Precision and Constructability: Formwork Design for the Pulitzer Arts Foundation in St. Louis

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ABSTRACT: *Construction means and methods and the ingenuity of tradespeople are often de-emphasized when discussing award-winning architecture. Means and methods are contractually isolated from the architect's design and regularly the specifics are not documented as tradespeople seek to protect their own knowledge. Through the example of the Pulitzer Arts Foundation, this paper provides a narrative on how excellence can be achieved, not just through design, but also through construction means and methods. As a case study, this paper considers the specifics of the design and installation of the formwork for the Pulitzer Arts Foundation in St. Louis which was completed in 2001. It frames construction decisions within a broader discussion of the difference between precision and accuracy. It examines measure in relation to constructability, and how error was handled not on a case-by-case basis but through an ever-evolving process of refined decision making. Discussion includes the selection of the formwork material, processes for maintaining consistency in attaching the formwork to the structure, adapting the Peri Formwork system to meet the specifics of the project, and how the team invented individual solutions to fit the particularity of the pours. It examines how the legacy of the precision of Japanese construction was scaled and translated to the United States, allowing this project to meet the standards of quality that Tadao Ando established in projects in his home country.*

KEYWORDS: Means, Methods, Constructability, Concrete

INTRODUCTION

When Pritzker Prize winner Tadao Ando presented Emily Pulitzer with his design for the Pulitzer Arts Foundation in 1993, the drawings expressed his ideas through a few juxtaposed rectangles. While extremely understated, these initial drawings served to define the geometry of the building and the rules for its construction. This form created photographic-like surface planes across Tadao Ando's architecture that captured the concrete's variation in color and pattern. Precision of construction allowed this variation to be ascribed to the nature of the material rather than to deficits in craftsmanship. Total alignment required total exactness, and the tradespeople on the project were tasked with developing means and methods to achieve scrupulous precision in each concrete wall. Fundamental to this was the design and erection of the formwork.

1. CRAFT, ENGINEERING, AND AESTHETICS

Tadao Ando's work seeks a Platonic purity of form. However, as one approaches the building closer and yet closer, new ranges of resolution show "new complexities of newly perceived formal elements."[1] For example, the aligned circles of the form tie holes are easily perceived many feet away. But as one moves closer, one notices the nearly imperceptible imprinted pattern left by the screw heads that attached the form liners to the formwork. Only 1/8th of an inch in diameter, those screw heads are perfectly aligned across the panel. As one moves closer to within inches of the surface, one loses focus on the screws, and now notices the crispness of the geometry of the holes left by the form ties. Each step forward reveals new layers of detail.

In handmade carpentry, craft can be evaluated by the skill of the hand using the tools of the trade. The carpenter's body is part of the making – the slight turn of the finger or imperceptible push of the hand is controlled by the well-trained eye. David Pye, in his book "The Nature and Art of Workmanship," coined the term the "craft of risk" as exhibiting work that is most attuned. Pye defines this type of workmanship as "the quality of the work is not predetermined, but depends on the judgment, dexterity, and care which the maker exercises."[2] He asserts that working in a manner that is predetermined, certain, or unchallenging fails to attain the craft of risk. The mind in concert with the eye and hand controls and advances the work. By contrast, in engineered production, calculated precision is accomplished through machining – or the design of tools and machines to produce goods. The engineer solves the problem, and the machines deliver the answer. The result is a consistent and interchangeable solution. It is calculated, and success is measured by how closely the product meets the tolerances as specified.[3] Both the concrete and the formwork system at Pulitzer are fundamentally engineered products. However, instead of designing machines and predetermined processes to deliver the goal of perfection, success relied on the individual skill and craft of the tradespeople as they tailored the use of these engineered materials to the specifics of the design.

The aesthetics of Tadao Ando's work emphasize alignment and smoothness. The perfection of the formwork is important to producing the beauty of this outcome, but the specific craft of making the formwork itself is not part of the overall aesthetics. The formwork is eventually cast away. Aside from the signature pattern of circular indentions that indicate the location of the form tie holes, no mark of the formwork construction methods shows in the final surfaces.

Additionally, Tadao Ando did not wish for the construction team to adopt Japanese joinery methods. Instead, he preferred that the team use the methods with which they were familiar, but at the highest level of craft. The construction team used traditional American cabinet joinery methods to maintain alignment, and to keep joinery tight. Biscuit joints provided alignment between adjacent form liners, while details such as light fixture inserts mounted to the formwork were connected with dadoes using routers, and then gasketed to prevent leakage. The differentiation of creativity and beauty as separate from exhibiting the mark making of craft (or techne) is recent in Japanese culture. The study of Aesthetics is an entirely Western construct, and it was only with the opening of Japanese culture to the West in the 1870's that this dichotomy was introduced. Previously, the making of the object and the object itself were considered inseparable.[4]

2. PRECISION, ACCURACY, AND MEASURE

Tadao Ando required no deviation and no variation. The pours had to be both precise and accurate. *Precision* gages how close measurements are to each other, while *accuracy* focuses upon how close a measurement is to a predetermined dimension or number. Physically, the eye can easily see roughly the width of a fine human hair. Objects smaller in width tend to visually converge when placed adjacent to each other. Touch is noticeably more sensitive with surface patterns at the size of a micron (1/25,400 of an inch) distinguishable as a fingertip moves across a surface.[5] Beyond sight and touch, measure is often in reference to an external device. As measurement is rounded up or down to a nearest mark, closer and finer fittings or increments allow for less error. At the Pulitzer, benchmarks for accuracy across the exterior of the building were equivalent to those established for millwork on the interior of the building.

> At Pulitzer, from pour line to pour line the dimension is exactly twelve feet. It is not 12 feet and a 1/16th. It's not 11 foot and 11 7/8". I can go any place in that building right now, and I can take anybody's measuring tape out there and I'll bet my life on the fact that it'll measure 12 feet exactly. The tolerances are that close, and the fact that the team was able to hit those tolerances, that's the amazing part.
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> Steve Morby, Project Superintendent

The formwork needed to be straight and plumb. Initially the surveyor could stand on the ground and use a transit to establish elevation heights into the lower level on pier caps and the lower walls. These elevations set the initial horizontal lines that were used to establish the expansion and control joints, and the pattern of the formwork. However, once the lower-level walls were done, the team recognized that alignment had to occur within the building. The team poured construction decks which were later covered with a poured concrete walk surface. The concrete construction deck became the place from which measurements were taken. To establish a reference line a straight line the length of building was scribed by saw into the deck surface five feet off the center line of where the walls would be poured. By establishing this datum line any variation in the edge of the concrete deck became unimportant. For an eighteen-inch wall the center line had a nine-inch offset. Thus, the exterior walls were set 5'-9" off from the inscribed datum line. All measurements were made off of the datum to preserve accuracy.

> Assembling the formwork, we had to ensure it was straight… The deck of a building is a perfect place to establish that straight line. You have already shot it in and it is level with the joists and it has a solid deck running back to where the top plate is in. Now you know that when you stand that wall, and you check the plumb corners that they are going to be plumb because you just measured it out on the deck. If you do that same wall on gravel, there is no guarantee that the wall is going to be straight.
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> Steve Morby, Project Superintendent

The structural grid of the building established the center lines for the walls. To create a reference vertically within the building, the team used the same datum line methodology to set a perfectly horizontal line along the entire building, set five feet up from the deck. All locations of elements in the walls, from openings to recessed lights, to cabinetry and interior details were measured up or down from the horizontal line. The construction team learned this method from a millwork company in Chicago. This horizontal datum provided quality control. An installed finish floor might not be completely flat, with varying elevation tolerances. To measure up from a finish floor to set millwork or openings could introduce error. Instead by measuring down from the datum accuracy could be controlled.

2.1 Units of measure

The Pulitzer was built using the Imperial system, while many of Tadao Ando's buildings are constructed using the Metric system. In Japan, the Metric system is considered in parallel with traditional dimensions of the Ken. The design of Japanese architecture is based upon a system of proportions between components (*kiwari-jutsu*) with Japanese aesthetics often defined by simplicity of these proportional relations. The Ken originates in the measure of the width of a post and lintel structural bay in traditional Japanese architecture, with that length depending upon the innate strength of wood.[6] The resulting proportional or fractional system is defined as follows: the Ken is divided into 6 Shaku, which is divided into 10 Sun, which is then divided into 10 Bu, and subdivided then into 10 Rin.[7] The Rin sets the tolerance of traditional carpentry. By contrast carpentry in the United States typically uses tolerances of 1/8Th to 1/16th inches at the scale of architecture and cabinetry. Smaller tolerances, +/- .1 mm, can be reached for engineered and machined objects.

Japanese Fractional System and Tolerances
1 Ken = 6 Shaku = 60 Sun = 600 Bu = 6000 Rin
1 Ken = 180 cm = 70 in
1 Rin = .3 mm = 1/96"

Imperial Fractional System and Tolerances
1/8" = 3 mm
1/16" = 1.58 mm
1/32" = .79 mm

Just as Tadao Ando's work adapts to tolerances specific to the measuring system of a culture, the overall proportional system of the design relates to the measurement of standard dimensional sheathing in the region. The Pulitzer Arts Foundation proportional module is based upon a standard 4x8 sheet of plywood. In Japan and in Europe, Ando's module is based on standard metric sheet goods. This smaller size changes the proportions of the standard formwork panel, resulting in one less horizontal row of form ties.

Despite the fact that Tadao Ando elected to adopt Imperial measurements, the construction team still had to contend with coordinating with metric. The team selected the Peri Formwork system to support the form liners. The form liners were 4x8 sheathing, but the shoring, whalers, and other support structures followed spacing based on metric dimension. The construction team developed processes for assembling the Peri Formwork system so that the 2'-0" form time spacing remained uncompromised.

2.2 Precision in installation

If accuracy was achieved through cutting a datum line in the building, precision occurred through the development of installation processes. For three years, it was one carpenter's job to prepare the 4x8 form liners for assembly, maintaining quality control across the building. Tadao Ando required alignment of the screws that connected the form liner to the support system. The screws had to align across a twelve-foot straight edge. Quality control was achieved by designating a single person to layout the formwork design and to screw the forms to the gang system for the entire project.

Additionally, tightening the wing nuts on the clamps needed to be consistent to maintain quality control. The clamps on the cone ties needed to be tightened enough that they did not leak, but not so tight that the form liner was imprinted. After eight months of developing a tightening procedure in the lower level of the building, two carpenters with three-pound sledgehammers precisely tightened the wing nuts across the remainder of the building.

3. CONTROLLING ERROR

To construct perfect formwork the construction team developed processes to anticipate and control error. The science of error analysis studies uncertainties, estimating and reducing errors in three areas:

1. Looking at the likelihood of an error to occur based on probability.
2. Recognizing how often an error happens, by focusing upon its pattern of distribution.
3. Understanding where an error may propagate or become larger or multiplied due to the way something is measured or made.[8]

The construction team addressed each of these areas with processes that emphasized reliability, traceability, and quality control. As a result, the team could identify errors quickly, isolate them, and then develop processes to reduce their impact.

The process of selecting and preparing the form liner exemplifies these error handling processes. At the Pulitzer Arts Foundation, the construction team tested four sheathing products: Enviroform, polyethylene coated plywood, plastic laminate, and Fin Form.

3.1 Enviroform and the likelihood of error

Tadao Ando's first project in the United States was Eychaner House. The team selected Enviroform as the liner system for the formwork. The construction team identified black stains on the surface of the concrete after pours. Consulting with the manufacturers, the team analyzed the error. Enviroform was made of rapidly renewable softwood, and the softwood contained significant sugar resin. During the curing process, the concrete reached high temperature. If there was a scratch on the surface of the formwork, sugar resin would move to the surface of the concrete, transported by liquid in the concrete. As it came to rest along the surface, and the temperature increased, the sugars would burn and turn black. After using Enviroform for Eychaner House, the team was hesitant to employee it at Pulitzer, as scratching in conjunction with the heat of curing increased the likelihood of quality control issues.

3.2 Plastic laminate liner and the distribution of error

As the team began pouring the lower-level walls at the Pulitzer Arts Foundation, they tested additional sheathing. Polyethylene coated plywood acted like a Visqueen coated plywood. The team also tested plastic laminated onto plywood. The plastic laminate was so smooth that it created a mirror like surface on the concrete. Tadao Ando was interested in this form liner, but the team could not guarantee that they could reliably achieve the mirror like surface across every pour as weather and temperature changed. In the end, Tadao Ando and the team selected Fin Form liner. This ½" thick panel could withstand up to five pours without degrading, and the resulting poured surface was reliably similar in terms of quality.

3.2. Variation in sheathing and the propagation of error

Error propagation can occur when variations in tolerance are not controlled. A thirty-second of an inch seems a small increment, but across the length of a building a recurring error can result in inches of difference. The Pulitzer Arts Foundation required alignment both vertically and horizontally, relying upon the expectation that all modules were the same. Tolerances of 1/16" across the 4x8 module, which might be allowable in a plywood mill, had to be accounted for so that variation would not be visually perceptible on the wall. Across the three-year construction span, the team labeled and marked different mill runs, and their associated variations in dimensions to ensure that the form liners would fit together like puzzle pieces, and appear perfectly aligned. This traceability enhanced quality control and decreased the propagation of error.

4. CONTINOUS IMPROVEMENT

One of the hallmarks of Tadao Ando's work is an emphasis on continuous improvement to the means and methods by which a project is constructed. This process is a feedback loop. As new construction processes develop ever smaller tolerances can be achieved in the design. Tradespeople are encouraged to rethink the ways they accomplish work to constantly improve their craft. These methods are not without risk - as one gets ever closer to perfection new hurdles appear.

Tadao Ando's emphasis on continuous improvement echoes processes that were developed in Japan by Dr. W Edwards Deming, Masaaki Imai, and Shingeo Shingo. These processes were initially introduced as management principles during the Marshall plan to aid in rebuilding Japan's manufacturing capability. Japanese culture embraced these principles and companies such as Toyota became known for continuous improvement processes that sought reduce inefficiency, decrease waste, and increase precision, and quality. Continuous improvement processes implement incremental changes, relying upon workers and tradesmen to suggest improvements. This encourages all workers to be active participants in design and production.

These methods are traditionally applied to replicable processes found in engineering and manufacturing. Codified in the ISO 9000 standard as Continual improvement Processes, these methods are embraced by sectors such as the automotive and aeronautical industry. By contrast, Tadao Ando introduced this kind of thinking to the craft-based work of design and construction. Through emphasizing improvement, Tadao Ando is able to motivate tradesmen to continuously engage in the 'craft of risk' as described by David Pye.

For example, at the Pulitzer Arts Foundation, the construction team selected the engineered Peri Formwork System to support the forms. The system is composed of a bulkhead at the bottom of the form connected to channel iron whalers supported by poplar trusses. The trusses are screwed to ¾" plywood sheathing, and then skinned with the Fin Form liner. The entire assembly, in addition to clamping assemblies, provided nearly three feet of thickness. The combination of elements made the system extremely strong and straight along its length.

However, when the building required a corner, the thickness became an obstacle. This thickness prevented locating form ties on the edge of the corner. The corner could not be fastened properly, and this became an opportunity for leakage. In most applications, a material would be used to clad the pour along the facade, so the corner would be hidden. But at the Pulitzer Arts Foundation, if water leaked from the corner, then discoloration, sand streaking, and the loss of cement around aggregate could occur. To resolve this, the construction team designed an outside corner detail, converting the last eight feet of formwork to stick built prefabricated corner panels. These panels were milled so that they tied into the Peri Formwork System, providing a hybrid solution that appeared seamless. The team were able to decrease the depth of the prefabricated assembly placing cone ties near the edge of the corner to achieve full seal of the corner. While the solution brought together two dissimilar assemblies, the final form of the concrete wall appeared pure and continuous.

Initially the Peri construction company sent their forms fully assembled. However, the team found it was difficult to align them along the vertical direction across the 24-foot-long panel sections. The construction team realized that in order to improve alignment, the Pulitzer Arts Foundation jobsite had to request becoming a factory in the field for Peri. Assembly needed to occur onsite by the construction team, instead of being prefabricated at the factory and delivered. This was highly unusual, but it was necessary to ensure that all the systems could coordinate across the layers of structure.

> To assemble the form, the inside and outside panel were laid across from each other…This allowed the through bolts to be centered in the panel from side to side locating the signature pattern of round indentions, or holes, across the face of the concrete walls in Ando's buildings.
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> Steve Morby, Project Superintendent

Because of the strength of the Peri formwork, the engineers calculated that it was not necessary to provide form ties across the face of the formwork at all locations. However, Tadao Ando still required the signature pattern of circular indentions indicating the location of the form tie holes spaced two feet apart. The construction team found this to be an opportunity for improvement and advancing quality control. The team developed drawings to document the design of each panel, similar to shop drawings but at the scale of the entire building. These drawings allowed the construction team to visually match both sides of each form to make sure that all dummy holes aligned. If a dummy hole was mismatched with a true hole, it could introduce a hole in the form, and a corresponding opportunity for leakage. The shop drawings also allowed for coordination and change to the form liners to accommodate placement of light fixtures, hose bibs, and outlet face plates. The drawings were produced in Autocad by the construction team, with the development of symbols and color coding to designate different form tie details and conditions. These drawings promoted the ability to reuse of form liners multiple times – allowing coordination between similar layouts, until enough inserts for electrical and plumbing infrastructure interrupted the form liner's surface, or repetition of pouring led to degradation of surface.

In addition to rethinking the assembly of the support for the formwork, and developing whole building shop drawings, the team also interrogated the form tie that Peri construction company used with the system. The "B-30 Dayton Superior Coil Tie" is a spreader that defines the width of the wall. The tie fits into a ¾" PVC pipe. A cone interlocks with the spreader to close the assembly and seal it to create the crisp edge along the round indentions that make up a grid on the surface of the concrete wall. During pouring, the construction team discovered that there was a manufacturing defect in the cones. A small chip missing in the sleeve resulted in the cone not fitting seamlessly against the PVC pipe. Water could leak through the chip, changing the cement water ratio to cause black rings around the holes, or in worse cases sand streaking.

> In a normal application, leakage was not critical; by contrast, in our situation leakage was really everything.
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> Steve Morby, Project Superintendent

The team developed a solution: a single layer of electrical tape wrapped once around the cone and PVC pipe provided the correct amount of seal, without spoiling the surface of the pour. It was this kind of thinking and attention to detail that exemplified the continuous improvement that Tadao Ando desired.

CONCLUSION

The selection of the formwork material, the adaption of the Peri Formwork System to meet the specifics of the project, and the invention of individual solutions to fit the particularity of the pours all serve as ways in which the construction team provided quality control, reliability, and traceability at the Pulitzer Arts Foundation. The tradesmen not only drew upon their existing construction knowledge but also developed new methods for assembly and installation. In so doing, they developed ways to best use resources and created flexibility when needed. The design, production, and installation of the formwork serves as a case study for establishing standards of precision, accuracy, and error control during construction, while maintaining hand crafted detail.

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