

Apple Park Precast – Integrated Architecture, Structure, and Mechanical Services in a Long Span Floor System

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Abstract

The centerpiece of the new Apple Park Campus - the iconic circular office building designed by Foster and Partners and Arup Engineers will be home to 12,000 Apple employees when completed later this year. While famous for its curved glass façade and glass canopy sun blades leading to the “space ship” nickname, the building is thought to be the largest precast concrete framed office building ever built. The signature interior design feature of the building is the precast void slab floor and ceiling system. This system innovatively integrates long-span prestressed concrete elements with exposed honed architectural surfaces, liquid radiant cooling systems, and forced return air plenums, as well as pre-plumbed fire sprinkler lines. This system is a key contributor to sustainable design while also providing a stiff and resilient floor system capable of resisting vertical accelerations in excess of 1g, providing a performance based design level of minimal damage in a 2,500-year seismic event. This paper will highlight the evolution of the system – originating with the desire for simple architectural precast soffits – and culminating into a final solution resulting in a highly prefabricated, long-span floor system, with integrated services.

Introduction

In 2010, Apple CEO Steve Jobs worked closely with Sir Norman Foster and his architects to develop the vision of the new campus (Isaacson, 2011). One of the key interior design features from the beginning was an ultra-white concrete or plaster-like ceiling throughout the building. No acoustic ceilings would be allowed. Once it was decided the final shape of the building would be circular, the design challenge was how to frame the floors with the white soffits. The design team reached out to precasters for a soffit solution and at the time the thought was to place precast panels on shores with anchors protruding out the top into the cast-in-place structural

pour. The soffits would be used as formwork for the field pour. System weight and depth were always a concern, so cast-in-place voided solutions using plastic spherical voids, or foam prismatic voids were also considered. Precast engineers also evaluated creating composite systems with the soffits connected to the bottom of stems of prestressed double tee members.



Figure 1 – Rendering of Apple Park Main Building

Building Configuration

The final configuration of the building resulted in an outside radius of 761 feet and a ring width of approximately 180 feet across. This ring was divided into 104 radial sectors with interior angle of about 3.46 degrees each. These radial sectors were grouped together in 9 radial wings of the building separated by 7 entrances and the cafeteria/restaurant wing itself (Figure 2). With column and wall lines placed on the radial grid lines, this required a floor system that could span up to 45 feet at the outer radius and 35 feet at the inner radius. The building consists of 2 subterranean levels of parking and 4 floors of office space above grade (Figure 3).

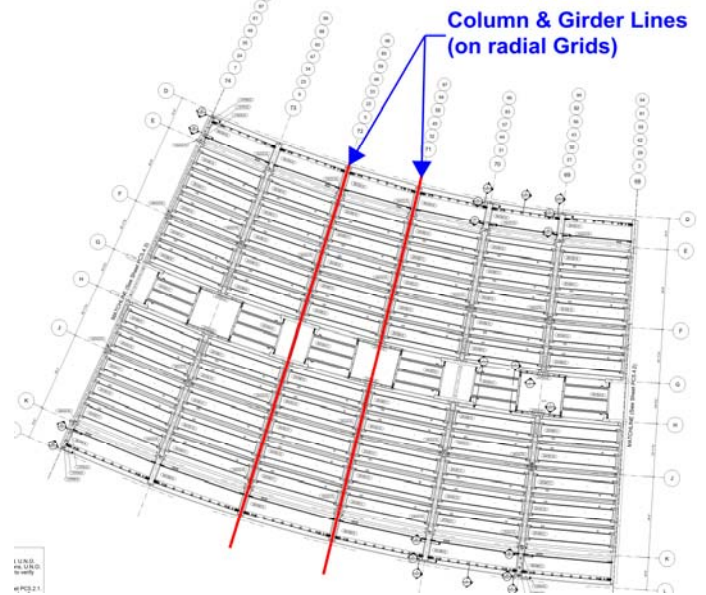
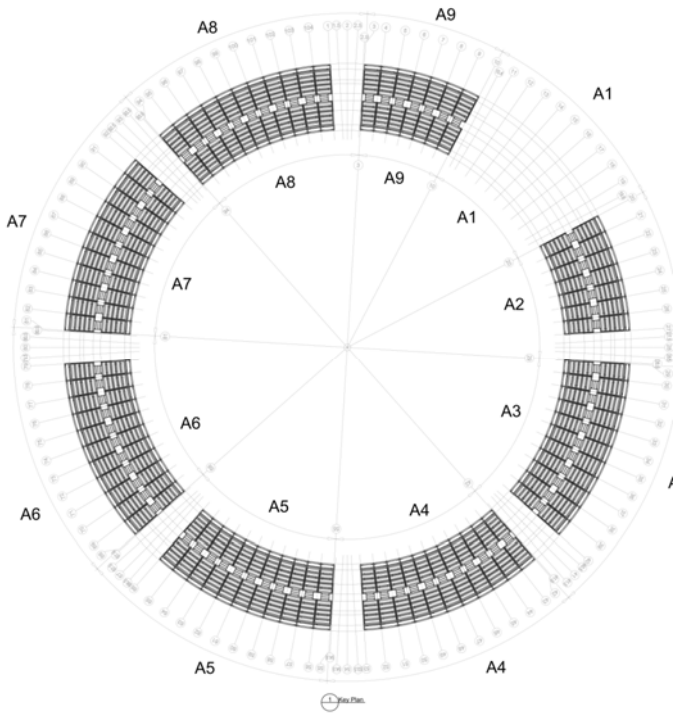


Figure 2A – Building Sector Configuration

Figure 2B – Building Sector Configuration

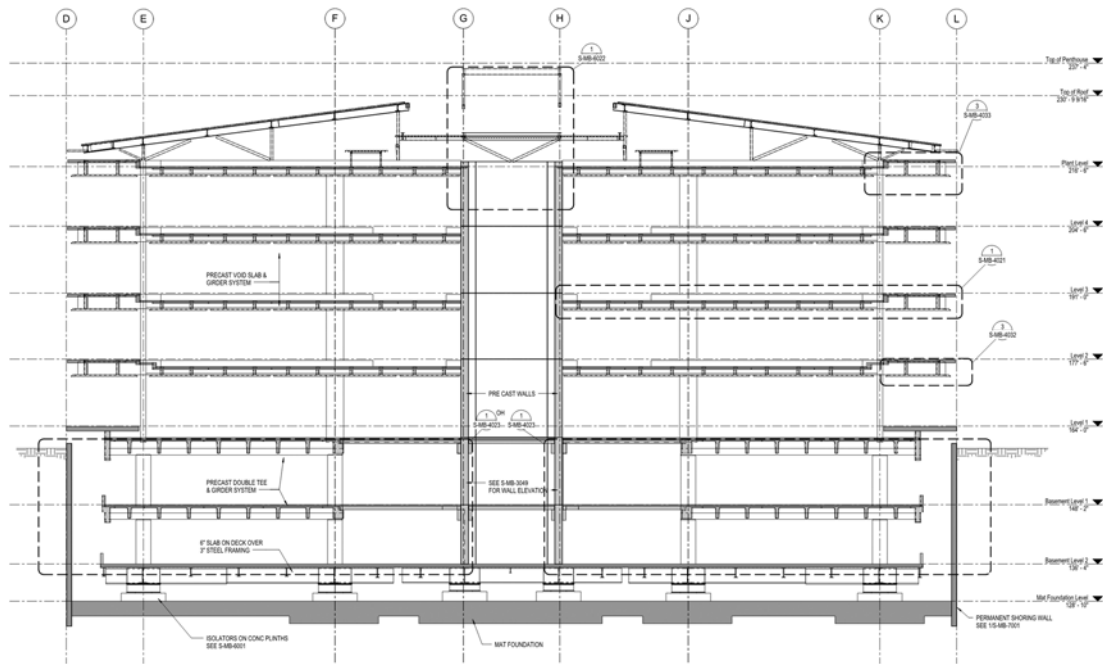


Figure 3 – Building Radial Cross-Section



Structural Challenges

One of the important architectural features of the office space is floor to ceiling glass partitions – with no visible metal trim top or bottom (Figure 5). That necessitated the soffits being the same size as the offices so the glass could recess above the ceiling line. This made a continuous slab spanning from grid to grid an unlikely candidate. Figure 4 depicts a typical cut through the soffits with the offices as square (roughly 12' x 12') off the radial grid lines and the open office space and common areas as wedge shapes in between.

Another key structural challenge was created by the seismic demands of the project. While the building is base isolated with very small horizontal accelerations, the vertical accelerations imposed by the performance requirement were significant. The building is designed above code requirements to a performance level of minimal damage in a 2,500-year return period event. This led to vertical accelerations of 1.2 g's on the floor slabs – and the design requirement that they remain elastic and produce an insignificant amount of non-structural damage. The span lengths of up to 45 feet combined with the mass of the soffits and a floor system depth limit of 24 inches made supporting the concrete soffits a major challenge.

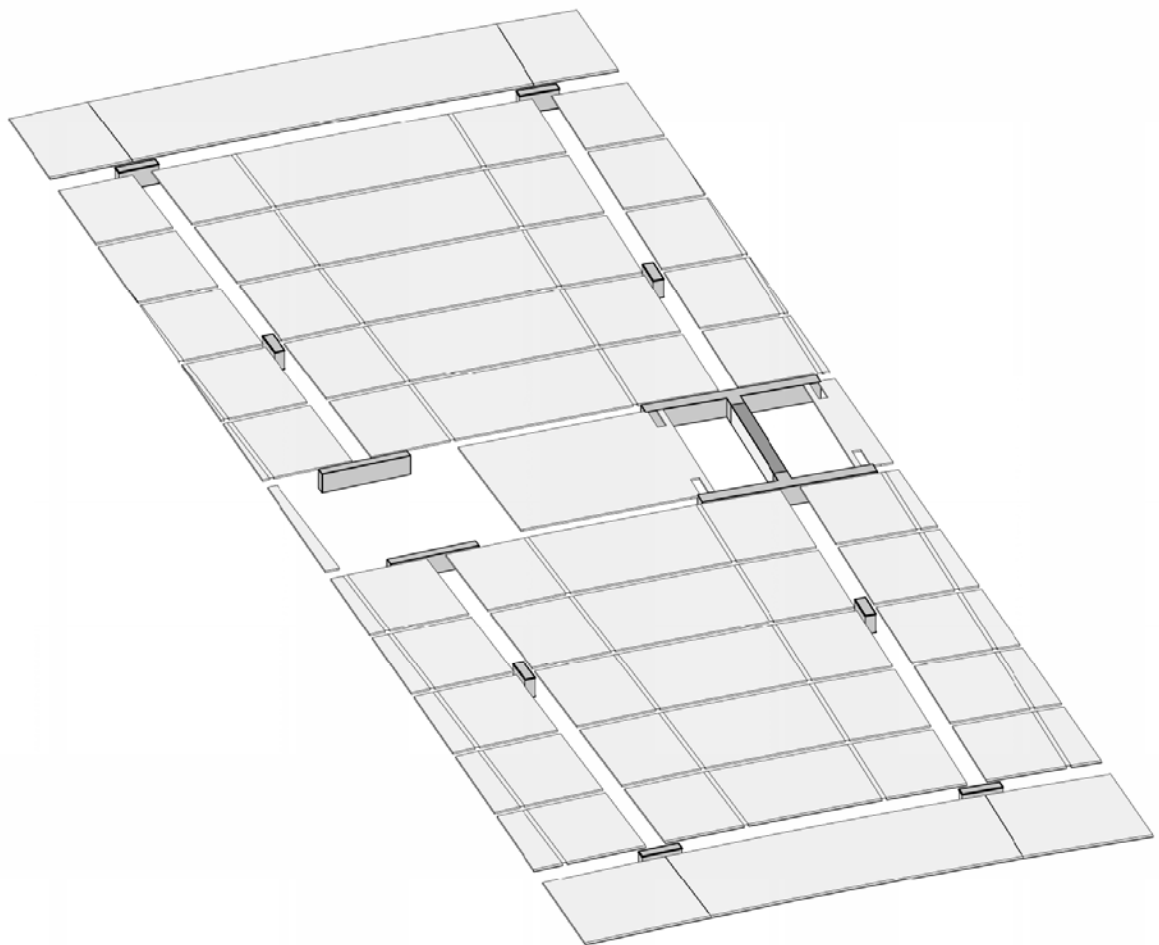


Figure 4 – Cut Through Ceiling Units



The precast double tee solution was proving to be ineffective. The 4-inch-thick concrete ceilings were leading to excessive deflections, while not contributing to the structural performance at all. The cast-in-place solutions were proving to be excessively heavy as well, and steel solutions were too flexible in the allotted space.



Figure 5 – Full Height Glass Partitions

The Void Slab Concept

The desire for the architectural ceilings to remain uncracked and for the members themselves to remain elastic in a 1.2g vertical acceleration event, combined with the narrow envelope of acceptable deflections led to the development of a prestressed long-span unit with a continuous bottom flange. The gross thickness of the flange would be 4 inches, but would be notched down to 1 ½ inches at the glazing tracks to allow a 2 ½ inch recess for partition glazing capture. Numerous early designs and prototypes were created. Figure 6 depicts a rendering of a “Double-I” formation. The top flanges of precast support metal decking and a concrete fill on deck diaphragm. This section was structurally effective, but difficult to form and strip in the precast plant. The final shape is pictured in Figure 7. Figure 8 shows the profile of the unit (with the glazing track notches at about ¼ span). Figure 9 shows the reinforcing/prestressed cross-section.

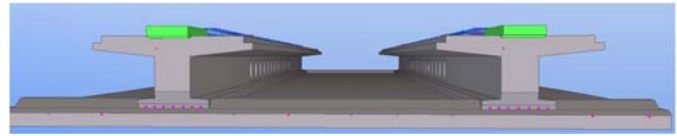


Figure 6 – Early Generation Void Slab

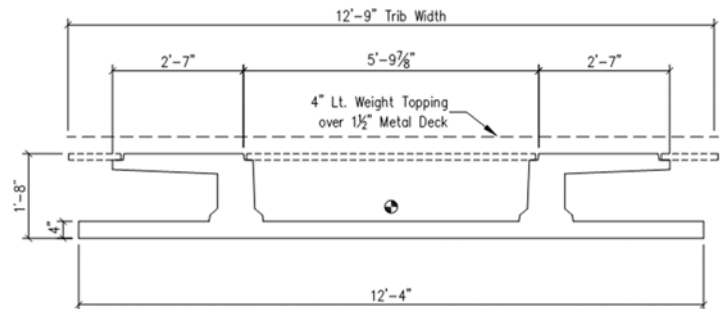


Figure 7 – Final Void Slab Shape

The total precast cross-section allowed the ceiling surface to be utilized as a structural flange in combination with the structural stem units supporting the floor above. This created a much more effective cross-section for both strength and deflection performance. The use of prestressing in the section kept the slabs from cracking under service loads and the limited deflections to at the 1.2g vertical acceleration event. The final design produced floor units with a deflection profile after creep of +1/4” to -1/4” on a 43-foot span. The live load deflections were less than 3/16 inch for the same span, and the seismic deflections at 1.2g were less than 3/4 inch at midspan. The shipped slab units included metal decking pre-installed spanning between the stems, and the narrow deck pieces that connect two units also shipped and hoisted with them. After the decking was complete, a conventionally reinforced 4-inch-thick lightweight concrete diaphragm was poured on top.

The 2 ½ inch deep notches in the flanges created challenges as well. The flanges were prestressed with 14 – ½ inch diameter strands at an elevation of 2 ¾ inch above the finished surface, meaning they touched the tops of the notches. Due to reduced cover, they were not considered effective for strength combinations in a fire. They were considered effective for seismic combinations and deflection considerations. The fire-resistant design relied on additional strands and mild steel up higher in the stems with adequate cover. These notches also created a shear lag effect during prestressing that required additional haunches to get the flange prestressing forces over the notches without inducing



principal axis cracking. Figures 10 and 11 show the FE analysis of stresses in the section due to prestressing.

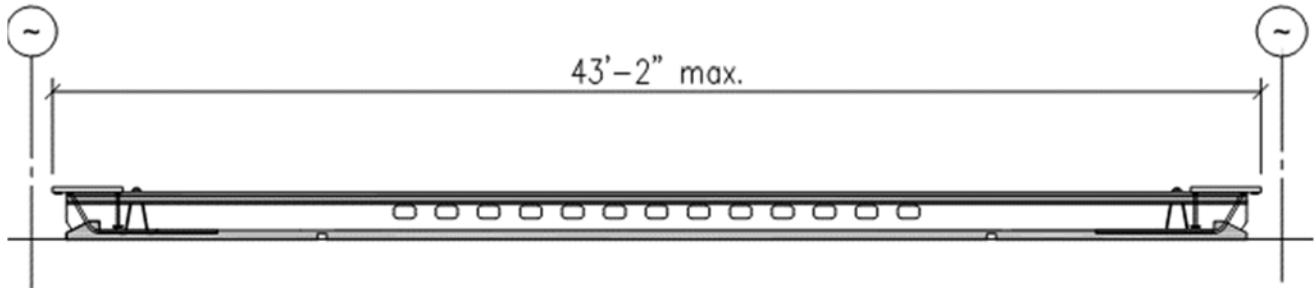


Figure 8 – Profile View of 20-inch Void Slab

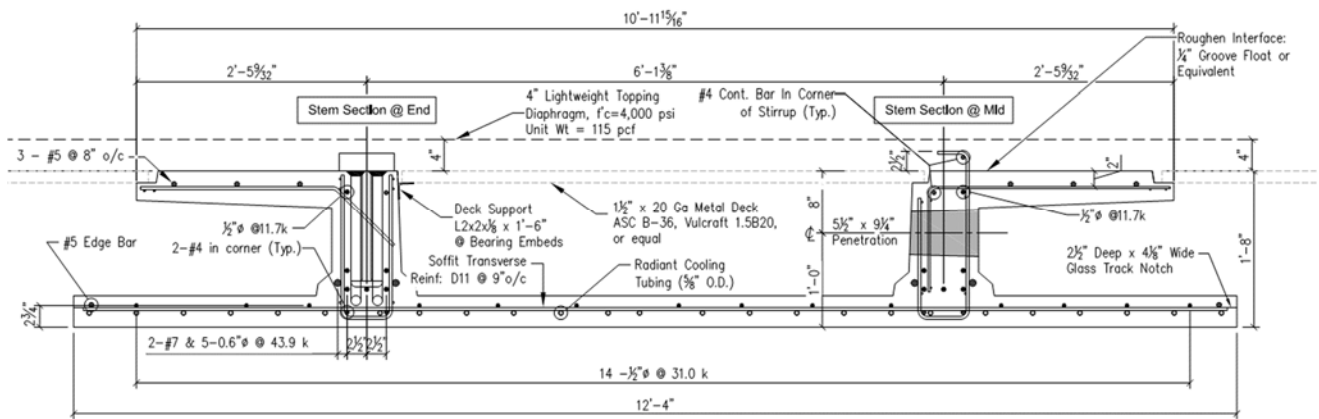


Figure 9 – Reinforcing Details

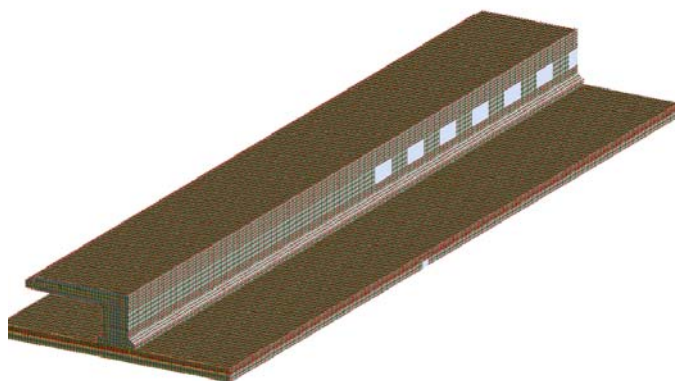


Figure 10 – FE Model of 1/4 Span Element



BOTTOM VIEW - PRINCIPAL NORMAL TENSILE STRESSES FOR SELFWEIGHT + PRESTRESSING (mPa)

Figure 11 – Shear Lag Stresses at Glazing Track due to Prestressing



The FE Analysis of the section accurately predicted hot-spots and local hour-glass patterned cracking that was observed in early prototypes of the slab section due to prestressing forces. The structural shape was improved with buttressing pyramids that allowed the compressive stresses to get over the glass track in a without these stress risers (Figures 12 and 13).

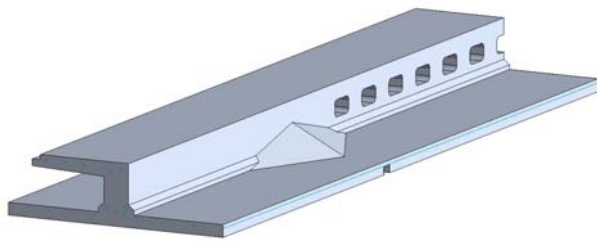


Figure 12 – Improved Shape with Buttressing

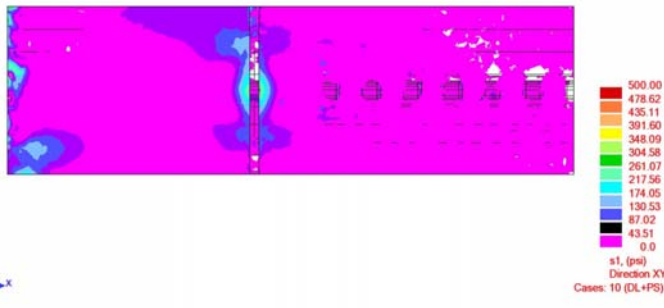


Figure 13 – Buttressed Shape Reduced Stresses

Supporting Girders

With the void slab cross-section and structural member design determined, the end supports of the void slab were all that remained to be solved. The void slabs rest on ledges of precast post-tensioned girders (or on a continuous ledge at the shear wall lines). The support connection chosen was a trussed hanger bar – a rectangular steel bar – (2 ¼ in x 7 in) with welded inclined rebars (2 - #10’s) that transfer the reaction into the stems of the units. The girder and wall ledges were designed for the concentrated reactions (up to 60 kips ultimate per hanger for 1.2g seismic combinations). The soffit space below the girder was shrouded with either an architectural beam cover, or partition framing where walls were placed. The slanted opening of the soffit provided space for return air flow up into the plenum (see section on mechanical services) as well as a place to mount lighting. The girders were arranged with 2 interior spans of 25’ and 39’ and a 15’-6” cantilever supporting the inner and outer

ring corridor void slabs. The heavy load on the girders required a 35-inch depth. This was achieved in the 42-inch floor system by allowing the stem of the girder to protrude up into the raised access floor area. The girders were reinforced with mild steel and post-tensioned in the precast yard with a draped profile of 19 x 0.6” diameter strands. The diaphragm was placed at the top of the void slabs and made continuous through them by way of Type 2 threaded rebar couplers. See Figure 14 for a cross-section through the girder.

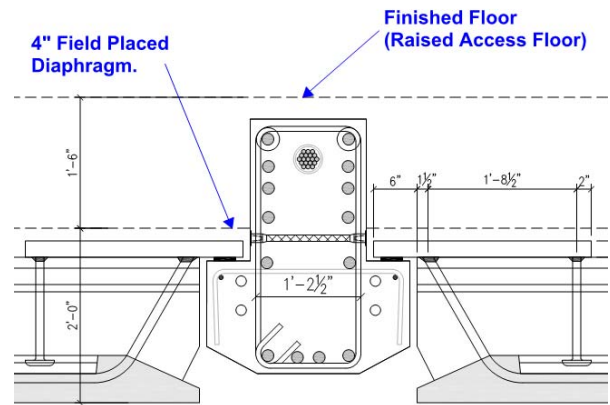


Figure 14 – Inverted Tee Girder Section

These girders repeated themselves at every interior radial grid line. And at every other grid, they aligned with an I-Shaped Core shear wall. In those locations, the girders also had to perform as collector elements, delivering more than 400 kips of force to the shear walls. This was achieved by doweling 4 - #14 bars into the girders and having them protrude into the stem of the shear walls (then cast in the field). Figure 15 depicts a diagram of the connection. The tied section in the diagram is the precast “stem” of the I-Wall.

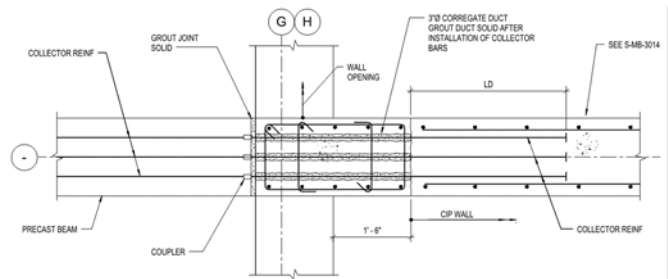


Figure 15 – Collector Beam to Shear Wall Connection



Figure 20– White Dolomite Aggregate



Figure 23– Vacuum Lift of Inverted Void Slab



Figure 21– Soffit Pour – SCC White Concrete



Figure 24– Honing of Void Slab

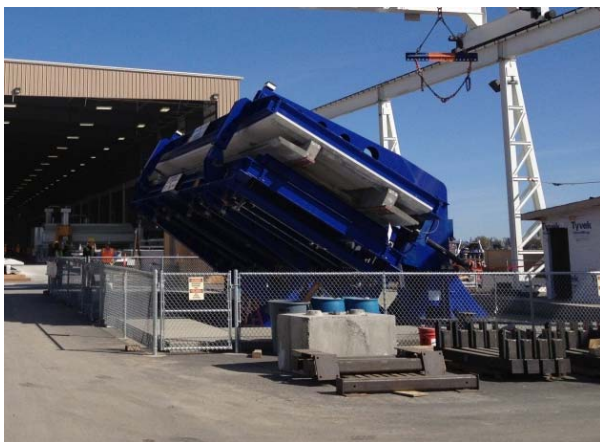


Figure 22– Flipping Table Inverting Slab



Figure 25– Honing of Void Slab



Integration of Services and Prefabrication

While limited floor system depth often challenges the structural engineer, the same held true on this project for the mechanical engineer. With mechanical, electrical, plumbing, and network services all slated for the 18-inch access floor space – and the ceilings thought to be inaccessible due to the solid ceiling slab, space became very tight for those services.

The first step in solving the “mechanical problem” was to reduce the forced air duct requirements by utilizing the thermal mass of the concrete and providing a radiant cooling system in the ceiling. This was achieved by placing coiled loops of chilled water PEX tubing into the soffits (Figure 26 and 27) and daylighting them in manifolds that would be accessible in the above the floor slab. The tubing was set up in circuits that coordinated with different climate control zones and thus did not have to pass over the 2 ½ inch glazing track notches. With 4 inches of section to work with, the tubing fit easily with the soffit reinforcing and prestressing. The chilled water radiant ceilings dramatically reduced the HVAC demands, but space was still limited.



Figure 26 – PEX Tubing being Tied to Soffit Cage



Figure 27 – PEX Tubing in Precast Form

Next, the mechanical engineering team asked if it would be feasible to utilize the void-space in the ceilings as a return air plenum, essentially re-capturing this space for mechanical use. To do this, the void slabs needed to have perforated stems so air could move radially through the soffit space to return air registers. The void slab units were updated with stem penetrations in the middle section of the span. See architectural floor section rendering in Figure 28.



Figure 28 – Floor Section Rendering

In addition to mechanical coordination, the perimeter void slabs were highly coordinated with other trades. The signature exterior feature of the building is the 10-foot cantilevered opaque glass and aluminum canopy blade system. These blades were connected to the 36-inch-deep perimeter void slabs at about 4’-6” on center. To facilitate construction and promote prefabrication, not only the embeds for the brackets were installed off site, but also the brackets themselves. The plumbing for the mist sprinkler system was pre-installed in these units as well (Figure 31). And lastly, the perimeter metal edge deck form and temporary handrail were also pre-installed off site. Prefabricating these activities off-site dramatically reduced on-site labor and equipment.

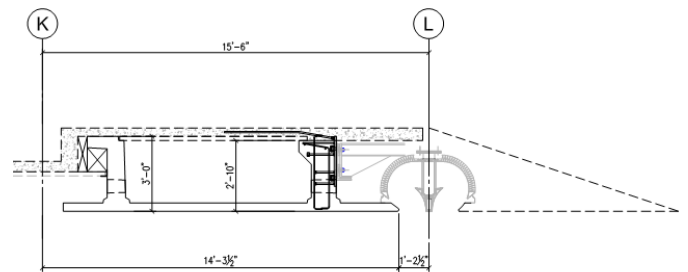


Figure 29 – Perimeter Void Slab Canopy Blade Section



Figure 30 – Void Slab Hoisting with Pre-Installed Canopy Blade Brackets, Handrail, and Edge Form



Figure 31 – Mist Sprinkler Plumbing Pre-Installed

Systems Integrated:

- Structure
- Architectural Ceiling
- HVAC
- Radiant Cooling
- Electrical
- Fire Sprinklers
- Glazing System & Shading Blade Support
- CIP Metal Decking & Edge Form
- Temporary Handrail

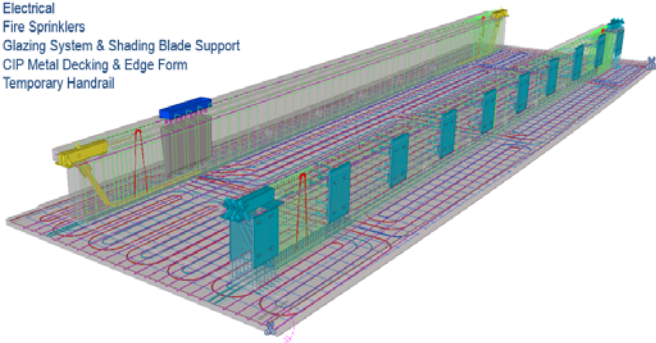


Figure 32 – List of Integrated Systems in Void Slabs

Virtual Design and Fabrication Level Modeling

The high level of complexity and need for cross-disciplinary coordination really made building information modeling a necessity for success. But the level of modeling required was much higher than the old standard of mass modeling and clash detection. There were simply too many systems being integrated to make use of a crude level of modeling. At the precast end alone the following partial list of benefits of modeling were realized:

- Project and piece metrics/costs (concrete volumes, steel tonnage, bills of material, construction progress)
- Project documentation (RFI tracking by model piece, RFID tagging of members)
- Parametric real time piece drawing updates
- Digital Prototyping of Fabrications – saving thousands of man hours in production to solve in-element clashes and congestion. (Figure 33)
- Creation of Exploded View Work Instruction Drawings (Figure 34)
- CNC data exports for fabrication – rebar bending, CNC and Plasma cut steel plate and members. (Figure 35)
- 3D Total Station Layout Control for Erection (Figure 36)
- Documentation in Plan Grid of inspectable items – welding, grouting, patching, inspection check-offs, and as-built modifications.
- Creation of jigs and construction aids. For instance, the modeling of PEX tubing led to the CNC routing of the large PVC jigs used to run the tubing. (Figure 26).
- 3D Tablet based models in the factory.

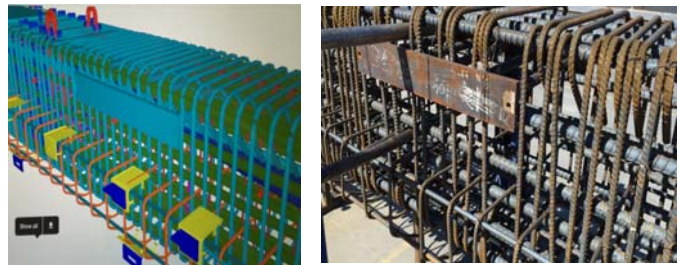


Figure 33 – Digital Prototyping of Complicated Work



Figure 38 – Erected Void Slabs

Conclusion

Over 4,000 of these highly-complicated void slabs were constructed to make up the signature interior feature of this iconic building. Another 10,000 pieces of structural precast elements comprised the frame of the building. This monumental building project redefined how multiple phases of design and construction can occur and interact. Through cross-disciplinary design and the motivation to premanufacture complicated elements and systems off-site, the complete integration of architecture, structure, and mechanical services in building elements was realized.

Complex systems were modeled and coordinated using BIM tools and fabrication level detailing directly from the models was leveraged to produce true parametric drawings, metrics, data, and CNC inputs for fabrication. Thousands of construction man-hours were moved off the job site and into plants – increasing safety performance and reducing job-site congestion. The Apple Park Office building is a monumental and unique building. It demanded just as monumental and unique changes in design and construction as well.



Figure 39 – Apple Park Nearing Completion

References

Isaacson, W., *Steve Jobs*, 2011, pp. 534 to 537, Simon & Schuster, New York, NY

Foster + Partners, *Apple Campus 2 Design Drawings*, 2013, Foster + Partners, London UK. (Figures 1, 28).

ARUP, *Apple Campus 2 Design Drawings*, 2013. ARUP, San Francisco, CA (Figures 3, 4, 15, 17).