

Salesforce Tower



NEW BENCHMARKS IN HIGH-RISE SEISMIC SAFETY

When completed in 2017, Salesforce Tower will be the tallest building in San Francisco at a height of 1,070 feet (901 feet to the top occupied floor). This super-tall building advances the state-of-the-art of high-rise seismic design through implementation of a number of first-ever design and analysis methods that push limits and set new industry benchmarks. The structural innovations required to create this record-setting, city-defining tower address enhanced performance objectives, foundation challenges, and interactions with adjacent buildings... issues applicable both to this building and future tall buildings in areas of high seismicity.

Reshaping the Skyline... Redefining the Future

In the 1980s, the City of San Francisco enacted policies restricting high-rise development, ultimately creating a skyline that “plateaus” at 500 to 600 feet – the historical maximum zoned heights (*Figure 1*). The restrictions also limited the city’s annual allotment of space for new office development. These limitations were implemented during an anti-growth era sweeping the nation in the 1980s, fueled by fears of overcrowding and inadequate city infrastructure.

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Figure 1. San Francisco Skyline – Pre-Transbay District.

When studies confirmed that job centralization in a sustainable, transit-oriented downtown core was critical to San Francisco's continued economic success, a new Transit Center District Plan was developed for a 16-block area referred to as the Transbay District. The plan called for a new Transbay Transit Center to co-locate eleven Bay Area transit systems and related surrounding development. The plan also designated a new zoning district around the Transbay Transit Center, reclassifying parcels to allow buildings from 600 to 850 feet tall versus the existing 500-foot cap. Through this plan, the City sought the development of office and residential buildings that were taller and more densely occupied to spur job and population centralization. The plan also targeted the creation of a "new, sculpted skyline formed by height increased immediately around the Transit Center" to mark the importance of the location and provide a new, vibrant image for San Francisco. To that end, the 50,515-square-foot site bounded by First and Fremont Streets, fronting Mission Street to the north and directly adjacent to the new Transit Center, was designated as the location for the area's tallest building. At the new 1,070-foot height limit, the record-making building would serve as a beacon for the revitalized area (*Figure 2*).

To help fund the new Transit Center, the rights to entitle and purchase the highly desirable "tallest building" site were awarded through a 2007 global invitation-only design competition sponsored by the Transbay Joint Powers Authority, a public entity created to develop the Center. The winning proposal was submitted by Hines, an international development firm, teamed with Pelli Clarke Pelli Architects. (Developer Boston Properties subsequently acquired 95% of Hines' stake in 2013.)

The team envisioned an iconic 61-story, high-density, sustainable office tower totaling 1.5 million square feet (and ultimately named "Salesforce Tower" for its primary tenant). Above the 26th floor, each elevation of Salesforce Tower curves and tapers away from the street, creating a narrow, slender top finished with a "sculptural crown". The crown, designed as an unenclosed latticework of structure, continues the expression of metal wrapping the occupied floors of the tower below and contributes to the slender proportions and total height of the building form. The building's curvature also reduces the apparent height and massing of the building when viewed by pedestrians immediately below.

Within the larger context of San Francisco's future skyline created by the increased building heights in the TCDP area, Salesforce Tower will be the tallest point, marking the significance of the adjacent Transit Center. Construction started in 2013, with completion expected in 2017.

New Benchmarks in Seismic Safety

Given the scale of Salesforce Tower, the calculated number of building occupants will far exceed the building code threshold of 5,000 people, triggering the building's consideration under Occupancy [or Risk] Category III. Category III buildings require additional safety for wind and seismic demands, thus prompting new challenges for the engineering team.

Traditional structural design methods adopt an "enhanced strength" approach when attempting to improve seismic safety and performance. This approach, while easy to implement by applying code-defined seismic forces that have been amplified by an Importance Factor (1.25 for Category III buildings), fails to ensure enhanced building performance when subjected to extreme seismic ground shaking. In fact, in the context of the historical seismic design philosophy of ductility and energy absorption, enhanced strength may, in fact, be detrimental to building performance. Stronger buildings *resist* more force rather than *absorbing* the energy of the ground's shaking. In resisting these higher forces, shear stresses and foundation demands increase to undesirable levels and building performance can be compromised. Instead, a rigorous Performance-Based Seismic Design (PBSD) approach was implemented to allow for, quantify, and control desired building performance at an enhanced level compared to other commercial office buildings.

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Figure 2. San Francisco Transbay District. Courtesy of Foster + Partners.

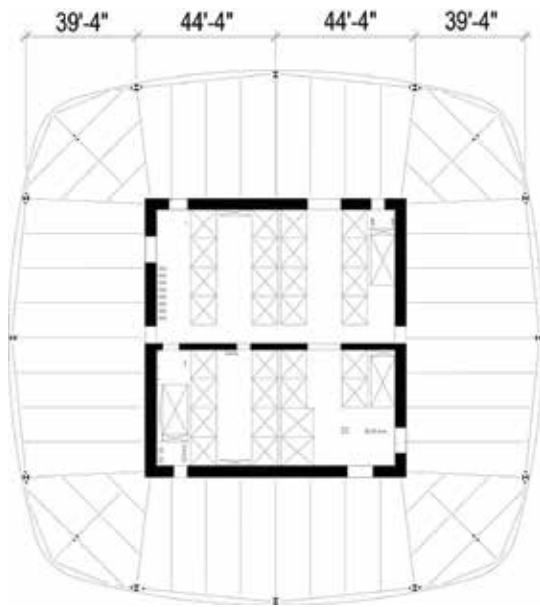


Figure 3. Typical low-rise structural floor plan.

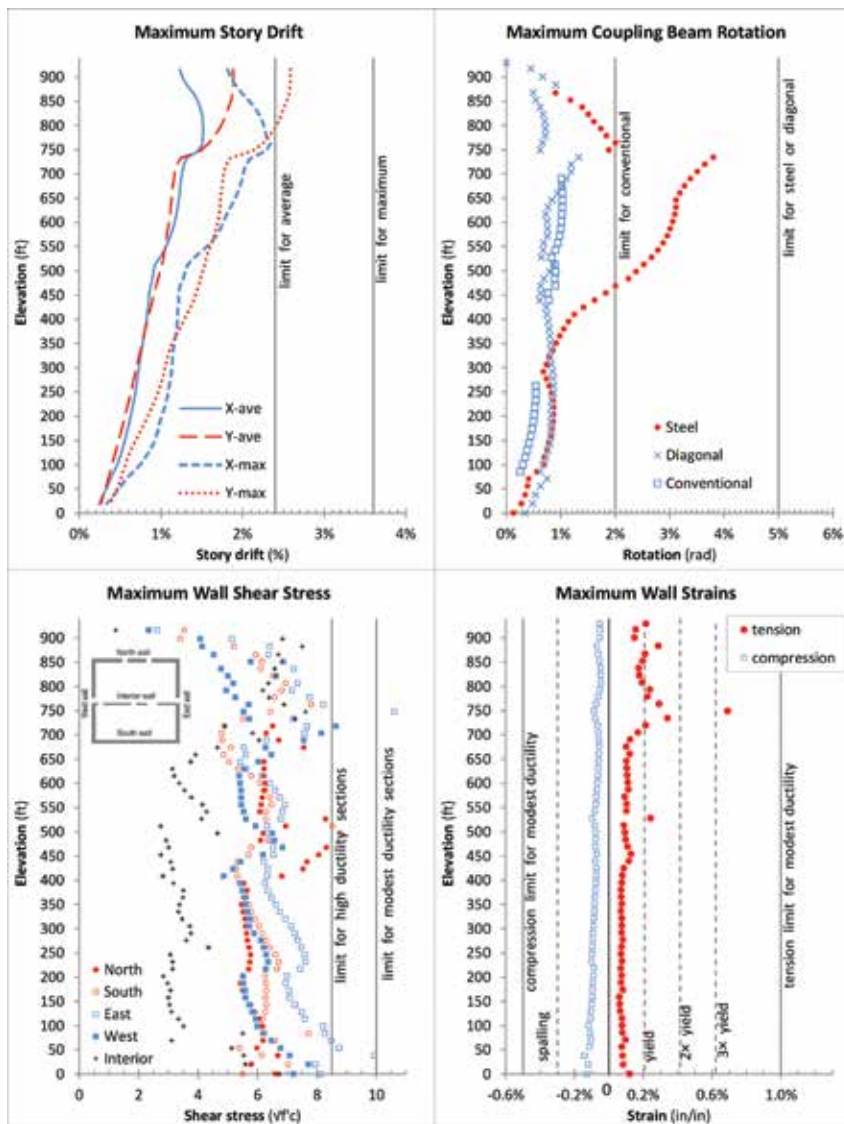


Figure 4. Confirmation of Salesforce Tower's enhanced performance.

The project's structural engineer, Magnusson Klemencic Associates (MKA), brought to the project decades of leadership in seismic design in San Francisco, including multiple high-rise towers. The firm also led the development and U.S. adoption of PBSD for high-rise buildings, a methodology that produces buildings that are safer and perform more predictably and reliably than buildings designed following a prescriptive code-based approach.

PBSD uses sophisticated nonlinear seismic time-history computer modeling – practical only in recent years thanks to advancements in computing capacity and user-friendly analysis programs – to examine building performance during multiple predicted seismic events. With PBSD, engineers can analyze complex and unique building geometries then precisely allocate appropriate strength and stiffness to achieve an efficient design that meets the desired performance objectives. PBSD methodology not only meets the intent of the building code but explicitly considers and quantifies predicted building performance under multiple ground-shaking scenarios. This explicit examination of building behavior provided through nonlinear time-history analysis, coupled with the application of enhanced performance standards, produces a safer, more reliable building.

MKA had already designed five PBSD high-rise buildings in San Francisco, but none that targeted the more stringent Occupancy Category III performance objective. Because PBSD is a relatively new and complex approach, building departments require that such designs be peer reviewed by a second engineering

team to verify that building performance meets code intent. This peer review process has been instrumental in the understanding, advancement, and acceptance of PBSD methodologies throughout the industry, as code-prescriptive intent becomes successfully “translated” into approved performance-based designs. After assessing the more stringent Category III code-defined performance objective, and evaluating that intent and application relative to PBSD methodology, the design team targeted a reduction to 6% (from 10%) of the probability of collapse under a Maximum Considered Earthquake (MCE) ground shaking. This is consistent with ASCE 7 *Commentary* related to Occupancy Category III buildings.

As stated in the ASCE 7 *Commentary*, the performance objective for Occupancy Category III structures is to “reduce the hazard to human life in the event of failure,” which relates most closely to a code-defined performance of Collapse Prevention with MCE shaking. The structural design of Salesforce Tower includes more stringent Acceptance Criteria for MCE shaking as explicit performance objectives, including the following:

- Reduced story drift
- Reduced coupling beam rotations
- Reduced tensile/compressive strains in shear walls
- Reduced shear demands on shear walls
- Risk Category II acceptance criterion was typically modified to be more stringent by applying a factor of 0.8

The detailed Acceptance Criteria used for the design of Salesforce Tower is shown in *Table 1*.

The structural system features a gravity load-resisting system with structural steel columns and floor framing supporting steel composite deck. The building's seismic force-resisting system comprises special reinforced concrete shear walls, 24 to 48 inches thick, at the central elevator and stair core. Since the vertical elements of the tower's seismic force-resisting system include

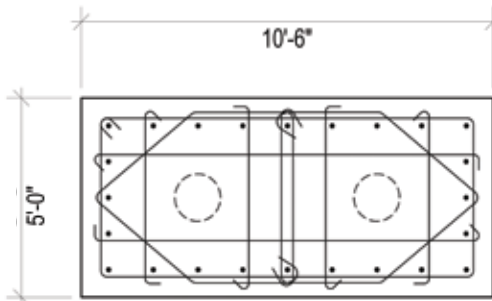


Figure 5. Typical LBE rebar detailing.

only shear walls (Figure 3), the City of San Francisco's Administrative Bulletin 083 (AB-083), *Requirements and Guidelines for the Seismic Design of New Tall Buildings using Non-Prescriptive*

Seismic-Design Procedures, applied. In addition to technical provisions, AB-083 called for a structural design review by a panel of independent experts. The four-member panel assembled for the detailed review of the analysis and design of Salesforce Tower included two practicing engineers, a research professor, and a geotechnical/seismic ground motion expert.

Although wind-loading conditions for the building are not trivial, wind tunnel testing confirmed that demand levels fell below seismic demands, and that occupant comfort standards would be met as judged against international standards. The lateral design of Salesforce Tower was driven by seismic loading conditions for three levels of ground shaking:

- Elastic performance targeted for service-level shaking (with a mean recurrence interval of 43 years)
- Moderate structural damage expected for design-level shaking (taken as two-thirds of code-defined MCE shaking)
- Collapse prevention, with a reduced probability of collapse consistent with Occupancy Category III, targeted for MCE shaking

The nonlinear time-history analyses used to confirm the structural response to MCE shaking employed two suites of 11 pairs of acceleration history. Two suites of ground motions were developed considering a Conditional Mean Spectra approach, targeting the first and second modes of vibration of the tower. This approach was deemed to more rigorously and appropriately test the building's design, given the importance of the tower's second-mode-of-vibration response. The suites were developed by performing three-dimensional, nonlinear site response analyses using input rock motions that were selected, scaled, and matched for Conditional Mean Spectra spanning the period range of interest from approximately 0.5 seconds to 9.0 seconds. One suite was conditioned to represent long-period motions, for which 8 of 11 motions include pulse effects. The other suite was conditioned to represent shorter period motions, for which 2 of 11 motions include pulse effects. Pulse effects were considered particularly important for this building given the proximity to the San Andreas Fault. The result-

ing acceleration histories, taken at the foundation level instead of the more traditional ground surface level, include kinematic soil-structure interaction effects due to base-slab averaging and embedment. A scale factor for each suite of motions was applied so that the corresponding linear response spectra satisfy the requirements of the building code.

The results of these 22 earthquake simulations were evaluated and compared against the targeted Acceptance Criteria. Where predicted demand levels exceeded Acceptance Criteria, design modifications were implemented. In particular, core wall thicknesses were tuned to reduce and control shear demands within acceptable limits at the tower's base and the location of a core setback at Level 50. Ultimately, it was demonstrated that all Acceptance Criteria had been achieved, and the building's enhanced performance was confirmed. As shown in Figure 4, story drifts and coupling beam rotations typically fall well within acceptable limits, wall shear demands remain elastic, and vertical wall strains are quite modest with only limited yielding predicted.

San Francisco's Deepest Foundations

The Salesforce Tower site is underlain with a complex soil strata including fill, sand, San Francisco's "old bay clay," and weak bedrock. These geotechnical conditions are subject to potential liquefaction, lateral spreading, excessive settlement, and inadequate foundation support. Given the poor soils and the sheer weight of Salesforce Tower, supporting the building on anything but bedrock was not feasible. Gravity loading and overturning demands at the foundation level from MCE shaking dictated a piled-mat solution.

Two foundation systems were considered during the design process: 8-foot-diameter drilled shafts and 5.0- x 10.5-foot Load-Bearing Elements (LBEs). As the

Item	Value
Story Drift	3.0x0.8 = 2.4 percent taken as the average of 11 analyses; 4.5x0.8 = 3.6 percent maximum from any single analysis.
Residual Story Drift	1x0.8 = 0.8 percent taken as the average of 11 analyses; 1.5x0.8 = 1.2 percent maximum from any single analysis.
Coupling Beam Rotation (diagonally reinforced concrete or steel composite)	0.06x0.8 ≈ 0.05 radian rotation limit, taken as the average of 11 analyses.
Shear Wall Reinforcement Axial Strain	Rebar tensile strain is 0.05x0.8 = 0.04 in tension and 0.02x0.8 = 0.016 in compression, taken as the average of 11 analyses.
Shear Wall Concrete Axial Strain	Fully confined concrete compression strain is 0.015x0.8 = 0.012, taken as the average of 11 analyses.
Shear Wall Shear	DCR limited to 1.0. Capacity calculated using expected material properties and a phi factor of 1.0, where ductility demands are modest ($\epsilon_c \leq 0.005$; $\epsilon_s \leq 0.010$) or a phi factor of 0.75, where ductility demands are greater. Demand taken as 1.5 times the average demand from each set of 11 analyses.
Level P1, P2, and Level 1 Diaphragms	DCR limited to 1.0. Capacity calculated using expected material properties and code-specified phi-factors ($\phi =$ 0.75). Demand taken as 1.5 times the average demand from each set of 11 analyses.
Basement Walls	DCR limited to 1.0. Capacity calculated using expected material properties and code-specified phi-factors ($\phi =$ 0.75). Demand taken as 1.5 times the average demand from each set of 11 analyses.

Table 1. MCE-Level Acceptance Criteria for Salesforce Tower.

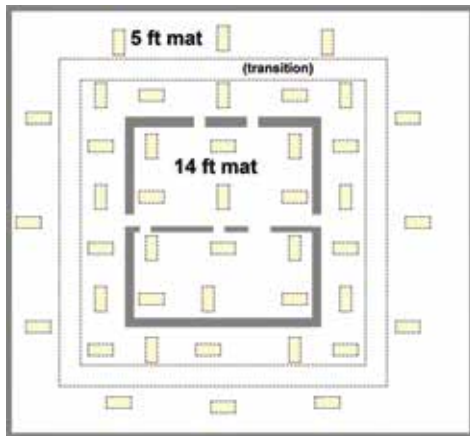


Figure 6. LBE foundation system.

same depth limitations as the equipment used to excavate the shafts was a combination of a line-supported clam shell and hydrofraise. Ultimately, the LBE foundation system was selected as the most appropriate for the project.

An extensive analysis of the LBEs, considering extreme seismic demands, was performed. Reinforcing detailing was incorporated to resist the high tensile, flexural, and shear stresses imposed on the LBEs by MCE ground shaking. Confinement reinforcement was also specified in the upper zones of the LBEs where compressive demands were the highest (Figure 5, page 47). As this was the first time LBEs would be used to support a tall building in San Francisco, an extensive review was conducted by the independent peer review panel. Also, two full-scale Osterberg Load Cells tests were conducted to confirm that the design parameters for the skin friction on the LBEs were appropriate. Through this test program, it was confirmed that the skin friction values were time sensitive (as expected) due to the build-up of filter caking of the bentonite on the side walls of the shafts, requiring time limits to be placed on the overall installation of each shaft.

Installation of the foundation system included first the construction of guide walls to control the location and excavation of the LBEs. Excavation then proceeded using a combination of a line-mounted clam shell in the sands and clay, switching to a hydrofraise when

depth to rock from existing grade was approximately 250 feet, and socketing into the rock would require drilling even deeper, the limits of available drilling equipment would be tested for a drilled shaft foundation. The alternate LBE, or “barrette” foundations, were not subject to the

same depth limitations as the equipment used to excavate the shafts was a combination of a line-mounted clam shell in the sands and clay, switching to a hydrofraise when denser rock material was encountered. Excavation stability was maintained throughout the process using a recycling bentonite slurry system. After the excavation was completed, full-length, pre-tied reinforcing steel cages were lowered into the bentonite-filled holes, and concrete was placed using dual tremie pipes. All 42 LBEs were constructed from existing grade, rather than the bottom of the 60-foot excavation. A temporary internal bracing system would be required to support the open excavation given the limitation of the

Center’s simultaneously open excavation, limiting the ability for heavy equipment to work at the bottom of the hole. As such, concrete placement in the LBEs continued through elevation of the future mat foundation, and the remainder of the shaft was filled with a lean mix for ease of later excavation.

The final foundation configuration for Salesforce Tower includes 42 LBEs interconnected by a thick mat foundation to enforce compatibility (Figure 6). The mat varies in thickness from 14 feet at the core to 5 feet at the perimeter. LBEs extend into the underlying Franciscan bedrock, some reaching more than 310 feet below existing grade with rock-sockets of up to 70 feet. The design and construction of this foundation system set new standards for the support of tall buildings in San Francisco’s unique geotechnical and seismic conditions.

Unprecedented Structure-Soil-Structure Interaction (SSSI) Analysis

As a condition of the Salesforce Tower site purchase agreement, the Transbay Joint Powers Authority required proof that the tower developed for the site, as well as its interactions with surrounding buildings, would not negatively impact the new Transit Center, especially during the strong ground shaking of an MCE event.

An unprecedented Structure-Soil-Structure Interaction (SSSI) analysis was conducted to investigate and confirm the performance of Salesforce Tower and its impacts on the adjacent Transbay Transit Center. MKA’s structural engineering team and the geotechnical engineering team at Arup performed three-dimensional, nonlinear SSSI analyses to assess the interactive performance of Salesforce Tower, the Transbay Transit Center, and another immediately adjacent high-rise tower. This extremely complex assessment involved extensive nonlinear computer models developed in CSI-Perform and LS-DYNA and considered multiple seismic ground motions. The results of these analyses confirmed the satisfactory performance of both Salesforce Tower and the Transbay Transit Center. The details and conclusions of this analysis were ultimately reviewed and approved by the Engineer of Record for the Transbay Transit Center. This was the first time that potential impacts of one building on a neighboring building during strong seismic ground shaking had been considered.

The Road Ahead

In addition to its height, the design and construction of Salesforce Tower set new benchmarks for seismic safety, foundation construction, and structure-soil-structure interaction. With many new towers planned in San Francisco and other seismically active cities, the details of Salesforce Tower’s design will help guide and inform future improvements in the safety and performance of high-rise buildings... and change the San Francisco skyline forever (Figure 7). ■



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Figure 7. Salesforce Tower recent topping out. Courtesy of Magnusson Klemencic Associates/ Michael Dickter.