Architectural vision and high seismic demands culminate in architecturally expressed megabraces for the most resilient skyscraper on the West Coast.

Braced for the FUTURE

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THE SAN FRANCISCO SKYLINE is soaring to new heights as the city's tallest mixed-use building rises in one of its most dynamic neighborhoods.

The project, simply known by its address, 181 Fremont, is currently under construction in the South of Market neighborhood (aka, SoMa). With its proximity to the financial district, Bay Area Rapid Transit (BART) and Caltrain stations, the Bay Bridge and major highways, SoMa is a haven for new development and is currently seeing a boom of office and residential projects. When completed next year, 181 Fremont, at approximately 800 ft, will be the second-tallest building in San Francisco, after Transamerica Pyramid; neighboring Salesforce Tower, also under construction, will surpass both buildings when complete. 181 Fremont contains 56 levels of office and residential space. The bottom 36 levels will make up 435,000 sq. ft of Class A office space while the upper levels will house 67 luxury condominiums.

Design Drivers

The building's location and geometry presented challenges for the design team from both a wind and seismic perspective. The tower is very slender, with a 100-ft by 100-ft footprint at the base that gradually tapers, and the architectural vision includes a faceted façade that folds along visually expressed diagonal lines. To preserve floor area, a traditional core was out of the question. The designers instead chose external megabraces to resist the shear demands in the office levels and standard buckling restrained braces (BRBs) in the residential levels.

Often, tall building projects in San Francisco take an exception to local code height limits. Specifically, owners are keen to avoid the code requirement for back-up moment frames, a requirement that also includes a performance-based analysis to verify that the design complies with the minimum perfor-



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◄ ▼ 181 Fremont contains 56 levels of office and residential space. The bottom 36 are office space while the upper levels house luxury condos.

▲ ► External megabraces (yellow at right) resist the shear demands in the office levels, and standard BRBs were used for the residential levels.

Arup

A cantilevered safety net protects an adjacent building.

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mance objectives intended by the code. While performance-based analysis is more robust than the standard prescriptive design approach, it does not imply higher performance, which is simply "life safety" in a design-level earthquake and collapse prevention in a maximum considered earthquake (MCE). This means that although the occupants of the building should be able to exit the building, it is likely that the building has sustained significant damage, preventing it from being usable or even repairable.

But the building's owner, Jay Paul Company, wanted more in terms of seismic performance. As such, the company opted to use Arup's (the project's structural engineer) Resilience-based Earthquake Design Initiative (REDi) rating system, which proposes an enhanced seismic design framework for buildings focusing not just on occupant safety but also on continuing the life of a building even after a major seismic event (search for "REDi" at **publications.arup.com**). Jay Paul was focused specifically on achieving the Gold level, which corresponds to the building being able to withstand virtually no structural damage, minimal non-structural damage and immediate reoccupancy following a 475-year earthquake. The project was also subject to a rigorous seismic review process required by the City of San Francisco since performance-based seismic analysis was used to justify the design.

Wind Vibration

Because the residential units are at the top of the building, wind vibration was a significant concern for occupant comfort. While tuned mass dampers (TMD) are often employed at or near the roof to mitigate wind vibration in tall buildings, Arup sought alternative solutions for multiple reasons. First of all, while TMDs are effective in reducing wind vibration, the damping they generate is not considered for reducing ultimate wind or seismic design forces. Secondly, TMDs are expensive since they take up valuable real estate at the top of the building—especially one as slender as 181 Fremont. Lastly, they are very heavy and reducing the building's weight was of upmost importance in the interest of reducing gravity and seismic demands.

So how did the design team eliminate 25% of the steel (3,000 tons) relative to a more conventional design while achieving stringent wind occupant criteria and enhanced seismic resilience objectives? They implemented an external damped megabrace system, eliminating the need for the TMD and introducing an uplift mechanism at the base of the megacolumns to eliminate tension demands in the foundation. In other words, instead of stiffening the building, they actually reduced the stiffness, elongating the building period to reduce seismic demands accordingly. As more steel was removed from the design, the building got lighter, and the seismic mass and related demands decreased. This cycle was repeated until Arup found an optimized design. In addition, eliminating the TMD freed up an entire floor; the mechanical penthouse was relocated to the roof, thus opening up the penthouse level for a luxury condominium unit.

Megabraces

Each of the externally exposed megabraces in the office levels is 200 ft to 250 ft long, extending across multiple floors to the meganodes. The megabraces comprise three braces in parallel: a primary brace with a secondary brace on either side. The primary brace is a built-up box section (14 in. by 16 in.) with variable thickness (~2 in.) and the secondary braces are essentially 9-in. by 9-in. boxes built-up from steel plate. The primary brace is fixed rigidly to the meganodes at either end of the brace, and the secondary braces are fixed only at one end while the other end is attached to a viscous damper, which in turn is attached to the meganode.

The building uses approximately 9,000 tons of structural steel.

Steel could only be erected from Fremont Street, and an assist crane was used for heavier picks at the back of the building.

While the strains are generally low in the primary brace, the total axial deformation accumulated over its entire length can be significant. To maintain deformational compatibility, the secondary braces must extend the same amount, though the majority of the deformation is concentrated in the damper itself. This generates a tremendous amount of damping, on the order of 8% of critical (far greater than the inherent damping in tall buildings considered for wind or even seismic conditions). The viscous dampers do double-duty, reducing both seismic and wind demands, as well as reducing wind vibrations. To protect this system in an MCE, BRBs produced by Star Seismic (now CoreBrace) are placed in the load path of the primary and secondary braces to act as fuses. This limits the amount of force in the primary and secondary braces and megacolumns, ensuring that they will remain elastic in an MCE, and also prevents the dampers from exceeding their capacity—i.e., when the dampers exceed their stroke capacity of +/- 6 in., the BRB will yield before the damper metal casing capacity is exceeded. The largest BRB was comprised of four units bundled together to form a single 5,000-kip-capacity BRB.

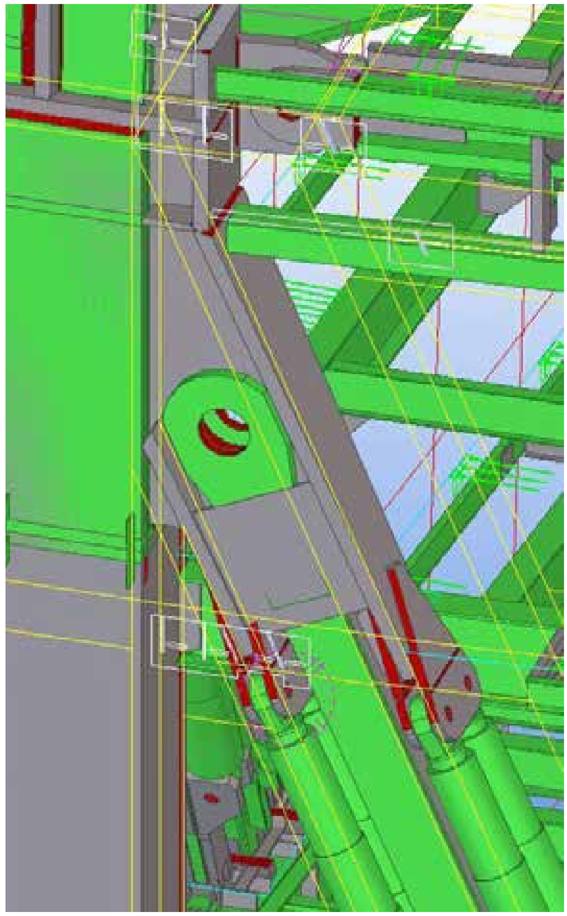
One specific challenge with the BRBs was determining how to keep them from buckling while simultaneously letting them move independently from each other and from the floors along their axis (a requirement of the damped megabrace system). Extensive coordination was required from the design team to find a solution that would fit within the curtain wall and glass skin system, which had largely been designed prior to the finalization of the structural system.

Arup designed a megabrace "cage" solution that allowed the braces to move freely along their axes relative to the floor while still providing lateral restraint. This was achieved by using polytetrafluoroethylene (PTFE) bearings attached to a built-up steel shelf, which was in turn attached to the perimeter moment frames. Mirror finish stainless steel was attached to each of the braces opposite each PTFE bearing, which allowed up to 10 in. of sliding between the braces and the floor system. Adding to the complexity of the system, the tapering, faceted geometry of the tower and the proximity of the brace to moment frame columns meant that no two cages were exactly alike.

In addition to the megabrace system itself, perimeter moment frames inset from the megabraces are used to resist the inertial seismic loads at each floor in the office level; this allows the megabraces to pass by the moment frame beams and columns. The moment frames transfer the loads up and down to the meganode locations and down through the megabraces. In the upper residential levels, the lateral system comprises internal core BRBs. Keeping the lateral system in the core of the building eliminated the need for perimeter moment frames, initially with 24-in.-deep beams and now using 14-in.-deep perimeter beams. This increased the floor-to-ceiling window height and reduced column sizes. As a result, the luxury condominium units boast 13-ft, 4-in. floor-to-floor heights, providing spectacular views of San Francisco and beyond.

Megacolumns

Once the lateral system was optimized, the design team was able to finalize the design of the megacolumns, which are designed to remain elastic in an MCE (1.5 times mean MCE demands for many of the structural components). The large seismic demands required built-up plate box columns, as large as 36 in. by 36 in. by 5 in. at the base. In order to verify material availability, Herrick, the project's steel fabricator and erector, met with the design team and a metallurgist at Dillinger Hutte (an ArcelorMittal company) in Germany, which provided the heavy plate. The large demands also prompted the design team



The external damped megabrace system eliminated the need for the TMD and introduced an uplift mechanism at the base of the megacolumns to eliminate tension demands in the foundation. Instead of stiffening the building, the design actually reduces stiffness, elongating the building period to reduce seismic demands accordingly.

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to use 65-ksi material in order to save on steel tonnage. Each megacolumn required extensive erection coordination and planning, with the heaviest pick being 52.5 tons.

The foundation supporting the megacolumns is a piled raft with a 3-ft-thick mat supported by 42 drilled shafts, 5 ft to 6 ft in diameter that extend approximately 250 ft to bedrock and are then socketed into the bedrock a distance of 20 ft to help control settlements. In addition, due to the fact that the also-under-construction Transbay Transit Center (TTC) is adjacent to 181 Fremont, complex soil-structure interaction modeling—using 3D nonlinear dynamic analysis in LS-DYNA software—was required to check interaction of the two buildings' foundations and confirm that any demands imparted to the TTC from 181 Fremont would not invalidate the performance objectives of the TTC.

The megacolumns are supported by large pilasters formed by embedding steel cruciform sections in the corners of the basement walls, which extend five levels below ground. The general contractor, Level 10, was keen to reduce or eliminate a steel truss that was embedded in the pile cap and would account for potential schedule delays. Arup sought a solution by allowing the megacolumns to uplift slightly at their base in an MCE (an M8.0 on the San Andreas fault). The bases of the megacolumns were prestressed down with 3-in. rods that extended to the bottom of the foundation such that no uplift occurred under design-level earthquake or wind demands. To allow uplift, the megacolumns were detached from the foundation along a plane, below which a steel cruciform provided the support for the megacolumn base plate. Across that plane, shear had to be transferred in the event of uplift.

Arup devised a shear key that resembles a solid steel "hockey puck" that floats inside circular holes in the megacolumn base plate and the top of the steel cruciform column. Given that this was a crucial component, it was designed for more than 6 in. of uplift, even though the nonlinear response history analyses indicated an uplift of 1 in. on average. By allowing the building to rock and uplift in a big earthquake, this solution relieves forces in the building and also reduces large tension demands at the foundation. This change eliminated the costly steel truss and reduced reinforcing requirements in the basement walls and piles.

The tower is very slender, with a 100-ft by 100-ft footprint at the base that gradually tapers, and the design incorporates a faceted façade that folds along visually expressed diagonal lines.

Access to the site for erecting steel was only available from Fremont Street. An assist crane was used for heavier picks at the back of the building when working at lower elevations. At level 20, two large nodes exceeded the capacity of the tower crane at the required working radius. The pieces were lifted to elevation with the tower crane and then transferred to a gantry crane, and the gantry crane was used to move the pieces horizontally to the appropriate grid. A factor further complicating erection was the presence of a day-care facility on an adjacent roof. This prompted the cantilevered safety net that protects the day-care center to be load tested at by Level 10 before being assembled on-site.

In addition to enhancing the San Francisco skyline, 181 Fremont will provide much-needed office and housing in one of the most desirable and accessible neighborhoods in the city as well as protect occupants and the building itself via unprecedented resilient seismic design. ■

Owner
Jay Paul Company

General Contractor
Level 10 Construction

Architect
Heller Manus Architects

Structural Engineer
Arup

Steel Fabricator and Erector
The Herrick Corporation