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The shells of the Miami Marine Stadium: Synergy between form, force and environment

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Abstract — The chosen shape of a shell can beneficially influence its structural and environmental performance. Designers of structural surfaces can create forms with minimal resources that maximize occupant comfort. A case study of the Miami Marine Shells is discussed in this paper, which exemplifies this desirable synergetic relationship between form, force and environment.

Key-words — shell, form, hypar, folded, environment, concrete

1 Synergy between force, form and environment

The chosen shape of a shell can beneficially influence its structural and environmental performance. Designers of structural surfaces can create forms with minimal resources that maximize occupant comfort. The case study of the thin concrete shell grandstand of the Miami Marine Stadium (see in figure 1) showcases this desirable synergetic relationship between form, force and environment.

FIG. – 1: Perspective, partial front and back elevation of the Miami Marine Stadium (Miami, Florida 1962 designed by Hilario Candela and Jack Meyer) (Photo courtesy Friends of the Miami Marine Stadium http://www.marinestadium.org/).

2 Early design influences on the Miami Marine Shells

The Miami Marine Stadium is a poured concrete waterfront grandstand inaugurated in 1964 as a venue for watching boat racing and other aquatic sports. Engineered by Jack Meyer of Norman Dignum Engineers and designed by Hilario Candela, a then-28-year old recently-arrived Cuban architect working for Miami's , the building's most striking feature is its cantilevered roofline, a structure composed of unpainted concrete hyperbolic paraboloids (hypar) supported by angled columns. According to Candela, this design was an aesthetic culmination of two related professional interests. The first of these was the use of structure "not as a tool to support a building but as a visible architectonic expression." The second was Candela's self-described "love affair" with concrete.[1] Candela's fascination with engineered concrete began in the mid-1950s when he was a student at Georgia Tech. As he describes, "the great figures of world architecture like Neutra and Frank Lloyd Wright" would come through Atlanta to impart workshops to the students. For Candela, the most stimulating of those encounters were with the practitioners who experimented with thin concrete structures, in particular the Italian structural engineer Pier Luigi Nervi, Spanish structural engineer Eduardo Toroja, and Spanish-Mexican architect Félix Candela. Hilario would form lifelong friendships with both Torroja and Félix Candela. The influence of Torroja's striking 1935 Zarzuela Hippodrome is echoed in the Marine Stadium's design. In summers, Candela would return to Havana to fulfill the apprenticeship requirement of his studies. Working at the firm of fellow Georgia Tech graduate Max Borges, Jr., Candela joined what was the inner circle of Cuba's innovative experimenters with thin shell concrete and expressive roof lines.[2] After graduation, Candela returned to Cuba and joined SACMAG, a firm formed by his boyhood friends Raúl Alvarez and Enrique Gutíerrez [3] in collaboration with engineer Luis Saenz. Considered experts in the design of highly complex roofs [4] for residential properties, the firm changed course less than a year later, when the Cuban revolution halted all private construction. Assigned to take over the design of Havana's National Theater in 1959, Raúl Alvarez brought Candela on board to assist with him. Candela recalled his eagerness to participate in his first public project. However, it was short-lived. By 1960, he also left Cuba, following in the footsteps of his mentor Borges and the majority of Cuba's architectural avant-garde. Working with Pancoast, Ferendino Grafton, Skeels & Burnham, Candela was finally able to realize the design of large-scale public projects. The first project was the 1960 campus of Miami Dade College, a compendium of concrete buildings and public spaces that according to Candela, merged the "postwar modern building regionalist trends… exemplified by the work of Mies [Van der Rohe], and the expressive 'concrete' architecture widely popular throughout Latin-America and Brazil." [5] The decision to use the exposed concrete was both an aesthetic and a civic statement that allowed for economic functionality while maximizing the "softness and strength" [6] of the material itself. In 1962, while beginning the design for the Marine Stadium, Candela flew to Washington, D.C. to visit his brother. He landed at the newly opened Dulles Airport, designed by Finnish architect Eero Saarinen. For Candela, this was a watershed moment. "I was in love with Dulles from the beginning," he states. " [Saarinen] placed the roof on top like canopy. Every column is gorgeous. The way the form of those columns gets to the ground and human beings can touch the concrete and feel it and be next to it… This is exactly what I was after."[7]

3 Structural efficiency in the thin folded hypar Miami Marine roof

In collaboration with the structural engineer Jack Meyer, Candela expanded the formal possibilities of reinforced concrete by cantilevering 8 joint-folded hypar shells. With no available computational analysis techniques at hand for the complex curved shapes, Meyer engineered the shapes as 20.2-meter-long cantilevering, 12.4-meter-wide varying depth beams, which have a back span of 10.5 m, by using a series of conservative analytical calculations based on flexure formulae and slope and displacement formulations. The complexity of the roof's form does not lend itself to only one type of structural behavior. In reality, the form is a hybrid between a folded plate structure and a hyperbolic paraboloid (hypar) shell. Four separate Finite Element (FE) models of the roof are presented in this paper to further understand the structural design and performance of the roof. The first model, a folded plate inspired FE approximation of the stadium, includes the longitudinal stiffening diaphragm that runs across the top of the roof as well as the thickening of the groins in both the roof's peaks and valleys (FEM-1). The groin thickening and the stiffening diaphragm are consistent with principles of folded plate design and most accurately represent what was proposed by Meyer and then actually built. The second model (FEM-2) redefines the stadium as a series of thin hypar shells, assuming a constant thickness of 7.62 cm throughout the entire portion of the cantilever in front of the diaphragm. The third and fourth models (FEM-3 and FEM-4) are presented as copies of FEM-1 and FEM-2, respectively, except without the stiffening diaphragm. Stiffeners, such as the one in the Miami Marine Stadium, are common and advantageous in folded plate structures but are unnecessary in hypar shells. On his visit to the site, Félix Candela, a master builder of hypar shells, had suggested to Hilario Candela that the diaphragm might be redundant. By removing this element from the FE model and determining how it affects the performance, it is possible to better understand if the structure's behavior tends more towards a folded pate, as designed by Meyer, or towards a hypar shell, as its shape implies. In Figure 2, a plot of the element middle surface stresses acting in the direction of the cantilever is given with similar scales for both FEM-1 and FEM-2 under self-weight.

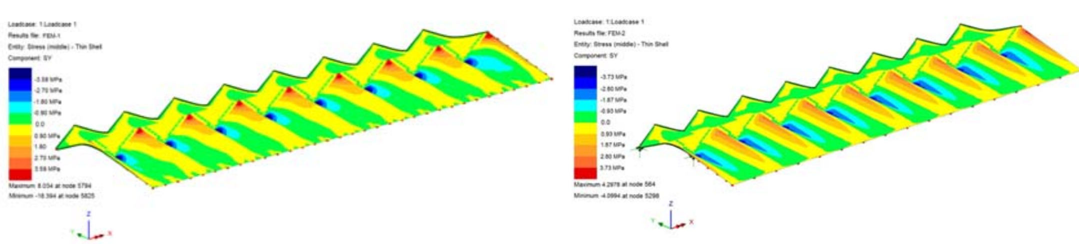

FIG. – 2: FEM-1 and FEM-2 FE models showing stresses at the middle surface

Both models exhibit classic hypar cantilever behavior, showing the peaks of the shells to be in tension (red-orange colors) and the valleys in compression (blue-green colors). However, when looking at the differences between FEM-1 and FEM-2, it is clear that adding material in the groins (FEM-1) improves the structural performance by reducing the stresses along the length of each peak and valley. If the stress concentrations at the supports are ignored (these areas contain considerable amount of steel, which is not modeled), FEM-1 does not show stresses greater than 0.90 MPa, as does FEM-2. However, this difference may not be important when considering that the stadium uses 26.75 MPa strength concrete in the front half of the roof. Removing the groin thickening in the design causes the stadium to have only slightly larger stresses while using 27% less concrete, as shown in Table 1.

TAB.-1: Material and stress quantities for the 4 different FE models

Model	**Material Reduction**	**Max Tensile Stress**	**Max Compressive Stress**	**Range of Typical Roof Stresses in Thin Cantilevered Portion**
	(est. from reactions)	(MPa)	(MPa)	(MPa)
FEM-1	0%	8.03*	-18.39*	-1.80 < x < 1.80
FEM-2	-27%	4.29	-4.09	-2.87 < x < 2.87
FEM-3	-5%	7.12*	-20.39*	-1.80 < x < 1.80
FEM-4	-32%	4.36	-4.69	-2.87 < x < 2.87
*Located In Stress Concentrations				
Note: All Stresses are measured in the middle of the shell acting in the direction of the cantilever (S_Y). There were differences in stress between the top/bottom of shell and the middle, but for the most part these differences were minimal as the material exhibited mostly membrane behavior				

In FEM-3 and FEM-4, the removal of the stiffening diaphragm did not substantially affect the performance of the roof models to which they corresponded (FEM-1 and FEM-2). In each case, the stress plot looks nearly identical with or without the diaphragm with the only differences being hard to detect visually. As can be seen in Table 1, the typical range of stresses in the cantilevered portion of the roof (including peaks and valleys) did not substantially change. The only main difference is that in the folded plate models (FEM-1 and FEM-3), removing the diaphragm decreases the magnitude of the maximum tensile stress and increases the magnitude of the maximum compressive stress, whereas in the hypar models (FEM-2 and FEM-4), removing the diaphragm increases both. The very small magnitude of the changes in behavior exhibited in the models without the diaphragm suggests that the roof’s form is more naturally suited to perform as a series of joined hypars than as folded plates; if it were the other way around, removing the diaphragm would likely drastically change the performance. Broadly speaking, the FE results show that Meyer did a good job of designing the structure within the knowledge and design principles that were in practice during the 1960s. Much more was known about the behavior of folded plate structures than hypar shells and folded plates were considered a safer design solution. Meyer’s folded plate design for the roof has performed well in the long term. However, even though a further reduction of materials was possible, a certain degree of structural efficiency and thus an economy of construction materials was still achieved. In the 1960s, material cost was high and labor cost was low. The construction of the plywood formwork for the shell was handmade and custom tailored on site. The total cost for the entire 6 600 seat stadium (tribunes and shells) did not exceed the a priori set budget of 1 000 000 USD.

4 Spectator’s thermal experience benefits from the folded hypar roof

This paper also presents the findings of an environmental analysis of the grandstand using BIM Energy Efficiency EcoTect Software. The results of this analysis suggest that the roof design attains environmental efficiency and maximizes spectator comfort in the warm, moist tropical climate of the Caribbean Region. More particularly, the analysis reveals that the hypar shapes and their orientation on site provide effective shading and temperature control, as the designer Hilario Candela intended in the initial design. Built directly on the water and oriented in parallel with the predominant strong wind from the southeast, the stadium benefits from the ocean driven cooling effects of high-speed winds in the heat of summer. These wind speeds initiate at least 200 average air changes per hour (200 ACH indicated in yellow on figure 3), which is the approximate value in Ecotect for windy, cross-ventilated structures. Givoni [8] states that thermal comfort exists when interior temperatures are between 18 and 26 degrees Celsius for a still, windless environment,18 to 32 degrees Celsius for a cross-ventilated environment, and 18 to 36 degrees Celsius for a cross-ventilated and nighttime ventilated building. As a result, the thermal comfort range for the Miami Marine Stadium was chosen to be between 18 and 35 degrees Celsius. The occupancy time was set at seven days a week between noon and midnight, which is the period spectators would be expected to occupy the stadium. Figure 3 shows how the combination of the open hypar shape and its orientation along the main southeast wind direction results in spectators experiencing natural thermal comfort for 94 to 97 percent of the set occupancy time during the hottest months of June, July and August. In the coldest month of January, spectators experience comfort 91 percent of time.

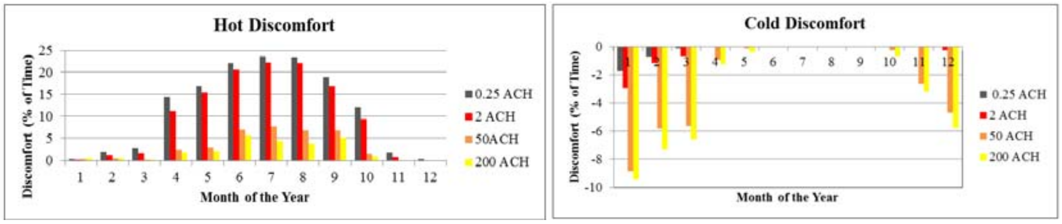

FIG. – 3: During the hottest months, spectators experience thermal comfort for up to 97 percent of time and during the coldest month, spectators experience thermal comfort for up to 91percent of the set occupancy time. The wind speeds relevant for the study of the Miami Marine Stadium initiate at least 200 average air changes per hour (200 ACH indicated in yellow on figure 3)

For the majority of the daytime, the spectators are shaded by the shells, which prevent bright sun glare and high heat gains from direct solar radiation. On average, the shells provide shading of the grandstands 80% of the time over the course of a year. However, seats still receive enough natural daylight that artificial lights are only required 9% of the day to maintain light levels above code requirements for corridors (See Figure 4). These analyses demonstrate how Candela successfully combined shape, site orientation and material selection to enhance the experience of the spectator while also creating strong formal gesture with the expressive hypar forms.

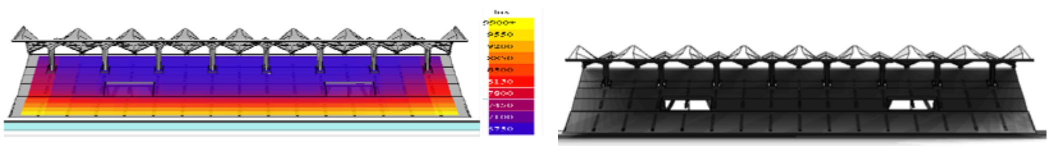

FIG. – 4a: Worst-Case Illuminance Values independent of time -4b: Shading range over 24 hours for sunniest day, 15th of March.

5 Conclusion

The designers of the Marine Stadium Shells, Candela and Meyer, rooted the complex curved shell development in the rational logic of engineering. Structural and environmental issues became drivers of the form generation instead of being constraints.

References

[1] Author's interview with Hilario Candela, October 3, 2011.

[2] Borges's 1952 Arcos de Cristal at the Tropicana Cabaret had set the national standard for the use of thin concrete shell vaults. However, Candela would be most intrigued by planar, folded and double-curved uses of the material, such as seen in Max's brother, Enrique Borges' 1956 design for the Antilla Flower shop, or the Borges brothers and Félix Candela's joint design for the Nuñez-Galvez tomb in Havana's Colón cemetery. See Eduardo Luis Rodriguez, The Havana Guide: Modern Architecture 1925-1965 Princeton: Princeton Architectural Press, 2000. Pp. 139, 171, 230-231; and Rosa Lowinger, Tropicana Nights: The Life and Times of the Legendary Cuban Nightclub. New York: Harcourt, 2005. Pp. 15-16; 100-103.

[3] Two years before Candela joined the firm, Alvarez and Gutíerrez had assisted Neutra on the design of the Alfred Schultweiss house—the Swiss masters' sole commission in Cuba. Eduardo Luis Rodriguez, pp.54-55. Also Eduardo Luis Rodriguez, Esther Sánchez, and Schweiz Botschaft. Modernidad tropical: Neutra, Burle Marx y Cuba: la Casa de Schulthess . Havana: Embajada de Suiza en Cuba, 2007.

[4] See Eduardo Luis Rodriguez, The Havana Guide: Modern Architecture 1925-1965 Princeton: Princeton Architectural Press, 2000. P. xxiii.

[5] Interview with Hilario Candela by José Vasquez, Miami Dade Community College, November 2005 and published in A Concrete Presence http://www.aconcretepresence.com/#!__page-0/overview.

[6] Author's interview with Hilario Candela, October 3, 2011.

[7] Author's interview with Hilario Candela, October 3, 2011.

[8] Givoni B 1992,'Comfort, climate analysis and building design guidelines',Energy and Buildings, 18:11-23.