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Authors:	Dennis Poon, Vice Chairman, Thornton Tomasetti Yi Zhu, Managing Principal, Thornton Tomasetti Paul Fu, Principal, Thornton Tomasetti Jianhai Liang, Associate, Thornton Tomasetti
Subjects:	Architectural/Design Building Case Study Geotechnic/Foundation Structural Engineering
Keywords:	Core Foundation Performance Based Design Structural Engineering
Publication Date:	2015
Original Publication:	Asia & Australasia: A Selection of Written Works on the World's Tall Building Forefront
Paper Type:	1. Book chapter/Part chapter 2. Journal paper 3. **Conference proceeding** 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Designing a Non-coplanar Exoskeleton Supertall Tower that Transforms the Skyline of Chengdu

Dennis Poon, Vice Chairman, **Yi Zhu**, Managing Principal, **Paul Fu**, Principal & **Jianhai Liang**, Associate, *Thornton Tomasetti*

The city of Chengdu is quickly becoming the center for high-rise development in southwest China. The focal point of this new vertical landscape will be the Chengdu Greenland project with its 468-meter mixed-use main tower. The tower's complex architectural geometry consists of facets sloping in all directions to resemble the region's snow-covered mountains. Accordingly, the structural design adopts a non-coplanar 3-D exoskeleton system that integrates columns zigzagging along the height and steel mega braces on the edges of the surface facets. The tower will also be China's first supertall building to adopt a tapered tower core. Tapering the core avoids the need for wall transfer or thicker walls at the lower levels to support the upper walls. The design features above allow the structural support elements to be seamlessly incorporated in the tower's complex multifaceted architectural shape, minimizing intrusion of structure into usable space, and thus increasing the building's efficiency.

Project Description

The city of Chengdu, with its dense population of more than 14 million, is the provincial capital of Sichuan Province in China. Being the second largest inland metropolis of Southwest China, the city is rapidly becoming a center for high-rise development in the region.

The focal point of this new vertical landscape in a seismic zone will be the Chengdu Greenland project, consisting of a 468 meter-tall project, comprised of a mixed-use main tower, two high-rise residential towers, and a podium.

Inspired by the unique ice-clad mountain topography around the city, the main tower's complex architectural geometry consists of facets sloping in all directions, including alternating inward and outward slopes to resemble the ridges and valleys of the snowy mountains. The tower ridges reflect the sky and the valleys reflect the earth, performing as a sculpture to diffuse light from 360 degrees of Chengdu's special local climate in all season. The architectural design creates a light connection between sky and earth – a powerful dynamic landmark "Peak of Sichuan " that will transform the skyline of the

Opposite: Excavation site as of July 2015. Source: Greenland Group

Top: Rendering of the tower. Source: Adrian Smith + Gordon Gill Architecture

Bottom: Chengdu Greenland project site plan. Source: Thornton Tomasetti

city of Chengdu. At 468 meters, the 101-story main tower consists of high-end offices, CEO executive suites, five-star hotels, and a sky club at the top. The skyscraper creates a "mini-city" offering upscale working, living, entertaining, meeting, and shopping environments for the densely populated metropolis.

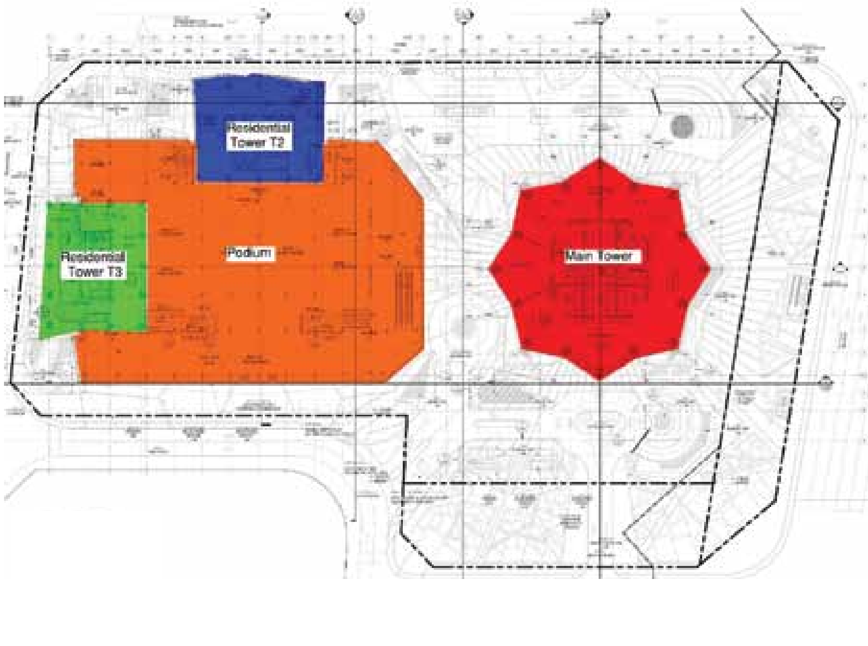
The Chengdu Greenland Center project has an overall site area of 24,530 square meters. Apart from the main tower, the two high-rise residential towers are 167 meters and 174 meters, respectively. Both towers also have faceted geometry, but to a lesser degree of complexity. Between the main tower and the two shorter towers, there is a four-story podium with a height of 30 meters. The podium also adopts a faceted design surface to be consistent with the rest of the project, and it mainly houses a conference center and meeting rooms. The total GFA of the project is 455,530 square meters.

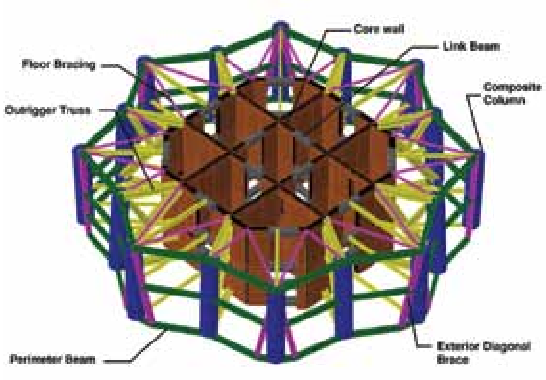
Tower Lateral System

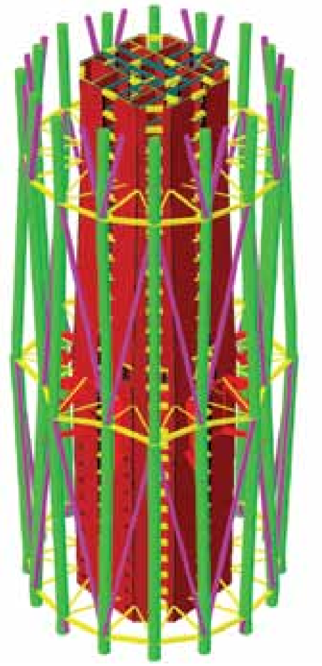
The faceted surface of the Chengdu Greenland Center main tower creates an iconic landmark for the city of Chengdu. At the same time, it also forms a unique, challenging 3D geometric surface for the structural engineer.

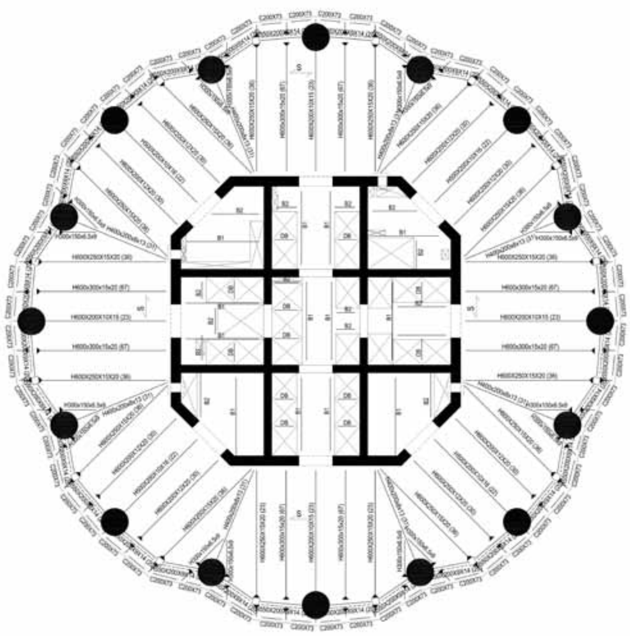
The lateral force resisting system adopted for the Chengdu Greenland tower is the "core + outrigger truss + mega exterior braced frame" system.

Typically, systems designed to resist lateral forces on high-rise towers consist of either









a center core with additional shear walls outside of the core, or a center core and perimeter moment frames. For a tower of this height, Chinese building codes do not permit the use of just a shear wall system. Perimeter moment frames must be used together with the core.

A nine-cell octagonal core is placed at the center of the plan. The shape of the core is similar to that of the tower floor plate. Therefore the distance between the perimeter and the core outer face is relatively constant. This not only makes the floor layout easier, but also results in more economical and uniform floor framing since most of the radial beams have similar spans. The overall dimension of the core is 28 meters by 28 meters at the bottom, and reduces to 24 meters by 24 meters above level 61 for better building efficiency. The core reduces dimension by having a segment of sloping walls from levels 51 to 60, making the tower the first high-rise building in China to have a sloping core.

Typically the center core of a tower is reduced in size at upper stories by stopping some flange (outer) walls and having the original web (interior) walls serve as flange walls above. This approach has its drawbacks. To maximize the stiffness of the building cores to meet code requirements, the upper flange walls have to be fairly thick and, to avoid wall offsets, the upper flange walls need to align with web walls below. Therefore, the web walls below are thicker than needed where they do not contribute much to the overall building stiffness, just

Opposite Top: Lateral force resisting system (left) & sloping core wall (right). Source: Thornton Tomasetti

Opposite Bottom: Typical floor plan of the main tower. Source: Thornton Tomasetti

"The core reduces in dimension by having a segment of sloping walls from levels 51 to 60, making the tower the first high-rise building in China to have a sloping core."

to support the thick walls above. As a result, the core is less efficient and much heavier than necessary. Since the self weight of the core wall is a major contributor to the total building weight (around 33% for the Chengdu Greenland main tower), a heavier core will dramatically increase the burden on the foundation and the seismic force experienced by the building.

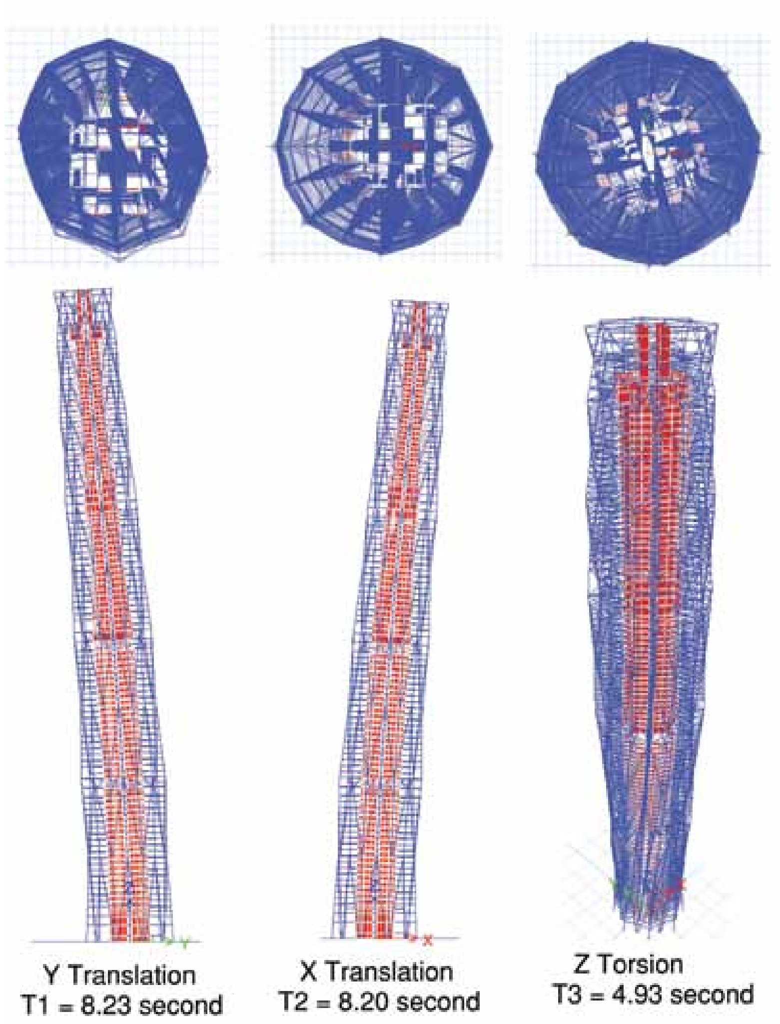
In contrast, by sloping the core flange walls in a tapering core system, upper flange walls are supported by the lower flange walls. Thus the building can be much lighter with much thinner web walls. For the Chengdu Greenland main tower, the flange walls are 1.1 meters thick at the bottom and 0.4 meters thick at the top. The web wall thickness is 0.8 meters at the bottom, which reduces to 0.4 meters at the top.

The core wall resists most of the lateral shear and serves as the fundamental line of defense to prevent the building from collapsing under severe seismic events. Embedded steel columns are provided at the boundary zones: wall corners and intersections. Steel plates are placed in the core walls at the bottom 15 floors to increase the compression and shear capacity. The embedded steel also improves ductility of the otherwise regular reinforced concrete walls to prevent sudden failure of the core.

Due to the faceted nature of the design surface, the tower's floor plates vary in shape between octagons, hexadecagons, and polygons with 32 edges. The moment frame uses 16 circular columns, one at each corner of the hexadecagon. If the columns were vertical or sloping constantly like those of most other buildings, the columns would frequently end up well within the interior spaces, reducing the efficiency of the building, as well as affecting the aesthetics. Therefore, the Chengdu Greenland main tower uses columns that keep constant slopes in each zone but kink at the boundary between adjacent zones. As a result, the columns zigzag along the height of the tower and always follow the design surface. The diameter of the circular columns is 2.8 meters at the bottom and reduces to 1.2 meters at the top. To minimize the size of the columns while simultaneously providing the required stiffness and strength, the columns are reinforced by wide flange steel shapes embedded within reinforced concrete columns. Including the wide flange shapes, the steel reinforcing ratio ranges from 5% to approximately 8%.

Not only do the columns reverse slope directions from zone to zone, adjacent columns in each zone also have opposite slope directions. For example, if one column slopes inward in Zone Two, the two adjacent columns must slope outward in this zone. If the façade surfaces simply connected adjacent columns, this configuration would generate warped surfaces impractical for curtain wall design and manufacture. By introducing a diagonal mega-brace between the two columns the surface is instead broken into two planar sub-surfaces. The braces go from zone to zone and also zigzag along the height of the tower. The mega-braces not only provide support for the curtain wall mullions, but also serve as one important component of the perimeter structural system. The final product is a non-planar 3-D exoskeleton system, or perimeter mega-braced frame system, that fits perfectly with the architectural design surface. The exoskeleton comprises of hundreds of triangular "units." Every unit is made up of one column, one mega-brace and one horizontal perimeter steel beam at the kink floor, which is reinforced to resist its share of the horizontal force caused by the mega-braces. The mega-braces are all square steel tubes. The numbers of floors in each zone varies. Accordingly, the mega-braces may span from as few as three floors up to as many as 13 floors. Therefore the member sizes are tailored to meet tower strength and stiffness requirements. The long mega-braces are braced at certain floors by floor beams to limit the maximum unbraced length to five floors. The sizes of the braces range from 400 mm x 400 mm to 800 mm x 800 mm.

Chengdu Greenland tower's exoskeleton made of triangles, the most stable planar geometric shape, offers a very stable perimeter lateral system which also has high stiffness. Unlike American building codes, China has a mandatory stiffness requirement for a dual system with central cores. In general, the perimeter frame, as the second line of defense, is required to be stiff enough (not just strong enough) to take at least 10% of the base shear. Normally it is very difficult for super tall building designs to meet this requirement. However, the non-planar 3-D exoskeleton of the Chengdu Greenland main tower is able to meet this requirement with ease.



Even though the exoskeleton of the Chengdu Greenland main tower is a very stiff lateral system by itself, its contribution to the stiffness of the entire tower cannot be fully realized without outriggers. Three sets of outrigger trusses are placed at levels 23 to 26, levels 47 to 50, and levels 98 to 100 respectively. All three zones are mechanical equipment floors, minimizing the impact of the outrigger trusses on occupied building space. When connected to the core through outriggers, the exoskeleton provides very large stiffness against tower flexure.

The outrigger trusses and the exoskeleton help provide a structural system stiff enough to meet the stringent story drift ratio limit required by China building codes. The maximum story drift is about h/500 under frequent earthquake seismic load (a 50-year return period seismic event) and h/1200 under the 50-year return period wind load. The fundamental first three building periods of the tower represents the X-direction translation, Y-direction translation and torsion, respectively.

Tower Gravity System

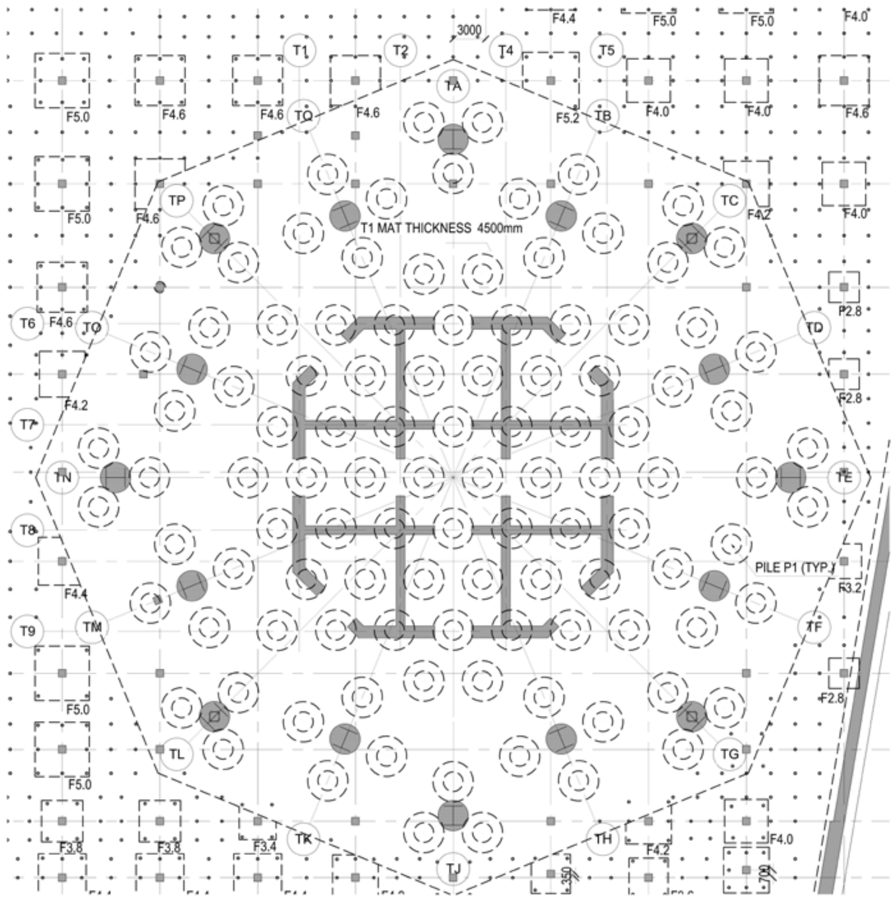
The typical office, CEO suite, and hotel floors use a 125 mm thick re-entrant profiled composite slab (60-millimeter-thick concrete slab on top of 65-millimeter-deep metal deck) that provides a two-hour fire rating according to laboratory tests. Typical mechanical equipment (MEP) levels use a 200 mm thick close-form composite slab (135 mm thick concrete slab on top of 65 mm deep metal deck) to support the heavy load on MEP levels and to provide noise isolation. Most MEP levels coincide with kink points of the columns. On non-MEP floors where column kink points occur, 150-millimeter-thick close-form composite slab (85-millimeter-thick concrete slab on top of 65-millimeter-deep metal deck) are used to take the additional in-plane stress caused by the column kinks. Steel floor beams and spandrel beams supported on the mega-columns and mega-bracings bring floor loads to the vertical gravity members.

Site Condition and Foundation System

Site conditions of the Chengdu Greenland project are relatively good. Shale or "mudstone" bedrock with varying degrees of weathering underlays five layers of top soil and clay totaling approximately 23 meters of thickness. Nonetheless, as with other supertall buildings, the foundation mat design of the main tower still poses challenges due to large gravity forces and large overturning moments from wind and seismic loads.

The foundation system of Chengdu Greenland tower is a 4.5-meter-thick reinforced concrete mat foundation supported on 112 1.8-meter-diameter concrete piles that bell out to 3.7-meter-diameter at the bottom. Following local construction practices, these will be hand-dug piles. Establishing suitable bearing elevation requires balancing the need for the piles to bear on soil layers with adequate bearing capacity, while not passing through layers too hard to permit excavation. So the production piles are effectively 13 meters to 19 meters long and bear on layer 6-3, which is moderately weathered mudstone.

The two high-rise residential towers will sit on two-meter-thick reinforced concrete mats that bear directly on soil strengthened and stiffened by non-reinforced concrete micro-piles. The podium and basement-only areas will be supported by spread footings. Average compressive stress under the effective main tower footprint (the tower footprint plus



Opposite: Fundamental building periods and mode shapes.
Source: Thornton Tomasetti

Right: Foundation plan of the main tower.
Source: Thornton Tomasetti

the mat area extending beyond the tower floor plate) is approximately 1500 kPa, the average compressive stress under the high-rise residential towers is around 1000 kPa, and the podium area experiences buoyancy due to the high water table. Because of the different loading magnitudes and foundation schemes of the project components, another foundation design challenge is controlling differential settlements. Pile lengths are tuned in design to minimize differential settlements. Also, delayed pour strips will be provided during construction between adjacent components with differential settlement. In addition, settlements will be monitored during and even after construction.

Optimization of the Lateral Force Resisting System Design

The ultimate goal of the structural design is to find the most economical design, meaning one that can be constructed easily, using the least quantity of building materials, without compromising architectural functions.

As mentioned previously, outriggers connecting the core and the perimeter columns are very important for the lateral force resisting system. However outrigger trusses can be very costly as to both the construction material consumption and construction schedule. During the schematic design phase, through preliminary analysis and comparison four sets of outrigger trusses were used, located at levels 23 to 26, levels 47 to 50, levels 68 to 71, and levels 98 to 100. During the design development phase, the architects largely finalized building geometry and lateral loads were determined with the conclusion of wind tunnel test and site specific seismic hazard analysis. With that additional information, a sensitivity study evaluated the relative contribution of every set of outrigger trusses to controlling story drift and outrigger member design forces. The outriggers located on levels 68 to 71 were least efficient and could be removed without severely impacting the overall behavior of the tower. By reducing the number of outrigger trusses to three sets, approximately 700 tons of steel is saved, and construction duration is reduced by about one month and the space on levels 68 to 71 is more useful.

The foundation of the tower constitutes a large portion of the building construction cost, so optimization of the hundreds of piles needed provided an opportunity for savings. The design capacity of each pile is the lesser of the capacity of the reinforced concrete pile itself and the capacity of the soil under and around the piles. Originally the bearing capacity of the soil was tested by drilling small holes directly from the ground. The bearing capacity of the moderately weathered mud rock was found to be only 3500 kPa, limiting capacity of piles supported by the moderately weathered mudstone. Increasing pile capacity by extending them deeper to less-weathered rock, or increasing total capacity by providing many more piles, were both very expensive approaches.

Instead, the design team evaluated the bearing capacity together with the geotechnical engineers. It was found out that the test method may have greatly underestimated the bearing capacity of the soil because loading plates that were too small were used. A retest with the so-called "deep plate loading test" was proposed. After the site excavation was finished, a much larger testing area (an 800-millimeter-diameter circle) was used. The adjusted bearing capacity of the soil came out to be 7200 kPa.

Opposite: Rendering of the completed tower.
Source: Thornton Tomasetti

"Establishing suitable bearing elevation requires balancing the need for the piles to bear on soil layers with adequate bearing capacity, while not passing through layers too hard to permit excavation. So the production piles are effectively 13 meters to 19 meters long and bear on layer 6-3, which is moderately weathered mudstone."

The bearing capacity will be confirmed by pile capacity tests. But with the increased bearing capacity, the number of piles can be greatly reduced. This resulted in a reduction in both construction costs and time required to complete the project.

Performance Based Design

Considering the geometrical and structural complexity of the Chengdu Greenland main tower and importance of the project, in addition to the prescriptive code design the performance based design (PBD) was also used to evaluate the performance of the tower under severe earthquake.

In contrast to code-based prescriptive design, which is mainly linear, PBD explicitly considers the nonlinearity and ductility of structural members. PBD can be used to evaluate overall behavior, member behavior, and even connection detail behavior under different levels of seismic events. However for the Chengdu Greenland main tower PBD was only used to evaluate the behavior under severe earthquake which is the earthquake with 2,500 years of return period.

The generic finite element analysis software ABAQUS was used for the project and the nonlinear stress-strain characteristics of material was modeled according to the constitutive relation curves of concrete and steel provided in the China building codes. Seven sets of ground acceleration time histories were selected to match the site soil profile and building dynamic property. And the curves were scaled to reflect the expected earthquake intensity at the site determined by a site specific seismologic analysis. Four sets of time history curves were based on actual earthquake records and the rest three were synthetic. Each set included two orthogonal horizontal components plus one vertical component.

The nonlinear time history analysis results were used to evaluate the performance of the tower with respect to the targeted performance goals of the building. The PBD analysis showed that most of the link beams yielded as expected to dissipate seismic energy under severe earthquake. Main vertical components of the structure including the core wall, the composite mega columns, and the steel mega-braces maintained adequate remaining capacity to support the tower after the earthquake. The steel outrigger trusses were designed to meet the stiffness requirements and remained elastic. The maximum transient and residual story drifts of the tower were within the code limit. The tower achieves the requested "Life Safety" performance level.

Final Thoughts

A non-planar 3-D exoskeleton system consists of composite mega columns, mega-braces, and spandrel beams at the kink levels, has been designed on the perimeter of the Chengdu Greenland main tower to fit seamlessly with the faceted architectural surface. A central core with sloping walls at transitions is used to effectively reduce the core dimension on top zones of the tower. This is the first time that a sloping core is being used in a super-tall building in China. Both prescriptive code-based design method and the new performance-based design method were used to evaluate the building's performance under different levels of seismic events as well as gravity and wind loads. The structural design has also been optimized to increase the material consumption and construction cost efficiency.

The exoskeleton and the center core, connected with three sets of outrigger trusses, provided a very stiff and efficient lateral force resisting system for this new skyscraper in the city of Chengdu, the rapidly growing capital of China's Sichuan Province.