conference preview

SHANGHAI SKY

BY DENNIS POON, P.E.

Steel outriggers and trusses help solve the challenges of a Shanghai super-skyscraper's twisting design.

THE SHANGHAI TOWER is in good company.

The super-tall skyscraper, currently under construction in the Pudong district of Shanghai, China, and scheduled to be completed next year, is in close proximity to two other giants that have transformed the Shanghai skyline in recent years: the Jin Mao Tower and the Shanghai World Financial Center.

As a matter of fact, once completed the Shanghai Tower will reach 2,074 ft high—121 stories—and will be the second- or third-tallest building in the world. The total floor area of 4,090,285 sq. ft will house Class-A office space, retail space, a luxury hotel, cultural venues and the world's highest non-enclosed observation deck; the building will anchor one of East Asia's leading financial centers, the Lujiazui Finance and Trade Zone.

The tower's program is organized into nine vertical zones, each rising from a "sky lobby," a light-filled garden atrium that creates a sense of community and supports daily life with a mixed-use program catering to tenants and visitors; the lobbies function much like traditional town plazas and squares, bringing people together throughout the day.

In the Zone

Faced with many geographical challenges—a windy climate, active earthquake zone and clay-based soils typical of a river delta—the structural engineers sought to simplify the building structure as much as possible. The heart of the building is a composite concrete core, about 30 sq. meters (323 sq. ft) in plan. Structural steel columns, beams and plates are embedded in the core in the low zones to increase the capacity of the core.

The core acts in concert with an outrigger and composite supercolumn system. There are four paired supercolumns, two at each end of each orthonormal axis. In addition, four diagonal supercolumns along each 45° axis are required by the long distances at the base between the main orthonormal supercolumns. The two-story-tall outriggers and belt trusses are structural steel and the supercolumns are composite structures with concrete-encased steel vertical sections.

The tower is divided vertically into nine zones, each with 12 to 15 floors, and an inner cylindrical tower steps in at each zone. At the interface of the adjacent zones, a two-story, full-floor area houses mechanical, electrical and plumbing equipment and also serves as that zone's life safety refuge area. This full-floor platform creates a base for the atrium spaces directly above.

Above the topmost zone is the tower crown. Built to enclose MEP equipment, the structure is framed with a series of vertical steel fin trusses and horizontal struts to kick back to the core wall. The fin trusses are spaced roughly 14.5 ft apart and are 6.6 ft deep, and the tallest truss is approximately 233 ft.

The lateral and vertical resistance of the tower is provided by the inner cylindrical tower, and the primary lateral resistance is provided by the core, outrigger and supercolumn system. This system is supplemented by a mega-frame consisting of all the supercolumns, including the diagonal columns together with a double belt truss at each zone that picks up the zone's columns and the mechanical and refuge floors. The supercolumn and outrigger assemblies act as "ski poles," stabilizing the building in high winds, earthquakes and typhoons common to the area, while also supporting the twisting-form curtain wall. The outrigger trusses and supercolumns derive stiffness from the concrete inner building, comprising an effective system for resisting wind and seismic loads for super tall buildings.

Ample Analysis

The building was designed to meet the performance-based design (PBD) requirements as specified in the China's seismic design code. In order to do this, the non-linear (plastic) behavior of the members and connections had to be determined. This was accomplished via the three-dimensional, finite element program, ABAQUS, which not only modeled the encased steel element, but also the concrete encasement itself. In ABAQUS, the concrete elements are modeled as shell elements and the steel elements are modeled as beam elements. The code provides the post-elastic behavior of the steel and concrete.

The encased steel sections in the supercolumns are the key element to ensuring the proper performance of the connections and

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➤ A trifecta of super-tall Shanghai skyscrapers: the Shanghai World Financial Center, Jin Mao Tower and the soon-to-be-completed Shanghai Tower.

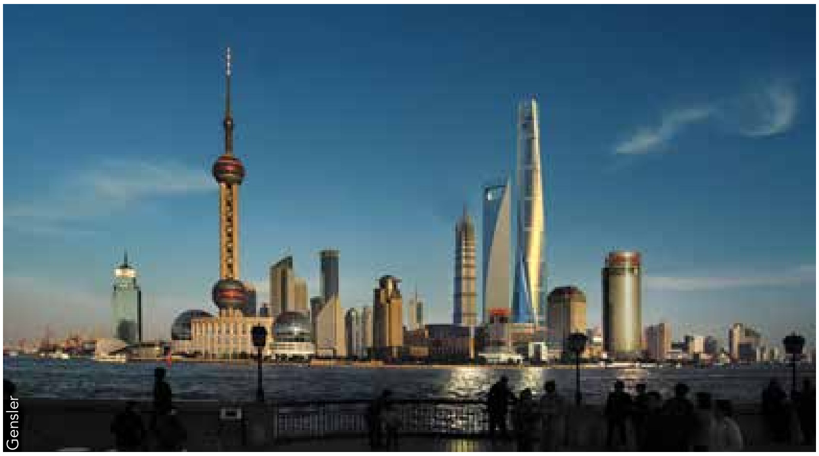
Gensler

thus the performance of the structure. At the building core, localized vertical steel members are used to facilitate the outrigger connections and a similar 3D finite element analysis was performed. From these finite element analyses using ABAQUS, a moment, axial force and rotational deformation profile was created. Based on these profiles, using a performance-based program (Perform 3D) and ABAQUS, the performance of the primary structure was developed using seismic time history graphs for a similar soil profile as that of the site.

The soil conditions in Shanghai are challenging from a seismic perspective—defined in China's technical specification for concrete and composite tall structures as type IV, which approaches Class F classification in the *International Building Code* (IBC). The resulting foundation for the tower consists of bore piles one meter (3.28 ft) in diameter and 52 to 56 meters (170 to 184 ft) long. In total, the tower is supported on a 6-meter-deep (20-ft-deep) mat reinforced by 947 bore piles. Seven sets of seismic time histories that matched Shanghai's soil profile and earthquake intensity were modeled.

From the performance-based design analysis, the following conclusions were reached:

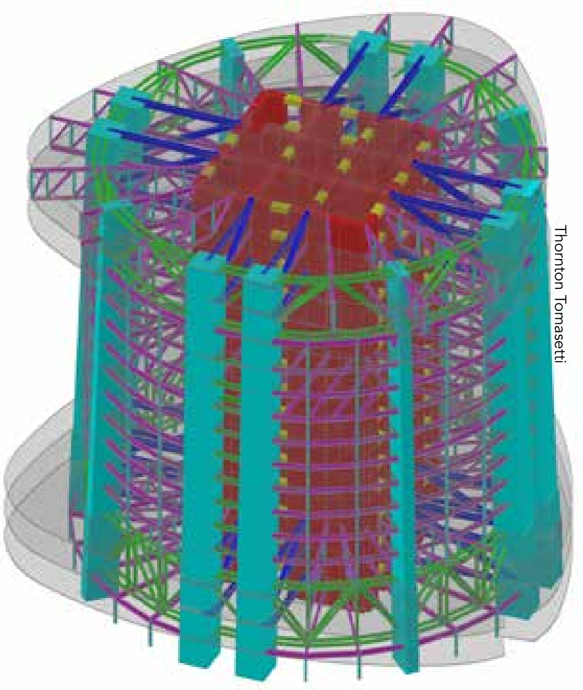
- The average maximum drift ratio in either axis is less than 1/130. This meets the 1/100 limit specified in the *China Building Code*.
- The core wall stresses are elastic, except in limited areas.
- Most core wall link beams exhibit fully plastic deformations, and plastic hinge rotations are still within the limit set for "Life Safety."
- Most outrigger trusses and belt trusses are within the elastic range.
- Embedded steel elements in supercolumns and core walls remained elastic.
- The Shanghai Center achieved the performance levels for "life safety" in the code.



▲ The Shanghai skyline as it will appear upon completion of the Shanghai Tower.

◄ A Revit model of the structure.

▼ A 3D stuctural model of one of the vertical zones of the building.



Starting with the supercolumn connections to the outrigger and belt trusses, the emphasis was on continuity of forces. The main axis of the supercolumns has an embedded steel built-up section coincident with the axis of the outrigger to simplify the connection. In the orthonormal direction, the belt truss frames into the supercolumn at a slightly non-orthonormal direction due to being in the circumferential direction. In the steel section of the supercolumns, there are perpendicular cross ribs that align with belt trusses. Any slight deviation of the cross ribs with the axis of the belt trusses is resolved by stiffeners within the embedded steel section. A similar detail is used at the intersection of the core and the outrigger. At this location there is a small embedded vertical steel column at the intersection, which simplified the outrigger connection to the core. At the levels of the outriggers, tie plates level with the outrigger top and bottom chord pass through the core.

Double Skin

Shanghai Tower will be one of the most sustainably advanced tall buildings in the world. A central aspect of its design—and a main contributor to its environmental efficiency—is the transparent, second skin that wraps the entire building. The ventilated atriums it encloses conserve energy by modulating the temperature within the void. The space acts as a buffer between the inside and outside, warming up the cool outside air in the winter and dissipating heat from the building interior in the summer.

▼ The tower is divided vertically into nine zones, each with 12 to 15 floors, and an inner cylindrical tower steps in at each zone.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▼ At the interface of the adjacent zones, a two-story, full-floor area houses MEP equipment and life safety refuge areas.


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The design process revolved around a series of advanced parametric software programs (Rhino and Revit for the geometry and SAP 2000 for structural analysis), which allowed the design team to manipulate and refine the project's complex geometry iteratively, as well as a building information modeling (BIM) approach. The parametric platform played a pivotal role in assisting the design team to define the tower's unique and environmentally responsive shape, structure and façade.

The façade is one of the defining features of the Shanghai Tower. The twisting design implements an inner and outer curtain wall system, which creates an inhabitable "double-skin" zone, and a flexible hanging curtain wall support structure was ultimately developed to suit the complex needs of the façade. The spiraling inclined curved outer skin features laminated glass panels that filter the sun, wind and rain. The inner skin encloses the interior space with a conventional low-E coated insulating glass curtain wall system with operable solar control devices. This double skin wall system takes advantage of the stack effect to provide natural ventilation and cooling. The buffer area between the inner and outer skins helps regulate the environment and collect and recycle rain water.

When completed, Shanghai Tower won't simply be a skyscraper—or even a super-skyscraper. It will represent a new way of envisioning and creating cities, and it will address the tremendous challenges faced by designers of super-tall buildings today. By incorporating cutting-edge sustainable design, weaving the building into the urban fabric and drawing community life high into the tower, the project is attempting to redefine the role of tall buildings for decades to come. MSC

This article serves as a preview of Session N34a/b at NASCC: The Steel Conference, taking place April 17-19 in St. Louis. Learn more about the conference at ***www.aisc.org/nascc****.*

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