Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

Performative perforations: structural and daylighting performance assessment of Candela's High Life Textile Factory

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Abstract

Felix Candela designed and built one of the simplest and most practical shells: umbrella shells. Among his built umbrellas, only a few are perforated, including the High Life Textile Factory. This Factory consists of aggregated umbrella shells with distributed perforations. Although the shells are tilted towards north to create a saw-tooth cross section that brings reflected light into the space, the perforations also played a role in providing daylight. After the building was used as an iron shop, the perforations were covered with asphalt to reduce overheating of the space caused by the hot Mexican climate and the program of the factory. However, it was never studied if glare might have been another reason for covering the perforations, and if covering the perforations would truly have been effective in mediating the overheating. This research speculates Candela's motivations in perforating the shells. It first examines where this building falls in his career and if he continued designing other perforated shells. Next, the building is simulated to assess its structural, daylighting, and energy performance, with and without the perforations. The goal is to understand the role of perforations on performance, and if covering them has helped to decrease the cooling load. The result of this study reveals design potentials of Candela's less-talked-about project, the High Life Textile Factory, to better understand his motivation in perforating the shells: Were Candela's perforations performative?

Keywords: perforated shells, concrete shells, parametric design, performance-based design, interdisciplinary design, structural performance, daylighting performance, energy performance

1. Introduction

Felix Candela (1910-1997) was a Spanish-born master builder and structural engineer. He enrolled at the Central University of Madrid where he took two demanding years of mathematics and physics before qualifying for enrolment in architecture or engineering. Eduardo Torroja had designed the mathematics curriculum of this program (Cassinello and Torroja [1]). After Candela finished his studies in 1935, he got involved in the Spanish Civil War and ultimately was exiled to Mexico in 1939. Therefore, many of his structures were built in Mexico.

Candela used hyparbolic paraboloids in the design of his shells and described them as the "easiest and most practical to build" (Garlock and Billington [2]). The shape is also referred to as *hypar* and has the property of being defined by straight lines. The edges of the hypar can be straight or curved. He used the hypar with straight edges in many structures. According to Garlock and Billington (2008: 98) "Candela's bread-and-butter structure was umbrella, a hypar with straight edges all in the same plane." In fact, he had roofed 3,000,000 sq. feet in the new industrial zones of Mexico City with umbrellas, in shapes of "square or rectangular, rhomboidal, polygonal" in "churches, warehouses, factories, hotels and restaurants, residences, in a bank and even in a casino" (Faber [3]). A straight-edge hypar consists of four tympans (Figure 1-left). The tympan is then retrieved from the hypar to create an umbrella structure (Figure 1-right). In many design projects, Candela placed multiple umbrellas in sequence to create large roof coverings. Candela introduced daylight to the spaces that were covered with multiple umbrellas either by tilting the umbrellas to create a sawtooth roof, or by varying the height of umbrellas in each row, or even by piercing the shell with glass blocks [2].

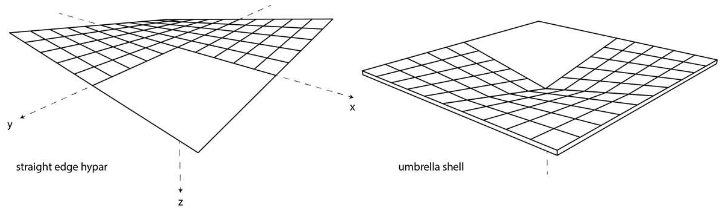


Figure 1: Straight edge hypar (left); umbrella shell (right)

Considering the design strategies that Candela employed to bring daylight into the space, his perforated aggregated umbrella shells are chosen to be examined from a multidisciplinary design lens. The High Life Textile Factory is one of the few perforated shells that he built, which is an example of a roof typology integrating form, structural performance, and environmental design. The umbrella shell is modeled in Rhino and Grasshopper to assess its structural, daylight, and energy performance. The Karamba plugin is used for structural evaluation, while the DIVA and Archsim plugins are used for daylighting and energy assessment respectively. Deflection and von Mises Stress are measured using the former, while Spatial Daylight Autonomy (sDA), point-in-time glare, and energy loads are measured for the latter. The daylighting and energy simulations are repeated for the aggregated shells with perforations only, and then for aggregated shells with side lights only. The goal is to understand the effect of adding perforations on the daylighting and energy, and to answer: were Candela's perforations performative? or were they a sculptural art work from a structural artist? And why did Candela rarely repeated building perforated shells later in his career?

2. Where does High Life Textile Factory fall in Candela's career?

Candela's first umbrella was built in 1952 and measured 10 by 10 meters (33 by 33 feet) with a rise of 1 meter (3 foot 4 inches) and a thickness of 4 centimeters (1½ inch). His second experimental umbrella was built in 1953 and measured 8 by 8 meters (25 by 25 feet), with a rise of 0.75 meters (2 foot 4 inches), and a thickness of 8 cm (3¼ inch). This second umbrella was subject to higher live load, and "despite the increased thickness and heavy reinforcement, the corner deflection was several centimeters under its own weight after a few weeks. Several men standing on the umbrella did not increase the deflections, so Candela assumed that the deflections were due to insufficient rise of the umbrella" (Garlock and Billington =98). After building these two experimental umbrellas, the Rio's Warehouse was built in 1954. It consisted of solid umbrellas measuring 10 by 15 meters (32 by 49 feet) with a 2-meter rise (6½ foot). Rio's Warehouse "initiated the umbrella shell as Candela's trademark for low-cost industrial construction" (Garlock and Billington =102). Candela later mentioned that the optimum rise depends on the area covered by the umbrella, and his formula was that the rise equaled 0.015 times the area. He also noted that umbrellas have a coverage size limitation of 185 square meter (2000 square feet), and deflections will be difficult to control if the area and the rise of the umbrella increases.

The High Life Textile Factory was built in 1954-55 in the Coyocan section of the Mexico City and after Rio's Warehouse. 44-year old Candela designed and built his first perforated umbrella shell which also presents a saw-tooth profile. The square-shaped perforations in this shell are rotated 45 degrees in the direction of straight-line generators. To understand the reason behind the rotation of the perforations, reinforcement placement in the shell needs to be examined. Candela analyzed the umbrella shells using the membrane theory, and he noticed that the direction of tension and compression forces along the umbrella structure is acting 45 degrees in the direction of the straight-line generators (Figure 2-left). He then placed steel reinforcement in a matching layout, which can be seen in a picture from the construction of one of his umbrella shells (Figure 2-middle). The practical placing of the reinforcement distribution in the shell explains 45 degrees rotation of square perforations so they fit in the grid created between the intersecting reinforcements (Figure 2-right).

Figure 2: The straight line generators (left); steel reinforcement in Candela's typical shells (middle); 45° rotation of openings from edge in the High Life Textile Factory (right) [2]

There is another important structural design element in the tilted umbrellas, examined in both Rio's Warehouse and the High Life Textile Factory (Figure 3). The vertical struts play a crucial role in maintaining stability of the entire roof system. As Faber (1963:111) explains, tilted umbrellas "were grouped horizontally and isolated by flat ribbons of light. Every three feet or so, slender struts connect their edges, adding rigidity to the shells, guarding against sway." Each pavilion is a huge cantilever which is self-supporting under symmetric loading, but very unstable under local patterned loading that would cause instability back to the supporting perimeter walls.

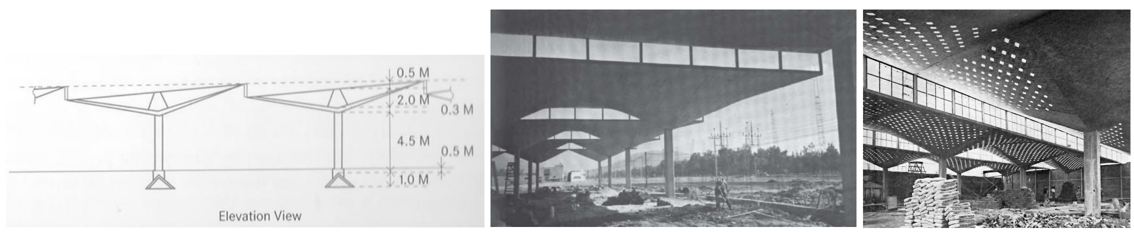


Figure 3: cross section of tilted umbrellas connected by vertical struts (left); vertical struts seen in the Rio's Warehouse (middle); vertical structs in High Life Textile Factory (right)

A summary of the dimensions of the experimental umbrella shells as well as Rio's Warehouse and High Life Textile Factory are summarized in Table 1. The Rise/Area ratio is calculated for each case to be compared to Candela's suggested ratio of 0.015.

Table 1: comparing dimensions and thickness of the first umbrellas built by Candela

	Length [m]	Width [m]	Area [m^2] (limit 185)	Rise [m]	Rise/Area ratio (optimal 0.015)	Thickness [cm]
First experimental umbrella (1952)	10	10	100	1	0.01	4
Second experimental umbrella (1953)	8	8	64	0.75	0.011	8
Rio's Warehouse (1954)	10	15	150	2	0.013	4
High Life Textile Factory (1954-55) [i]	12	12	144	2	0.013	4

Once the High Life Textile Factory shell was built, glass blocks were installed in the perforations, and the factory was used as a sewing and ironing shop. After building was in use, the glass bricks were covered with heavy asphalt paper and tar. Garlock and Billington (2008:2012) explain that it was due to overheating problems: "the factory was used as a sewing and ironing shop, where women ironed all day with steam. Combined with the hot Mexican sun, the heat inside the shop was more than anyone could bear. In the end, it was necessary to cover the glass bricks with heavy asphalt paper and tar." Colin Faber (1963: 111) admires the daylighting quality of the space covered by perforated shell but considers glass bricks as one of the reasons for overheating problems. He states, "at frequent measured spots, the roofs are pierced by glass bricks. Light floods the factory, as if there were no roof at all. But the brilliant mosaic provoked such heat and insulation problems that it was never repeated." The use of glass block in this manner was not repeated by Candela, although he used tilted umbrellas to allow light to enter the structure in other projects (Garlock and Billington [2]). In fact, Candela only built one other perforated umbrella shell. Later in 1958, he worked in collaboration with the American engineer O'Neil Ford to erect a series of hypar structures for the Insignia of the Great Southwest Corporation in Forth Worth, Texas (Mendoza [4]). These shells are perforated too, however, the perforations are fewer than the High

Life Textile Factory, and the purpose seems to be for aesthetics rather than for introducing daylight, as they are built in an open space.

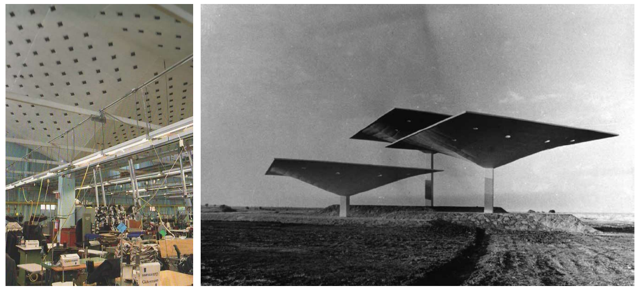


Figure 4: interior image of the iron shop (left); Insignia of the Great Southwest Corporation, Texas (right) [4]

3. Geometric properties and methodology

The dimensions of the factory were not found in the literature. However, it was measured using google maps (Decimal Degrees = 19.354074, -99.162826). The width and length of one umbrella is measured 12 by 12 meter. Looking at the site plan, an array of 4 by 3 umbrellas is recognized (Figure 5-left). Looking at the perspective view, the saw-tooth roof is recognized facing North (Figure 5-middle). The plan view of the High Life Textile Factory is reproduced using the measured dimensions of a unit umbrella, suggesting that the building measures 48 by 36 meters (Figure 5-right). Having not visited the site nor finding the dimensions in the literature, the rise and thickness of the High Life Textile Factory is assumed to be the same as Rio's Warehouse (the aggregated umbrella shells that were built right prior to this project). Therefore, the rise is assumed to be 2 meters and thickness is set to 4 cm. Since the perforations are currently covered, the dimensions of the square perforations could not be measured on Google maps, therefore, based on the available images, they are assumed to have a length of 10 cm.

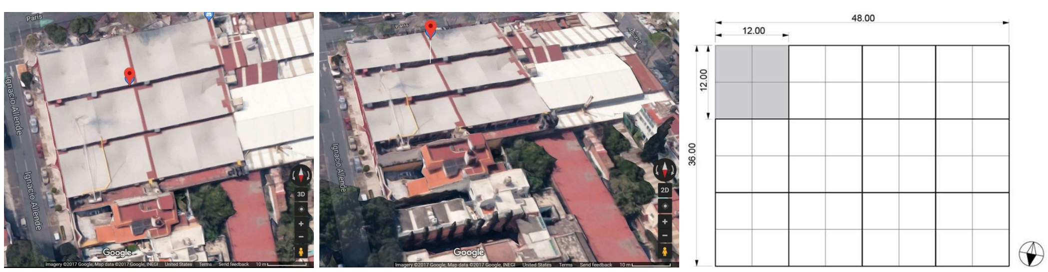


Figure 5: Plan view of the aggregated shells (left); tilted shells towards North (middle); reproduced plan (left)

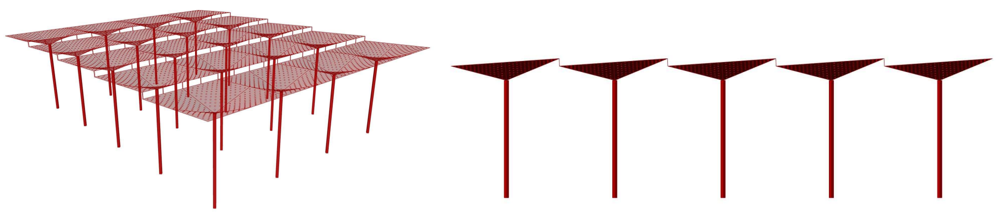


Figure 6: Recreated perforated shells using Rhino and Grasshopper

Once the shells are computationally modeled in Rhino and Grasshopper, the structural performance of the shells as well as the daylighting and energy performance of the space is simulated. Karamba plugin for Grasshopper is used for structural analysis, while DIVA and Archsim plugins for Grasshopper are used for daylighting and energy analysis respectively. Each simulation setup and the results are explained in the following sections.

4. Structural simulation setup and results

Karamba plugin is a Finite Element Method simulation engine in Grasshopper. The umbrella shells are supported on the valleys, and their movement and rotation are restricted in x, y, and z direction (Figure

7). In addition, there are vertical structural elements between each row of umbrellas connecting the tilted umbrellas to the adjacent row. These are modeled as monolithic pieces to the whole system. A distributed symmetrical global load is applied to the shell and self-weight is included in the simulation. The thickness of the shell is set to 4 cm, and concrete is used as the material. The material properties and load values are summarized in Table 2.

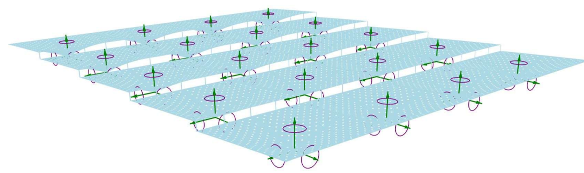


Figure 7: Boundary conditions for structural analysis

Table 2: material properties for structural simulation

Load 1_ distributed [KPa]	Load 2 [KPa]	E (Elastic Modulus) [MPa]	G (Shear Modulus) [MPa]	Fy (yield strength) [MPa]	Density [Kg/m^3]	Specific Weight [KN/m^3]
-1	Gravity	26,000	10,800	30	2400	23.5

The simulation results are presented in Table 3, and simulation images are presented in Figure 8. The total deflection is 1.1 cm, which is within the limits (span/300 = 1200/300=4). The edges of the umbrella are going through maximum deflection as seen in the simulation image (Figure 8-left). The maximum von Mises stress is seen in the umbrella valleys (Figure 8-middle). Looking at the principle force flows where blue represents compression and red represents tension, it's also suggesting that the umbrella edges are going through tension and need additional steel reinforcement, as Candela did in his designs.

Table 3: structural simulation results for 4-cm umbrella shells

Mass [kg]	Weight [tonne]	Deflection under D.L. [cm]	Deflection under L.L. [cm]	Total deflection [cm]	Von Mises at Q3 [MPa]	Maximum Von Mises [MPa]
268,141	268	0.99	1.1	2.1	1.41	8.76

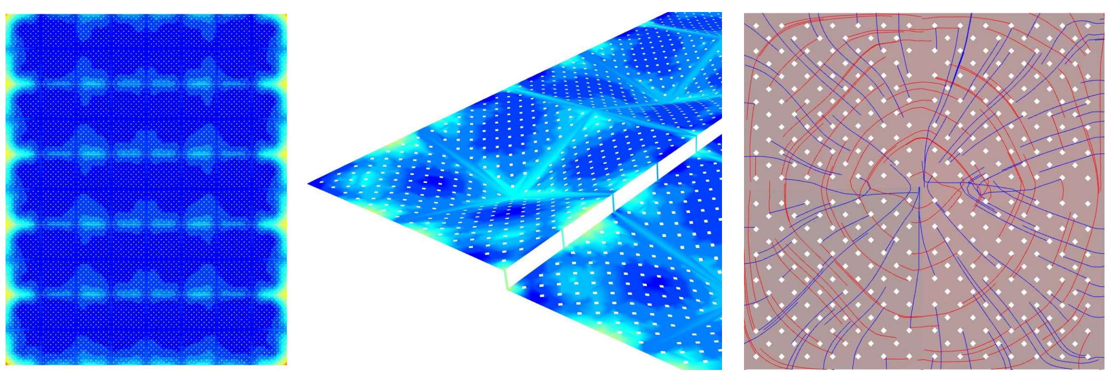


Figure 8: maximum deflection in the whole roof(left); von Mises Stress (middle); principle stress lines (right)

5. Daylighting simulation results

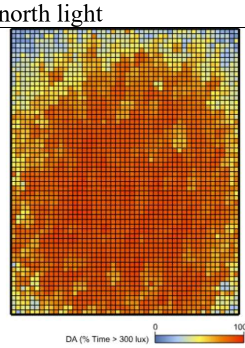
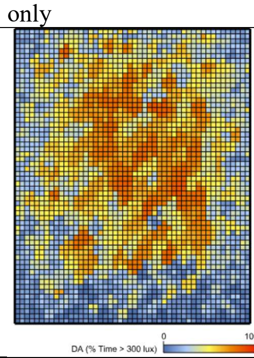
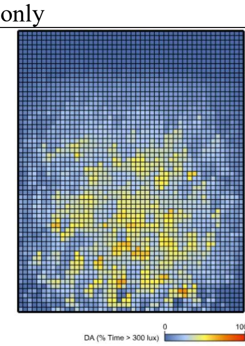
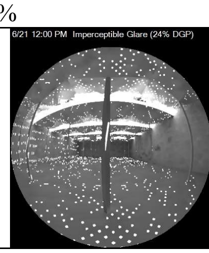
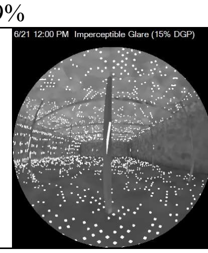
The surface properties of the walls used in the daylighting simulation are summarized in Table 4, affecting the daylighting performance of the space when Mexico City is set as the location.

Table 4: surface properties for daylighting simulation

Location	Measurement plane	Floor material	Interior wall material	Roof material	Glazing material	Outside ground material
Mexico City	0.9 meter above ground	Generic floor (20)	Outside façade (35)	Generic ceiling (80)	Single pane glazing (88)	Outside ground (20)

The daylighting simulation is computed for three scenarios: first, original umbrella shells designed by Candela having both perforations and north lighting; second, a hypothetical condition for umbrella shells having perforations only; and third, the current condition of the factory where the perforations are covered with asphalt and north light is the only source of daylight. The Spatial Daylight Autonomy (sDA) in the first scenario is simulated to be 85%, meaning that the daylight alone would have been sufficient to meet the daylighting needs of the space, (300 lux on the horizontal plane). The second scenario with perforations only has a sDA of 40%, which is not considered a daylit space, but is partially providing daylight. The third scenario has a sDA of zero, implying that the building is highly dependent on electrical lighting for illumination. The point-in-time glare at noon on June 21st is computed for all three scenarios and is “imperceptible glare” in all. Based on the daylighting simulations, covering the perforations in Candela’s original shell has significantly reduced the daylight availability in the space. The comparison of the daylighting simulation result is summarized in Table 5.

Table 5: Visualization and performance values for different design scenarios of umbrella shells

	Scenario 01: Original Umbrella, perforations + north light	Scenario 02: Hypothetical Umbrella, perforations only	Scenario 03: Current Umbrella, north light only
Plan view of Daylight Autonomy			
sDA (%Area>50%, DA=300 lx)	85%	40%	2.6%
DAv oversupply	32%	29%	0
Fish eye view of the interior space			
Glare (06/21 at noon)	Imperceptible glare	Imperceptible glare	Imperceptible glare

6. Energy simulation results

The area of the space is calculated as 1720 m^2 (36 m* 48 m). The area of the perforations and the north light panels is calculated as 121.2 m^2, and 121.9 m^2 respectively. For internal heat gain, the factory is assumed to have equipment heat gain of 46 W/ m^2 [ii], artificial lighting heat gain of 10.4 W/ m^2 [iii] and an occupancy of 0.1 person/ m^2 [iv]. The factory is assumed to be fully occupied on weekdays between 8 a.m. and 6 p.m.

Table 6: settings for the energy simulation

Walls and roof	Ground	Glazing	Zoning	Equipment power density	Lighting power density	Occupancy load	Occupancy Schedule
15 cm concrete-	Adiabatic	Single pane clear	Factory considered as one zone	46 Watt/ m^2	10.4 Watt/ m^2	0.1 people per m^2	8 a.m. to 6 p.m.

Looking at the simulation results for the energy consumption of the shop in Mexico City (Figure 9-left), cooling loads are significantly high compared to the heating and lighting loads. This trend is consistent in all design scenarios. From a different perspective, the cooling loads have small variation in different scenarios. In fact, the cooling load of the current umbrella (scenario 3 with north light only) is only 10,000 KW/hr less than the original design (scenario 1 with both north light and perforations). The simulation results imply that covering the perforations has had minor effect on reducing the cooling load of the factory and mitigating its overheating problem. It can be concluded that the high internal heat gain loads caused by irons is not effectively addresses by reducing the sources of natural daylight.

The energy simulations are repeated using a different climate: Boston. The goal is to see the effect of context on cooling loads, and how the performance of the factory would have been improved if it was built in a heating dominated climate as opposed to a cooling dominated. Looking at the results (Figure 9-right), when Boston is set as the location, the pattern of cooling loads being considerately higher than lighting loads is observed again, while heating loads also increase.

Figure 9: Heating, cooling, and lighting load of different design scenarios in Mexico City (left); and Boston (right)

From a different perspective, by changing the context from Mexico City to Boston, the cooling loads in each design scenario drop by 5.7e5 KW/hr on average. In other words, if Candela could have built the factory in Boston having the same program, cooling loads would have been about half (Figure 10).

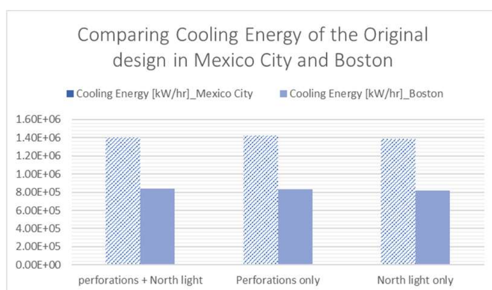


Figure 10: Comparing Cooling Energy for the same program in two different contexts

5. Conclusion

This research employs computational design and simulation tools to recreate one of the less-talked-about perforated umbrella shells designed by Candela: High Life Textile Factory. This shell covered a sewing and ironing shop in Mexico City, and its perforations were covered with asphalt and tar after the building was used. Candela never repeated building a perforated shell in this manner.

One of the goals of this study is to understand the effect of perforations in the structural performance of Candela's shells. Being built after two experimental shells and then Rio's Warehouse, we believe Candela added perforations to this shell for structural speculations. He might have tried to lighten it, and also see if he would have needed to increase the thickness upon adding perforations. In other words, it has been his first experimental perforated shell. The perforations reduce the deadload, and the rational for placement and rotation of the square perforations relates to the design of underlying reinforcement layout. Perhaps using circular openings would have been structurally more effective. The effect of perforations' size on the structural performance is an interesting subject for further speculations.

Another goal of this research is to understand if the perforations were performative in the daylighting discipline, and if they were designed for increased daylighting performance or if it was purely structural art. The daylighting simulations revealed that the contribution of perforations towards providing daylight is quite significant, as the current situation with north-light only does not meet the daylighting requirements of the space. The perforations were playing a role in bringing adequate daylighting into the space, and by covering them, the daylighting performance has significantly declined. Regarding glare, although the point-in-time glare simulation shows "imperceptible" glare, the patterning of the light might have been problematic for factory workers upon working with the machinery. In case of existence of glare or patterning, internal blinds could have been used to bounce the light back onto the underside surface of the shell and better diffuse the light. Candela's perforations were performative in the daylighting discipline, and the decision to cover the skylights is a lost opportunity of good daylighting.

Another goal of this research is to speculate if perforations have been one of the reasons of overheating of the space as stated in the literature, and if yes, then how covering them has mitigated the problem. The energy simulation results for the shells with and without the perforations[v], suggests that there is insignificant reduction in cooling loads in the shells without the perforations. In fact, the heat gain from the irons from inside the building is the driving force in overheating the space. The role of hot Mexican climate on the overheating of the space is also studied by repeating simulations using a different climate from Mexico City (Boston here). The results reveal that the cooling loads would have been half in a heating-dominated climate such as Boston, as compared to its original climate, Mexico City. We believe it was unfortunate that the program of the factory created the overheating problem and perhaps the owners of the shop covered the perforations in the first step assuming that it will mitigate the overheating problems caused by the irons. The energy analysis shows insignificant change in cooling loads before and after covering the perforations.

Future research that builds on this study is focused in two areas. First, to get more accurate information on the building and site, by going to archives to find the accurate dimensions of the shell and visiting the site to see how the perforations are covered, and if the accurate dimension of the perforations can be retrieved. This might also lead to answering questions regarding if the factory is still functioning the same. Second, to understand why Candela did not repeat building a perforated shell for another space? The only other perforated shell that he has built belongs to the Insignia of the Great Southwest Corporation in Forth Worth, Texas, which is a free standing sculptural shell. Maybe the disappointment from covering the perforations prevented him? Maybe there were some leaking problems at the connection of glass blocks and concrete due to nonexistence advanced synthetic sealants? Or maybe the costs of making the performed shells were too high at the time, and so he decided not to repeat it?

References

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[i] The length and the width are measured from Google Maps, while the rise and the thickness are assumed to be similar to Rio's Warehouse.

[ii] 40 irons each consuming 2000 Watts/hr, divided by the 172 m^2 floor area.

[iii] 2.5-meter fluorescent lamps with 2 lamps are assumed to be used. It is assumed that 19 lamps are used in a row to lighten 48-meter width of the space, which is then repeated in 6 rows. A total of 114 fluorescent lamps are used each consuming 158 Watts/hr, totaling to 18012 Watt/hr. This number is divided by the floor area (172 m^2) to arrive at 10.4 Watt/m^2 lighting heat load.

[iv] This assumes that 172 workers were working in the factory

[v] Single pane glazing is used for energy simulations as opposed to glass bricks.