profile is created which allows light to enter the space.

Throughout his career, Dieste continuously used two principal shapes: the Gaussian vault and the barrel vault. As the umbrellas were Candela’s typical structure for large roof spaces, Gaussian vaults and barrel vaults were so for Dieste. Dieste’s free-standing barrel vaults (e.g. Figure 5) were supported by columns and were strengthened and stiffened by flat thin cantilevered edges. These vaults were also attractive for industrial use, since long spans could be achieved without columns at the junctions of the vaults, unlike Gaussian vaults, which necessitated columns between each row of vaults.

Gaussian vaults resolve the instability of a long span arch by adding double curvature to the form, which increases the moment of inertia of the cross-section without increasing its thickness. The Gaussian form is essentially “a series of connected catenary arches with varying rises that share a common springing” (Figure 6) and possesses enough stiffness through form to resist buckling (Anderson [1]). In between each vault, glass connected the top of one vault to the bottom of the next one, permitting light to enter and provide an equal distribution of light inside the buildings (Figure 1b).



Figure 4: Candela’s umbrellas: A sketch showing straight lines generating the surface and Rio’s warehouse (right) under construction.



Figure 5: Dieste’s municipal bus terminal in Salto (Anderson [1]).

3.2. Materials

The heavy appearance of brick masonry repelled designers who strived for a lighter, more modern aesthetic. However, Dieste accomplished the “re-discovery and re-interpretation of a traditional material in a modern, technically sophisticated manner” (Pedreschi [16]). Although brick masonry was often associated with massiveness, Dieste reduced their

weight by using hollow bricks and realized that lightness could be achieved by using correct form for the structure – lightness that could even compete with that of reinforced concrete (Dieste [9]).

Dieste proved that the inherent qualities of brick masonry could, in fact, be favorable for construction. He presented an optimistic view of the commonly avoided material. The bricks he used demonstrated “a high mechanical resistance,” which even exceeded that of certain concrete mixtures. These “high quality bricks” were readily accessible in less industrialized countries such as Uruguay as well.

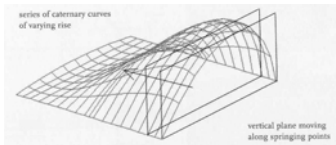


Figure 6a: Form of the Gaussian Vault (Pedreschi [16]).



Figure 6b: Dieste's Port Warehouse showing the Gaussian Vaults (Anderson [1]).

Both brick masonry and concrete have excellent strength in compression and relatively no strength in tension. Therefore, both Candela and Dieste used steel bars to reinforce the concrete and brick masonry. Candela did not speak of reinforced concrete as a ‘choice’. For his shell forms, reinforced concrete was the only choice, perhaps for practical reasons related to cost and construction as well as the Mexican context.

3.3. Structural Response

Detailed structural analyses of Candela's significant structures indicate that the stresses in the shell are far below the capacity resulting in large safety factors (Garlock and Billington [12]). Similar results are found for Dieste's designs (e.g., Lee [14], and Pedreschi and Theodossopoulos[17]). The forces in Candela's and Dieste's structures are mostly in compression with little or no bending through the thickness despite the long spans.

Such a favorable structural response was achieved despite Candela's typical concrete thinness of 4 centimeters and Dieste's 11 centimeter hollow masonry bricks. Since the form of the shell was proper, the resulting stresses were insignificant. In fact Dieste's Gaussian vaults could span as much as 50 m, or approximately 160 ft, with a thickness of about 11 cm (5 in.), yielding a “span to thickness ratio of 384” (Pedreschi [16]).

4. Economy

Economy signifies minimum construction costs and low maintenance expense. Low cost was important in the economic context of Uruguay and Mexico and both Dieste and Candela had to competitively bid for their projects. Dieste believed that economy “in the financial sense” should not be the only consideration in design, but the structures should “be in accord with the profound order of the world” (Dieste [9]). We interpret that to mean that the designs should consider the social context in which they are being built. This section describes that social context for Uruguay and Mexico and also describes the creative and sometimes innovative construction processes that Dieste and Candela used to achieve economy.

4.1. Social Context

Dieste’s designs were more concerned with conforming to the existing environment and the country’s needs. He was not discouraged, but rather inspired, by its meager resources. While many architects and engineers focus on the designs in themselves and often times neglect to analyze the project on a more macroscopic level, Dieste placed much consideration on the social context of his projects. He decided to work with reinforced masonry due to the modest economic conditions and the availability of the material in Uruguay. Because brick masonry was considered a more traditional material and was losing its appeal at the time, it was an affordable material. Uruguay’s low resources prompted Dieste to build with this local material, so he did not have to import any materials, which would have significantly increased costs. (Dieste [9])

After World War II, Mexico enjoyed a period of political stability and economic growth (Foster [11]). Within this context, Candela was able to take advantage of the unprecedented building boom that Mexico, and especially Mexico City, underwent. In Mexico of the 1950s, there were no restrictive codes that made thin shells difficult to build, and labor was sufficiently inexpensive that new construction methods did not unduly burden costs. Spurred by industrial growth, many factories and warehouses were constructed in the northern part of town, where the freight deliveries were handled. In addition, a new city ordinance abolished the open street markets, and covered stalls were built in their place (Bowman [3]). Candela’s “bread and butter” structures – the umbrellas – could be built rapidly and inexpensively for such factories, warehouses and markets. By 1957 he was covering Mexico City with umbrellas at a rate of over 25,000 square feet per week (Faber [10]).

4.2. Construction

Dieste and Candela were both builders and emphasized the importance of the construction process in design. Dieste admitted that the most notable structures were designed by builders and explained that “the project for a building is not really complete if it doesn’t consider how it will be built and the ways in which a building can be built have a notable power of inspiration”(Dieste [9]). Similarly, Candela found the construction process of paramount importance in a project. In his words:

“...few people realize that the only way to be an artist in this difficult specialty of building is to be your own contractor. In countries like this [the United States], where the building industry has been thoroughly and irreversibly fragmented and the responsibility diluted among so many trades, it may be shocking to think of a contractor as an artist; but it is indeed the only way to have in your hands the whole set of tools or instruments to perform the forgotten art of building, to produce ‘works of art’...” (Candela, [6])

On another opportunity Candela commented that “any development that saves money and effort in construction contributes more to the general well being of mankind than all the messianic claims so common in the profession” (Candela [7]). Candela was able to achieve economy of construction by using straight wood boards for the scaffolding and form boards to generate doubly curved surfaces; such is one advantage of using the hyperbolic paraboloid geometric shape. For example, Figure 3b shows the straight board falsework that was used to build Chapel Lomas de Cuernavaca. Unlike Candela, Dieste used curved formwork for his brick masonry vaults. He was able to achieve economy by reusing them about ten to twenty times to construct the series of vaults (Pedreschi [16]). The construction of the formwork for his Gaussian vaults is shown in Figure 7.



Fig. 7 Construction of the formwork of one of Dieste’s vaults. (Dieste [8])

Both Candela and Dieste used steel (in two directions) to reinforce the shell. Candela placed a steel mesh on top of the form boards and then placed the concrete. Similarly, Dieste laid the brick masonry on top of the formwork and placed a thin layer of mortar on the sides of the hollow bricks to avoid the mortar from entering the holes in the bricks and making the bricks heavier.

The hollow masonry bricks, called *bovedillas*, were designed with wings, so that steel bars could be embedded in the joints in both directions for reinforcement. Finally, an external layer of mortar was placed on top of the bricks.

After the concrete or mortar cured, the laborers lowered the falsework. This process, called *decentering*, is the most crucial part of the construction process and has to be done cautiously. For Candela’s umbrella structures, the falsework was reused several times on a project. For example, for Rio’s Warehouse he concreted four umbrellas at a time using early strength cement so that one week later he could decenter the forms and concrete another set of four (Faber [10]). Dieste employed movable formwork for his Gaussian vaults. After each vault dried and obtained enough strength to stand alone, he used the hydraulic jack to lower the formwork and shift it to the next vault.

The thinness and spans in Dieste’s barrel vaults were possible by prestressing the structure. Dieste could have used more steel reinforcement, instead of prestressing, to build

his structures, but the vaults would have required a much thicker brick section to include the larger steel bars and the structures would have been more prone to cracking. For his barrel vaults, Dieste employed looped prestressing wires to reduce or eliminate the tension and produce a uniform distributed load in the vault (Pedreschi [16]). Dieste designed his own hydraulic jack to prestress the brick masonry vaults and designed his own machine to drill the foundations for his structures. These innovations eased construction and reduced expenses by avoiding foreign assistance or resources (Dieste [9]).

5. Elegance

Elegance must be disciplined by efficiency and economy. As Candela explained:

“But an efficient and economical structure has not necessarily to be ugly. Beauty has no price tag and there is never one single solution to an engineering problem. Therefore, it is always possible to modify the whole or the parts until the ugliness disappears. This aversion to ugliness is quite the opposite of the task of the professional artist who has to produce beauty as an obligation or of today’s star-architect who has to be original at any cost in each new project.” (Candela [6])

A component of Dieste and Candela’s elegance was the expression of thinness. For example Candela pushed back the edge stiffeners in the Bacardi Rum Factory (Figure 8) so that the thinness of the shell is visible. Dieste also expressed the thinness of his shells in the free standing barrel vaults (Figure 5). Where walls surrounded his Gaussian or barrel vaults, he often overhung the shell so that the thinness was visible.

Both Candela and Dieste expressed the construction process and material in their designs. For Candela, the imprint of the straight line form boards used for construction leave a texture on the concrete surface that reminds one of the construction technique and the geometric form. Similarly, Dieste’s colorful bricks, which are visible from the inside, (Figure 9) are a strong visual appeal and also an indication of the process of construction. In fact, Dieste preferred the local handmade bricks to those manufactured by factories, since the handmade bricks provided a heterogeneous, and therefore, more colorful, pattern. He used a material that many designers would consider imperfect to create something beautiful.



Figure 8: Candela's Bacardi Rum Factory (photo by Bruce White).



Figure 9: Interior of Dieste's Gimnasio Hno. Artigas de Agostini.

6. Summary and Conclusions

Although they never met, Dieste's and Candela's thin shell structures exhibit numerous overlapping features, which were inspired by their values regarding design. They were both in search of forms that were efficient, economical and elegant. They considered the entire picture, incorporating a structure's feasibility, stability, and durability, and did not readily accept what was thought to be unattainable. These limitations, in fact, led to creativity.

Dieste and Candela were determined to find solutions to overcome the regional limitations that emerged and developed an expertise in all aspects of structural design. They may not have invented the use of Gaussian or hyperbolic paraboloid forms with brick masonry or concrete, but they were rational in choosing them and innovative in their practices of them. Both designers continuously improved their designs, achieving works of structural art that are highly competent especially in terms of structural performance. Dieste and Candela formulated creative, clever, and elegant designs that have been in service for about half a century and are still in excellent condition today. By meeting the standards of structural art, the standards of sustainability were also achieved.

The comparison shows that while both Dieste and Candela built with a different material and geometric form, both had similar design values and talents that made their structures efficient, economical, and elegant. These values and talents are: discipline of form, a builder's approach, an aesthetic intent, sensitivity to the social context, and a strong knowledge of engineering analysis. When one examines the works of other structural artists (e.g. Maillart, Nervi, and Isler), one sees the same values and talents, which are the ingredients for exemplary designs.

Acknowledgements

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