

FELIX CANDELA, ELEGANCE AND ENDURANCE: AN EXAMINATION OF THE XOCHIMILCO SHELL

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Editor's Note: Manuscript submitted 9 September 2005; revisions received 20 September and 17 November 2006; accepted for publication 18 November 2006. This paper is open for written discussion, which should be submitted to the IASS Secretariat no later than August 2007.

SUMMARY

Studying landmark works of structural engineering is essential to the advancement of the field and to the continuing education of the engineer. This report presents a study of such a structure, Felix Candela's Los Manantiales shell in Xochimilco, Mexico City. The shell's structural action is discussed, and then examined through finite element analysis using SAP software. Analysis results are supplemented by field observations of the shell's current condition, and examinations of archival photos of the shell taken during its construction.

Keywords: Felix Candela, concrete shell, hyperbolic paraboloid, free edge, creep, shrinkage

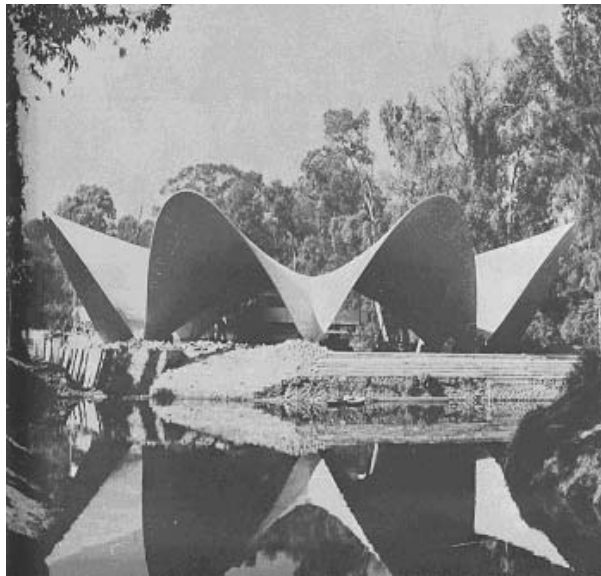


Figure 1. Restaurant Los Manantiales [5]

1. INTRODUCTION

In 1958, Felix Candela completed his most significant work, the Los Manantiales Restaurant shell, in Xochimilco, Mexico City. It sat at the edge of a wide waterway, surrounded by floating gardens (Fig. 1), and could be reached directly by embarcaderos, long, colorful gondolas that still ferry passengers along the canals of Xochimilco.

Today, the romantic setting has faded. The canals have sunk and the floating gardens have disappeared. The enduring shell, however, has not lost its majesty.

Los Manantiales is an eight-sided groined vault composed of four intersecting hyperbolic paraboloid saddles. An elevation reveals canted parabolic edges, which display its striking thinness

of 1-5/8" (40mm). Candela was taking a risk when he built Los Manantiales. The form was original, unexplored, and impossible to analyze precisely. Candela's career, however, habitually flew in the face of precise analysis. In his first acclaimed shell, the Cosmic Ray Pavilion of the University of Mexico City, he also designed an unprecedented form, using almost no calculation; a University committee requesting equations for review was instead presented with a written explanation [5, p. 14]. Candela's subsequent designs relied increasingly on structural understanding and practical experience. As a designer-contractor, he had the unique responsibility of building his own solutions. By closely observing his buildings, and using smaller projects to test new ideas, he developed an acute sense of concrete shell behavior. When he began his work on free shell edges, an exact analytical solution was nearly impossible to derive. But Candela sensed that free edges were possible, even without complex equations.

This report examines the structural action of Los Manantiales, using SAP2000 software to conduct a finite element analysis. A trip was also made to Mexico City to see the shell firsthand, and to document its current condition. The findings of this trip ultimately enhanced the significance of the analysis, but more importantly, it brought this study out of the laboratory and into the field.

2. CANDELA'S CONCEPT

Prior to Candela's free edge shells, most shells used edge ribs. Hypar shells generate large forces normal to their edges, but their uniquely thin cross sections, allowed by double curvature, have little stiffness in the normal direction. Left unchecked, a shell's normal forces would crack it from the edges inward. To prevent this, most engineers of Candela's time secured their shells' edges with ribs. These effectively reined in the normal forces, carrying them down to the supports tangentially along the edges. Unfortunately, such ribs made a shell appear heavy by obscuring its true thinness. A form existed that generated forces only tangential to the edges, with no normal forces, but it was nearly impossible to calculate. Ribs appeared the only viable solution.

To Candela, the edge rib seemed cumbersome; the shell, while sturdy, was not true to form, not pure, and could not visually express its thinness. In his

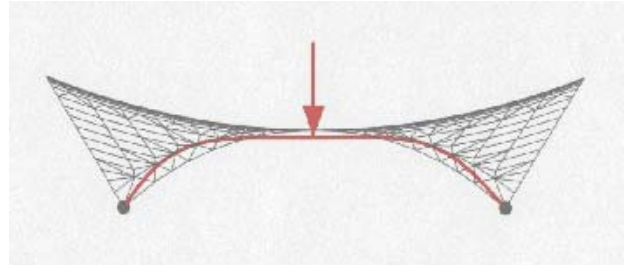


Figure 2.1. Sketch of groin deflections

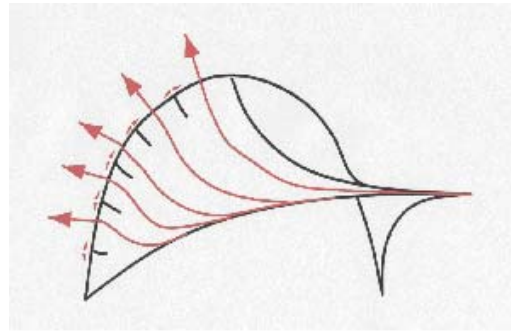


Figure 2.2. Normal forces

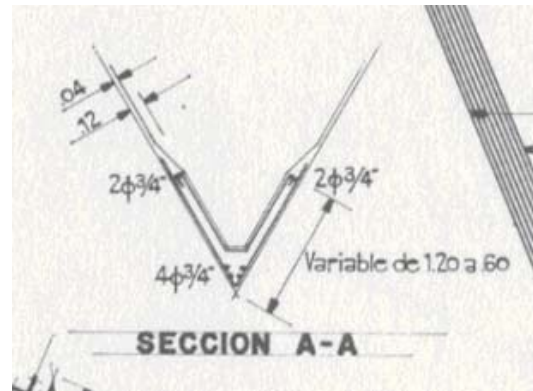


Figure 2.3. V-beam (groin) cross-section, 1''=25.4mm

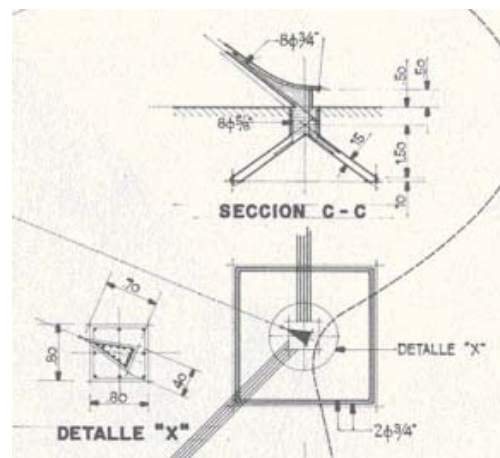


Figure 2.4. Umbrella footing, 1''=25.4mm

technical writings, Candela never boasted of his structures as ‘works of art,’ but in many ways, he considered himself an artist. He enjoyed integrating aesthetics and sound structure, using his imagination to find new solutions. He saw the free, thin, crisp edge as the ultimate shell builder’s challenge, and his solution, found after less than a year of research, is simultaneously an elegant and efficient innovation. Colin Faber describes how, in 1955, Candela began working on the free-edge problem for the roof of the Mexico City Stock Exchange [5]. The project ended with a ribbed shell, but Candela continued exploring the problem on his own. His next large project, the San Antonio de Las Huertas Church, built in mid-1956, was completed with free edges.

Normally, a shell’s dead load causes bending in its groins, bowing them outward (Fig. 2.1). The resulting deflection pushes against the saddles, generating forces normal to the shell’s surface. At the edges, the normal forces cause the shell to balloon out, forming cracks that propagate from the edges inward (Fig. 2.2). Edge ribs can be used to mitigate these cracks, but Candela, recognizing the behavior described above, addressed the groins rather than the edges. Each of Los Manantiales’ eight groins is thickened into a V-shaped beam, as seen in Fig. 2.3. These beams enhance the groins’ stiffness, reducing bending and deflection, and thereby eliminating normal edge forces. Instead of membrane stresses reaching the shell’s edges and generating tension, as in Fig. 2.2, they are essentially “pulled” to the groins, making edge ribs unnecessary. At the supports, the V-beams anchor into inverted umbrella footings, seen in Fig. 2.4. These unique footings cup the earth, preventing the shell from sinking in the wet Mexican soil. To resist lateral thrusts, adjacent footings are linked with Ø1” steel bars. Candela’s design produced startling thinness; between V-beams, the shell’s saddle spans are only 1-5/8” thick.

3. FINITE ELEMENT ANALYSIS

Prior to a full stress analysis, SAP2000 was first used to calculate the shell’s support reactions. These are presented in Table 1. Moments about the supports were negligible.

A global equilibrium check was conducted against the vertical reaction, V, to test the finite element model’s accuracy. First, Rhinoceros 3D drafting

Table 1. Finite element model reactions, 1k = 4.45kN

Model Reaction (moment reactions ≈ 0)	Value (k)
Vertical, V_model	57.21
Horizontal, H_model	35.92

software was used to tabulate the shell’s surface area, as shown in Fig. 3.1. The surface area was then used to calculate the shell’s total dead load. This method deviated from ideal hand-made calculations, but as the software accurately produced surface areas for simpler shapes, its use was decided an acceptable break with intended procedure. The results are presented in Table 2 below.

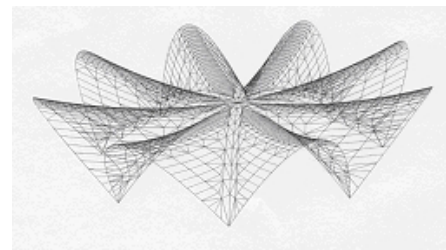


Figure 3.1. 3D surface model

*Table 2. Dead load calculations
1ft = 0.305m & 1k = 4.45kN*

Shell Portion	Surface Area (ft^2)	Thickness (ft)	Concrete weight (k/ft^3)	Dead Load (k)
V-beam	2,758	0.3937	0.15	162.7
Saddle	14, 975	0.1312	0.15	294.7
Total Dead Load =				457.6

Vert. reaction = 457.6/8 = **57.2 k (255 kN) = V_{hand}**

V_{hand} exactly matched V_{model}.

A second check was conducted against the horizontal reaction, H. While not required to validate the model, as an exercise it provided a useful opportunity to compare the arch behavior assumed for a 2D calculation and the more complex shell behavior modeled by SAP.

From Fig. 3.2, tanα = 4d/L, where α is the angle between N and the horizontal, d is the rise, and L is the span.

tanα = 4d/L = (4 x 5.8m)/(32m) = 0.725
H_{hand} = V/(tanα) = 57.2/0.725 = 79 k (351 kN)

H_{model} = 35.92k (160 kN), less than half of H_{hand}.

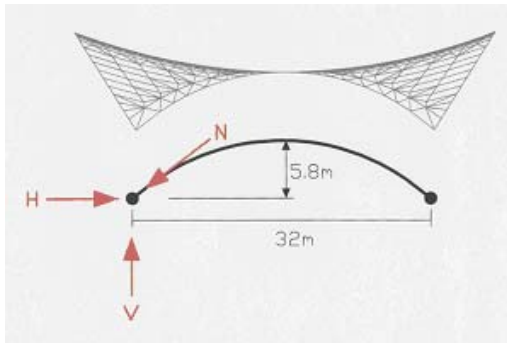


Figure 3.2. Reaction diagram for hand calculation

Two aspects of the shell's structural action explain this large discrepancy in the two calculated values of H . First, the total dead load of the shell does not reach its supports exclusively through its groins. As the shell surface between the groins approaches the supports, an increasing portion of the dead load descends directly through the surface itself, rather than through transfer to the groins. Reducing the load on the groins reduces their outward thrust, thereby reducing H . Second, the shell's edges extend past its supports. The vertical load generated by these outer sections must therefore travel to the supports against the direction of H , reducing H even further. The finite element model implicitly takes these two considerations into account, and therefore gives a lower horizontal reaction.

The two most stress-critical areas of the shell are its groins and the edges. These were examined using two lines of data points along the model's surface: one along a groin, from the center of the shell down to the support, and one just before the edge, from just behind the support up to just behind the apex of an edge parabola (due to the limitations of the finite element model, in it was impossible to obtain stresses exactly at the edge, and points slightly behind the edge were deemed sufficient). Since snow loads are not a concern, only a dead load analysis was conducted for this study. Stress values given in the following sections were calculated by averaging SAP top-surface and bottom-surface stresses, which are shown in the accompanying figures. Positive stresses indicate tension, negative stresses compression. The difference between the top and bottom-surface stresses gives an indication of the bending. For all graphs in this Section 3, $1\text{ft} = 0.305\text{m}$ & $1\text{k}/\text{ft}^2 = 6.94\text{psi} = 6.89\text{ kN}/\text{m}^2$ (For a more comprehensive description of the analysis presented here, see [2]).

3.1 Groin (V beam)

The groin was examined first, using membrane stresses S_{11} , S_{22} , S_{min} , and S_{max} . S_{11} stresses (Fig. 3.1.1) are circumferential, perpendicular to the groin and crown lines. S_{11} compression in the shell is greatest at the groins, where the full weight of the saddles descends to their corresponding groins. As the groins descend from the center of the shell, these stresses begin to taper, due to the slope of the shell's saddle surfaces increasing as they near the supports. As the slope perpendicular to the groin increases, the component of the saddle's weight perpendicular to the groin (the component producing the S_{11} stresses) decreases. The maximum S_{11} compression stress therefore occurs at the shell's crown, where the slope is smallest and the danger of buckling the greatest. However, at -101 psi ($-696\text{ kN}/\text{m}^2$), the S_{11} maximum is low, presenting little danger in terms of buckling. S_{22} stresses (Fig. 3.1.2) are radial, parallel to the groin and crown lines. Maximum S_{22} compression also occurs at the shell's center, but at -71 psi ($-489\text{ kN}/\text{m}^2$), it is even smaller than in S_{11} . As the groin descends, S_{22} compressive stresses shrink to approximately 0 psi at the center of the groin, and then rise to -78 psi ($-537\text{ kN}/\text{m}^2$) near the support. These stresses are extremely small, but they do hint at the 'bowing' trend in the groin suppressed by the groin's increased thickness, previously discussed in connection with Fig. 2.1.

S_{min} stresses (Fig. 3.1.3) represent the greatest compression resultants of the S_{11} and S_{22} stresses. Maximum compression occurs at the shell's crown and the supports. The crown, the area most vulnerable to buckling, experiences a total compression of -124 psi ($-854\text{ kN}/\text{m}^2$), while the support experiences -142 psi ($-978\text{ kN}/\text{m}^2$). Between these two points, compression lessens slightly due to the 'bowing' trend. S_{max} stresses (Fig. 3.1.4) represent the greatest tension resultants of S_{11} and S_{22} . About the crown, SAP produces no S_{max} stresses above zero, indicating the area is in pure compression. Again due to bowing, tension occurs one-third down the groin, quickly peaking at 20psi ($138\text{ kN}/\text{m}^2$) and gradually decreasing to zero at the support. Actual bending induced in the shell, however, is negligible. All S_{min} and S_{max} stresses are small, proving that Candela's choice of form renders the stresses in the groin insignificant, and provides superbly high safety against buckling in the thin shell.

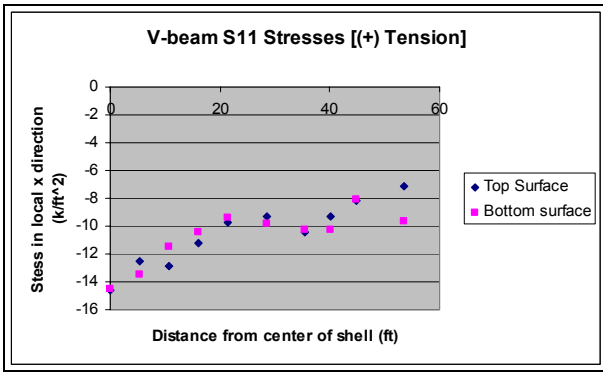


Figure 3.1.1. S11 stresses along groin

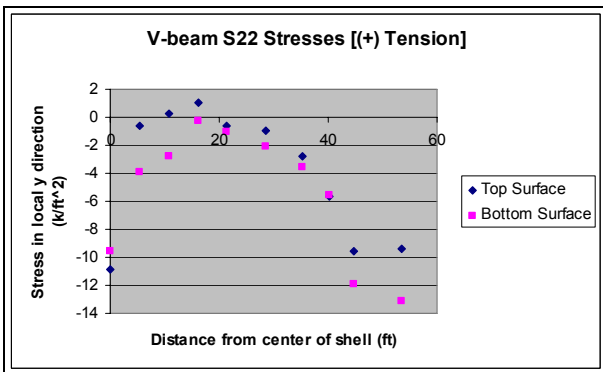


Figure 3.1.2. S22 stresses along groin

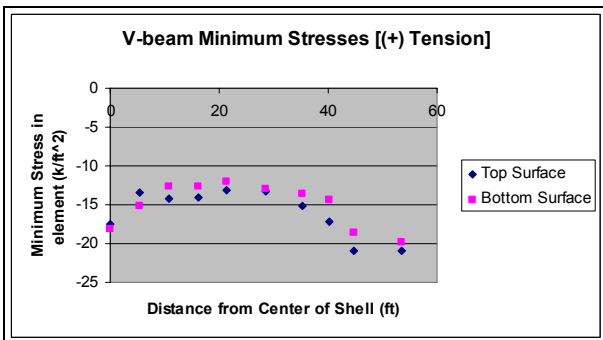


Figure 3.1.3. Smin stresses along groin

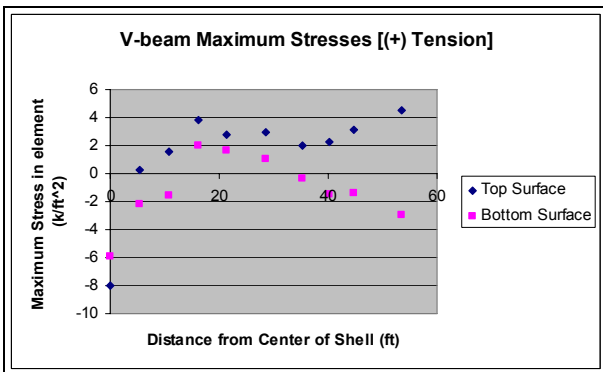


Figure 3.1.4. Smax stresses along groin

3.2 Edge parabola

The line just behind an edge parabola, the area of the shell most vulnerable to tension cracking, was analyzed next. The maximum S11 compression (Fig. 3.2.1) is -30psi (-207 kN/m^2), just above the support. Compression then decreases steadily to zero at the apex. S22 compression (Fig. 3.2.2) begins at zero at the apex, and steadily increases to a peak of -68 psi (-469 kN/m^2) two-thirds down the edge. Compression then decreases again, but returns to a final peak of -118 psi (-813 kN/m^2), in the V-beam at the support. These stresses are small, even for the shell edge. However, their rise and fall suggests that as the shell leans outward past its supports, its cantilevered weight bends the edge slightly inward, as if pulling it into one wide inward curve. Compression rises to a peak two-thirds down the edge, the deepest point of the curve, and then steadily decreases as the edge moves away from that point. At the groin, the full weight of the saddle bears down on the support to create a final compression peak. Bending in the thin shell is negligible, but the stress pattern itself is notable and will be discussed later, with respect to evidence of slight creep in the concrete.

The Smin and Smax stresses (Fig. 3.2.3 & Fig. 3.2.4) follow the same trend as those of S11 and S22, respectively. Of special interest are the Smin stresses, which begin at -122psi (-841 kN/m^2) at the support and steadily decrease to negligible values at the apex. This trend expresses the function of the groins as stress attractors, effectively pulling stresses away from the edges. Deformations due to edge stresses are on the order of 0.001in (0.025mm), impossible to observe with the naked eye and completely negligible in terms of the structure's behavior. Normal edge stresses output by SAP, S23 and S13, are on the order of 0.1psi (0.69 kN/m^2), practically nonexistent, and most likely attributable to finite element approximations. The miniscule deformations, and the absence of tension and normal stresses in the edge, affirm that Candela's design successfully eliminated tensile edge stresses. (The full analysis appears in [2].)

4. PRESENT-DAY LOS MANANTIALES

Figure 4.1 shows Los Manantiales in its present condition. It is currently under renovation, but many sealed cracks can still be observed on the shell's inner and outer surfaces. The most probable causes of these cracks are shrinkage and creep.

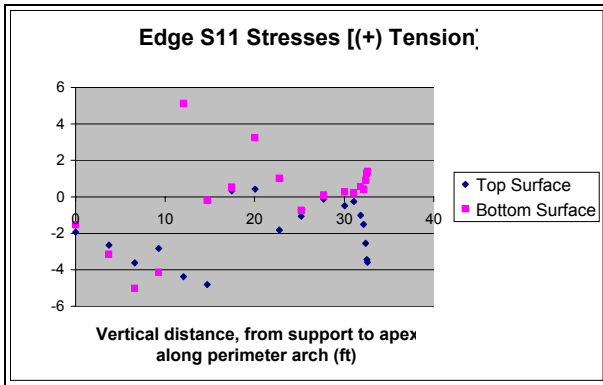


Figure 3.2.1. S_{11} stresses (k/ft^2) along edge parabola

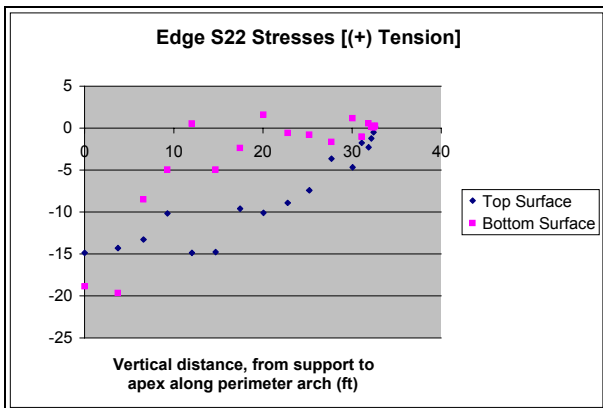


Figure 3.2.2. S_{22} stresses (k/ft^2) along edge parabola

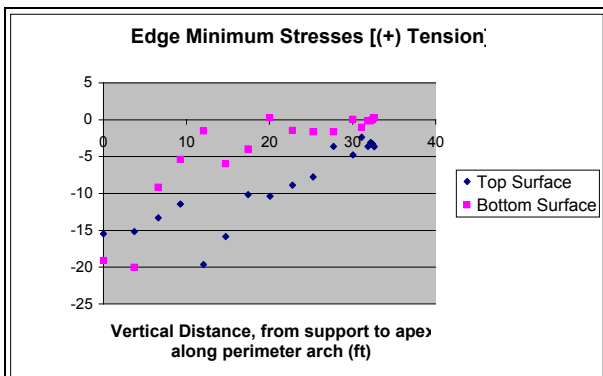


Figure 3.2.3. S_{min} stresses (k/ft^2) along edge parabola

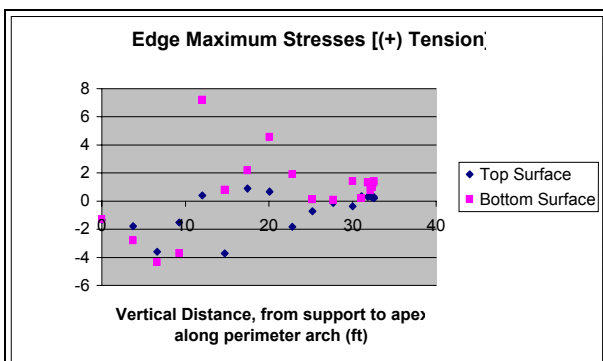


Figure 3.2.4. S_{max} stresses (k/ft^2) along edge parabola



Figure 4.1. Present-day Los Manantiales

Figure 4.2, a photograph of the shell taken shortly after concrete had finished being poured, shows faint, damp cracks on the shell's surface. Figure 4.3, a photo taken after construction was completed, shows a network of cracks spreading in hard lines over the shell's surface. That the cracks became more prominent from the initial pouring to the finishing of construction indicates they developed as the concrete dried. Los Manantiales was poured by hand, one section at a time, and as workmen moved over the formwork, finished areas were left to dry uncovered. The shell's exterior surfaces thus dried faster than its interior, creating "mud-cracks" as shrinkage pulled the outer surface into tension. Over time, moisture and pollution deepened some of the cracks, and today, a number of drip stains can be observed where cracks once broke completely through the shell, as show by the patched leaks in Fig. 4.4. A number of these cracks are still in the process of being sealed, but none has done any significant damage to the shell.

A second crack pattern can be observed on the underside of the shell. In Fig. 4.5, a now-sealed crack propagates in from an edge along the underside of each saddle. These cracks appear on each side of every edge, about 10ft (~3m) up from each support and symmetric about the saddle's center.

While the cracks occur systematically, they are not the result of form. Their correspondence to the edge stress trends of the finite element analysis instead suggests they have occurred due to creep. Xochimilco is hot all year round, threaded with canals, and suffers the air pollution abundant



Figure 4.2. Photograph showing shrinkage cracks during construction. The cracks are most visible on the left side of the image.



Figure 4.3. Photograph showing more diffuse shrinkage cracks after the structure has been completed

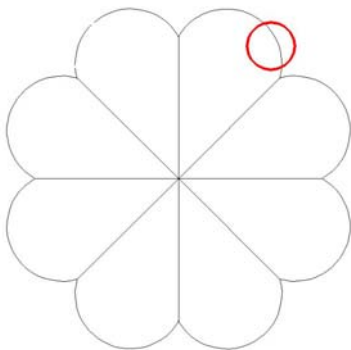


Figure 4.4. Patched leaks and drip-stains on the underside of the shell, and their location in plan

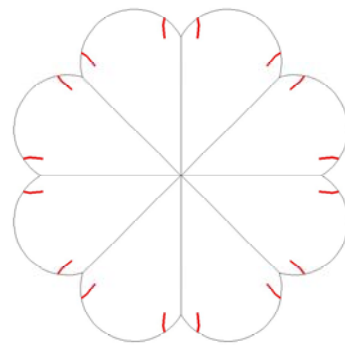


Figure 4.5. Patched creep crack and crack pattern layout

throughout Mexico City. Heat, moisture, and pollution all accelerate creep, and for decades, Los Manantiales' small mud cracks increased its susceptibility to these three elements. As with any concrete structure in permanent compression, Los Manantiales most likely experienced some small degree of creep independent of its environment. This natural creep, however, would then have been magnified by its unfavorable surroundings to produce the cracks. It is important to note that the cracks have in no way compromised the structural integrity or safety of the shell, and that any deformations in the shell's present state are so small as to be invisible to the eye, even in the cracked areas. After 46 years, the concrete is still in good condition, and with vigilance and occasional maintenance, will most likely last through another 46.

5. CONCLUSION

Because the finite-element analysis in this report is relatively straightforward, it has substantial educational value, especially when connected to field experiences and simple calculation to explain structural behavior. However, the analysis ultimately demonstrates not that such analysis was necessary for the design, but rather that the design renders the stresses essentially insignificant. It confirms the correctness of the design while reinforcing Candela's insistence on the *unimportance* of such analysis when the designer chooses a structurally appropriate form. As Candela was fond of saying, "the quality of a structure is in inverse proportion with the amount of calculations..."[3] (For further insight into Candela's ideas, see [1] and [4].)

Even more important is the first-hand inspection of the 46-year-old shell, and its evaluation as still in fine condition. This is a dazzling accomplishment for such a thin shell, and is further testimony to Candela's high merit as a structural artist. With Los Manantiales, Candela succeeded in creating an

elegant structure that avoided what he called "extravagant architectural dreams"[4] that can lead to great expense and questionable structural performance. It is critical to the future of structural engineering to recognize the high quality of such work, significant for its technical virtuosity and sensitivity to aesthetics.

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PHOTO CREDITS

Figure 1 – Erwin Lang. Photo taken from [5, p. 159].

Figure 2.3, 2.4 – Cubiertas Ala. Drawings obtained from Avery Library Archive of Architectural Drawings at Columbia University.

Figures 4.1, 4.4, 4.5 – Noah Burger

Figures 4.2, 4.3 - Antonio Candela. Photos obtained from Avery Library Archive of Architectural Drawings at Columbia University.