

## Félix Candela's legacy

Maria E. Moreyra GARLOCK\*, David P. BILLINGTON

Princeton University

Department of Civil and Environmental Engineering, Princeton, NJ 08544

mgarlock@princeton.edu

### Abstract

Félix Candela was a world-renowned engineer, builder, and structural artist of thin-shell concrete-roof structures in the mid 20th century. Although a native of Spain, his exile to Mexico at the end of the Spanish Civil War provided the New World locale in which he created all his major works. Through an examination of his self-proclaimed favorite structures (Miraculous Medal Church, Restaurant at Xochimilco, the Bacardi Rum factory, and the Chapel at Cuernavaca), plus his first hyperbolic paraboloid shell (Cosmic Rays Laboratory) and his umbrella shells that comprised the bulk of his work, we give insight into Candela's ideas and genius. In this way the legacy of such structural artists provides an essential part of engineering education and of the means for greatly improving the practice of structural design.

**Keywords:** Candela, concrete, thin shells, roofs.

### 1. Introduction

Félix Candela (Figure 1) was a world-renowned engineer, builder, and structural artist of thin-shell concrete-roof structures in the mid 20th century. Candela's works show three essential engineering ideas: 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. Candela's great concrete works show evidence of all three: thinness of shells, imprint of straight-line form boards, and grace in the refinement of form. This paper illustrates how Candela's works came into being, that is, the technical process by which they were built and the social process that made them possible to build in the first place. In all cases Candela was approached to be the builder – and then he proceeded to make his own engineering designs as well as calculations. The stimulus for the general plan sometimes came from somewhere else, and Candela played with it to make his own design and then create structural art. This art can only arise when that play is disciplined by efficiency and economy and when one has control of the three parts of design as Candela did: he engineered his designs, he built them, and he formed them to be elegant.



Figure 1: Félix Candela (1910 – 1997)

This paper is a brief summary of material contained in a textbook recently published by the authors (Garlock and Billington [8]). The argument of structures as works of art is made visual not only in this heavily illustrated book on Candela, but also in a major exhibition centered on elegant scale models built by Princeton engineering undergraduates and graduate students who also researched and wrote chapters in the book. The exhibition (with the same title as the book) was in the Princeton University

Art Museum (Oct. 11, 2008 to Feb. 22, 2009) and is now at the MIT Museum (April 2 to September 27, 2009). Here we present Candela as both master builder and structural artist and provide definitions for both. We also show evidence of Candela as an engineer, builder and artist who arrived at the forms, but, contrary to popular belief, he was not practicing as an architect of his concrete shell works. This paper also provides brief descriptions of his significant structures and describes Candela's stimulus for their shape. Finally we conclude with the significance of Candela's legacy in education and practice.

## **2. Master Builder and Structural Artist**

When a work of structural engineering is elegant, it is regularly described as architecture and the designer is called an architect. In the case of Candela, the confusion is understandable since he was trained as an architect, but as this book and exhibition make clear, he practiced as one of the greatest structural engineers of the twentieth century, and hardly at all as an architect. Our evidence comes from (1) his early career as an experimentalist, which prepared him to be a builder and a designer, (2) his role as a builder and designer of his best works, and (3) Candela's own words.

By the early 1950s, as Candela was gaining local fame in Mexico and architects were giving him contracts, he no longer worked as architect. He remarked at the time that "every day I feel less and less an 'architect'; I am losing interest in making plans and window details and things like that." (Faber [7]) He identified himself more as an engineer and builder: "I must say . . . that although an architect by training, in practice I am a constructor and building contractor," (Candela [4]) and one who makes his own engineering designs. This disassociation from thinking of himself as an architect was reflected even more pointedly in an essay he wrote for a symposium honoring Robert Maillart at Princeton University in 1972. The organizers who invited him to speak suggested "New Architecture" as a title for his paper. Candela began his paper and lecture saying, "The title of my lecture is 'New Architecture'; but I cannot avoid the feeling that I have not too much to do with this subject. I don't think I can speak of my work as of any

new architecture or even as architecture at all.” (Candela [5]) Later, when Candela republished this paper in Spanish, he renamed it “La Herencia de Maillart” (Maillart’s legacy).

Modern master builders exhibit two characteristics that are fundamental to the best-engineered structures: the ethos of efficiency and the ethic of economy. Efficiency in this sense means the search for forms that use a minimum of materials consistent with sound performance and assured safety; economy signifies a minimum of construction costs consistent with low expense for maintenance. These two fundamentals imply a plan that pays attention to both design and construction. An engineer who designs efficiently and with a builder’s mentality is considered a master builder. Such a person was Félix Candela. But he was more than that; he was also a structural artist—that is, an engineer who has all the qualities of a master builder and in addition possesses a strong aesthetic motivation. An engineer can be a master builder without being a structural artist, but one cannot be a structural artist without being a master builder. Many master builders are engineers who work for architects and consider the aesthetic to be the province of the architect; hence, they think of their structures as part of architectural art. Structural artists are engineers who consider it their mission to create the form—the aesthetic of a structure—as well as to conceive the technical design and the construction plan. 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.

### **3. Engineer and Builder**

Shortly after completing his degree in architecture in Madrid, the Spanish Civil War broke out and in 1939 Candela was exiled to Mexico. Once settled, he supported himself by building. He placed himself in the field and saw designs materialize. The built structures represented engineering and architecture in action, but they provided him almost no intellectual stimulation. He returned to reading the publications on thin shell analysis and design (which he had begun to read as a student in Madrid) and then began to experiment with building thin shell structures. His work was directed toward understanding the performance of thin-shell concrete structures under load, but, in addition, he was gaining insight into the building process for such forms. At that time, the idea of publishing a research paper in a peer-reviewed journal was not something he considered. Rather, he was beginning to think like a builder, making forms—not on paper out of drawings but in the field out of concrete. Thus, when he formed his company, it was decidedly neither an architectural nor a consulting-engineering firm but rather a business devoted to building—he became a construction contractor. Candela then had control of the three parts of design that make one a structural artist: he engineered his designs, he formed them to be elegant and, he built them. In Candela’s words,

“[F]ew 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 [5])

We would slightly revise Candela’s prescription for engineering works of art by expanding the term “be your own contractor” to include “to have a builder’s mentality”. When asked to name his favorite structures, Candela replied: Miraculous Medal Church, Restaurant at Xochimilco, the Bacardi Rum factory, and the Chapel at Cuernavaca (Basterra [2]). These works form the core of our book and exhibition because as a group they provide the key to Candela’s genius. Omitted from his list are his first hyperbolic paraboloid shell (Cosmic Rays Laboratory) and the many umbrella shells that comprised the bulk of his work but that he seems not to have considered worth identifying specifically. We discuss that missing set separately, also with the goal of offering further insight into Candela’s ideas.

#### 4. Candela’s Significant Structures

From all these works, the same pattern emerges. Candela the builder makes a simplified analysis to justify the engineering design and then takes the overall form, which sometimes comes from somewhere else, and plays with it to make it structural art. This art can only arise when that play is 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 [5])

By contrast all of Candela’s significant structures were of one geometric form, the hyperbolic paraboloid (hypar), and with that discipline he could build them only 1.5 inches (4 cm) thick. The doubly curved surface of the hypar form (Figure 2) is developed with two straight line generators; thus, Candela achieved economy of construction by avoiding curved boards for his falsework in construction. While the climate in Mexico is more moderate than that in the United States, other designers successfully have built similar thin shell structures in harsh environmental conditions. For example, Heinz Isler designed many thin shell concrete structures in Switzerland; typically these were 3 inches thick and, like Candela’s designs, they serve as models of efficiency, economy, and elegance.

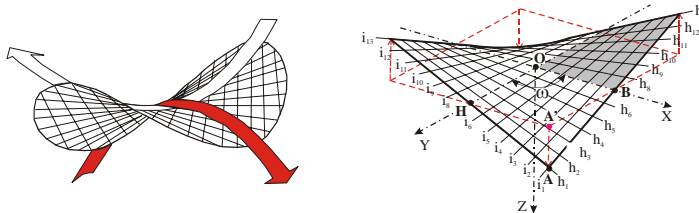


Figure 2: The hyperbolic paraboloid (hypar) with curved (left) and straight edges (right)

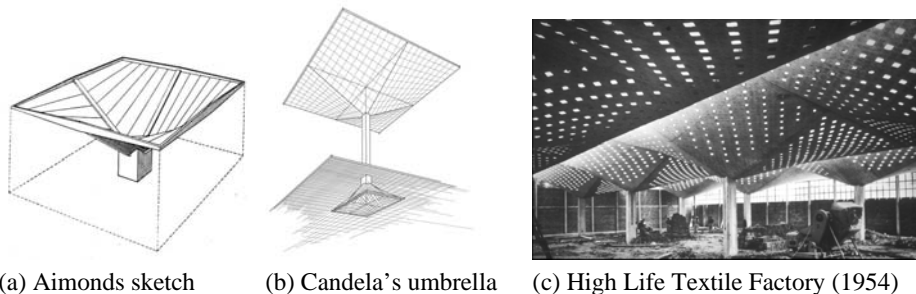


Figure 3: Cosmic Rays Laboratory (1951)

Taken together, Candela's major thin shells have in common the manner in which he secured the commission, the stimulus for the shape, and the vision that led to the final completed structure. In each case, Candela was approached to be the builder. In the Cosmic Rays Laboratory of 1951 (Figure 3), the architect already had a form—barrel shells—and when Candela took on the construction, he decided to change the barrels to hyperbolic paraboloids, his first such structure. Although no calculations seem to have survived, Candela certainly became the structural engineer, calling

on his earlier study of French and German publications from the 1930s. In this project, he began with a construction contract in which he then acted as the structural engineering designer; thus, he started his career as a structural artist by modifying someone else's form to avoid its bland image and to express also its thinness visually (Kelly et al. [9]).

With the umbrella shells, he recalled his earlier study of a 1936 paper by Aimond (Aimond [1]), who showed a single umbrella with the same basic form that Candela would follow. Since he considered Aimond's umbrella shape (Fig 4a) visually defective, he refined it by 1952 to achieve a more elegant appearance (Fig 4b,c). Along the way, he had to find a means to analyze the structure to ensure its satisfactory performance. The umbrella he transformed into a church in 1953, Iglesia de la Medalla Milagrosa (Fig 5), which resulted from an unusual opportunity that afforded Candela to be the builder, designer, and artist for a structure that is traditionally a work of architecture. The church leaders wanted a gothic style church to be designed by an architect and built by Candela. He proposed a different design to the clergy who thinking it still to be gothic accepted it, but what they were getting was a true work of structural art. Again, however, the project was first a construction and a design second. Candela had great freedom because he had to work under the constraints of a banker's budget. The clergy were appalled at the resulting completed design but the local people were greatly pleased and the church has become a landmark of structural art. (Thrall et al. [11])



(a) Aimonds sketch (b) Candela's umbrella (c) High Life Textile Factory (1954)

Figure 4: Umbrellas

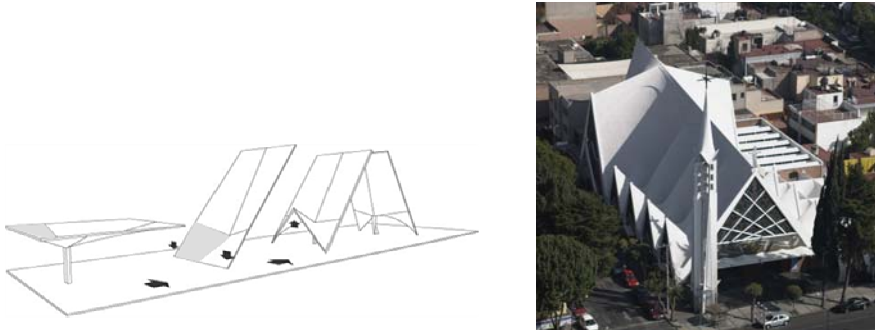


Figure 5: (left) transformation of the umbrella to the (right) Church of Our Lady of the Miraculous Medal (1953) – photo by Bruce White.

In 1958, he completed, the restaurant at Xochimilco (Fig 6). The same pattern emerges as in Milagrosa, the umbrella structures, and the Cosmic Rays Laboratory. He was asked by colleagues to take the project as both designer and builder, but once again the basic shape was not his idea. Colin Faber, working then at Candela's company Cubiertas Ala, made a sketch similar to what eventually became the shape of the restaurant. Candela considered the sketch a good beginning and proceeded to refine it carefully. He seems never to have created a new form in the sense that some architects do, often without any relationship to efficiency and cost. The restaurant is pure structure and reflects the sure hand of a structural artist. (Burger and Billington [3])

For the Cuernavaca chapel (Fig 7), also in 1958, an architect brought him a sketch of a triangular raised roof, which Candela reshaped into the thin curved structure that made the chapel unique and dramatic. Though the architect approached Candela the builder, the result was a work of pure structural art by Candela the artist. (Draper [6])



Figure 6: Restaurant Los Manantiales in Xochimilco, 1958.



Figure 7: Chapel Lomas de Cuernavaca, 1958, under construction.

Finally, for a new project he was stimulated by the cylindrical the groin vaults of the St. Louis Airport terminal building designed by the architect Minoru Yamasaki and modified strongly by the engineer Anton Tedesko. For the next project he gained, whatever its function, Candela was determined to create three groined vaults as in St. Louis. It so happened to be a Bacardí Rum bottling plant (Fig 8). Once again, the client employed Candela as builder first, but that assignment also included, as did most of his other projects, functioning as structural designer too. The building is pure structure in a series of hyperbolic paraboloid groined vaults. (Segal et al. [10])



Figure 8: Bacardi Rum factory, 1960.

## 6. The Legacy of Structural Art in Education and in Practice

Because structural engineering since the Industrial Revolution has become a new art form parallel to but independent from architecture, it must form an important part of the education of civil engineers. Just as other forms of art – painting, sculpture, music and literature, structural engineering should focus on the exemplary works of structural artists in the education of engineers and in the broader education of all students. In studying the structures of the greatest structural artists such as Robert Maillart, Heinz Isler, Pier Luigi Nervi, and Christian Menn, both educators and practitioners can recognize the potential for this new art form in the 21st century. Felix Candela belongs in that class of the greatest of structural artists and thus of an essential and integral figure in the reinvigoration of our profession.

## References

- [1] Aimond F., “Étude statique des voiles minces en paraboloid hyperbolique travaillant sans flexion,” Publications, *International Association for Bridge and Structural Engineering (IABSE)* 4 (1936)
- [2] Basterra, A. and Valero, E., “La Aventura Mexicana: Entrevista con Felix Candela,” *Arquitectura Viva* 58 (January–February 1998)
- [3] Burger N. and Billington, D. P., “Felix Candela Elegance and Endurance: An Examination of the Xochimilco Shell,” *Journal of the International Association of Shell and Spatial Structures* 27, no. 3 (December 2006): 271–78.

- [4] Candela, F. “Encuesta espacios” (an interview with Felix Candela), *Espacios: Revista integral de arquitectura*, planificación, artes plasticos 28, (November – December 1955).
- [5] Candela, F. “New Architecture,” *The Maillart Papers*, ed. David P. Billington et al. (Princeton, 1973), 119–26.
- [6] Draper, P., Garlock, M., Billington, D. (2008). “Finite Element Analysis of Félix Candela’s Chapel of Lomas De Cuernavaca” , *Journal of Architectural Engineering*, 14(2), p 47-52.
- [7] Faber, Colin, *Candela: The Shell Builder*. New York: Reinhold Publishing, 1963.
- [8] Garlock, Maria E. M. and Billington, David P. *Felix Candela: Engineer, Builder, Structural Artist*. New Haven: Yale University Press, 2008.
- [9] Kelly, K., Garlock, M., Billington, D. (2008). “Felix Candela’s First Hypar: The Cosmic Rays Laboratory”, *Proceedings of the International Symposium IASS-SLTE 2008*, Acapulco, Mexico, October 27-31.
- [10] Segal, E., Garlock, M., Billington, D. (2008). “A Comparative Analysis of the Bacardí Rum Factory and the Lambert-St. Louis Airport Terminal”, *Proceedings of the International Symposium IASS-SLTE 2008*, Acapulco, Mexico, October 27-31.
- [11] Thrall, A., Garlock, M., Billington, D. (2008). “Analysis of Iglesia de la Medalla Milagrosa”, *Proceedings of the International Symposium IASS-SLTE 2008*, Acapulco, Mexico, October 27-31.