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Tall Buildings of the Future as Seen From the Present



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SawTeen See, PE, co-founded Leslie E. Robertson Associates (LERA) in 1986 and was Managing Partner from 1991 to 2017. With more than 40 years' experience, and a pioneer in the field of tall buildings, SawTeen led the structural engineering design of the 555-meter Lotte World Tower in Seoul. Her next tallest, the 644-meter PNB118 is currently under construction in Kuala Lumpur. She was partner-in-charge also of the Shanghai World Financial Center; and peer reviewed two 530-meter-tall buildings in China, and several others over 400 meters. She has designed many museums, educational buildings, convention centers, and pedestrian bridges.

Abstract

Aerodynamic damping through the use of vertical long slots reduces the dynamic component of the wind loads on the building. Seminal examples include the three-legged Al Burj, Dubai, the four-legged Nakheel Tall Tower, Dubai, and the competition design of the Jeddah Tower, Riyadh. The multi-legged tower provides enhanced life-safety, efficiency, sustainability, and robustness. Wind tunnel tests demonstrate clearly the benefits in reducing wind loads on the building due to the vertical long slots in between the "legs" of the tower. The structural system of these towers is integrated into the architecture, such that the architecture and the structure is one. These designs influenced the mile-high Next Tokyo Tower, in Tokyo, envisioned for 2065. The proposed tower is the leader of a new generation of high-rise buildings to be constructed 45 years hence.

Keywords: Aerodynamic Damping, Robustness, Slots Through Buildings, Supertall, Wind Engineering

Introduction

Innovations in the design and construction of several key buildings: The Bank of China Tower, Hong Kong (1982–1989); Shanghai World Financial Center, China (1995–2007); the 555-meter Lotte World Tower, Seoul, Korea (2008–2014), together influenced the design of the 644-meter PNB118 in Kuala Lumpur, Malaysia (2010–2020), now under construction.

Aero-dynamic damping, through vertical long slots, reduces the dynamic component of the wind loads on a building. This is evidenced in the three-legged Al Burj, Dubai, with Pei Partnership Architects (2004–2006); the 1,000-meter, four-legged Nakheel Tall Tower in Dubai, with Woods Bagot and WSP (2006–2008); the competition design of the 1001+-meter Kingdom Tower in Riyadh, with Kohn Pedersen Fox Associates (2009); and the 1,600-meter (mile-high) Next Tokyo Tower in Tokyo, Japan, with Kohn Pedersen Fox Associates (designed in 2014, looking to 2065), which was envisioned as a leader of a new generation of high-rise buildings.

Additionally, the structural grouping of towers provides enhanced life-safety, efficiency, sustainability, and robustness. Wind tunnel tests demonstrate clearly the significant reduction in wind loads through the vertical long slots between the "legs" of the tower. Designs include three slots, as in the Al Burj; four slots, as in the Nakheel Tall Tower and the Kingdom Tower; and three slots offset in plan, as in the Next Tokyo Tower. The structural system of these towers is integrated into the architecture, such that the architecture and the structure are one.

Bank of China Tower, Hong Kong, 1989

The 368-meter Bank of China Tower was the tallest building in the world outside of New York and Chicago at the time of its completion (see Figure 1). The lateral loads acting on the tower from the typhoon winds of Hong Kong are four times the seismic load of towers built in Los Angeles, and twice the wind loads of New York City. Unlike most tall buildings in Asia and the Middle East, the Bank of China has all of its lateral load-resisting system on the perimeter; that is, the central services core, made of structural steel and not reinforced concrete, is not a part of the lateral load-resisting system.



Figure 1. Bank of China Tower, Hong Kong—all of its lateral load-resisting system are on the perimeter. © Terri Meyer Boake

The floor framing consists of concrete slabs over profiled metal deck, acting compositely with the steel floor beams which, in turn, are supported on small steel perimeter columns. The loads in the perimeter steel columns are transferred out at every belt truss level, which are on a 13-floor module. The belt trusses in turn transfer their gravity loads to the megacolumns, where the gravity loads help counteract the large uplift loads from the wind overturning moments.

Full height steel columns are embedded in the composite megacolumns to transfer the vertical load from the perimeter steel bracing to the concrete work of the megacolumn. As well, these steel columns allowed the construction of the steelwork to proceed in advance of the concreting of the megacolumns thus speeding up the construction; in addition to the vertical loads from the steel bracing, the embedded steel columns were designed to support the weight of about fourteen floors of steelwork.

The building structure was designed to be robust and redundant. Every member in the perimeter steelwork was designed for disproportionate collapse. For the disproportionate collapse scenario, built into the structural design were multiple load paths for the structural members. As an example, the small perimeter columns were designed to act as columns in compression, and as hangers in tension.

This composite megastructure system was the first in the world. The amount of structural steel used in the project is low compared to many other projects. As well, according to the steel contractor, the steel welding per ton of steel was half of what they have found in other projects.

Shanghai World Financial Center (SWFC), Shanghai, 2007

The first use of outriggers in a major high-rise building was in the original twin towers of the World Trade Center in New York. There, the outriggers, located at the top of the towers, reached out from the structural steel columns of the services core to the perimeter columns. These outriggers played a critical role in redistributing the column loads, allowing the towers to stand up as long as they did in the September 11 attacks.

For the Shanghai World Financial Center (SWFC), the original 460-meter design, by another engineer, was a perimeter moment frame system coupled with a heavy concrete services core. When Mori Building, the developer, decided to increase the height from 460 meters to 492 meters and to make the building 16 percent larger in area, all while re-using the existing piling which had been constructed for the shorter building, the structural system was changed to a lighter, but stiffer, perimeter bracing system which allowed the thinning of the concrete shear walls of the services core (see Figure 3). The redesigned building was modestly lighter than the original shorter building, thus permitting the use of the existing piling. It was the tallest building in China at the time of its completion. The

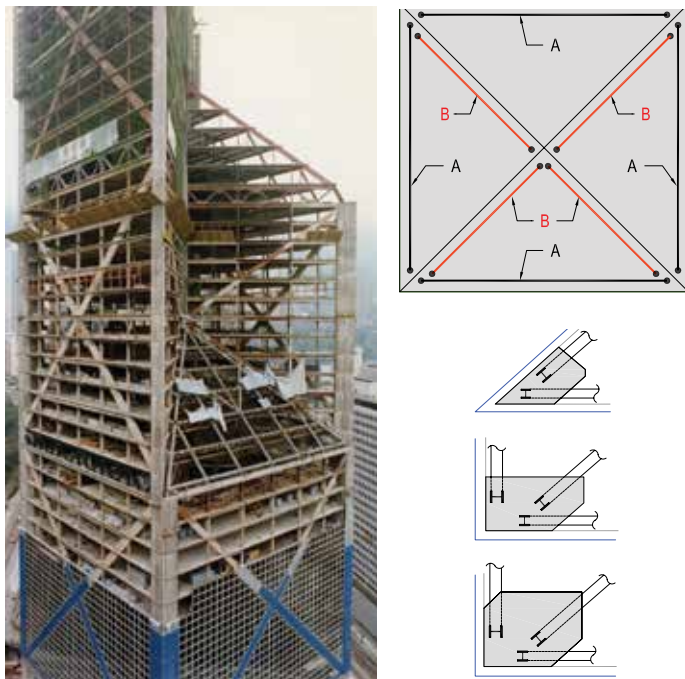


Figure 2. The composite megastructure system acts as a space truss but devoid of three-dimensional connections. © Pei Cobb Freed & Partners (left) & Leslie E. Robertson Associates (right)

The composite megastructure system, consisting of the perimeter plane trusses, knitted together by reinforced concrete at the joints, acts as a space truss but devoid of three-dimensional connections (see Figure 2). Note that the plane trusses do not intersect with each other; the design allows the transfer of their loads to the composite megacolumn without creating bending moments in that column.

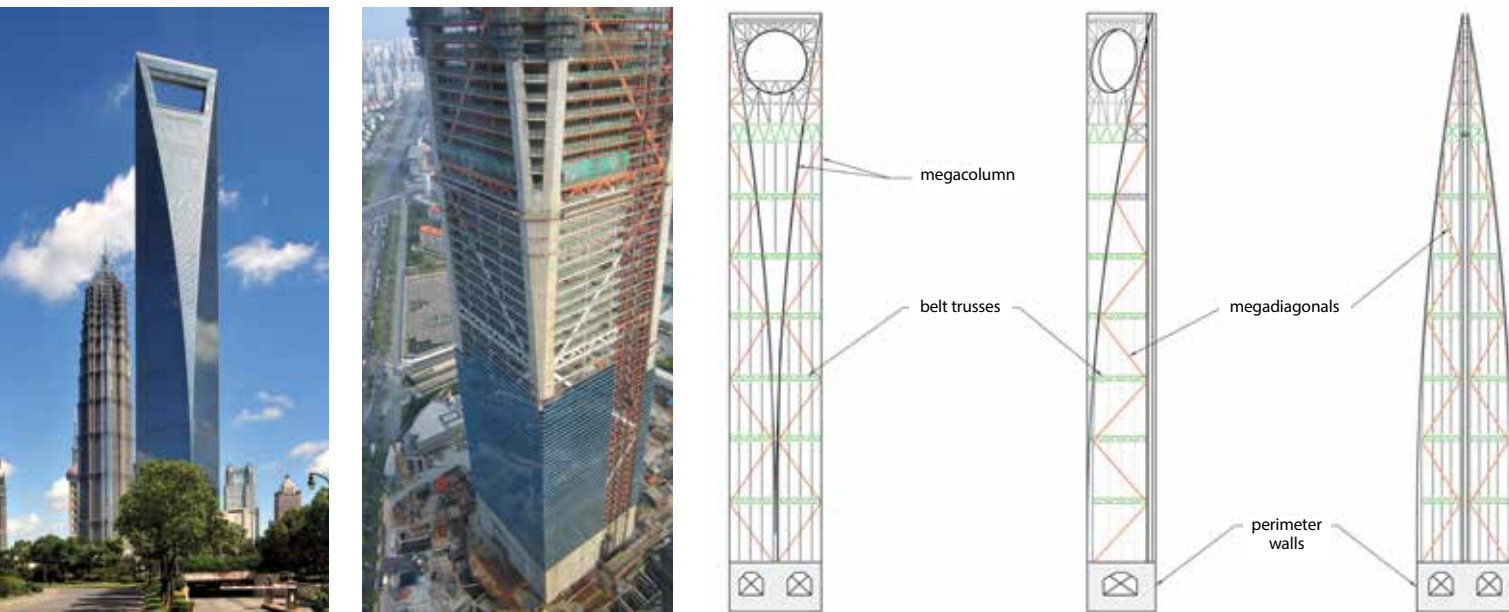


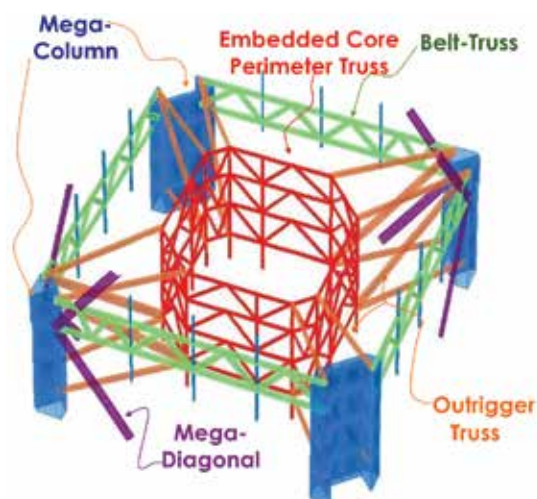
Figure 3. The composite megastructure system acts as a space truss but devoid of three-dimensional connections. © Mori Building (left), © Leslie E. Robertson Associates (middle and right)

steel outriggers reduce the wind-induced overturning moment acting on the concrete shear walls of the central services core. Due to the connection of the outriggers to the services core and to the composite megacolumns, the stance of the tower, in resisting the overturning moments from wind and earthquake, was enhanced. Unlike other buildings, the outriggers were located around the services core instead of through the core (see Figure 4).

Full height steel columns were embedded, both in the concrete core walls, and in the composite megacolumns, to transfer the vertical load from the steel outrigger diagonals and the perimeter steel bracing to the concrete work of the megacolumns. As well, these steel columns allowed the construction of the steelwork to proceed in advance of both the concreting of the concrete services core and of the megacolumns; in addition to the overturning forces created by the wind, the embedded steel columns were designed to support the weight of about fourteen floors of steelwork.

As for the Bank of China, Hong Kong, small perimeter columns, on a twelve-story module, are transferred to the one-story belt trusses which in turn transfer their load to the megacolumns. However, the perimeter diagonal bracing is not always architecturally modular with the floor because of the slope of two faces of the building. The design for robustness and disproportionate collapse, while similar in some ways to the Bank of China, was complicated by the presence of the concrete services core. With the creep and shrinkage of the concrete core, in addition to the creep and shrinkage of the composite megacolumns, the small, steel perimeter columns were designed with higher yield strength steel to reduce their stiffness, thus ameliorating the attraction of additional loads from creep and shrinkage.

Floor 28 to Floor 31



Outrigger Truss – Floor 67

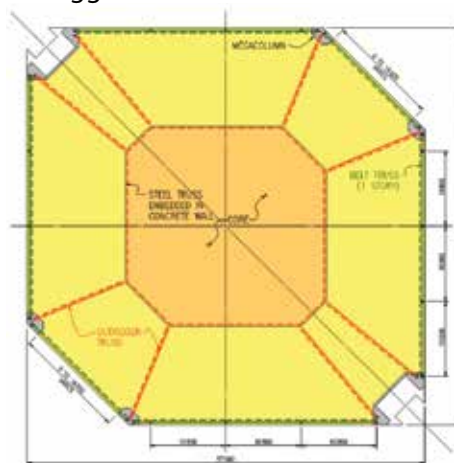


Figure 4. The connection of the outriggers to the services core and to the composite mega-columns; unlike other buildings, the outriggers are located around the services core instead of through the core. © Leslie E. Robertson Associates



Figure 5. The Lotte World Tower is the tallest building in South Korea. © Lotte Group (left), Leslie E. Robertson Associates (right)

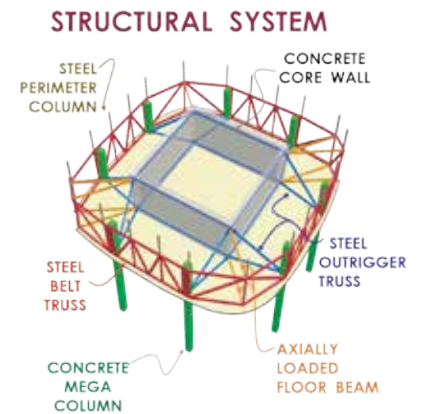


Figure 6. The primary lateral load-resisting system for Lotte is the concrete shear walls at the services core. © Lotte Group

In much of the Far East, refuge floors are required, and they occur on a twelve-to-thirteen floor module. Hence the belt trusses are located at the refuge floors, and not at the occupied floors.

Lotte World Tower, Seoul, 2014

The Lotte World Tower at 555 meters is now the tallest building in South Korea (see Figure 5). The megastructure consists of a concrete services core coupled to the eight megacolumns via steel outriggers. Unlike the Bank of China and SWFC, both of which had perimeter steel bracing, the primary lateral load-resisting system for Lotte is the concrete shear walls at the services core. Therefore, the jump-forming of the concrete core walls, before the erection of the steelwork, was critical to the stability of the temporary construction (see Figure 6).

Except at the outrigger floors where there are short stubs of steel columns for the outrigger diagonal and chord connections, there were no embedded steel columns in the concrete core walls nor in the megacolumns. The steel belt trusses frame to the outside face of the megacolumn, allowing the jump-forming of the mostly concrete megacolumns, to proceed without the erection of the belt trusses.

As Lotte preferred to have large clear spans at the office floors, there were no small perimeter columns between the megacolumns. The distance between the centerlines of the megacolumns range from 27.5 meters at the ground floor to 21.7 meters at the 75th floor. The small perimeter columns were constructed only at the hotel floors occurring above the office floors.

The design for robustness and disproportionate collapse was along the same principles as for the Bank of China and SWFC.

PNB118, Kuala Lumpur (estimated completion in 2021)

This 644-meter tall mixed-use tower, now under construction, will be the tallest building in Malaysia when completed. The megastructure has many of the components found in current high-rise buildings: steel outriggers, steel belt trusses, megacolumns, and concrete shear walls in the services core (see Figure 7).

The geometric profile has heavier wind loads than one would anticipate from the relatively benign wind climate of Malaysia. This was confirmed by two separate wind engineering laboratories. As in Lotte, the primary lateral load-resisting



Figure 7. PNB118, Kuala Lumpur, will be the tallest building in Malaysia when completed. © PNB Merdeka Ventures Sdn. Bhd.

system for PNB118 consists of the concrete shear walls at the services core. Therefore, the jump-forming of the concrete core walls, before the erection of any of the steelwork, was critical to the stability of the temporary construction.

Drawing from the experience and lessons learned from the previous projects, and with steel subject to significant import duties in Malaysia, the megacolumns were designed to be primarily of concrete, with only a minimal amount of structural steel. Where the steel outrigger diagonals connect to the concrete core walls and to the megacolumns, the transfer of the vertical load is accomplished through bearing plates. Therefore, except at the outrigger floors, there are no embedded structural steel columns in the core walls nor in the megacolumns. This is quite different from the Bank of China and SWFC. However, as in all those projects, robustness and redundancy are built into the critical structural systems.

Al Burj, Dubai (design 2004–2006)

This three-legged tower was originally designed to be 1,000 meters tall. There are three separate buildings interconnected to each other at intervals, creating the skybridge levels. Additionally, there are trusses in the vertical slots “zipping” the legs together, thereby making the three sections of the tower act as one (see Figure 8). Between the legs of the tower are vertical slots where the wind may flow freely through the spaces between the buildings. The air flow through these vertical slots enhance aerodynamic damping, thus significantly reducing the wind loads on the tower. The concrete core walls provide the bulk of the lateral stability. There are skybridge floors over the height of the building where all three legs are fully connected across through full-floor diaphragms. At these skybridge floors, occupants are able to transfer from the elevator/stair of one tower to any of the other towers, thus enhancing life-safety, robustness and redundancy.

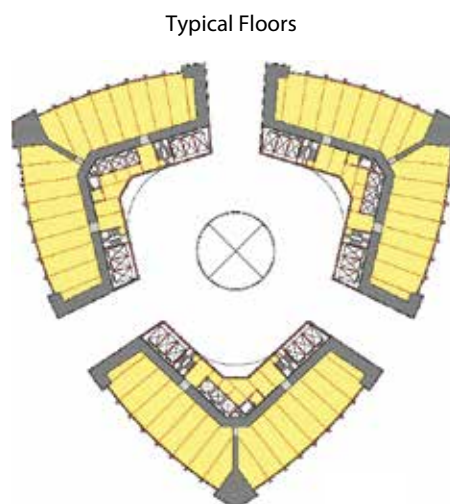
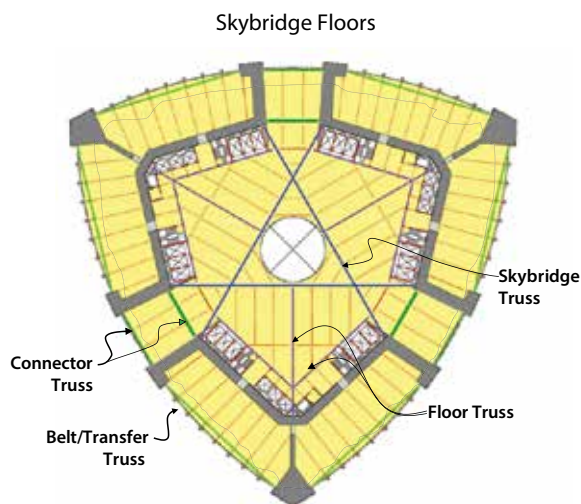


Figure 8. Al Burj, Dubai, there are trusses in the vertical slots “zipping” the legs together, thereby making the three sections of the tower act as one. © Pei Partnership Architects

Nakheel Tall Tower, Dubai (design 2006–2008)

With a change in the design team, and other programming changes, the Al Burj, Dubai project was modified to a four-legged tower (see Figure 9). However, the four-slot configuration was less effective than the three-slot tower in reducing wind loads and dynamic response of the building. Foundations were constructed before the project was put on hold by the economic recession of 2008.

Within the vertical slots are vertical trusses—so-called “zippers”—connecting the four concrete towers. These trusses then change the stiffness and the strength of the building from four isolated towers into a unified whole. They are essential to both the wind- and the earthquake-resisting structural systems. The trusses are a continuation of and in the plane of the inner concrete drum.

There are five small perimeter columns in each of the four quadrants. The loads of these columns are transferred at every skybridge level by a five-story perimeter belt truss. There are six skybridge levels where all four towers connect via full floors and where occupants are able to transfer from the elevator/stair of one tower to any of the other three towers, thus provides enhanced safety to building occupants.

Kingdom Tower Competition Design, Riyadh, 2009

The competition was for a 1001+-meter-high tower. Here, the use of vertical long slots, combined with a three-legged tower, and a gently tapering profile, proved to be very efficient in reducing wind loads on the building and created an exciting building form (see Figure 10).

Each of the three buildings is constructed as a stand-alone entity, but linked by trusses within the slots between the

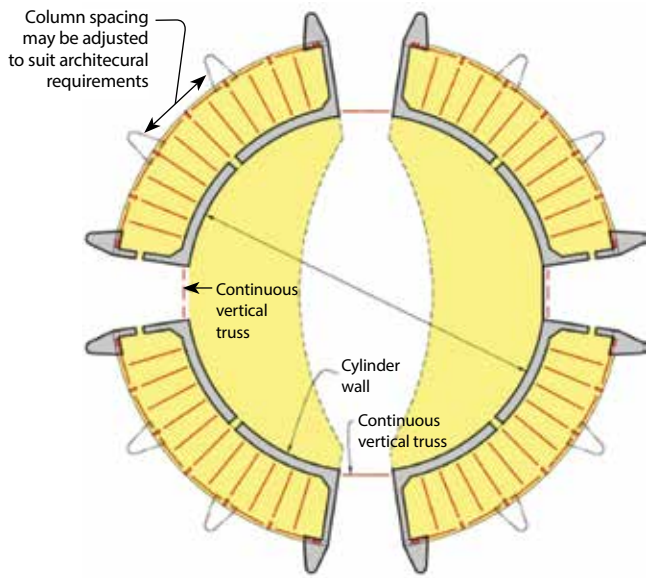


Figure 9. Nakheel Tall Tower design, Dubai. © Woods Bagot

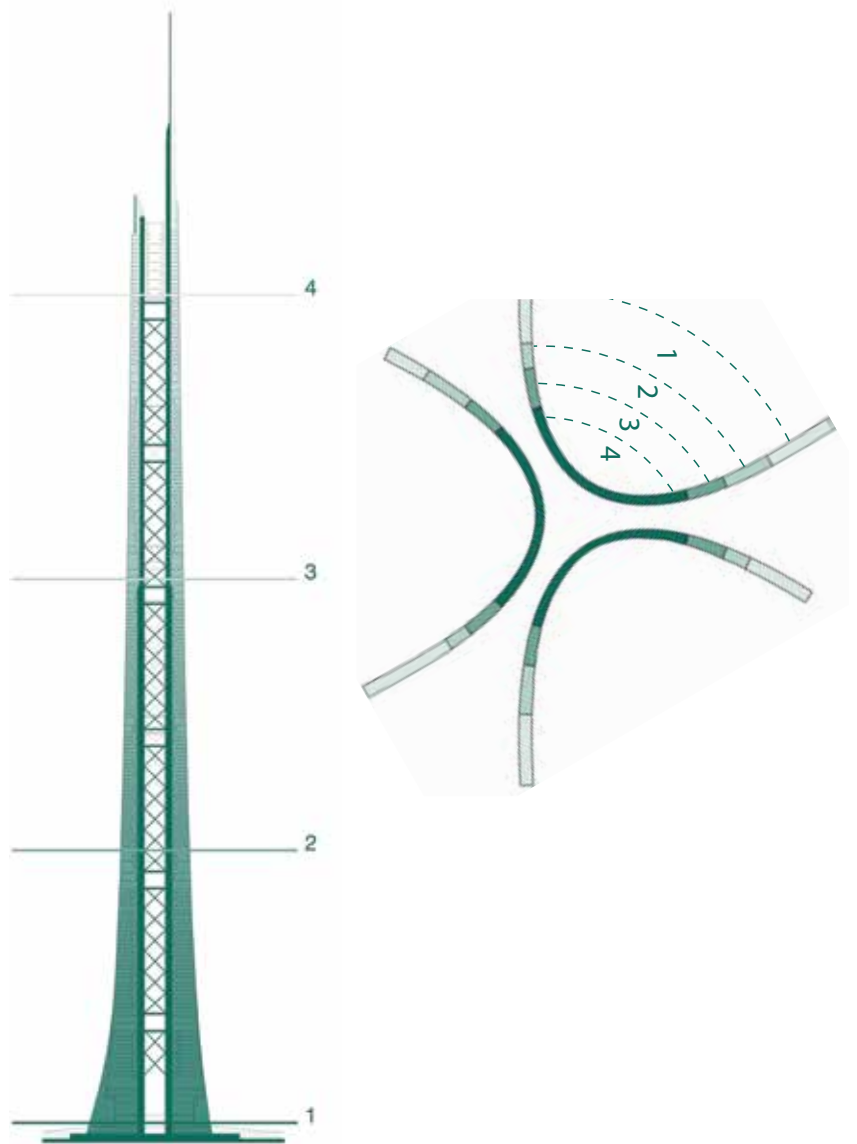


Figure 10. Kingdom Tower competition design, Riyadh—a gently tapering profile efficiently reduces wind loads on the building. © Kohn Pedersen Fox Associates

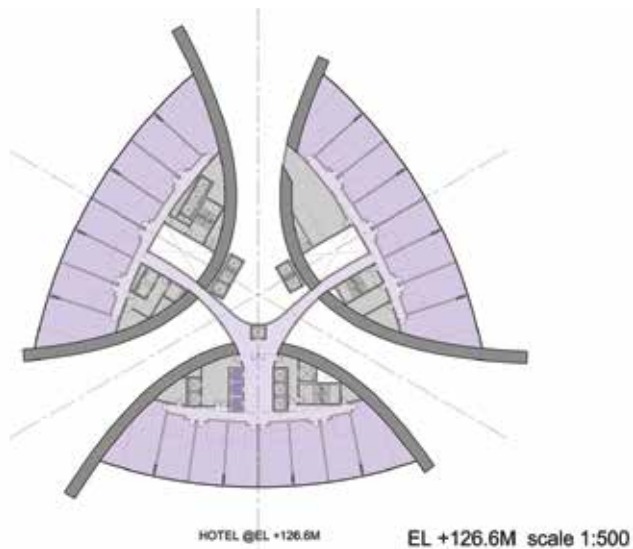


Figure 11. Integration of the three buildings provides the fundamental gravity- and lateral-force resisting system. © Kohn Pedersen Fox Associates

buildings and at the lift transfer floors. The swooping concrete walls of the three buildings are linked vertically with trusses and horizontally at the lift transfer floors. This integration of the three buildings provides the fundamental gravity- and lateral-force resisting system (see Figure 11).

The slots provided significant levels of aerodynamic damping, in excess of that provided by more conventional construction. Air flow through the slots is effective in reducing significantly the level of wind-induced aerodynamic excitation.

Unlike conventional structures for high-rise buildings, the structural design contemplates only one structural system. That is, the gravity- and the lateral-force (wind and earthquake) resisting systems are one and the same. Because of this approach, with wall thicknesses determined largely by gravity loads, the lateral forces are carried with little cost or construction time penalties.

There is no need for outrigger trusses, or other complexities. Curving gracefully and efficiently up the building, the plan shape of the concrete walls is constant over the full height of the building, with only the two extreme edges tapering toward the center of each building. Enlarging the lengths of the concrete walls in the lower reaches of the building creates an elegant form while simultaneously creating a stronger and stiffer structural profile.

Wall thicknesses change in digital steps, the outside (convex) face of the concrete walls is held vertical for the full height of the building. With the concrete walls being longer at the lower portions of the building, wall thicknesses are substantially reduced, thus reducing substantially the requirements for specialized curing, thermal control, and the like.

Intrinsic in the continuum of the sweeping concrete walls, is a level of robustness and redundancy that may never have been achieved in the structural systems of prior high-rise buildings.

Next Tokyo Tower, Tokyo, Japan (concept design in 2014, envisioned for 2045)

This was a study of a theoretically possible super high-rise to be built at some time in the future. The concept was part of an initiative called “Next Tokyo” and was broadcast on Japanese television. The proposed structural designs, unlike anything constructed in the past, include sets of three buildings rotated 60 degrees with respect to the three buildings both below and above (see Figure 12). The system is uniquely open, allowing for the free flow of wind-driven air between the sets of three buildings, creating a high level of aerodynamic damping and thus reducing the wind-created oscillation of the towers. Additionally, the tower tapers as it reaches to the sky, further reducing the wind loads on the tower.

The 1,600-meter tower is a slotted, tapered form with a hollow, open-air center. The overall footprint is hexagonally-shaped, with trapezoidal building legs staggered and shifted vertically. At each of the tower’s full-floor transfer decks, the six building legs are linked together over several stories, integrating the six buildings into a single tower. At these overlaps, elevator transfers, stair transfers and other life safety services are integrated. Hence should elevators or stairs be disabled in one of the buildings, alternate paths exist at these overlapping common floors. This concept was first employed in the Al Burj Tower.

Even in the highly seismically active regions of the world, for high-rise buildings, the design requirements for wind exceed that for earthquakes; for buildings of this height, the lateral pressures from the wind exceed the imposed vertical loads on the floors. The primary concern is to ameliorate the structure motions and stresses imposed by the wind.

At the perimeter, small columns support the floor framing. These perimeter columns are supported on belt trusses spaced at 30- or 40-story intervals; these belt trusses transfer all the perimeter column loads to the concrete walls.

Megabracing on the inner face of each of the buildings, combined with concrete shear walls at the sides, provides the basic lateral force system for each of the three buildings in each set. Concrete, then, is used to carry the larger loads—essentially, the entire weight of the building—and does so with small levels of bending moment. This becomes possible because of the high level of stiffness of the perimeter walls.

At the overlapping common floors, large-scale steel trusses connect the two sets of three buildings into a unified structure. These are plane frames in structural steel, bound into a space structure by the concrete work. In this way, the steelwork does not have three-dimensional connections, thus eliminating cross-grain stress in the steelwork. Steel-to-steel connections, whether welded or bolted, are robust and redundant, two dimensional, uncomplicated, constructible, and economical.

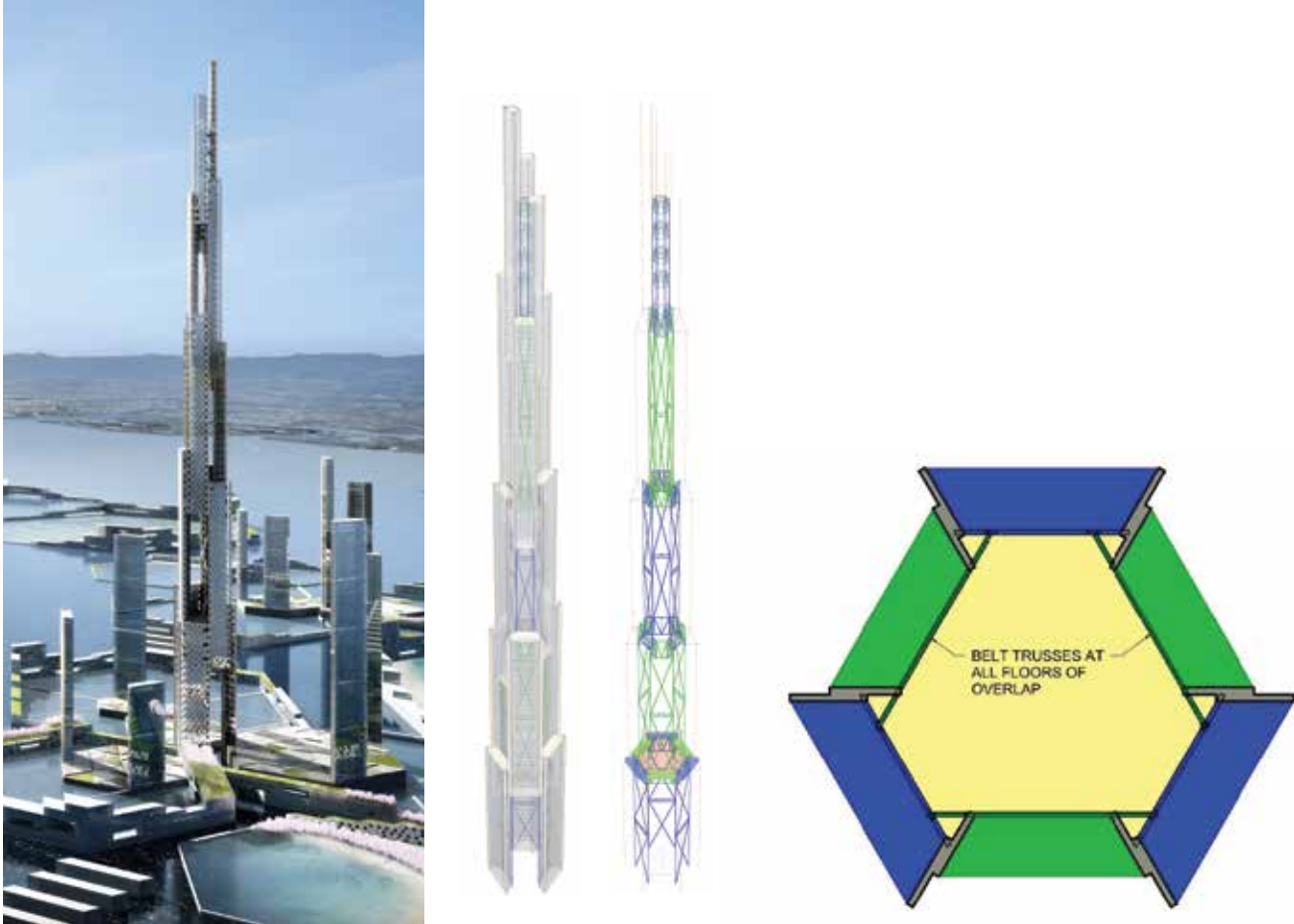


Figure 12. Next Tokyo Tower is unlike anything constructed in the past. © Kohn Pedersen Fox Associates

Conclusion

The design of the twin towers of the World Trade Center in New York in the early sixties included many innovations and firsts, some of which include: the first use of outriggers in a high-rise, the first use of the boundary layer wind tunnel testing for the design for wind loads, the first use of dampers to mitigate a building's motion due to wind, the use of pre-fabricated structural assemblies, the first use of digital information in the bidding and construction documents; and the first testing of humans for the perception to building motions. Since then, the structural engineering of tall buildings has progressed to include more outriggers, belt trusses, composite construction,

more varieties of structural damping systems; all of which are commonly found in all major tall buildings. Some of the current slender tall buildings rely on the use of dampers and "holes" through the buildings to make them perform well in the wind.

The next generation of very tall buildings should incorporate vertical long slots and multiple towers grouped into a building; the structural grouping of towers provides enhanced life-safety, efficiency, sustainability, and robustness.

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