



# FLAT PLATE CONCRETE CONSTRUCTION

A New Milestone for High-Rise Buildings

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**B**y re-examining standards long taken for granted by developers, 350 Mission received LEED® Platinum certification and is reinventing a ubiquitous building type. The form, structure, and systems of this Class-A office tower are generated by rigorous goals of environmental performance, social engagement, and material efficiency.

The 30-story volume embodies the higher workforce densities and flexible space planning of 21<sup>st</sup>-century offices, thanks to floor plates that span nearly 45 feet between core and perimeter. 350 Mission achieves a new paradigm for office tower structures by utilizing post-tensioned long-span flat concrete slabs, a method traditionally reserved for residential construction. The innovative structure lifts the first office floor to create a transparent 50-foot-tall by 43-foot-deep lobby, dubbed the “urban living room.” Energized by a 70- by 40-foot LED screen, the generous public space has 90 linear feet of glass panels that slide open to the sidewalk and blur the threshold between public and private realms.

## Performance-Based Seismic Design

Dual seismic force resisting systems are required by ASCE 7 for buildings over 240 feet unless appropriate justification is provided. Administration Bulletin 82 and 83 of the *San Francisco Building Code* prescribe the design and peer review process needed to demonstrate code-equivalence of the core-only seismic force resisting system. This performance-based seismic design approach permits the core-only seismic force resisting system and avoids traditional dual systems which often include costly moment frames.

The latest advances in nonlinear time history analysis, seismic design methods, and reinforcement detailing were incorporated into this project, drawing upon the knowledge and experience of the city-appointed seismic design review panel. All gravity framing members and their associated effects on building performance, including P-delta effects and nonlinear behavior, were modeled. Due to the potential interaction of the slabs on the gravity columns and their cumulative effect on the tall lobby condition, this was vital. Additionally, ground

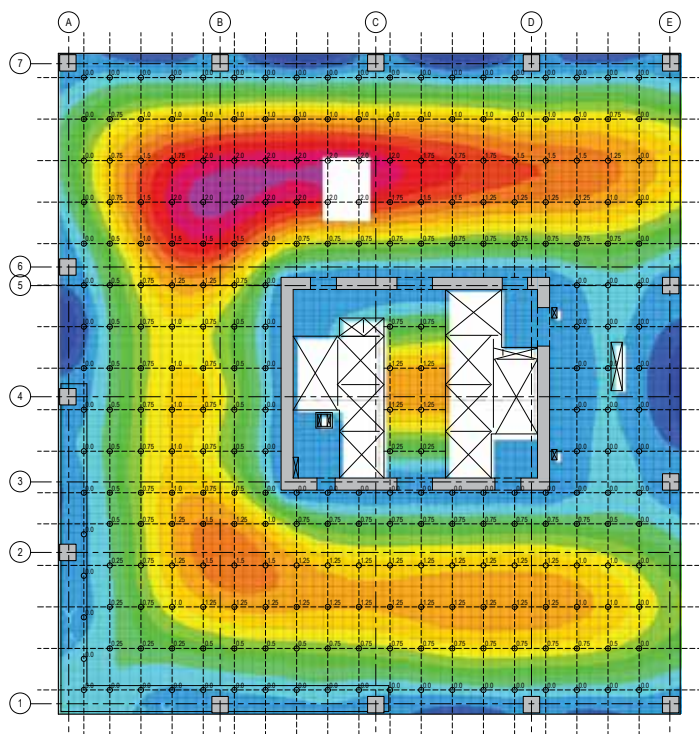
floor and all basement diaphragms were modeled with shell elements, as the ramp and basement levels are sloped in a ‘corkscrew’ basement.

## Long-Span Flat Plate Slab Design

A flat plate solution using conventional practices would need to be at least 14 inches thick, with very high quantities of post-tensioning and reinforcement. To reduce the slab thickness to 11 inches and post-tensioning quantities to levels commonly associated with 30-foot residential spans, a cambered solution was proposed in tandem with the post-tensioning system. The primary purpose of the post-tensioning system is to counteract a large portion of the slab self-weight while mitigating flexural cracking. Due to the magnitude of the span and modest post-tensioning, elastic and inelastic creep deflection of the slab, up to 2.5 inches, was anticipated. This would not be acceptable for non-structural components such as partitions and could be visually perceivable in an exposed ceiling condition. Thus, a digitally mapped camber plan and camber values for individual shoring posts were developed with the collaboration of the concrete contractor. Changes in camber slope were also coordinated with the concrete contractor, Webcor Concrete, to ensure the specified geometry could be achieved without significant changes in labor. The direct collaboration of the structural design team with all concrete field superintendents, including those responsible for shoring, forming, placement, and finishing, were vital.

Conventional 5,000 psi concrete was utilized along with A615 Gr. 60 reinforcement for both the post-tensioned floor slabs and in non-cambered, mild-reinforced below-grade slabs. Average compressive strength determined in cylinder testing from the below-grade slabs was to be 7,200 psi. The high strength was due to contractor requirements for early strength to tension tendons to keep the project on schedule. Thus, the camber of above-grade decks was adjusted using this more accurate concrete strength.

Two comprehensive analytical investigations were conducted in parallel using separate software packages to ensure both strength and serviceability were satisfied. The primary software used for



Chamber overlay diagram.

analysis was SAFE® by Computers and Structures, Inc., while a checking analysis model was built in ADAPT Floor® by ADAPT Inc. Both analysis tools calculated cracked section properties based on actual rebar placement for increased accuracy. With the incorporation of camber, post-tensioning material quantities were competitive with shorted 30-foot spans often encountered in high-rise residential towers.

For calculation of long-term deflection, methods recommended by ACI Committee 435 in ACI 435R-95, *Control of Deflection in Concrete Structures*, were utilized. As noted in the ACI 435 document, methods recommended by Graham and Scanlon (1986) are appropriate where stiff lateral systems such as shear walls are utilized. The concrete modulus of rupture is lowered from  $7.5\sqrt{f'_c}$  to  $4\sqrt{f'_c}$  for calculation of cracked section properties. Also, the computed deflections using cracked section properties are amplified by a factor of 3.5 to determine the total long-term deflection.

While both analysis models could amplify ACI 435 recommend values of cracked section deflections, SAFE was found to be more accurate with its age-adjusted modulus of elasticity method which accounts for long-term creep and shrinkage based on methods suggested by ACI 209.

Although recommendations of ACI 318 for the modulus of rupture ( $7.5\sqrt{f'_c}$ ) and long-term deflection multipliers (3.0) are appropriate when compared to laboratory testing, they do not account for critical construction effects such as early shrinkage cracking due to restraint and early loading of the concrete when shoring is removed. It is highly recommended that appropriate provisions be made in ACI 318 to give guidance to structural engineers designing concrete gravity framing which more appropriately addresses these important issues, and that practicing engineers consider this during design.

Slabs are engineered to be flat and to deflect no more than  $\frac{3}{4}$  inch between the core and perimeter 90 days after casting when raised flooring is to be installed. The  $\frac{3}{4}$ -inch deflection limit is important as that is the maximum deflection a standard partition slip track can accommodate. Slab elevations were surveyed at casting, as well as 30,



Exterior at night.

60, and 90 days afterward. The tracking of deflections was determined to be very close to analysis model predictions, which incorporated a novel iterative cracked section analysis procedure recommended by the ACI 435 committee and creep and shrinkage methods recommended by the ACI 209 committee. This design, with contractor collaboration, has set a new standard in office buildings and created a new efficient architecture which gives further enhancement to core-only tall buildings.

An important feature of the concrete framing design is a dramatic 30-foot corner cantilever achieved with a 25-inch deep post-tensioned upturned beam. The upturn is concealed in a raised floor system which permitted underfloor mechanical air circulation, electrical conduits, and plumbing lines. Thus, the underside of the slab is kept free of these visual hindrances. The corner post-tensioned beam has a unique tendon profile that differs from conventional post-tensioned layouts. Instead of starting high at the support and draping linearly to mid-depth at the cantilever tip, it has a slight parabolic drape between the two ends. This was incorporated to avoid sagging at the cantilever mid-span which can occur in very long cantilever conditions.

In elevation, the tower superstructure appears as 11-inch plates. The depth of similarly performing steel or waffle-slab construction would measure nearly 3 feet. If the concrete slabs remain exposed overhead, then the typical office floor will reach over 11 feet high, a dramatic increase from the 9-foot heights traditionally associated with Class-A office buildings. Using ultra-thin concrete instead of steel maximizes perimeter glass, achieves more daylight, and supports energy efficient HVAC systems.

## Innovative Multi-Story Construction Methods

Construction methodologies were coordinated among the concrete, rebar, post-tensioning crews, and the place and finish crews. Handset Pro-Shore formwork was used to achieve non-traditional camber profiles and reduce the floor-to-floor cycle from 7 to 5 days. The design team met with the crew superintendents to ensure a full





*Lobby.*



*Lobby at night.*

understanding of the design intent was conveyed and to receive feedback on improving the specified camber profiles and post-tension layout. The steps required to achieve the soffit profile, before concrete placement, included:

- 1) Measure deflection of lowest reshored level during placement;
- 2) Measure shortening of formwork system during placement;
- 3) Interpolate values based upon shore location relative to supports;
- 4) Agree upon method of strike-off (screeding) during concrete placement;
- 5) Add deflection plus formwork shortening to specified camber values; and
- 6) Survey and record deck soffit formwork elevations before placement.

There were preliminary and follow-up discussions regarding what placement methods would be best for providing the indicated camber at the tops of the slabs. Since concrete placement strike-off is done with straight edges, the resulting camber is initially corded. Ordinarily, on flat building slabs, strike-off is done with screeds measuring up to 20 feet long. After consideration of both production requirements and the required surface geometry, it was decided by the contractor and engineer that the maximum screed length would be 10 feet. The direction of screeding was also discussed and agreement made on a standard direction. During the first placement, an additional observation was that ride-on trowel machines, using float pans, had the effect of planing or leveling the surface, which reduces camber. From this point forward, neither ride-on machines nor float pans were used. The camber profile was finished by using walk-behind trowel machines with combination blades. In addition to setting top profiles with a laser level, both 10-foot screeds and the use of walk-behind machines contributed in producing the required camber tolerances at the tops of the slabs.

The ongoing process of taking measurements before and after each placement provided necessary feedback to the formwork and placing crews of where the processes needed fine-tuning and helped to keep the quality consistent. Top-of-slab elevation surveys were made at specific locations, relative to Project control, so that they could be exactly repeated for future monitoring.

The result was a design and construction methodology that could be applied to other multi-story buildings. Understanding long-term slab deflection characteristics, monitoring as-built tolerances, and incorporating predicted slab performance characteristics into the design of architectural finishes and work scopes after concrete placement and finishing, aligns expectations through both the design and construction processes.

## Field Verified Embodied Carbon

The Environmental Analysis Tool™ is an embodied carbon accounting methodology and software published as a free download by SOM at [www.som.com](http://www.som.com). The EA Tool considers embodied carbon from materials, construction activities, and probable seismic damage. Embodied carbon accounting metrics were used in all design decisions and led to an efficient design employing the use of recycled materials. During construction, engineers made weekly site visits, creating detailed reports of all construction activity and equipment used. This information, as well as actual material information, was used to adjust and validate embodied carbon accounting associated with structural materials and construction activity from the beginning of excavation through topping out. Results reveal the EA Tool methodologies are quite accurate, especially for above-grade work. Results also indicate that below-grade work is very carbon intensive, more than twice that of above-grade work.

## Performance

Performance is often quantified, but not often proven. For 350 Mission, seismic performance has been validated through nonlinear time history analysis, cambered slab deflection analyses have been proven through numerous surveys, and embodied carbon associated with materials and construction activity has been verified through field observations. This assurance in performance is important to advance design techniques towards a new standard in building construction and design methodologies. ■



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