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Saarinen’s shells: The evolution of engineering influence

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Abstract
This paper will examine the collaborative practice relationship between Eero Saarinen & Associates and Ammann & Whitney Engineers during their decade-long partnership in designing and documenting three concrete shell projects: Kresge Auditorium, TWA Terminal, and Dulles Airport Terminal. The variable range of the buildings’ formal expressions can be traced back to a corresponding level of involvement and influence from the structural engineers, resulting in a shift of Saarinen’s designs.

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1. Evident Influence
“Today you and I are concerned with the integration of architecture with different kinds of engineering and construction.” – Eero Saarinen, Address to AIA Regional Convention, October 24, 1952 [19].

A half-century ago, Eero Saarinen and Associates collaborated with the structural engineers of Ammann & Whitney in the design of three very different, and completely unprecedented, concrete shell projects: Kresge Auditorium (1951-55), TWA Terminal (1956-62) and Dulles Airport Terminal (1958-63). The broad formal variance, technical aptitude, and structural design logic of the projects can be explained, in part, by considering the evolving nature of their collaborative design relationship—specifically how an increased level of influence imparted by the engineers affected the building designs.

Because these designs were truly anomalous in technical complexity and form at the time, the project teams devised ways to work collaboratively to address the particular challenges of designing, analyzing, documenting, and supervising the construction for these concrete shells. Initially this process resulted in more compromises than collaborations, in part because the projects weren’t intended to reflect an optimized engineering-based solution, but each successive design demonstrated how proactive engagement in structural, material, and construction considerations could better benefit the overall design from both perspectives.

2. Progressive Technology & Adverse Behavior: Kresge Auditorium; (1951-55)
“The strongest, most economical way of covering an area with concrete is with a dome and a dome of thin-shell concrete seemed right for a university interested in progressive technology;” - Eero Saarinen on Kresge Auditorium, June 1955 [20].

Upon completion, Kresge Auditorium at M.I.T. was to be the largest thin shell concrete building in the United States, but when the scaffolding-supported formwork was removed in March 1954, the building’s structure failed to perform as designed. Because of interruptions to the double-curved shell geometry dictated by the triangularly shaped segmented spherical form, the membrane stresses were transferred the shell’s stiffest element—the three curved perimeter arches. This produced a large amount of unanticipated bending stress and as a result, the structure underwent six weeks of unhindered creep, eventually sagging more than three times the anticipated amount (Cohen et. al. [9]). The roof had to be re-shored until

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supplementary structural elements could be added permanently as part of the window system below the arches. A non-structural top-coat of lightweight concrete, placed atop the shell as a substrate, cracked as a result of the movement and created long term water infiltration problems (Boothby et al. [7]).

These structural failures, in addition to the difficult and costly construction conditions that proceeded it, bolstered the critical view that the building form was neither derived from functional or engineering-based logic—both points readily conceded by Saarinen. However, many of the decisions that directly affected the adverse structural behavior were initially caused as the result of a flawed collaborative design process.

2.1 A Vulgar Freak Becomes the Loved One

In 1952, Saarinen drew sketches for Kresge that boldly proposed anticlastic thin-shell spatial enclosures, shaped to enclose a fan-shaped auditorium, with sweeping elliptical profiles in section (Figures 1A-1C). The firm built dozens of plaster models of the proposals, including spherical forms that alluded to the nearby domed roofs on campus (“Saarinen Challenges…” [2]). One of the schemes was oddly shaped hybrid solution: a curved equilateral triangular trefoil, geometrically derived from a 1/8th segment of a spherical dome, supported only at the end points of the triangle on three buried buttresses. Because its form didn’t comply with intuitive configurations for thin shell design or domes, it was dubbed a “Vulgar Freak” by the design team, but after two weeks of consideration, Saarinen felt it best expressed the functional, aesthetic, and structural priorities for the project, so he re-named it The Loved One and it became the basis for the final building design [18]. The form was highly experimental and the structural challenges were formidable so Saarinen hired Ammann & Whitney, the nation’s leading expert in concrete shell design.

Figures 1A-1C (left to right): Fig. 1A & 1B, Sketch options for shell geometry and support, 1952 [2], Fig. 1C, Final model showing three points of support and edge beams, 1953. (Yale University Archives).

2.2 Compromise over Collaboration

“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, Feb. 1955 [21].

Two of the founding partners at Ammann & Whitney involved with the project, Charles Whitney and Boyd G. Anderson, were considered experts in the relatively new field of concrete shell engineering (Whitney [23]). Whitney’s expertise was in the analytics and economics of concrete shells, while Anderson was known as more of a clever problem-solving designer and an “open-minded collaborator that never dealt in absolutes” (Roche [15]). Whitney was largely absent from design interactions and focused on overseeing the process while Anderson was tasked with working with Saarinen—a role he would assume for the next decade as the project engineer for all three projects. Although Anderson would eventually become more involved in preliminary design discussions with Saarinen, the collaboration for Kresge was quite one-sided.

The engineering challenge was exceedingly difficult, in part because the established shell form didn’t comply with any previously tested or constructed forms. The engineers endeavored to make the building work by simply modifying parts of the existing form. They believed a uniform shell thickness of 3.5 inches (9 cm) would be adequate to resist against the membrane action of the dome, but because of the lack of continuity in the form, Anderson suggested that the shell be thickened into an edge beam at the perimeter to
stiffen the building and support the inevitable bending stresses. The thinness of the shell and the resulting 18 inches (46 cm) deep arched curved edge beams complicated the construction of the building and unfortunately contributed toward the building’s inadequate structural performance (Penn State Univ. [11]).

The construction documents and specifications only marginally acknowledged the unique construction challenges of the shell, choosing instead to focus more effort on defining the building’s geometry (Bates, [6] & “Tripod Built…” [4]). By not extending their collaborative relationship and collective expertise into the documentation and oversight phases thoroughly, Kresge’s contractor, George A. Fuller Company, had to sort through certain unique complications of forming the curve and placing the concrete with only marginal instruction (Figures 2A-2C).

The design elicited two different responses from Whitney and Anderson—skepticism and enthusiasm. At a Conference on Thin Concrete Shells, hosted by M.I.T. in June of 1954, Whitney only mentioned the project once, tersely stating that shells like Kresge have, “…no general rules as to their justification.” [24]. Anderson was more enthusiastic about the process of working with Saarinen, later describing it as, “…difficult, but fun.” (Leubkeman [12]). In 1956, less than a year after the completion of Kresge, the two firms would have a chance to collaborate again on a very different concrete shell structure, this time for Trans World Airlines terminal building in Idlewild, New York. The design process would be somewhat more inclusive, but new challenges would arise that forced an extended level of collaboration.

3. A Soaring Achievement: Trans World Airline Terminal; (1956-62)

“…the reason why these (plastic forms) are being built now...is really aesthetic and not economic; and we should face that.” Eero Saarinen, Speech to Architectural Association, August 1957 [16].

Saarinen invited Anderson to meet near the beginning the TWA’s design process because he had been “very patient, and gentle with his guidance” (Roche [15]. Saarinen wanted to discuss options for how to “express the drama and wonder of air travel” through a dynamic building form made of concrete (Eero Saarinen & Assoc. [10]). Anderson recalled that, “Each time (Saarinen) got a new project he would call us specialists to come and sit together with him so that he could probe us for ideas. Sometimes this would go on for days or weeks!” (Leubkeman [12]). The challenge, according to Saarinen, was “how to make the vaults, whose compressive forces are always downward, become soaring rather than earthbound” (Eero Saarinen & Assoc. [10]). His initial design, sketched on the back of a menu, showed the entire roof as one continuous undulating elliptical paraboloid shell—an ambitious but intuitively reasonable structural form that wasn’t too different from his initial sketches of Kresge (Figure 3). The center portion of the shell was held down by four angled buttress-like columns that allowed the two outside edges of the shell to cantilever up and outwards in the form of wings.

Although structural logic informed the initial proposal, Saarinen wouldn’t allow it to become prescriptive, stating, “(The) structural and rational cannot always take precedent when another form proves more
beautiful. This is dangerous but I believe true” (Saarinen, [17]). Again, dozens of large-scale models and drawings were used to develop the design, but each modification veered the design progressively away from thin shell behavior (Figure 4). At one point, a curved and undulating cantilever edge beam ran around the perimeter while four separate bulges projected upward from the continuous slab surface with sectional geometries prescribed by intersecting arched profiles (Figure 5). These modifications frustrated Abba Tor, a young engineer tasked with helping Anderson, because the membrane action of the shell was now compromised by the ridged arches—an entirely different means of engineering analysis would be needed and the slab would have to double in thickness (Ringli [14]). Saarinen was presented with the consequences of his decisions for further consideration and as Tor describes, “You had to kind of argue your way into it…it brought out the possibility of creative solutions and compromises” (Ringli [14]).

Figures 3, 4, & 5 (left to right): Fig. 3, Saarinen's initial sketches, 1956, Fig. 4, large scale model with variations in background, 1957, Fig. 5, model of continuous roof form, 1957. (Yale University Archives).

3.1 A Common Cause for Formal Evolution

“It took a considerable amount of interaction with the architect to impose some structural logic or discipline on it…it was a creature which started out wild and needed to be tamed and domesticated.” – Abba Tor, Ammann & Whitney, [22].

Although most of the engineering efforts were attuned to help solve the inherent complications of the project without requiring significant design modification, an increased level of collaboration between the firms helped to identify the continuous roof form as a potential liability. The engineers saw major complications related to the eventual construction and structural behavior of the roof if it were cast as one continuous piece. Meanwhile, Saarinen was contemplating ways to make the shells more gestural and open. A common solution was proposed that solved both issues: the roof 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 (Figures 6A-6C)—interestingly, both Tor and Saarinen both take credit for proposing the change ([14] & [15]).

Figures 6A-6C (left to right): Fig. 6A, Buttress model showing ruled surfaces, Fig.6B, Model of skylight, Fig. 6C, Model of four-quadrant roof scheme (Yale University Archives).

Breaking the roof into four different pieces meant that it no longer behaved like a shell structure—although it hadn’t for quite some time—but it also created a clear structural logic. The perimeter beam for each

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quadrant was supported at three points: gestural Y-shaped column buttresses were placed at two of the quadrant corners, and all four shells were conjoined in the middle of the building with a 44 inch (112 cm) thick center-plate slab “keystone.” 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 in one day which eliminated concerns for concrete shrinkage and construction joints (avoiding one of Kresge’s major problems). The slabs were all held in equilibrium to each other and the open space envisioned by Saarinen was achieved. This final scheme wasn’t structurally efficient but it was structurally innovative. Roche describes the project as “…more of a structural problem than a structural solution. It was never meant to be a thin shell” [15].

3.2 Descriptive Documentation and Elevated Performance

Improving upon their efforts at Kresge, this collaborative effort included a thoroughly coordinated, and original 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 (“Shaping a two-acre…” [3]). Contour line plans showed variations in slab thickness, gridded serial sections described the evolving geometric forms, and rigorous specification requirements were developed—Tor’s name was even noted on the documents as the source for how the shell valley would be shaped in the field (Figures 7A-7B). Both firms were immersed in the two year construction administration process, and worked closely with the contractors, Grove, Shepard, Wilson & Kruege for nine months to prepare a manual which outlined requirements for forming, finishing, tolerances of the concrete (Figure 8)—each quadrant was poured as planned within the allotted 24-30 hour window (Yeakel [25]). The thoroughness was rewarded as the finished shell form sagged considerably less than anticipated upon the removal of the formwork right before Saarinen’s death in the fall of 1961 (Figure 9).

Figures 7A-7B, 8 & 9 (left to right): Fig. 7A, Contour plan of shell thickness, Fig. 7B, Structural drawing of keystone, Fig. 8, Workers shirts are numbered to correspond to locations in field, Fig. 9, Terminal just after removal of scaffolding, (Yale University Archives).

Even though there were meaningful improvements made in the collaborative design efforts for TWA, the team had yet to incorporate the inherent structural and economical benefits of spatial shell design—topics frequently promoted by the engineers (Cohen [8]). While the firms were preparing construction documents for TWA in 1958, Ammann & Whitney was selected by the U.S. Civil Aeronautics Administration as the prime contractor for the nation’s first jet airport terminal in Washington D.C.—they hired Saarinen as their architect and the process began again, albeit from a much more experienced perspective on both sides.

4. Expressing Time and Convenience: Dulles International Airport; (1958-63)

“We tried to give a completely logical, imaginative, and responsible answer.” – Eero Saarinen, 1960 [10].

Representatives of both firms completed a detailed analysis of existing airports in an effort to understand how the movements of passengers and jets could be optimized to provide a more convenient, flexible, and effective set of operations. Ultimately Saarinen proposed the use of “mobile lounge” vehicles to transport passengers from the terminal to the jets allowing the terminal building to be smaller, more efficient, and more precisely illustrative of its purpose—the building form was intended to express this. In the past, Anderson noted that Saarinen “had absolutely no problem in simply throwing out a design and starting anew” but the range of proposed solutions for Dulles was rather concentrated (Leubkeman [12]).
The design need to accommodate expansion, so Saarinen focused on easily repeatable and developable sections to create a large open room under a sweeping roof flanked by colonnades (Figures 10A-10B). Interestingly, according to Roche, one of the main influences for the building’s proposed structural form may have come from a structural engineer not on the design team but from Fred Severud, Saarinen’s consulting engineer for the recently completed Ingalls Hockey Rink at Yale (Figure 11). Saarinen lauded Ingalls’ “structurally effective and beautiful” design and the way that the building expressed the “unique twentieth century technology” of tension—a notable departure of attitude from the previous compression-based shells (Eero Saarinen & Assoc. [10]). Ultimately, Saarinen determined that a catenary roof shape would allow for the desired sweeping form with a repeatable sectional profile. Saarinen considered Anderson as a “trusted collaborator” and Anderson’s expertise in long span suspension structures helped validate this proposal (Roche [15]).

4.1 Formal Expression of Forces

The initial development drawings showed sixteen columns on each side of the open room, spaced 40 feet (12m) apart, and sloping outwardly away from the inward pull of the suspended catenary roof (Figures 12A-12B). The different column heights created a highly visible sweeping catenary curved roof that covered the entire 90,000 square foot area (8,361m²). Because the form expressed an inherent structural logic, very little about the building’s concise and elemental form was required to change for either architectural or structural reasons; the main collaboration efforts were in the translation of this simple design idea into an efficient but expressive structure. The most visible of these efforts was in the roof and column design.

The hanging roof was suspended between the two upwardly curved, cast-in-place, concrete outer edge slabs that connected to the columns below. At every ten feet of length along the perimeter of the edge slab, two pairs of 1 inch steel cables were extended more than 120 feet across the span. Eighteen-hundred lightweight precast concrete roof panels spanned the between these cables, forming the majority of the roof surface (and the formwork for the topping slab). The cables were pre-tensioned to the exact funicular geometry then the roof was weighed down by sand bags until both the cables and panels could be encased in a lightweight poured concrete. The extra weight made the entire roof system structurally integral and resistant to uplift (“Four Great Pours” [1]). The roof drainage and expansion joints were integrated into the system without compromise, and atop the roof surface, an innovative system of layered neoprene
membranes was used to preserve the visual clarity of form and material (Lessing [13]). The precast panels on the interior were sprayed with an acoustical / insulating foam to create the visually uniform surface desired and to improve the building’s functional performance.

4.2 Considerate Integration

Although the building’s form was quite expressive, because of the repeated elements and consistent building section, only a conventional number of drawings were required to document the columns and roof structure. Critical requirements for tensioning the steel cables, setting the precast panels, and placing the concrete were thoroughly documented in drawings and specifications. The first line in the specifications Invitation to Bidders set the project expectations high by warning that, “The work herein proposed for development is highly original in character and will require considerable ingenuity and very skilled workmanship in its construction for obtaining the form and effect contemplated.”

Although the overall project had cost overruns, the construction process was relatively economical thanks to the collective integration of specific strategies for spatial shell construction. Remarkably, the main roof was constructed without any scaffolding because the precast panels served as the formwork and the finished roof surface. Because the structural elements were regular and repeating, multiple trades could be working simultaneously as construction progressed from one end to another—in fact, the large steel towers that were used to cast the edge slabs were simply rolled to their new location and the formwork was re-used again (Figures 13A-13C).

Although they held the primary contract for the job, Roche claims that Ammann & Whitney did not try to influence Saarinen’s design priorities, even though Dulles features many of the economic and construction advantages long promoted by the engineers [15]. The changes from Kresge to Dulles seem to be the result of two major factors: 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 an increased level of expertise in concrete shell design by the project teams in both offices born from these collaborations.

5. Imparting Influence

Sadly, Saarinen only lived to see one of the cables hanging across the great space before his sudden death in 1961. He told his wife, Aline, “I think this terminal building (Dulles) is the best thing I have done…Maybe it will even explain what I believe about architecture.” (Saarinen [10]). As a result of his work with Saarinen, Anderson won an award for “Metropolitan Civil Engineer of the Year” in 1962 and continued to collaborate with many of the nation’s leading architects, including Roche, for decades. After his death in 1995, the ASCE described Anderson’s engineering achievements as “legendary” and called him “one of the great structural engineers of our time” (ACSE [5]).
Their collaboration was both unique and instructive as few early experiments in thin shell design were collaborative efforts between willful architects and expert engineers. The work 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 shell. Additionally, these efforts demonstrated the benefits of a more integrative practice model that questioned the traditional notions of design influence and authorship. Roche summarizes the efforts concisely, “It was a great moment in modern architecture...even if some were appalled by the work, it was incredible” [15].

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