TADAO ANDO'S CHICAGO ROOF: CREATING POST-TENSIONED BEAMS AND THERMALLY ISOLATED REINFORCED CONCRETE CANTILEVERS

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Abstract

This paper examines technical aspects related to the creation of a precisely designed and detailed site-cast concrete roof which covers a new Chicago museum building called Wrightwood 659. Designed by Osaka, Japan-based architect Tadao Ando in 2013–14, completed in 2018, and located in a mixed-residential area in the Lincoln Park neighborhood, this entirely new fourth floor and rooftop structure is constructed within an existing former (1929–30) apartment building's three-wythe thick Chicago common brick perimeter shell. A complex hybrid steel frame and reinforced concrete structure, engineered by Thornton Tomasetti, is crowned by two long, narrow skylights, one of which diagonally bisects the roof. Furthermore, deep cantilevers extend 12′-3″ (3.73m) outward beyond the core bearing walls, which define the internal art gallery spaces. In order to ensure the longevity of the exposed concrete structure (roof fascia and eaves), thermally isolated, insulated reinforcement members were incorporated into the roof slab to separate the cold-weather exposed concrete cantilevered elements from the top-insulated roof structure. This also yielded both heating and cooling energy-savings through the prevention of a thermal short-circuit between insulated and uninsulated roof portions.

Further complicating the engineering solution, the size of the aforementioned skylights required a significant quantity of post-tension members to achieve required structural beam strength. Lastly, in anticipation of future uncertain weather conditions, snow live loads were doubled from conventional code minimums, requiring further roof reinforcement. The overall outcome of the engineering, design, and construction solutions for this project yielded a visually stunning building, approved by the concrete master as equivalent in quality to what has been achieved in his native environment.

Introduction

A 7,197-square-foot (668.6m²) reinforced concrete roof capping a fourth story of a repurposed building is not an unusual nor large project in the city the size of Chicago. However, this is far from an ordinary project, for the structural requirements mandated for each exhibit gallery floor level below was 300 pounds per square foot (equivalent to 14.36 kN/m²)! This live load performance demand is almost unheard of in most non-industrial structures built today. Most buildings are designed and constructed to bear a live floor load in the range of 60 to 100 pounds/ft² (2.87 kN/m² ~ 4.79 kN/m²) (ASCE, 2010, Chapter 4).

Hence, a far-above-average strength composite structural steel frame combined with reinforced concrete encasement work together to bear all forces and bring them safely into the earth's supportive bedrock. The reinforced concrete roof possesses a full-perimeter 12'-3" deep (3.73m) cantilever on all four sides, along with two major linear skylights, one of which diagonally separates the roof into two different asymmetrical planes. In addition, compounding the complexity of the roof structural system is the desire and design edict that all exposed concrete surfaces (soffit and fascia of cantilevers) *must* be cast and finished to a uniformly smooth texture and visual appearance. The last, but equally important construction element required by design, is that all concrete exposed to the elements and weathering must be thermally separated from the main body of the insulated roof. This necessitated the first use in the City of Chicago of a German pre-manufactured structural thermal-break unit, whereby all structural performance criteria is met through a hybrid assembly. Within the unit, standard steel rebar is factory-welded to low thermal conducting stainless steel rebar elements, which are fully embedded in an insulating matrix, topped with a 1.4cm-thick × 10cm-wide fire-rated protective cementitious concrete board.

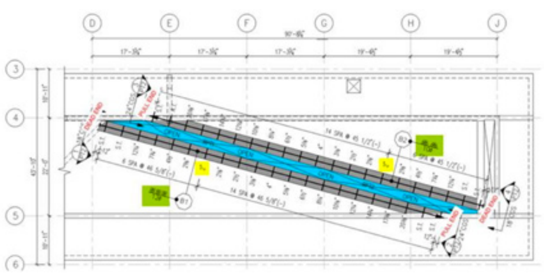

Figure 1: P.T. beam diagram. (Source: Murphy et al., 2016.)

Roof Structure

The main roof is composed of a 9'' thick (22.86cm) reinforced concrete slab, with no post-tension cables. It was designed for live load snow loads far in excess of what various code minimums require. For example, while American Society of Civil Engineers (ASCE, 2010, Chapter 4), founded in 1852, requires roofs to accommodate a minimum of 17.5 pounds/square foot (0.83 kN/m²), the City of Chicago increased this requirement two-fold. Hence, roofs within the municipal boundaries must be designed to bear a minimum of 25 pounds/square foot (1.19 kN/m²) (Figures 1 and 2) (Murphy, 2016). For this project, the engineers were given the directive to double this figure, to 50 pounds/square foot (2.39 kN/m²) (Whittaker, 2014). This was requested to prepare the building to be capable of handling any 100- or 500-year snow and or ice storm event; also for general longevity, because the roof is the apex of this structure. Separate engineering was done at a later phase of the project to ensure the structure could support the air conditioning system's chiller, which in an earlier scheme was located in a louvered chamber within a partially open, vented basement space. Later, after full-building engineering was complete, it moved to the more conventional roof-top locale, where Ando's office designed a special reverse-louvre screen to visually and acoustically mask its presence.

The fins of the louvres angle and point upward, instead of typically down, since the equipment that is desired to be shielded from view is positioned on the roof, and will be viewed most often at an upward angle by pedestrians walking along the sidewalk. The rectangular 'shroud' contains baffled noise-abating components to reduce the drone of white noise emanated by the air conditioning equipment's six fans and scroll pumps. Standard equipment springs, flexible conduit and pipe couplings, and vibration isolators are present to minimize any telegraphing of vibrating motor movement into the galvanized structural steel framework and cage supporting and surrounding the roof-top air conditioning dry coolers. Lastly, computer-modeled sound distribution studies were performed to ensure no excessive noise would pass beyond the enclosure into the side or rear yards of adjacent properties (Moritz, 2015). A computer sunlight-shadow tracing study was also executed to verify that no shadows from the louvered screen would be cast upon the northern-most tip of the adjacent diagonal skylight, which is fortunately located south of the roof-top equipment.

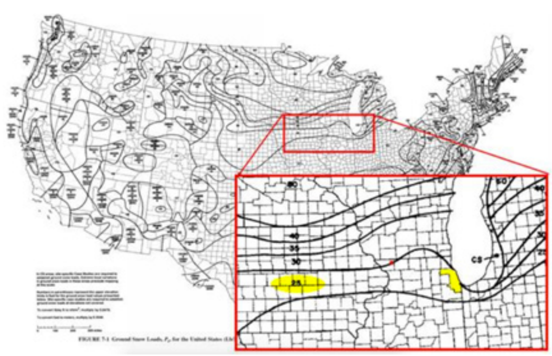

Figure 2: Snow loads: 25 pounds… (Source: Murphy et al., 2016.)

Diagonal Skylight

The aforementioned diagonal skylight is one of the most dramatic design elements in this building. Accomplishing the ultimate degree of fidelity to the original design intent, as described by Tadao Ando's schematic architectural drawings, proved to be yet another challenging task to the team. The overall skylight dimensions necessitated a beam span of 85'-6" (26.06m), which diagonally splits the fourth floor gallery in half. Only narrow thermally broken aluminum window mullions cross the opening, segmenting the entire skylight length with large sheets of triple-pane glazing, each approximately 9'-7"x37" (2.921m × 0.939m). No electrical conduit nor mechanical ducts providing heating, air conditioning, and humidity control could cross over or through this sacred linear space admitting natural daylight. Hence, all ducts had to snake around the gallery, with specifically positioned portals pre-formed into the bearing reinforced concrete perimeter walls to admit ducts containing the forced air system along with return air plenum apertures. This strategy for conveying air was problematic in two areas: the ceilings of both fire exit stairs, which are directly adjacent to the polar ends of the east side mechanical room, contain zero plenum clearance. Linear LED trough lights, illuminating the staircases, no longer had any plenum space for the incorporation of recessed pockets, due to the area above the finished ceiling being solidly occupied by ductwork and conduit, and encased in a two-hour, fire-rated, non-penetrable finished gypsum board ceiling enclosure.

Figure 3: Skylight acute angle corner.

Senior structural engineer Bill Bast, supervised his team led by Michael Murphy, at Thornton Tomasetti engineers, Chicago, to design the immense concrete beams (Figure 3) which enable the diagonal skylight to span such a great distance and support the weight of both of the adjacent roofs and the reliant cantilevers. Their solution incorporated two large beams, each about 32′′D × 28′′W × (at maximum) 85′-6′′ L (81.2cm × 71.1cm × 26.06m), with embedded post-tension cables (tendons). The western beam contains 12 tendons, with an "Effective Prestressing Force" of 300 kips (136 Tonnes). The eastern beam contains 10 tendons, with an "Effective Prestressing Force" of 250 kips (113.4 Tonnes) (Murphy, 2016). The eastern beam required unequal and lesser bearing strength due to a lower amount of mass resting upon the beam, since a portion of the roof on the east side is structurally anchored into one of two full-height shear walls that exist in that portion of the structure. Fascinating asymmetry within the structural system exists to achieve desired uniform strengths and proscribed camber. The west beam's 'pull end' is at the south end of the beam, whereas the east beam's 'pull end' is at the north end of the beam (Murphy, 2016). During the post-tensioning process, there fortunately were zero reported tendon failures, as expected in a beam of this size and density.

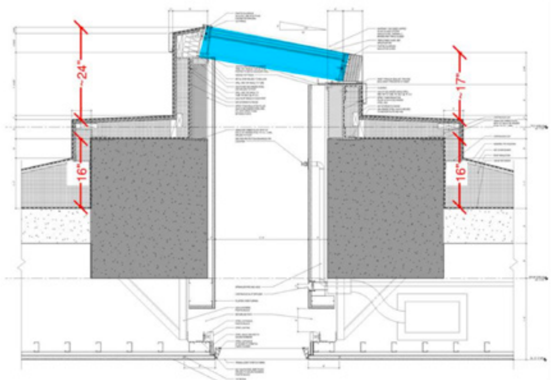

Figure 4: Section through P.T. beams. (Source: Murphy et al., 2016.)

The skylight frames (Figure 4), identical to all the new window frames custom designed for and installed in this project, incorporate a thermal break which is made of a low-thermal conducting polyamide resin (1,000-times less conductive than the past commonly used all-bauxite ore-based frame) (Muessig, 2004). The thermal break was made exceptionally thick to accommodate the triple-pane Insulated Glazing Units (IGUs) that were 1-15/16′′ thick (49mm). The raw extruded frames were Computer Numeric Control-milled (CNC) in Elmhurst, Illinois, by Glass Solutions, Inc. The triple-glazed Insulated Glazing Units were manufactured by Viracon glass of Owatonna, Minnesota. Atypical from normal IGUs, these were one of the earliest IGU shipments installed in Chicago featuring custom-fabricated perimeter double black-coated aluminum glass separating units (each containing a desiccant, Figure 6), instead of standard spectral (shiny) aluminum glass separators. The black bands reduce visual attention garnered by non-desired reflected sunlight within the inside (visible) edges of the IGU.

Figure 5: Within skylight 'open plenum.'

Figure 6: Thermally broken aluminum frame.

Thermal Breaks

The reinforced concrete cantilevers, while not required to be thermally broken by Chicago's energy code, were designed as such due to two reasons: First, a precedent had been set at another recently completed Tadao Ando-designed museum building. The Clark Art Institute in Williamstown, Massachusetts, completed June 2014, incorporated structural thermal breaks, a primary feat for an Ando project, due to the extreme climate conditions present in America's northeast. These details were executed by Turner construction, the general contractor, in compliance with contract documents created by Gensler in their New York office. Secondly, the Chicago client's specific architectural knowledge (partly acquired while building [1994–97] and living in an Ando-designed home for nearly two decades) (Whittaker, 2013), informed decisions and influenced the desire to construct a building that would, in theory, last for 300 years. Due to the inherent stress imparted into the concrete (and reinforcing bars) during seasonal weather conditions producing vicious seasonal freeze-thaw cycles, the incorporation of thermal breaks were determined to be the best practice to reduce one major source of potential cracking and spalling of exterior-exposed concrete in the future.

Figure 7: Schöck Isokorb with drain.

A German company (satellite offices in Princeton, New Jersey), based in Baden-Baden, manufactures Schöck Isokorb, a pre-assembled thermal break unit with very low thermally conducting stainless steel rebar threaded through a thermal insulation block (8cm thick × 6.6cm high) made of rigid expanded polystyrene (Figure 7). This product arrives at the job site packaged on a palette in 1-meter linear blocks, pre-assembled with reinforcement bars ready for placement, integration and coupling. It contains stainless steel rebars welded to conventional steel reinforcement rods (rebar), enabling coupling to the existing roof's structural steel rebar system prior to pouring concrete. The remainder of new, site-installed rebar incorporated into the exposed, uninsulated cantilever consists of epoxy-coated rebar (traditionally visually identified on-site by its light green dyed epoxy coating color) (Cutler, 2015) as a precaution against oxidation of the steel, resulting from inadvertent contact with moisture. Schöck advertises their product as able to "reduce heat loss by up to 50% while preventing condensation and mold..." (Schöck Isokorb, 2017). The building was completed during the summer of 2018; hence, cold winter seasonal testing of the manufacturer's claims have not yet commenced.

Figure 8: Thermal break at reverse corbel supporting upturned beam.

FinnForm, a 12-layer cross-grain, laminated Finnish birch plywood, ¾″ thick (19mm) with a red phenolic resin coating on both sides (FinnForm, n.d.), is specifically made for precise concrete forming applications. This product was used to form and define the exposed-concrete surfaces of the cantilever's soffit and fascia. Uncharacteristic extreme care and precautions were taken on this job site to ensure the concrete formwork never received a nick, ding, or scratch (see rebar worker kneeling upon white foam protective padding laid on top of FinnForm formwork in the photo in Figure 9). In order to support the 12′-3″ (3.73 m) deep cantilever at the north end of the structure, two main upturned beams with reverse-corbels carried the weight of the 'floating' concrete back to two 16″ square bearing columns (40.64cm).

In order to create a requisite 'drip edge' on the underside of the soffit, a convex radiused bead of Corian-brand material (made by DuPont; a homogenous acrylic polymer mixed with alumina trihydrate) (DuPont, 2018) was attached to the face of the FinnForm to leave a concave surface indentation into the soffit, near the outside corner edge (Figure 12). This traditional geometric solution successfully prevents most rainwater drips from crawling back along the horizontal face of the soffit, which could cause both irregular surficial concrete staining as well as deeper, more destructive water penetration into the concrete soffit (Figure 10).

Due to the reverse-slope detail of the cantilever, in order to ensure rainwater collects and is channeled to numerous roof-trough drains, the cantilevers had to maintain a thin profile as well as remain uninsulated. The cantilever is only covered with a (reflective white) thin, thermoplastic Polyolefin (TPO) roof membrane. There are 22 drains in total around the perimeter of the roof (at the lowest point, inside corner of the cantilever), funneling water from a total surface area of 7,197 square feet (668.6m²). The bulk of the gently sloping roof is covered with tapered insulation (layered polyisocyanurate boards), ranging from a minimum of 4" (10.16cm) to a maximum of 14" (35.56cm). A protective glass-mat gypsum board substrate allows personnel to safely walk upon the finished surface. The aforementioned 22 drains ring the inner insulated portion of the roof, totaling 358'-11" (108.8m) in perimeter.

There was obvious concern to do everything possible to prevent on-site corrosion of dissimilar materials or future corrosion, post-construction. It has long been known that copper and concrete do not cooperate well in direct contact with one another, hence the soldered copper drainpipe leading from the cast bronze roof-trough drain collection grille was surrounded by flexible, compressible foam pipe insulation, ensuring that the wet concrete, when poured into the formwork surrounding the roof drain pipe, would not come in contact with the copper pipe (the concrete did envelope the cast bronze drain receptacle, as per design).

Below the cast-in-place concrete roof assembly, within the very tight plenum space, a coupling transitions the copper pipe after about 3' (0.91m) from its origin, to traditional 'hubbed' cast iron roof drain soil pipes. In Cook County, 'no-hub' (rubber couplings with adjustable stainless steel friction-connected collars) are not code compliant. For over 130 years, traditional spun oakum (tarred jute fiber) is packed into the cast iron hubs and then a ladle of molten lead is poured over the oakum to create a water-tight seal. This can even be accomplished at vertical hub joints with the aid of special forming clamps which direct the molten lead around the circumference of the hub joint.

Near dimensionally perfect site-cast exposed soffit and fascia concrete was achieved through precise placement and fitting together of shop-crafted Finnform 12-ply phenolic resin-coated formwork (Figure 13). The finished exterior perimeter totaled 396'-7" (120.879m) of exposed site-cast concrete fascia. A custom double-layer aluminum L-shape coping covered and concealed the terminating edge of the white adhered thermo-ply roof, while also providing a functional protective ledge edge that window washer's rope can safely bend around, all while supporting the weight of personnel.

Figure 9: Forming deep cantilever.

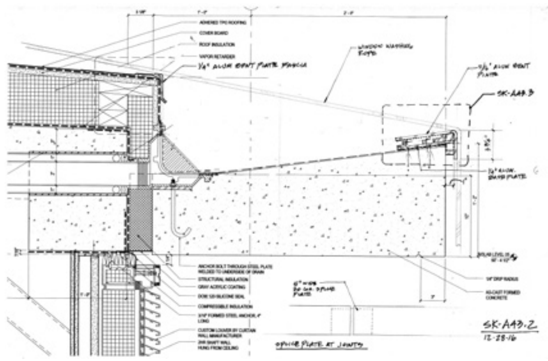

Figure 10: Section through soffit.

Figure 11: Raw concrete ceiling.

Conclusion

In conclusion, the creation of a Tadao Ando designed museum structure, placed in the cold-winter weather environment of Chicago, necessitated an array of complex construction method innovations previously not necessarily utilized in other projects built in more temperate environments. The ability of the Union laborers, general contractor, and Chicago-based architects to work together to search for both technological off-the-shelf manufactured design solutions, coupled with custom installation methodology, yielded a superb set of results heretofore unachieved in concrete in the city. Such collaboration not only satisfied the design architect from afar, but also produced a more talented pool of people with advanced skill sets ready to teach, apply, and create future projects with greater efficiency and efficacy.

Figure 12: Forming soffit drip edge.

Figure 13: As perfect as possible: Flat fascia and cold joint at cantilever.

Figure 14: Tadao Ando visits the IIT wood shop.

Lastly, a greater degree of energy savings was achieved through the incorporation of both long-tested and accepted building technologies (such as window thermal breaks and triple-glazed window units) as well as nascent technologies imported from Europe (the German-made structural thermal break units, originally intended for exposed concrete balcony supports). Innovative hybrid building materials coupled with collaborative and cooperative labor forces, begot the best exposed architectural concrete ever crafted in the city of Chicago. As intended, this structure shall last for generations to come, and also stand as a monument to a higher standard of thermally efficient performance for current and younger generations to learn from. Mr. Ando san himself has had a long history of interacting with collegiate youth enrolled in architecture and engineering programs across the world. He is featured in the photo in Figure 14 visiting the architecture wood shop at the Illinois Institute of Technology to inspect a major student-built large scale model of his Chicago museum project prior to its completion.

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Note: All un-noted photographs were taken by the author, Daniel Joseph Whittaker, on the job site for this project, between summer 2013 and summer 2018, while employed as Owner's Representative for the Wrightwood 659 private art gallery project, designed by Tadao Ando, and built in Lincoln Park, Chicago, Illinois.