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Formative Experiences: Saarinen's Shells and the Evolutionary Impact of Construction Challenges

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Abstract
A half-century ago, Eero Saarinen and Associates collaborated with the structural engineers of Ammann & Whitney in the design, documentation, and oversight of two very different, and completely unprecedented, concrete shell projects: Kresge Auditorium (1951-55) and TWA Terminal (1956-62). The building designs were intentionally anomalous from traditional shell projects, particularly in the manner by which they deviated from conventional structural logic of their forms—albeit in very different ways.

Unsurprisingly, the construction challenges for the projects were equally different and profound, requiring a great deal of innovation and collaboration. Design teams had to devise ways to work collaboratively to address the particular challenges of designing, analyzing, documenting, and supervising the construction for these concrete shells.

The paper will examine how the notorious construction complications and the resulting structural failures of Kresge Auditorium led to an evolution in the collaborative design relationship, more thorough and inventive documentation, and the development and integration of a rigorous plan for construction of TWA. By examining original construction documents, construction photos, and correspondence between the firms, the paper will demonstrate how an increased focus on the constructability became a common goal between the two firms and how this resulted in a more technically thorough process of design and construction for TWA, in spite of its more complicated form and elevated technical challenges.

Keywords
Saarinen, Kresge Auditorium, TWA Terminal, Concrete Shell Construction

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Abstract

“Today you and I are concerned with the integration of architecture with different kinds of engineering and construction.” – Eero Saarinen, Address to AIA conference, October 24, 1952

“In many cases (Saarinen) has relied upon the sheer ingenuity of modern technology to get him out of difficulties that would have presented insurmountable obstacles a quarter of a century ago” – N. Keith Scott, 1955

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A Tripod Dome Built on Tricky Framework: Kresge Auditorium (1951-55)


In May 1954, soon after a majority of the scaffolding was removed from below the new roof of Kresge Auditorium on the Massachusetts Institute of Technology’s campus, TIME magazine photographed the project’s architect, Eero Saarinen, in a series of contemplative poses in which the architect stood on, in, and under the largest free-standing concrete shell building in the U.S. (Figure 1). Saarinen knew of the difficult and costly construction conditions that proceeded this moment, and he knew that the roof was currently undergoing a steady and unabated six-week long phase of sagging that threatened the viability of the structure itself (Cohen et. al., 1985). Seemingly unaware of the pending complications, or Saarinen’s role in creating these issues, the article lauded his boldness and contemplated the impact of the work (source). The work was certainly impactful, but mostly as a warning for what could happen if the architectural form and engineering efforts aren’t properly coordinated with the inherent constraints of thin shell construction.

Many of the problems started with the design process. Saarinen’s office frequently worked in models at the beginning of projects to give the proposals a sense of scale and to suggest potential materials and construction methods. In 1950, they created a plasticine model with a triangular curved form that rested only on the three end points. It was named the Vulgar Freak and quickly dismissed because the shape (a 1/8th segment of a sphere) didn’t match any conventional structural logic for concrete shells or auditoria acoustics (Figure 2). However, over the next two weeks Saarinen made the case that the form would work functionally with a triangulated auditorium, that the dome shape would be contextual on campus, and that the three points of consolidated support would allow huge floor to ceiling glass windows under the roof. Saarinen renamed it the Loved One and work proceeded (Saarinen, 1953).

Although Saarinen was confident publicly that the unique form was “structurally appropriate” it was, in fact, highly speculative. Not only was the scale of the project unprecedented for a concrete shell (160’ clear span), there was no relevant example for how it would be drawn, engineered or even constructed.

Saarinen hired Ammann & Whitney to be his structural engineers, and even though they were the nation’s leading experts in the relatively new field of concrete shell engineering, Saarinen didn’t seek their advice about how to design the roof form; they were simply asked to “make it work” (Roche, 2014). The engineering challenge was exceedingly difficult, in part because the
overall shell form established by Saarinen didn’t comply with any previously tested or constructed shells. The engineers endeavored to make the building work by simply modifying parts of the existing form but their untested (and untestable) suggestions simply wouldn’t work as planned. As an example, because the geometric shell configuration wasn’t structurally efficient they suggested the inclusion of deep curved arch beams springing from the three support points as a way to compensate for the inevitable bending stress. The theory was that this would allow the double-curved roof form to act as a structural shell and retain its modest 3.5” (9 cm) structural thickness. Instead, the arched beams took on more stress than planned and became the root of the structural problems the building endured (Penn State Univ.). Ironically, these changes were made to try and retain Saarinen’s vision for the building’s form, not for reasons of structural or construction efficiency, and yet because they didn’t work as planned, they inadvertently impacted this vision.

Somewhat surprisingly given Ammann & Whitney’s reputation on shell design, the Kresge construction documents only marginally acknowledged the unique construction challenges of building a shell. Mostly standard language about concrete casting and formwork was used in the specifications and they abdicated much of the responsibility for coordinating this work to the contractor, including the ability to determine the “design, fabrication, and erection of the shell falsework and forms, the pouring procedure (one pour or in sections with joints), and the decentering procedure” (Project Specs, 1952). These are incredibly broad expansions of authority to give to a contractor, particularly because these choices can adversely affect structural performance. When construction began in May 1953, George A. Fuller Company, had to sort through the unique complications of construction with only marginal input and instruction from the design team.

Because the contractor chose to pour the concrete foundations and auditorium seating first, the formwork for the double-curved roof would need to be formed atop the sloped seating—an incredibly difficult, and not very accurate process for setting the proper geometry (Eng. News Record, 1954). To get an accurate reference points, the contractor logically set the arched beams first. Using a full-sized template built in a hangar, the framework for all the arched beams were made off-site and then placed around the building perimeter accurately and shored below with scaffolding (Bates, 1954). The beam heights were used as reference points to complete the double-curved shell form. The roof’s formwork was a jungle of scaffolding topped with a custom

Figures 3A-3C (L to R): Fig. 3A. Formwork plan, Fig. 3B. Scaffolding under roof, Fig. 3C. Incomplete formwork
wood bracing and framing that allowed a series of 1 x 7 wood beams to run horizontally, like contours, at the critical heights of the roof slope (Figures 3A, 3B & 3C). All of the work was customized and there was no repeating the formwork so the process was very labor-intensive and expensive.

The job’s foreman, Douglas Bates described how the roof was poured in separate segments because the “single continuous operation” option given in the specifications wasn’t realistic (Bates, 1954). By pouring the roof after the auditorium, the roof construction was pushed to the winter months which complicated things considerably. The pouring process was very difficult, not only because of the cold weather, but because they had an inexperienced crew pouring very thin shell with raised edges and steep slopes. Because the slope was incredibly steep near the supports, the first pours needed counterforms which obscured the visibility of the concrete placement at the critical junction to the foundation. The thin roof depth barely had an acceptable thickness of cover around the large criss-crossing rebar during ideal pouring conditions. The edge beams were formed and poured separately from the roof which was a problem as they were intended to be structurally integral throughout. (Figure 4). A 2” layer of Gunite was added atop the roof shell to be used for securing the roofing material (originally lead-coated copper tiles) but this layer was cracked severely by the building movement and had to be fixed with a pourable acrylic polymer binder, which also failed (Boothby et. al., 2005). Ultimately, it took nearly 100 days to complete the roof and it performed terribly structurally once the forms were removed. The arched beams sagged three times the acceptable distance (5” total) before they were re-shored with scaffolding, only to be eventually supported by steel columns embedded in the glass curtainwall. There remained persistent problems with roof cracking and leaking for the next 25 years, and when Ammann & Whitney was asked to investigate their work in 1979 they found that significant portions of the arched beams and shells had cracked and deteriorated, mostly near the buttresses, to the point at which they needed to be replaced (Cohen et. al., 1985).

It was clear that much of the problems on Kresge stemmed from the fact that the building simply wasn’t designed with its means of construction and structural performance in mind. Instead of proactively addressing these potential problems as part of the design and documentation process, these responsibilities were either ignored or abdicated. Even Saarinen joined the criticism, “In retrospect, one has to criticize this building...we learned that one cannot depend on geometry for the sake of geometry” (Saarinen, 1958). To avoid these consequences on subsequent projects, he could have opted for more conventional or structurally logical forms going forward, but instead aspired to create an even more complex design for the TWA Terminal that his partner Kevin Roche described as “more of a structural problem than a structural solution” (Whitehead, 2014). The project teams were committed to learn from these mistakes of Kresge and they devised ways to work collaboratively to address the particular challenges of designing, analyzing, documenting, and supervising the construction for this project that Ada Louise Hux-
table called a “stunning manipulation of reinforced concrete into unconventional forms of arbitrary but dazzling grace” (Huxtable, 1962).

A Soaring Experiment: Trans World Airline Terminal; (1956-62)

“It wasn’t meant to be a thin shell—it was a sculpture placed around a process of movement.” – Kevin Roche, 2014.

Saarinen’s first sketch of TWA showed the building as one large undulating elliptical paraboloid shell structure—an ambitious but intuitively reasonable shape for a concrete shell. He expressed his desire to make a “dynamic building form” and he clearly understood from Kresge that the challenge was, “how to make the vaults, whose compressive forces are always downward, become soaring rather than earthbound” (Eero Saarinen & Assoc.) But as the project developed Saarinen intentionally strayed from structural logic, stating, “(The) structural and rational cannot always take precedent when another form proves more beautiful. This is dangerous but I believe true” (Saarinen, “General Statement,” undated). Saarinen’s office again built dozens of small initial models, casting many of them in complex double curved forms similar to Saarinen’s furniture designs. Eventually a clover-shaped continuous roof shell with four separate bulges and a cantilevering edge beam around the perimeter was proposed. But because this scheme repeated many of the same structural mistakes as Kresge (e.g., it couldn’t be poured without roof joints which would cause the shell to fail, the edge beam would counter-act the membrane action, etc.), an opportunity presented itself for Abba Tor, a young engineer tasked with developing the TWA engineering, to point out these problems and to seek out a mutually beneficial solution.

Although Tor called TWA a “creature which started out wild and needed to be tamed and domesticated,” his suggestions weren’t intended to radically change the building form, only to make sure the project could be successfully engineered and built as intended—a sentiment shared by Saarinen (Ringli, 2011). Tor wanted to see the four bulges somehow split apart so they could be cast independently and operate more autonomously structurally. Happily, Saarinen was also contemplating ways to make the shells more gestural and open on the inside and so the project was changed from one large undulating shell into four separate, arched, barrel-vault quadrants, separated by continuous skylights, with expressive, continuous, curving, and cantilevered beams along the edges, connected back to a central keystone in the middle (Figure 5). Each portion of the roof shell could now also have a varied thickness, depending on the desired geometry and structural constraints, and each quadrant could be poured continuously, ideally in only one
day, which eliminated concerns for concrete shrinkage and construction joints. This final scheme wasn’t structurally efficient but it was certainly structurally innovative, and unlike Kresge, this scheme was also motivated by a certain construction logic. Both parties take credit for the design change and each set about documenting and engineering these complex forms.

Saarinen’s office turned again to model-making as a way to refine the design, but these new models were so huge that the only way they could accurately build the model was to generate sectional templates for the different arch profiles of the roof at the edges and the middle of the shells and then to join the pieces together to form a surface with rectangular pieces of paper mimicking the formwork pattern (Figure 6). Roche, who helped build the models, described it as a very methodical process with an underlying logic of 2D to 3D translation that was then used reversed to document the form accurately again in 2D for the construction documents (Roche, 2014). At Ammann & Whitney, they had no choice but to engineer the building from first principles, like any piece of huge sculpture, and they relied upon certain assumptions on basic equilibrium and engineering principles for the engineering. The challenge was in carefully coordinating the construction.

Although the new scheme was more logical, it was still an unprecedented undertaking to try and construct a project like this and so both firms spent a great deal of time producing a thoroughly coordinated, and unprecedented set of construction documents and oversight efforts. More than 130 architectural and structural construction drawings were required to represent the unique geometric and structural properties of the building’s elements. In addition to the arch profile drawings used to make the models, the architectural and structural plans showed contour line and spot elevations to indicate variations in slab thickness, gridded serial sections of plan and elevational drawings of the columns that described the evolving geometric forms, and a unique and rigorous set of specifications and requirements for submittals (Figure 7).

Both firms were immersed in the two-year construction administration process, placing representatives from each firm on-site throughout construction where they worked with the contractors, Grove, Shepard, Wilson & Krüge every day. Unlike Kresge, the plans for how to form and pour the shell were developed collaboratively with all parties on-site in accordance with the
drawings and specification which called out “every detail of the construction operation...from forming to finishing” (Yeakel, 1962). Because of the uncompromising requirements in the documents for construction process and structural behavior, specifically the requirement that each shell must be poured continuously in one-day with only minimal allowable dimensional deflection after the scaffolding was removed, it took nine months to prepare a manual which outlined the plans for forming, finishing, and testing the tolerances of the concrete.

Forming the underside of the roof was again done with scaffolding, but unlike the somewhat random arrangement at Kresge, this scaffolding was laid out on a rigorous grid that dictated the exact placement of the scaffolding vertical elements. The only computer used on this project was used by the contractor to calculate the exact height of each vertical scaffolding post, all 1,800 of them, to make sure the anticipated curvature was met. Each post was held in place with prefabricated wedges (cut at the proper angle) with a u-shaped end receiver to hold the main support beams of the formwork. They were within 1/16" tolerance throughout, even with the complicated geometry of the forms proposed (Arch. Forum, 1960). After the bottom surface was fully formed and sealed, the contractor spray-painted spot elevations on top of the formwork (in the same locations as the construction drawings showed) to guide the pouring process from above (Figure 8). Three test panels were constructed to simulate the most difficult placing conditions of angle of incline and amount of reinforcing to fully prepare for the pouring process which had been pinpointed with “unforgiving tolerances” (Yeakel, 1962).

Because of the need to have different concrete slump mixes for different portions of the shell, there was a mobile concrete batch stations on-site that would mix and deliver the concrete to the crane operator. Over 150 workers helped pour each section of the roof; they wore a shirt with a giant number on it that corresponded with an assigned work position on the roof (Figure 9). Two 180-foot, 45-ton cranes hoisted the concrete to the workers in modestly sized one cubic yard loads—the process was so coordinated that each bucket was color coded with paint to assure that it was being placed in the right location on the shell slope to ensure workability, and it was placed at a staggering rate of one cubic yard every two minutes. Inspection crews of engineers and carpenters, stationed under the formwork and at the ground level below observed a system of hanging plumbs from the roof so that the next bucket load could be placed at a compensating point for counter-
balance if the formwork moved. The largest roof section was 1,000 cubic yards and it took a full 30 hours of continuous labor to pour and finish. To leave the concrete roof visible to planes above, the roof was coated with 1,500 gallons of silicone waterproofing material that prevented freeze/thaw damage to the concrete and facilitated faster runoff of rainwater to keep the roof looking clean.

The Evolution of Intent and Expertise

"...the reason why these (plastic forms) are being built now...is really aesthetic and not economic; and we should face that." Eero Saarinen, “Function, Structure, and Beauty,” August 1957.

The thoroughness of the design construction process was rewarded as the finished shell form sagged considerably less than anticipated upon the removal of the formwork and there were no noticeable shrinkage cracks (Figure 10). The project foreman Kenneth Morris, gave high praise to the process and people, calling the work the “The biggest challenge to concrete and concrete men I’ve seen in my 30 years of construction...the teamwork was the finest I’ve ever seen...and the 5,000 tons of sculptured concrete you see standing there is the best proof I know” (Yeakel, 1962). Saarinen never saw the building complete, but did see the scaffolding removed and boasted in a letter that, although there was a lot of concrete, “it is the least earthbound shell that has ever been built” (Saarinen, 1960).

The construction challenges and structural failures at Kresge led to the incremental evolution in the structural responsiveness and constructability of TWA. This was in part due to Saarinen’s willingness to accept and embrace a greater level of influence and expertise from the structural engineers during the early stages of design formation, and the correspondingly increased level of expertise in concrete shell design by the project teams in both offices born from this collaboration. And although TWA was intentionally divergent from an efficient structural form, and it wasn’t easy or economical to build, it advanced much of the early formative dialogue about the degree of influence that function, structural performance and constructability should (or shouldn’t) have in the derivation of a spatial shells. Roche summarizes the efforts concisely, “It was a great moment in modern architecture...even if some were appalled by the work, it was incredible.”

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