Casting Concrete Artwork

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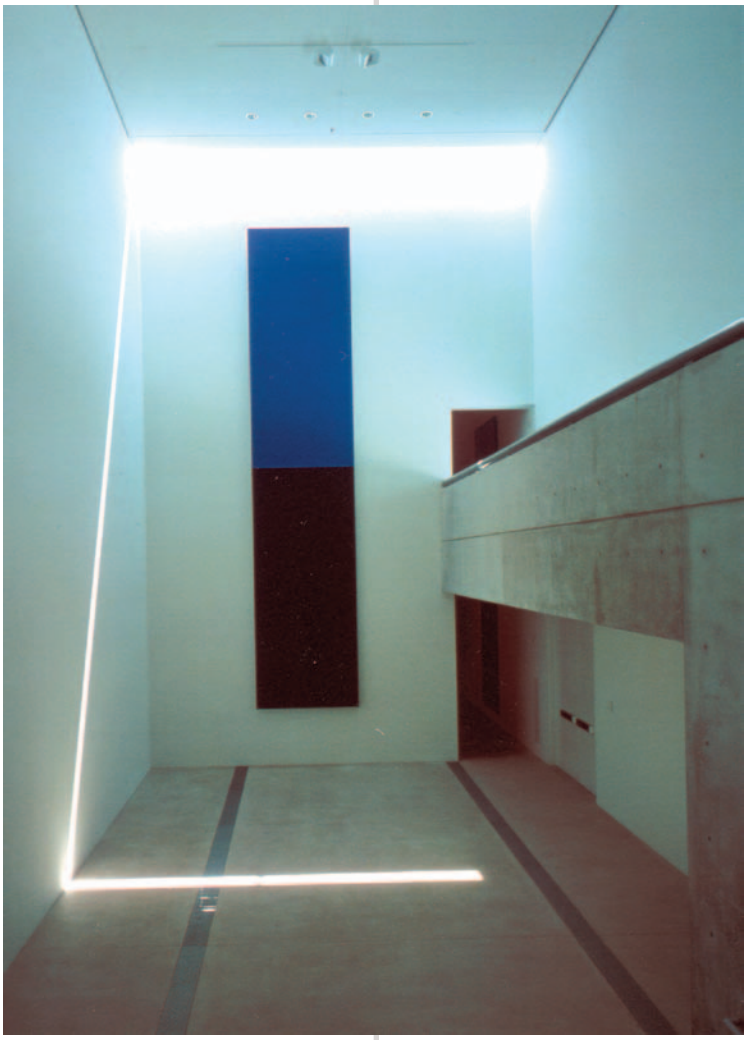
When a structural engineer is awarded a "once in a lifetime project", the initial perception is that the project will be challenging and difficult. And so it was when The Pulitzer Foundation for the Arts, established by Emily and the Joseph Pulitzer Jr., needed a space for their collection of contemporary works of art. They were introduced to the architecture of world-renowned Japanese architect Tadao Ando. Ando was commissioned to design a museum in St. Louis, MO.

Ando, a proponent of modernist architecture, designs with basic materials of concrete, water and light in a simple but elegant form. He prefers concrete with a "smooth as-cast finish" with a consistent color and crisp sharp corners. For the project, a modular grid based on multiple 4-foot by 8-foot panels with exact tolerances and alignment was selected.



Pictured above: The Pulitzer Foundation for the Arts building raises the state of concrete design and construction to artwork. Photo by Robert Pettus

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Defect Free Concrete

Project specifications required surfaces free of defects and cracks, as repairs leave noticeable blemishes and are typically not allowed. The concrete walls were required to have a maximum flatness tolerance of 1/16-inch in 24 feet, and to be plumb within 1/8-inch for the overall height of the building. Extremely tight construction tolerances are critical for the alignment of subtle details essential for the interior and exterior of Ando's architecture. Doors, window frames, switch boxes and lights are recessed into the concrete and require openings to be perfectly square, as there is no trim to mask misalignments.

Structural Challenges

Ando's design is basically two parallel concrete rectangles of different heights. The form appears simple, but involved several structural challenges.

- Settlement cracking was avoided by founding the concrete bearing walls and site screen walls on drilled piers that are socketed into limestone bedrock.
- Thermal and shrinkage cracking was nearly eliminated by the use of contraction joints aligned in the walls and slabs, and spaced at 24 feet on center along the entire building length. The joints consisted of smooth epoxy-coated dowels in plastic sleeves on one side of the joint, with only a bond breaker between concrete pours. The initial shrinkage between pours allows for future thermal expansion. It was critical that the dowels be positioned perfectly parallel with the wall to allow for uninhibited movement.
- One-way concrete slabs supporting a landscaped roof and water court floor were required to span 24 feet without inducing noticeable stress cracking at supporting concrete walls. The negative moment of the slab was carefully analyzed and reinforced, such that it would not exceed the cracking moment of the visible 10-inch thick exterior concrete walls.
- The taller rectangle element of the museum has an 8:1 plan aspect ratio. The concrete roof diaphragm is completely discontinuous from the shear wall at one end to allow for a skylight. The diaphragm shear transfer was accomplished through reinforcing a portion of the wall to function as concrete coupling beams at each end of the skylight. *(Pictured left: Gallery A skylight isolates the roof diaphragm from supporting shear walls. Photo by Robert Pettus)*

Pictured above: The two-way cantilevered roof was required to be perfectly level (showing completion).

The Cantilevered Roof

The most unique design challenge was the 48-foot by 48-foot cantilevered roof over the lower rectangle. The slab underside is exposed to the lobby and lounge below. The concrete ceiling incorporates a recessed pocket for the glass curtain wall and lights. The concrete roof appears to float on the glass walls. At one end, the concrete roof slab cantilevers two ways from a single 24-inch diameter concrete column, which is located 24 feet over and 12 feet in from the free corner. Ando required that the overall structure depth could not exceed 18 inches while remaining perfectly level. The team only had one shot at this roof element, and left nothing to chance.

Up-turned concrete beams in both directions were selected as the structural systems, to minimize weight. Initially, 6 inches of deflection at each of the free corners was anticipated based on cracked concrete section properties. The addition of post-tension (PT) tendons along with mild steel reinforcing to the beams and slab countered 4.5 inches of excessive deflection. The post-tension design was based on the "load balancing method". In this method, the parabolic curvature of the PT tendons is replaced with series of positive and negative uniform loads that are superimposed with gravity loads, resulting in minimal flexural stresses.

Pictured above: At the mezzanine, the cantilevered roof slab appears to be supported by the recessed glass wall

Pictured below: The two-way cantilevered roof was required to be perfectly level (showing construction).

Determining the amount of PT force and profile for a two-way cantilever slab with abrupt changes in cross-section is an iterative process to balance the roof dead load. During the analysis, the intensity of the uniform balanced loads is adjusted by discontinuing some of the PT tendons in the lower stress beam segments. The axial PT stress was required to be as high as 840 psi at the reduced beam sections over the window slots.

The remaining 1.5 inches of deflection at the free corners was accounted for by form camber to achieve a level slab. The contractor was required to shim the form liner panels above the falsework for camber to a tenth of an inch on a 4-foot grid. The camber plan was based on an accurate estimate of the *expected* modulus of elasticity, not the minimum, for long-term deflection calculations. Creep estimates were based on ACI 209R. One key variable in creep calculations is the age at which the concrete is loaded. Long-term creep deflections were minimized by maintaining the supporting formwork for the first 28 days and only stressing 25% of the beam PT tendons in first 3 to 5 days.

At completion of the project, the contractor indicated that the free corners are within ½ inch of level. Minor long-term creep deflections are expected to continue for about 10 years.

Constructing Artwork

Construction of this 25,000 sq. ft. museum took 4 years to complete. All aspects of concrete mix, formwork, reinforcing steel, concrete placement and vibration were carefully explored to achieve consistent finish during the wide range of seasonal variations in St. Louis.

The structural engineer and contractor evaluated several trial mix designs of varying proportions to achieve the required structural properties versus workability and finish. The most suitable concrete mix was found to produce a minimum compressive strength of 5000 psi at 28 days, with only water-reducing and air entrainment admixtures, producing a moderate slump of 4-inches. It was desirable to have a concrete mix that could be controlled throughout the year. A well graded mix of coarse and fine aggregate was utilized to improve consolidation of the concrete during placement. A local coarse aggregate, Meramec River stone, was selected over limestone because the smooth hard surface allowed air bubbles to be cleared more easily.

To achieve the sharp corners and finish required by Ando, the contractor made the formwork rigid and leak-proof. A black plastic form liner, with plywood backing and Teflon tie hole inserts, was used. In a temporary building on site, the contractor crafted the form panels with splined butt joints and silicone gasketed seams. The form panels were mounted on strong-back trusses at 12-inch centers to maintin the 1/16-inch deflection limitations during concrete placement. The contractor was required to submit precise form shop drawings depicting all blockouts and embedded items to the nearest 1/16-inch for each 12-foot high and 24-foot long wall pour.

Pictured above: Epoxy –coated reinforcing bars and leak-proof forms at block-outs and construction joints were necessary to achieve a nearly blemish-free concrete

Project Participants

Structural Engineer of Record:
ABS Consulting (formally EQE-Thiess), St. Louis, MO

Owner:
Pulitzer Foundation for the Arts, St. Louis, MO

Design Architect:
Tadao Ando, Osaka, Japan

Architect of Record:
Christner Inc., St. Louis, MO

General Contractor:
BSI Constructors, St. Louis, MO

Architectural Concrete Partner:
Zera Construction, Skokie, IL

Epoxy-coated reinforcing bars used for exposed concrete walls were specified to minimize corrosion and reduce resistance to clear air bubbles during concrete placement. Threaded bar splice couplers were used at slab-to-wall connections to eliminate dowel penetrations through the wall formwork. The flexural capacities of the 10-inch thick concrete walls were designed such that the horizontal reinforcing bars were placed outside of the two vertical bars layers. This bar placement maximizes the clearance between horizontal bars for improved internal vibrator access. The concrete was placed by a bucket and tremie. Pumped concrete was not used because of added equipment cost for numerous small pours, and the elimination of another variable in the concrete composition.

Timing of concrete placement and lift heights was absolutely critical in achieving a uniform finish. The concrete was extensively vibrated to minimize surface defects while avoiding aggregate separation of the concrete matrix. Over-vibrating and consistency was controlled by inserting vibrators at marked positions on the formwork for a defined amount of time for each insertion. The contractor learned, through experience, when the wall forms could be stripped. Strip the forms too early, and the sharp corners could be damaged. Leave the forms on too long, and staining would occur. Sealants were applied to the concrete surface shortly after stripping, which causes the free water to remain in the concrete for a longer than usual time, which also slows shrinkage effects.

A Greater Appreciation

Due to the modest size and long duration of the project, the team worked together in close collaboration. What started out to be a challenging project on the drawing board became a great experience in designing and constructing a concrete building that itself is a work of art. The creative process can be very tedious, which in this case has led to a greater appreciation of the art. The Pulitzer Foundation for the Arts is open for public tours by appointment, so that anyone may experience, perhaps, the finest concrete in the country.