

A low-angle photograph of the Milwaukee Art Museum's facade, showing a series of white, curved structural ribs that fan out against a clear blue sky. The ribs are supported by a grid of horizontal and vertical beams. The foreground shows the curved, white structure of the building's entrance area.

Example Case Study:
Milwaukee Art Museum

ARCH 631: Structural Systems
Prof. Anne Nichols
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Overview

On May 4, 2001, a much-anticipated addition to the Milwaukee Art Museum first opened its doors to the public. The \$125-million-dollar project, designed by architect Santiago Calatrava, became an icon for the museum and the city of Milwaukee, Wisconsin even before its completion.

This report presents a case study of the project. Background information regarding the architectural context for the addition will be provided, as well as a synopsis of the architect's mastery of structural design. A number of unique elements of the building will be discussed in detail. In addition, the building's complex structural design will be reviewed through component and system evaluation, diagrams, and simplified computer-based structural analysis.

The Milwaukee Art Museum

The Milwaukee Art Museum (MAM) traces its beginnings to two institutions, the Layton Art Gallery, established in 1888, and the Milwaukee Art Institute, which was established in 1918. In 1957 the groups joined together, forming the private, nonprofit Milwaukee Art Center, now known as the Milwaukee Art Museum. At this time, the Center moved to its present location on the Milwaukee waterfront

Finnish architect Eero Saarinen, known for his St. Louis Arch, designed the Center's new home. Saarinen designed a unique structure incorporating floating cruciform sections with cantilevered portions; the building is now considered a classic in the development of modern architecture. The building opened in 1957, at which time the Milwaukee Art Institute and Layton Art Gallery merged their collections and projects to form the Milwaukee Art Center.

An addition was added to the Milwaukee Art Center in 1975, after the Center had received a number of donations and contributions to its collection. In addition to exhibit space, the Center added amenities such as a theater, educational center and a small restaurant.

In 1980, the Center changed its name to the Milwaukee Art Museum. The Museum's collection continued to grow during the '80s and '90s, leading to consideration of another major addition. Attendance and membership had increased dramatically, with nearly 200,000 annual visitors.

With higher attendance, record numbers of art acquisitions, and new programs continually being added, the facilities of the MAM were becoming inadequate.

Museum officials looking for a style which would complement the existing Saarinen structure turned to architect Santiago Calatrava in 1994 to design the new addition. Calatrava was asked to provide a strong architectural statement in an exciting yet functional building—to “set an architectural standard for the next millennium” [1].

Calatrava's dynamic expansion design was unveiled in March 1996. The Milwaukee community was elated with the result. Groundbreaking took place on December 10, 1997, and the entire expansion project was complete by October 2001 (after opening in May of that year).

The Quadracci Pavilion (Figure 1) was the first building designed by Calatrava to be constructed in the United States. Since its completion, record numbers of visitors have enjoyed the new exhibition galleries, larger museum store, auditorium in the Quadracci Pavilion, and the completely renovated and reinstalled permanent collection galleries. Despite cost overruns and financing setbacks resulting from the expansion project, the Museum foresees a prosperous future, and the city of Milwaukee has a new waterfront icon.



Figure 1: Quadracci Pavilion

The Architect

Internationally-acclaimed architect Santiago Calatrava was born on July 28, 1951, in Valencia, Spain and earned a degree in architecture from the Escuela Tecnica Superior de Arquitectura. Following his training in architecture, Calatrava pursued post-graduate studies in civil engineering at the ETH (Federal Institute of Technology) in Zurich and received his Ph.D. in 1979.

After completing his studies, Calatrava began his career by accepting small engineering commissions. He also entered design competitions, believing this was his most likely way to secure commissions. His first winning competition proposal in 1983 was for the design and construction of Stadelhofen Railway Station in Zurich.

In 1984 Calatrava designed and built the Bach de Roda Bridge commissioned for the Olympic Games in Barcelona. This was followed by such projects as the Alamillo Bridge and viaduct commissioned for the World's Fair in Seville (1987-92), Campo Volantin Footbridge in Bilbao (1990-97), and Alameda Bridge and underground station in Valencia (1991-95).

Calatrava established his firm's second office (Paris) in 1989, and his third (Valencia) in 1991. His major project in Valencia, the City of Arts and Sciences, is an ongoing effort. Other notable projects from this period include the BCE Place mall in Toronto (1987-92), the Oriente railway station in Lisbon (1993-98, commissioned for Expo '98), and the winning proposal in the design competition to complete the Cathedral of St. John the Divine in New York City (1991, unbuilt).

More recent major projects include Sondica Airport, Bilbao (2000), the Bridge of Europe, Orléans, France (2000), the Bodegas Ysios winery in Laguardia, Spain (2001), and the expansion of the Milwaukee Art Museum (2001).

Projects currently approaching completion include the Turtle Bay Bridge, Redding, California (summer 2004), the Athens Olympic Sports Complex (summer 2004), and the Valencia Opera House (2004), the last major building in his City of Arts and Sciences.

Calatrava was recently selected to design Christ the Light Cathedral for the Roman Catholic Diocese of Oakland, California and Symphony Center for the Atlanta Symphony Orchestra in Atlanta, Georgia – both major commissions in the United States.

The architect has received numerous honors and awards from internationally-recognized architecture societies, as well as 12 honorary doctorates to date. For his expansion of the Milwaukee Art Museum, Calatrava earned Time Magazine's "Best of 2001" designation. In addition, he was awarded the International Illumination Design Award of Merit by the Illuminating Engineering Society of North America for the interior lighting design of the MAM expansion [2].

The Quadracci Pavilion

Design Concept

The city of Milwaukee was looking for a "strong architectural statement in an exciting yet functional building" that would "set an architectural standard for the next millennium" [1]. Calatrava's response was to design "a glowing 'lantern' on the downtown lakefront, radiating light in all directions" [3]. He chose to execute this concept through a pavilion featuring a "vast, glass-enclosed reception hall" with a "transparent, boat-like prow of unique design, facing the lake" and a "huge, wing-like sunscreen" [4].

Building Layout

The five-level Milwaukee Art Museum, including the four-level Calatrava addition, was diagrammed by David Arbanas of the *Milwaukee Journal-Sentinel Online* [5,6] as shown in figures 2–6. The Quadracci Pavilion is shown intersecting the main building at the south end.

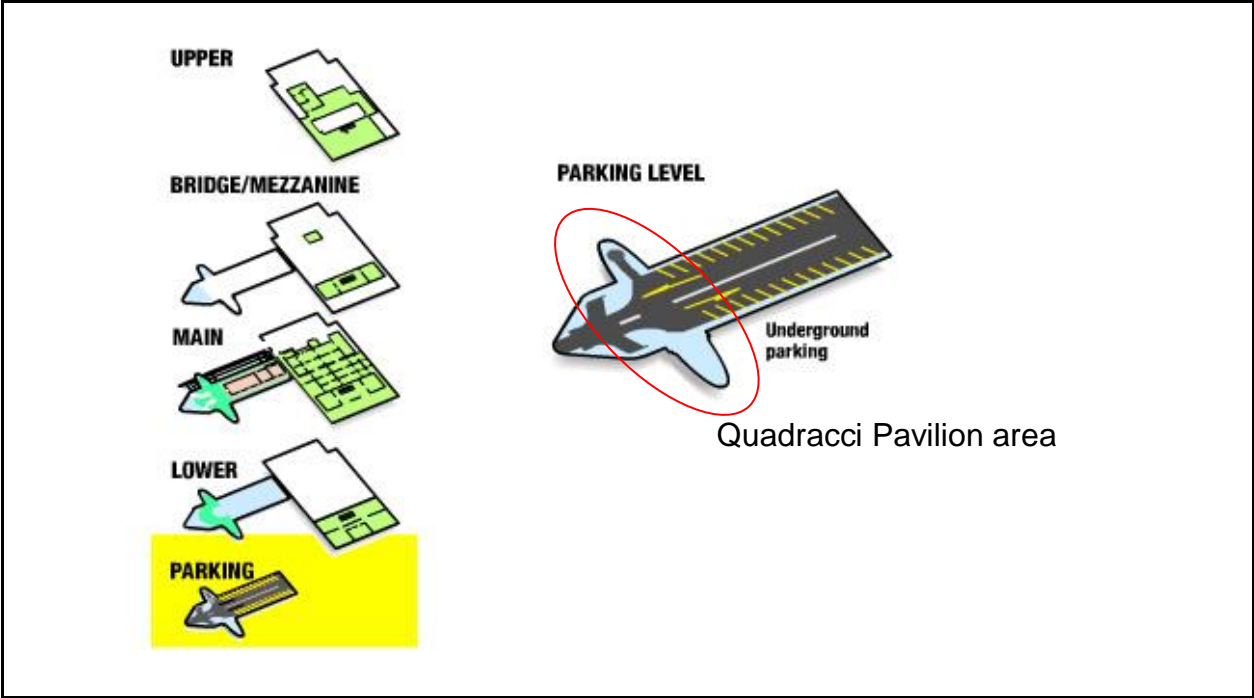


Figure 2: Parking Level

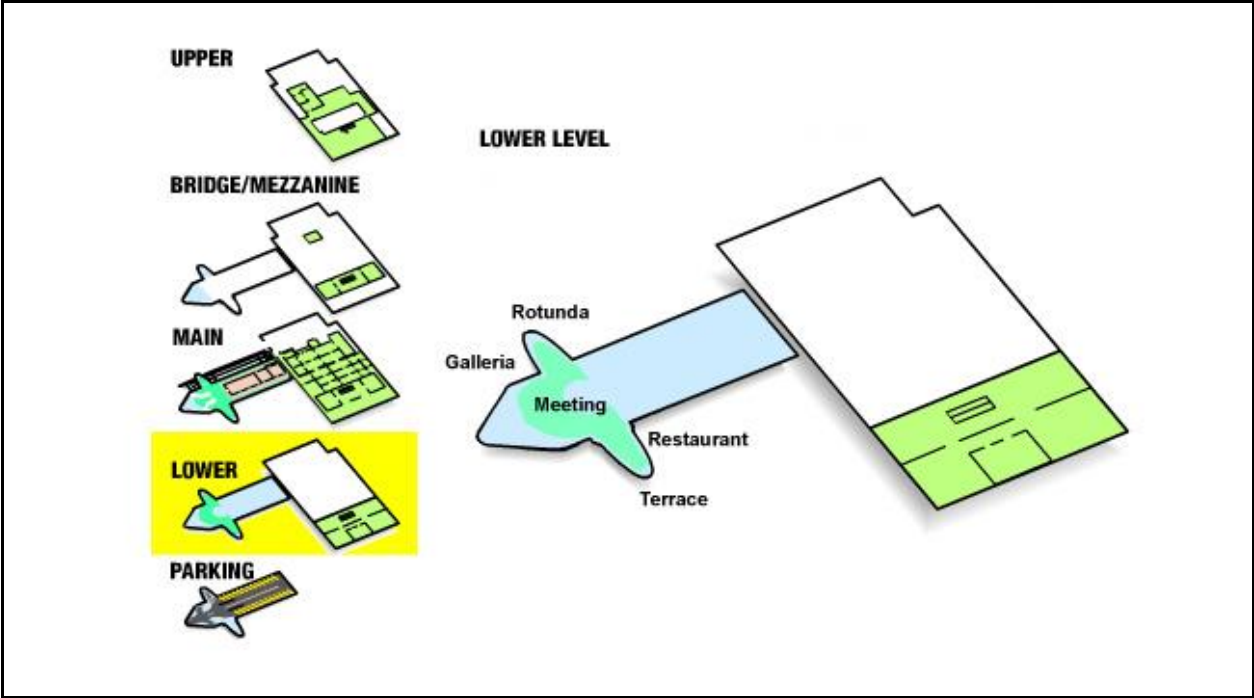


Figure 3: Lower Level

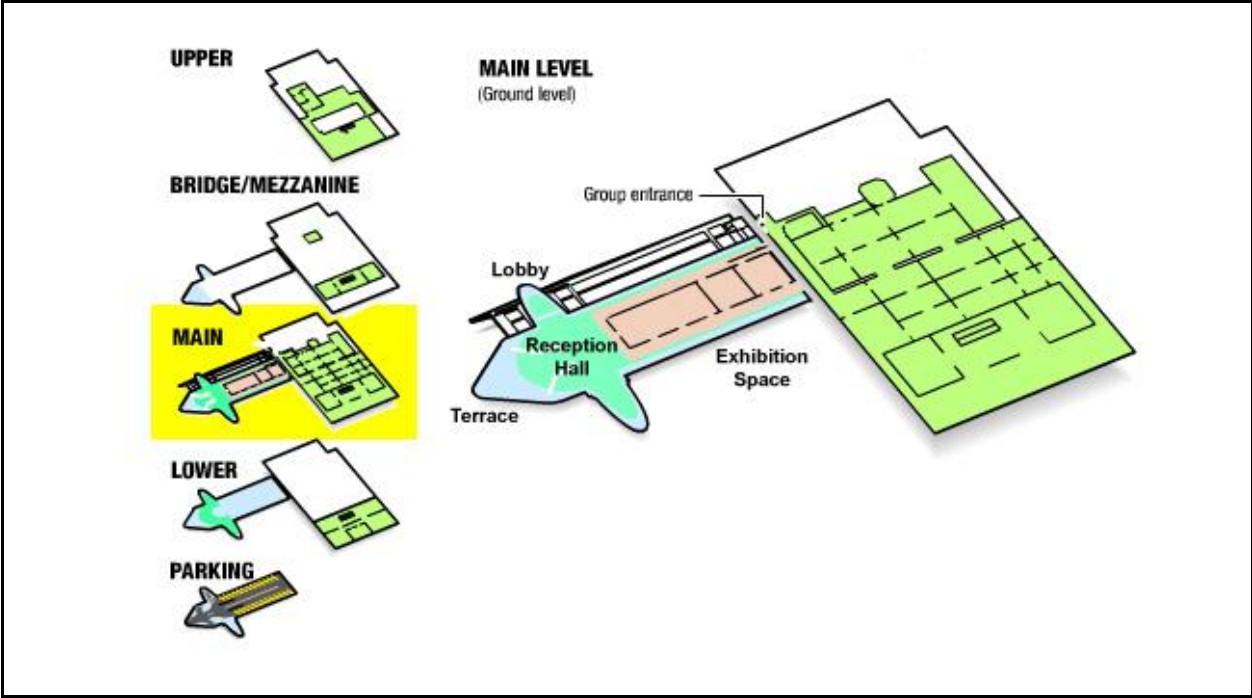


Figure 4: Main Level

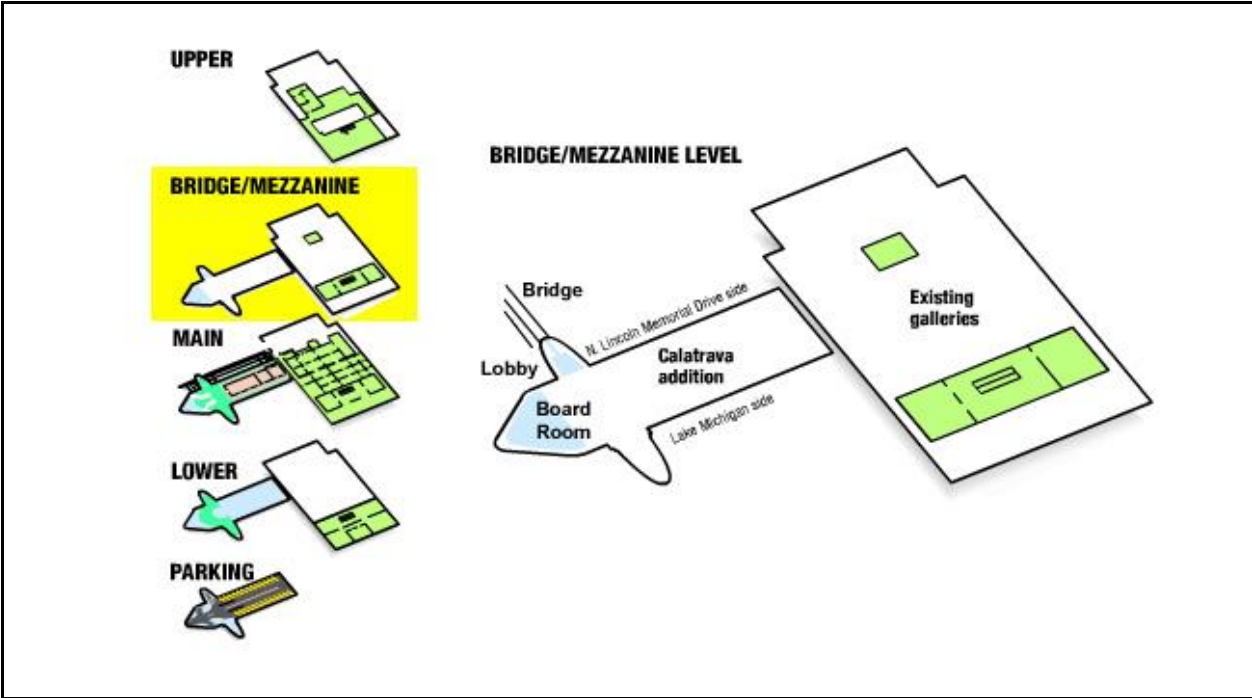


Figure 5: Bridge/Mezzanine Level

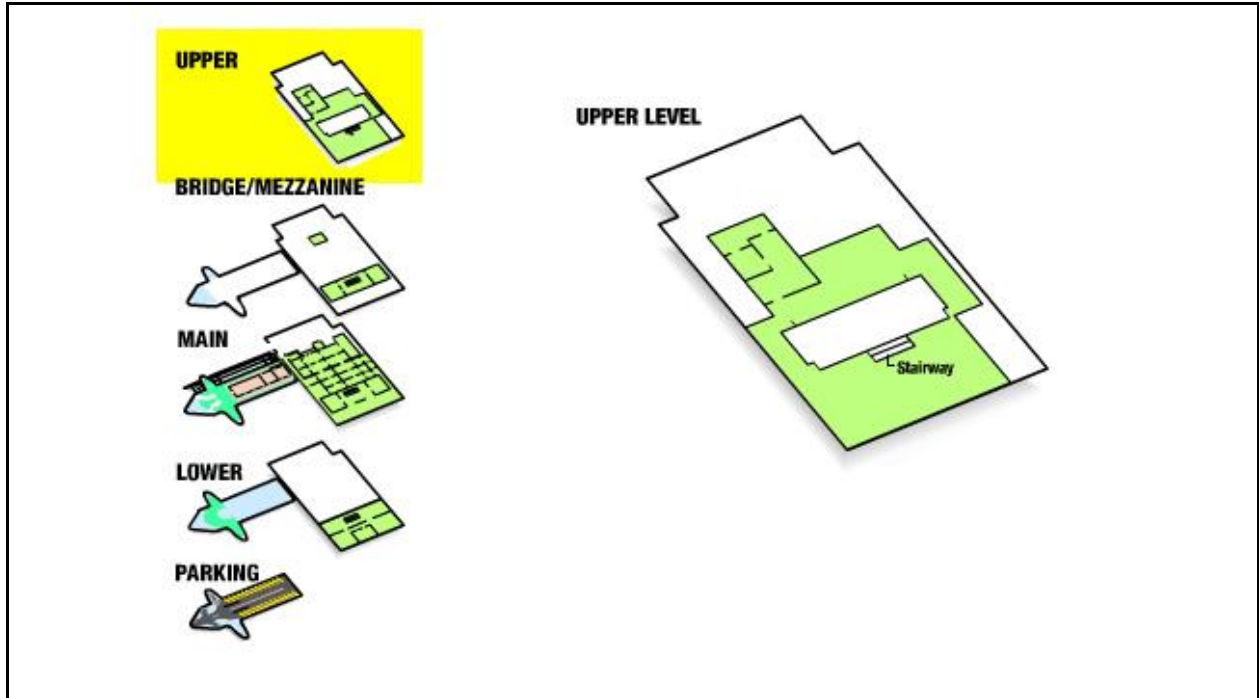


Figure 6: Upper Level

A closer look at the main level of the new addition in figure 7 reveals the ship-like detailing Calatrava envisioned (drawing by Arbanas [7]). The Quadracci Pavillion is directly in line with the pedestrian bridge.

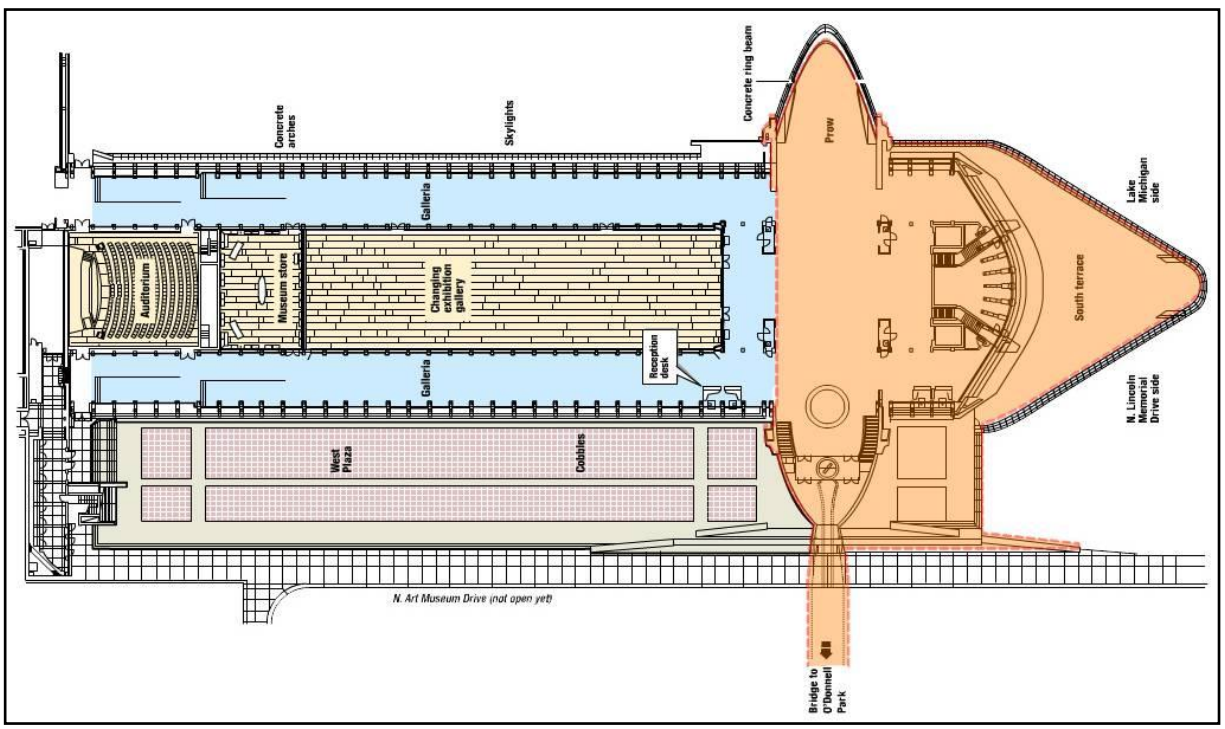


Figure 7: Main Level Plan

Structural Features

A concise description of Calatrava's elaborate design was put forth by James Auer of the *Milwaukee Journal-Sentinel Online*:

"The project's steel-and-glass Quadracci Pavilion, which will serve as the grand entry into the expanded museum, will be erected over a concrete ring beam immediately south of the low-lying galleria [see figure 8]. Seventeen specially built A-frames, ranging in length from 98 feet to about 27 feet, have been trucked in from Portland, Ore., for assembly and placement on the work site. Erection is slated to begin this week. The A-shaped rafters were computer-designed and custom-fabricated by Columbia Wire and Iron Works, a specialty steel fabricator in Portland. Together, they'll give the pavilion its shape, strength and transparency. Components for the A-frames were cut out of big sheets of steel



Figure 8: Pavilion Ring Beam (perimeter) and A-frames

plate, welded together, ground and finished. Shapes were determined digitally, from a computerized model of the pavilion and its underlying structure. Once the A-frames have been placed on the oval-shaped ring beam, glass panes will be inserted, followed by a three-piece steel spine. The fixed 'building spine' will top off the A-frames. Above it, two rotating spines will support the movable wings of the Brise-Soleil, an enormous sunscreen that can be positioned to admit or keep

out sunlight. Light is crucial in the concept and operation of the pavilion. By day, it will have natural light. At night, artificial illumination will be provided by powerful lights set low around the concrete ring beam. Thus, said David Kahler, president of architect-of-record Kahler Slater, the pavilion will be precisely as architect Santiago Calatrava originally envisioned it: a glowing 'lantern' on the downtown lakefront, radiating light in all directions.” [3]

Building Components and System

The functional areas of the main building include the parking garage, the gallery space, the pavilion (ring beam and A-frames) and the south terrace. Except for the A-frames, which are comprised of plate steel and the Burke Brise-Soleil support, the structural material is reinforced concrete.

The building sits on a 0.6-m-thick mat foundation spanning 18 m from the foundation walls to a center foundation beam measuring 2.7 m wide by 1.4 m deep which spans the length. This beam in turn supports the lower arches every 6 m that form the roof of the parking garage and floor of the exhibition space wing. The foundation slopes 2.1 m to the mechanical rooms at the north end.

A partial section of the wing connecting the Quadracci Pavilion to the original Eero Saarinen structure is shown in figure 9 [8]. The garage level elements are spaced 2.9 m on centers and alternate between C and D elements. The C element is a semiarch spanning approximately 18 m from a pinned connection with the mat foundation center beam and a center transfer beam to the foundation walls. The D elements are similar, but are supported by the center transfer beam and foundation walls without an arch to the foundation center beam to provide more clear space for parking. This supporting arch element is regularly reinforced except for the introduction of post-tensioning to resist the lateral thrust force produced by the arching action of both the C element and the upper arches. As the mechanical equipment is located in the interstitial space from garage ceiling to floor, the depth of the horizontal portion of the C and D elements is dictated by mechanical equipment space requirements rather than structural requirements.

The 152-mm-thick mildly-reinforced concrete ceiling slab of the parking garage is supported on the lower portion of the C and D elements, while the 203-mm-thick concrete/metal composite

floor slab for the galleria above is supported on top of these elements, providing the interstitial space previously mentioned.

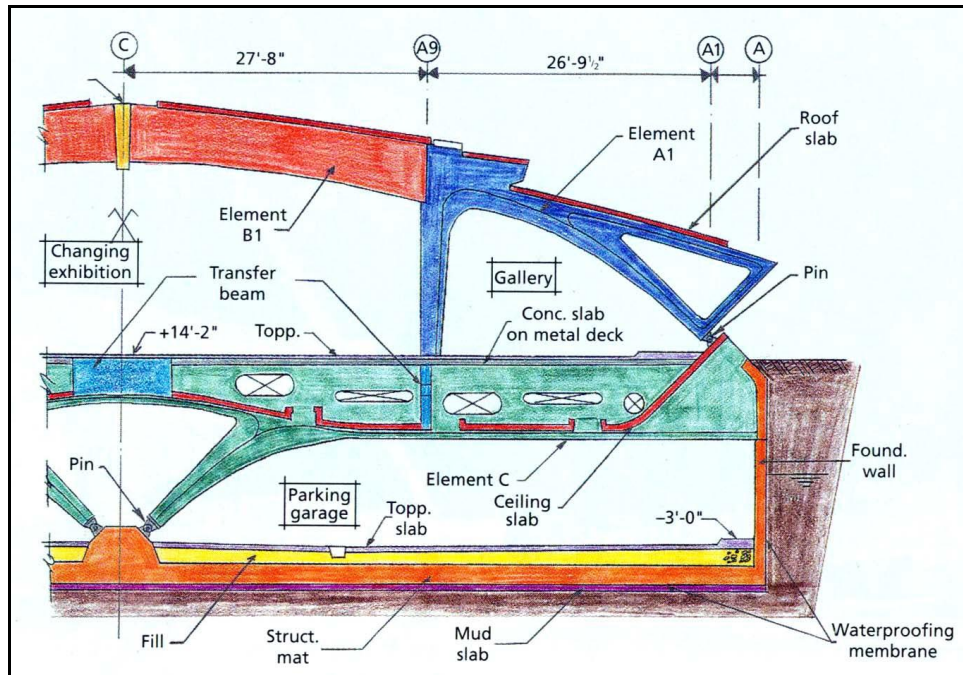


Figure 9: Partial Section

The gallery space is housed in a low-slung concrete arched structure. The arches are variable-depth hexagons, narrow at the base and deeper at the crown. The galleria framing is composed of three structural elements – the east A1, center B1, and west A1 elements – spaced 2.9 m on centers in the N-S direction. The east A1 and center B1 elements are visible in figure 9. Together, these three elements form the complete upper arch, spanning approximately 33 m between pinned connections at each end. Individually, the A1 elements act as buttresses and support the center B1 element, which itself spans approximately 17.6 m. All of the elements forming the upper arch are reinforced. The vertical members of element A1 are supported by the C and D elements. To limit the deflection of the simply supported D elements, transfer beams are used for lateral stability and stiffening like a grid system provides.

The pavilion, constructed of mildly-reinforced concrete and shown in Figure 10, is the support for the A-frames that in turn support the movable Burke Brise-Soleil. Badreddine describes the pavilion as “an oval tabletop that incorporates a substantial opening for the atrium and is supported on four legs” [8]. The four legs mentioned here refer to an east set of piers (I) and west set of piers (J) at the foundation walls.

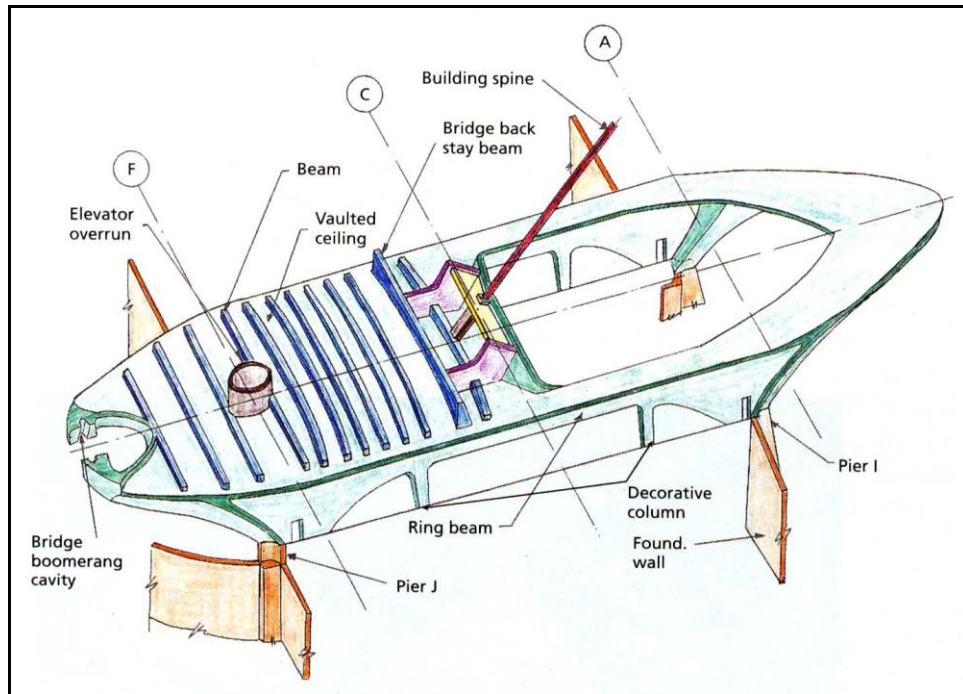


Figure 10: Isometric View of Pavilion

Spanning 8.8 m in the N-S direction and 41.6 m in the E-W direction, the pavilion also supports the back stay beam (shown in purple in figure 10) and the east pier for the cable-stayed pedestrian bridge located at the bridge boomerang cavity. Because of the shape and depth of this element, and to better predict vertical deflections, the pavilion was modeled as a truss in the finite element analysis (shown as gray in figure 11). [8]

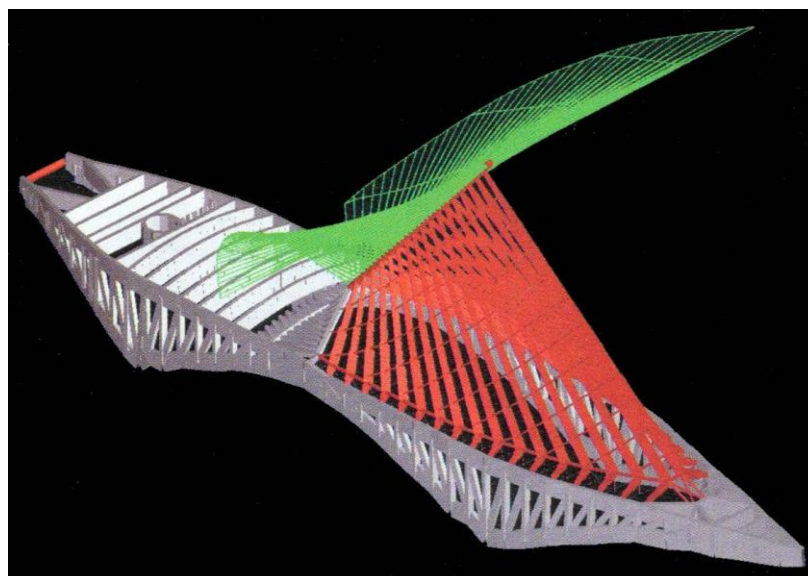


Figure 11: Finite Element Model

Post-tensioning was incorporated into the top chord of the pavilion to control deflection and cracking, as well as to resist the pulling force of the pedestrian bridge “boomerang” abutment, (shown as red in figure 12).

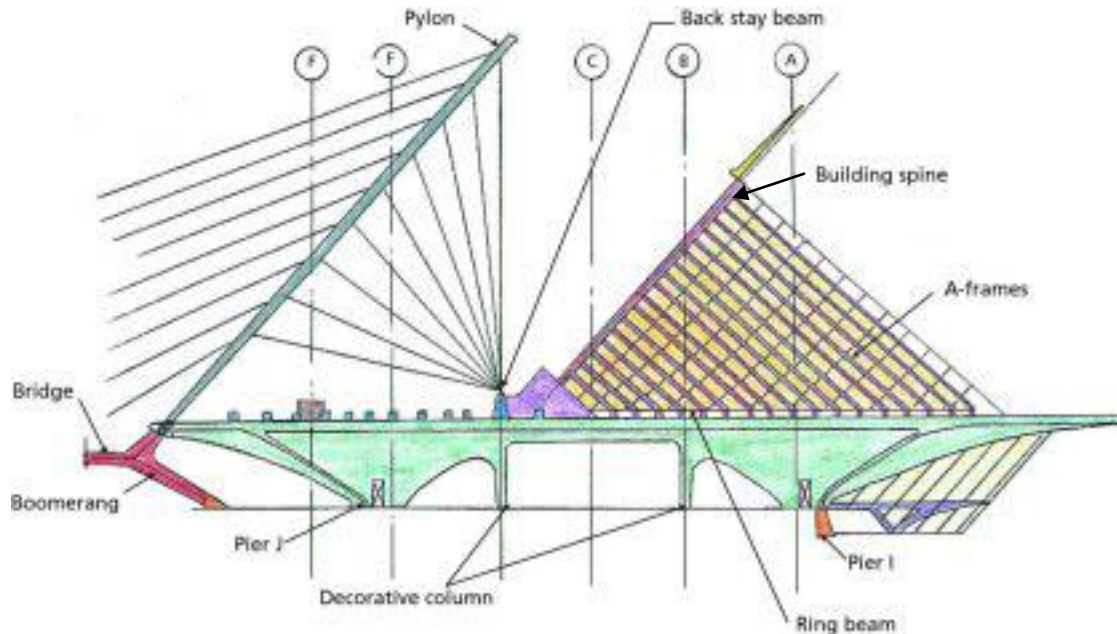


Figure 12: Pavilion Elevation

Framing of the glass atrium, consisting of the rigid A-frames and building spine, rests atop the pavilion and back stay beam. These framing elements support each other. The building spine is a 635-mm-dia., 13-mm-thick steel pipe. The A-frame is constructed with a variable-depth channel cross-section, with a network of leaning members with bracing connected to a second group of vertical members. The vertical members, standing 1.4 m high from the pavilion, are braced around the perimeter providing lateral stability of the entire A-frame assembly and transferring it to the ring beam. On top of these members, 17 leaning A-frames connect to the building’s spine, which leans 48.36 degrees towards the pavilion (parallel with the cable-stayed bridge pylon). [8]

Burke Brise-Soleil

The movable Burke Brise-Soleil constitutes the signature element of the Calatrava addition, resting on top of the breathtaking glass and steel atrium above the Quadracci Pavilion. This element features two very large wings, each composed of 36 steel rectangular tube fins having a constant cross-section width of 330 mm, but varying in length, depth, and thickness (figure 13

[9]) which are rigidly connected by steel spacers. Each wing is supported by a rotating spine, to which all fins are connected. The two rotating spines are in turn supported by the building spine, and 11 pairs of hydraulic actuators turn the rotating spines 90 degrees to fully open or close the wings. This mechanism is described in more detail in figure 14 [9].

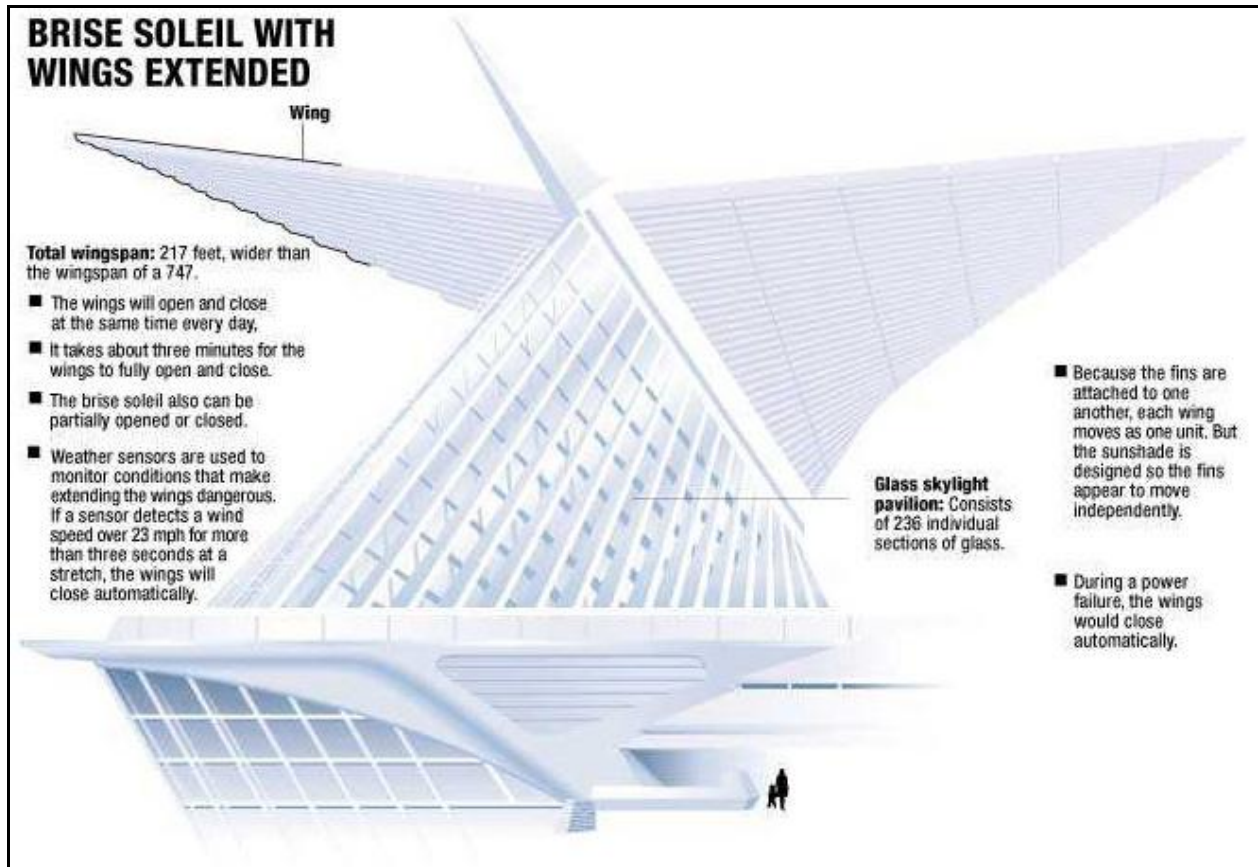


Figure 13: Brise-Soleil

The biggest challenge in the design of the Burke Brise-Soleil was to understand the behavior with wind load on the structure. A wind tunnel study was conducted using a 1:400 aeroelastic model which included the sunscreen, a portion of the underlying structure, and surrounding buildings in downtown Milwaukee. [8]

deflection. The “boomerang” bridge abutment is formed from welded plate steel plate and is anchored at the top to the west end of the pavilion ring beam and supports the pylon base. [8]

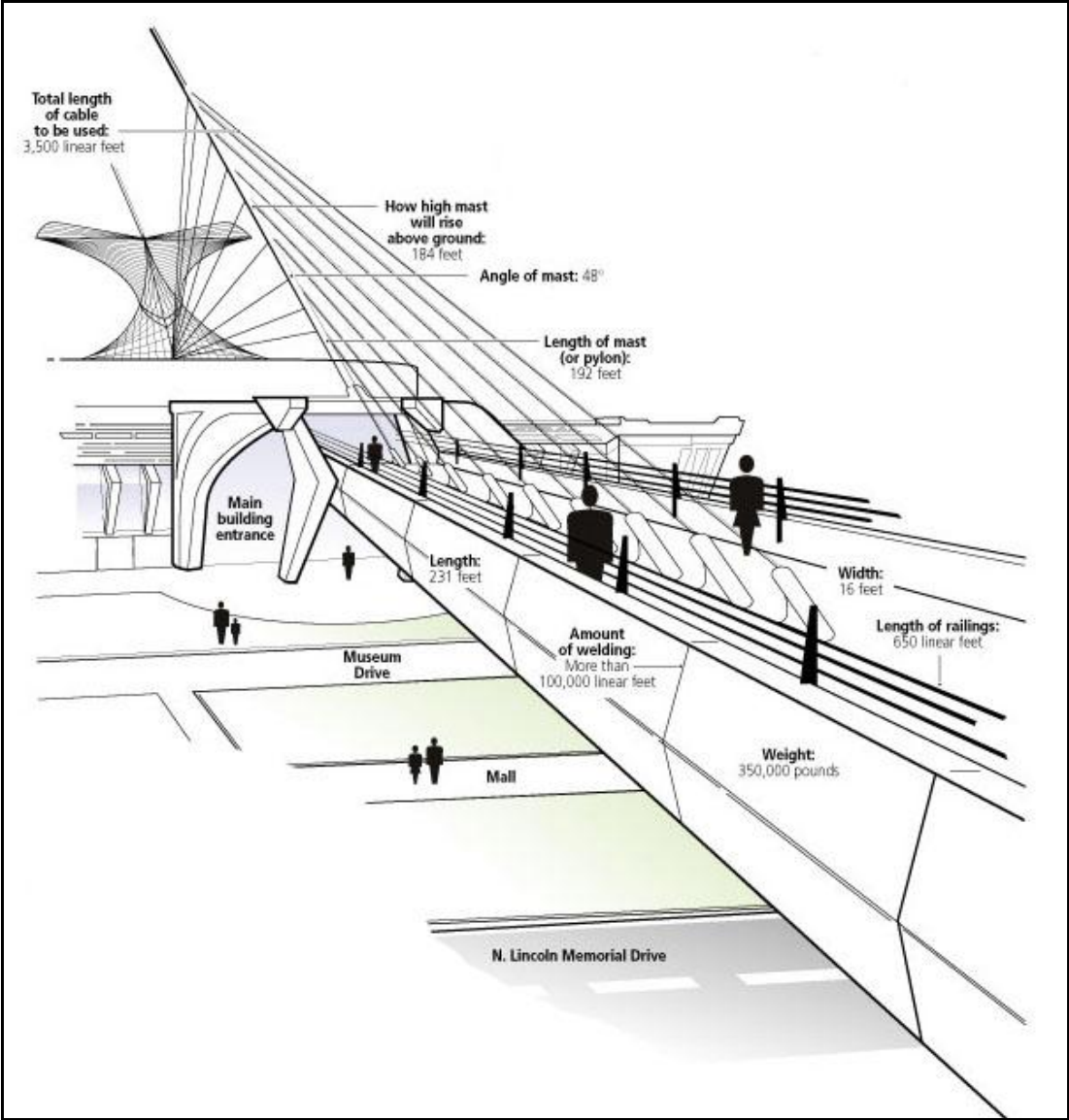


Figure 15: Cable-Stayed Pedestrian Bridge

Loading Summary

In his design for the Milwaukee Art Museum expansion, Calatrava employs reinforced concrete for the vast majority of elements. He carefully balances the forces within the members using a series of arches and pinned connections. In addition, the concrete material lends itself well to achieving the smooth, flowing appearance that the architect found appropriate for this project.

The museum expansion was designed with a strong horizontal emphasis achieved through elongated arched segments, creating large open galleries. As a result, compressive forces dominate the building cross-section. For this design, concrete is clearly the most appropriate material for the flexibility of form and for the structural efficiency in compression.

Gravity Loads

To illustrate the load transfer of gravity loads, a simplified diagram of the main building cross section is shown in figure 16. Roof loads are shown to develop into a horizontal thrust along the three-part arched section, transferring directly to the foundation walls. The semiarch C1 section is partially supported by the center foundation beam through an elegant double-pinned connection. Post-tensioning through this element resists the lateral thrust force produced by the arching action of both this element and the upper arches. Gravel fill, in addition to the parking garage floor slab, contributes to the floor dead load.

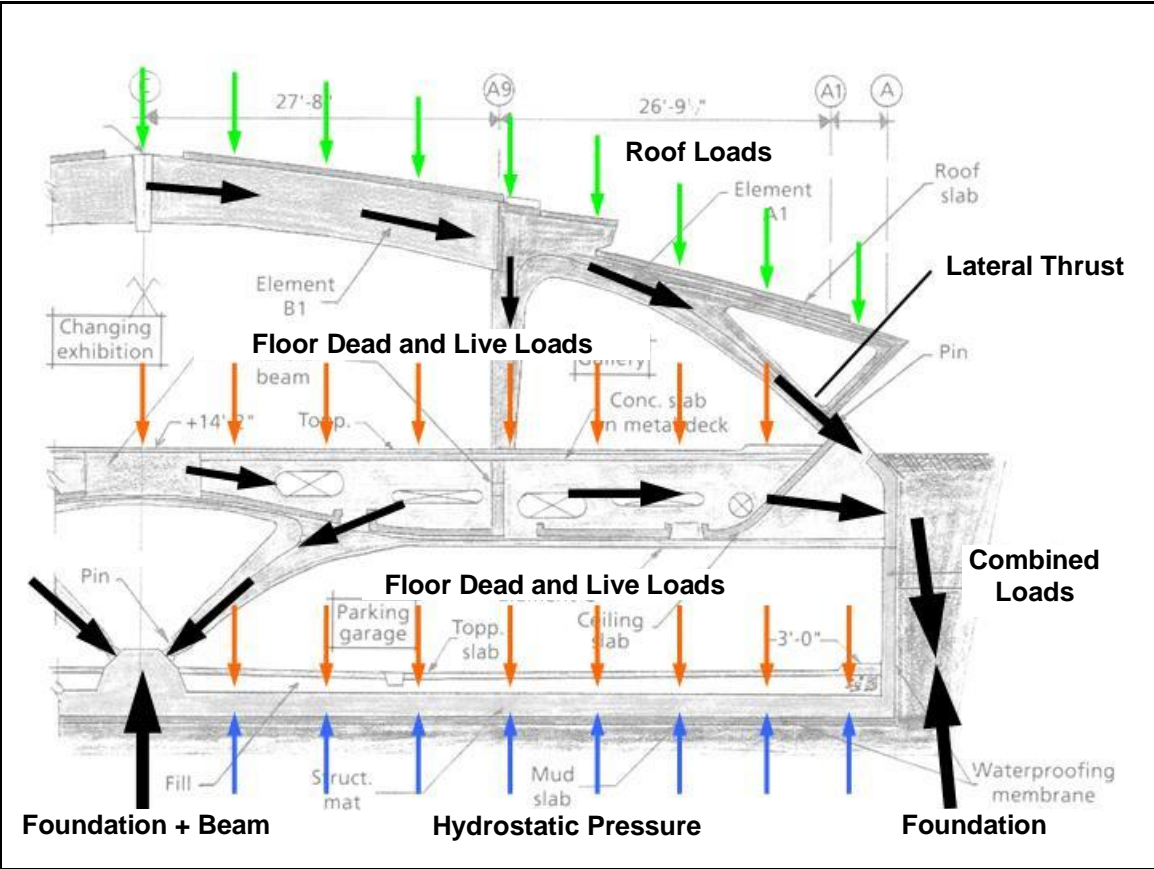


Figure 16: Load Transfer Diagram

To study the cross-section of the MAM expansion more closely, a simplified model was constructed within the structural analysis modeling program Multiframe 2D [11]. Figure 17 shows the arches and non-uniform elements approximated by multiple straight-line segments. Rigid joints are indicated with solid circles, while pinned joints and supports are represented by open circles. The stiffness of the center transfer beam between elements 4 and 16 is represented by a pin support.

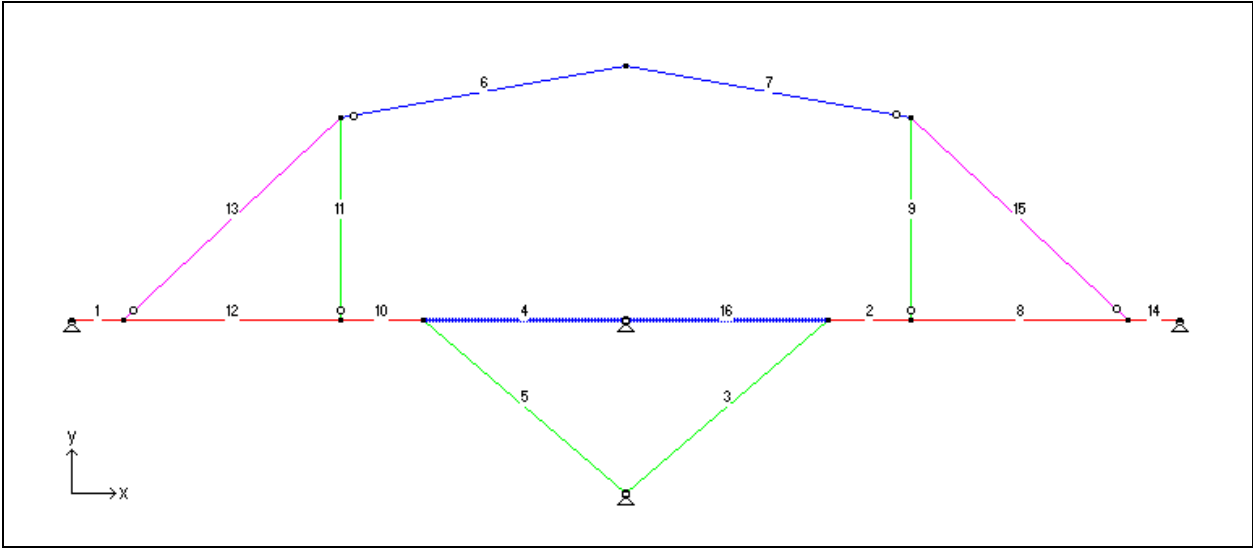


Figure 17: Multiframe 2D Model of Building Section

In addition to the self-weight of the members, dead and live loads on the roof and floors were approximated by uniform distributed loads based on a tributary width of 9.5 ft. The estimated loads include 50 lb/ft³ for snow, 16 lb/ft³ for roof live load, 50 lb/ft³ for concrete floor and roof dead load and 100 lb/ft³ for the occupancy live load. The roof load for analysis is taken as 1100 lb/ft and floor load of 1500 lb/ft as show in figure 18.

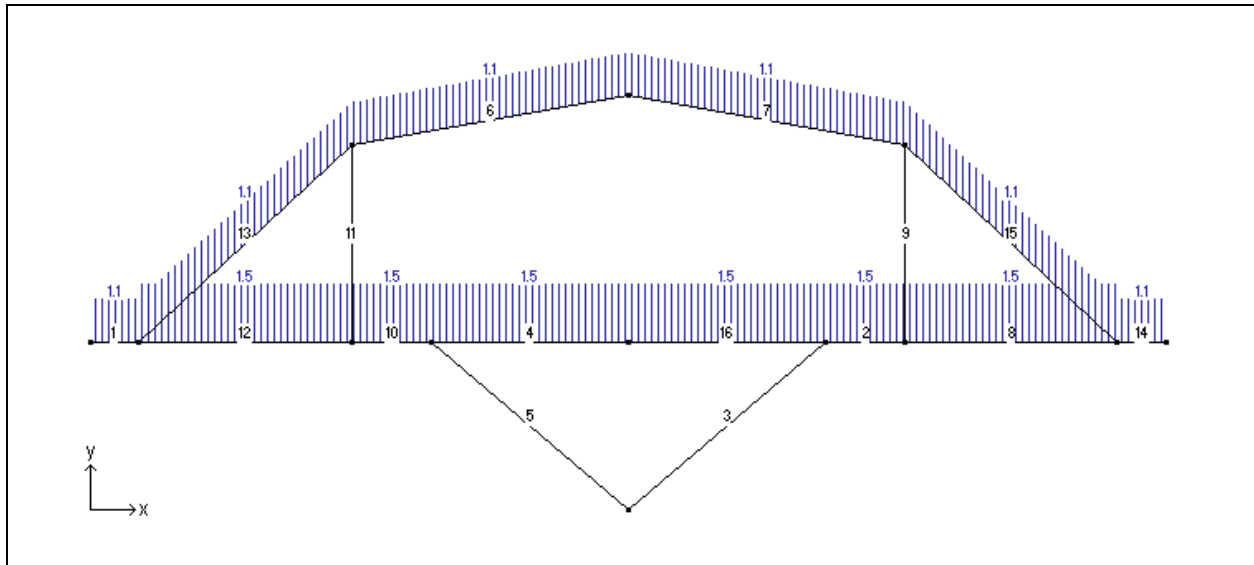


Figure 18: Loading Diagram

Member sizes were determined by relative depth and the relative moment of inertia in bending. The relative resulting reactions, shear forces, moments, and deflections are provided graphically in figures 19-22. Figure 19 illustrates the predominance of compression forces shown as purple in the arch elements. It also shows that there may be tension in some frame members shown in aqua, including part of the floor and vertical components.

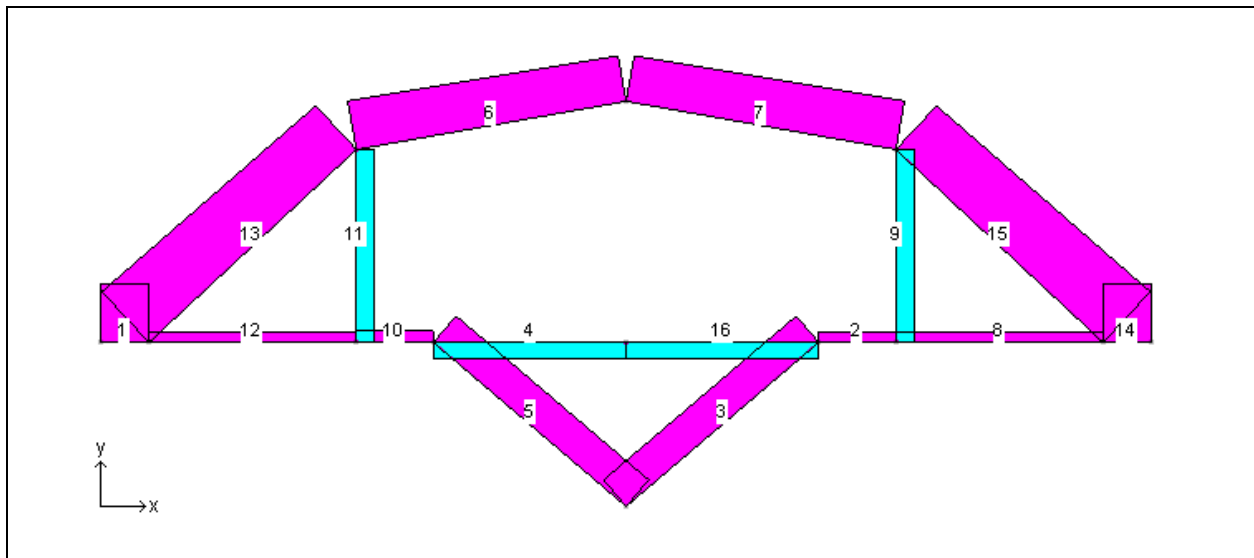


Figure 19: Member Axial Reactions

Figure 20 shows the transverse shear in the frame members as green. As expected, the supports at the foundation walls show the highest level of shear which corresponds with the reaction force.

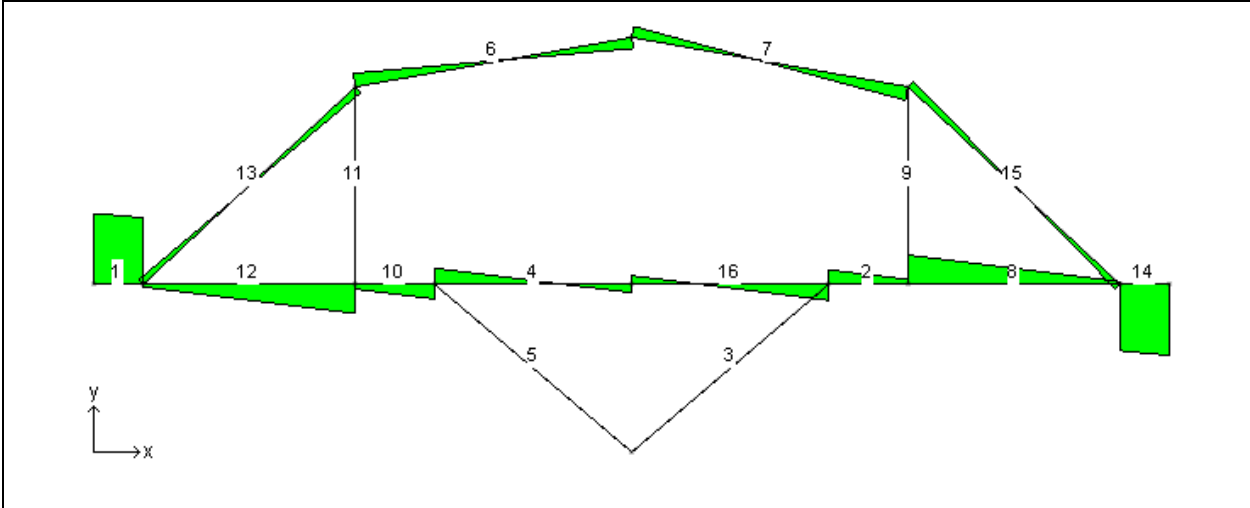


Figure 20: Shear Diagram

Figure 21 shows the bending moment distribution in the frame members. There is very little bending in the arch members, as well as the members that are primarily in tension. The largest bending moment appears at the foundation wall in element C. This member has post-tensioning reinforcement, presumably on the top to resist the bending upward.

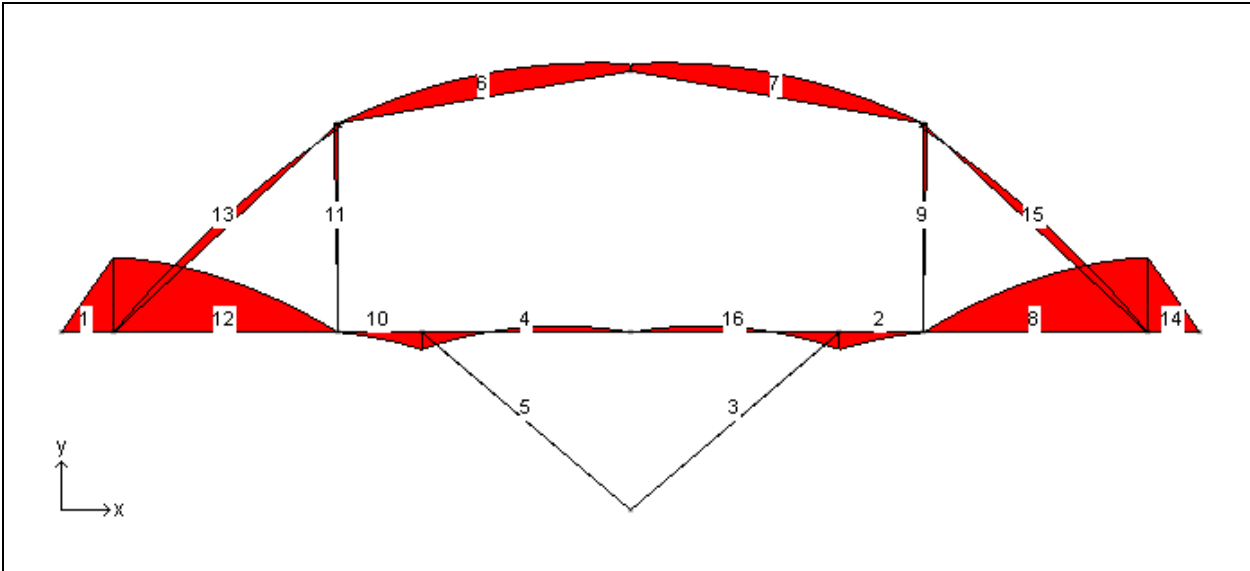


Figure 21: Moment Diagram

Figure 22 shows the deflected shape with respect to the relative sizes of members and distributed loading (exaggerated). The A1 element shows the most deflection, but the actual member is built with a deeper section than modeled because of the slope of the roof.

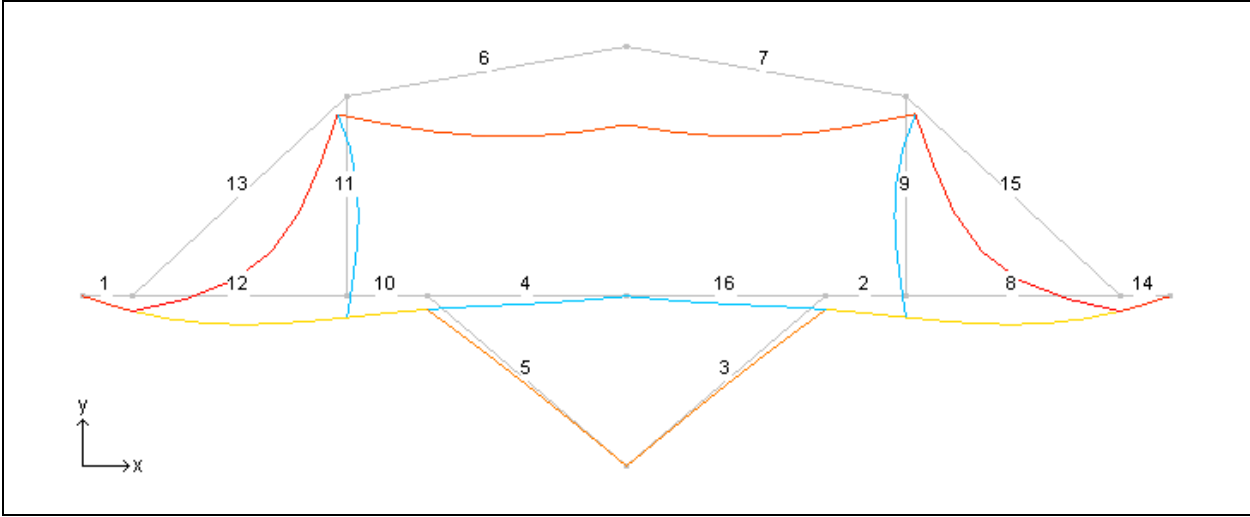


Figure 22: Deflection Diagram

These diagrams indicate that the east and west A1 arch elements serve as buttresses which redirect loads from the upper half of the structure down to the C elements. These C elements flow the loads down to the center foundation beam and mat foundation, as discussed in previous sections.

Although the results obtained here vary somewhat from that which was shown in figure 16, they are only intended to provide a general approximation of the structural behavior. For example, the effect of post-tensioning was not considered and would have a significant impact on the load distribution through the C1 element. Arches and non-uniform elements were not fully modeled, and loads were assumed to have uniform distributions.

Lateral Load Resistance

In order to investigate the lateral resistance of the modeled section, a wind load of 200 lb/ft normal to the roof was assumed blowing from the left and lifting up on the right. The live roof load and snow load were removed, while the dead loads remained. The bending moments increase in the left members and the center left floor section changes from tension to compression. The foundation walls must transfer the horizontal reaction force to the

surrounding soil or rigid connection at the base of the wall. Figure 23 shows the deflected shape under lateral wind.

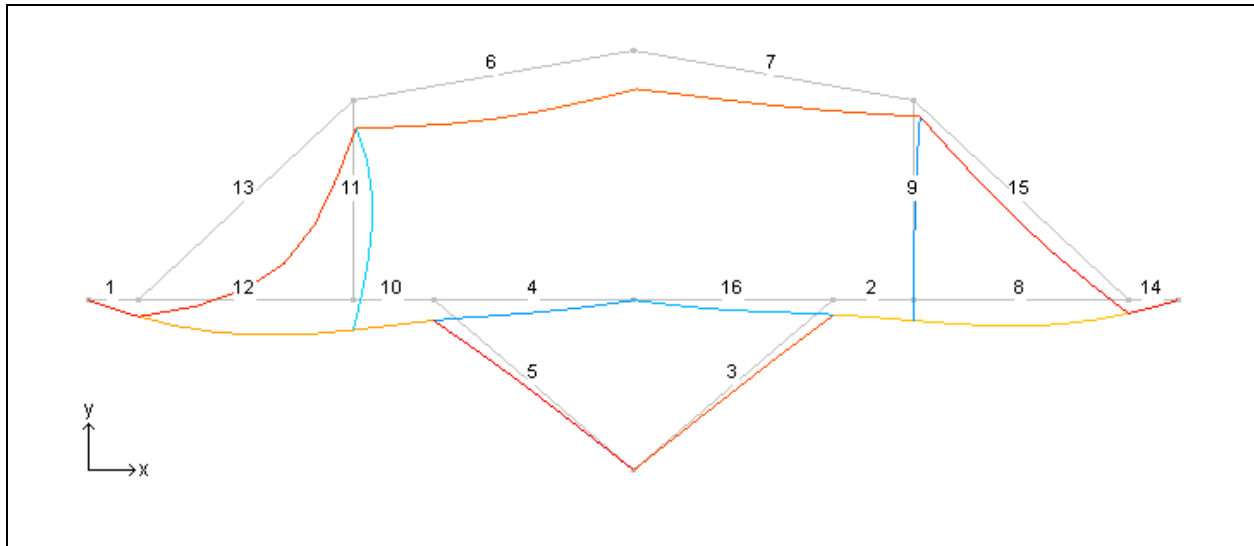


Figure 23: Deflection Diagram

Because of the complexity, the design of the mat slab, as well as the design parameters of the pavilion, A-frames, ring beams, and Burke Brise-Soleil was conducted through finite element model analysis. An illustration of this model was shown in figure 11. Wind or lateral loads must be transferred from the A frames to their base in the plane of the ring beam and further distributed to the piers and finally to the foundation. The ring beam and horizontal elements of the pavilion are sufficiently rigid to transfer the forces to the four piers. If it was not able to do so there would be distortion or significant loading at one pier only.

As was mentioned, the effect of wind on the Burke Brise-Soleil was evaluated to understand the load transferred to the spine while relying upon the lateral resistance and load transfer of the A-frames.

This structure is complex due to the non-uniformity of cross-sections, as each is designed to taper as needed to handle moments generated within the structure. But it is obvious that the section size increases with the bending moment in most members. In locations where the increase in section size would be impractical or aesthetically undesirable, post-tensioned steel reinforcement provides additional support.

Foundation and Soil

Because the water table from Lake Michigan is above the level of the parking garage, a mat foundation was designed to distribute the load over a greater area to the saturated soil (having lower allowed bearing pressure) and to withstand the hydrostatic pressure. The building is designed to float in the soil and relies on the dead load of the structure for stability. In fact, a 0.6-m-thick layer of gravel for added weight was placed on top of the mat slab to ensure an adequate safety factor against buoyancy. Sheet piles were driven to de-water the area and allow for construction [8], after which the water was allowed back (with waterproofing in place). The foundation walls are quite thick with respect to the mat depth (see figure 9) which may be due to the primary orientation of this section of the building being parallel to the shore and prevailing winds in addition to resisting outward thrust from the structural loads.

Summary

This report comprised a case study of a recent addition to the Milwaukee Art Museum by renowned architect and engineer Santiago Calatrava. The project, which has become an icon for the museum and the city of Milwaukee, has received praise as a masterwork of artful design and advanced structural engineering.

A brief history of the Milwaukee Art Museum was presented, as was the architect's background. This was followed by more detailed information on the project, specifically the Quadracci Pavilion and attached galleries. In addition to the building layout and floor plans, architectural features including the Burke Brise-Soleil and cable-stayed pedestrian bridge were presented in detail. A simple explanation of the structural system was put forth with accompanying diagrams. The results of a two-dimensional computer-based structural analysis of the building's cross-section were presented with respect to gravity loads and lateral loads as a result of wind. Finally the foundation system and soil conditions were presented..

Calatrava envisioned "a glowing 'lantern' on the downtown lakefront, radiating light in all directions." [6] His Quadracci Pavilion achieves this goal through a complex but elegant and well-executed structural solution in concrete, steel, and glass. The end result appears both powerful and effortless, and exploits the potential for dynamic design through structural expression.

Acknowledgement

This report was modified from the original work submitted by Aaron M. Vorwerk, MArch candidate, August 2004.

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