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# Anything Goes?

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**Abstract**

When Cole Porter wrote the song "*Anything Goes*" in 1934, he did not include skyscraper examples. The recently completed Chrysler and Empire State buildings followed decades of tall building development in a logical and predictable line. Today, dramatic improvements in materials and methods of analysis, design and fabrication have given architects and engineers freedom to imagine, and contractors to build, towers in configurations never seen before. If writing now, Porter would surely have mentioned such designs to demonstrate anything goes. Or does it? This article explores the possibilities and challenges of tall building structural design through current and proposed projects. Examples include engineering buildings with outward forms that appear structurally unfavorable and taking advantage of load reduction through shaping opportunities.

**Keywords:** High-rise buildings, Anything goes?

## 1. Introduction

'Pushing the envelope' and 'Thinking outside the box' are widely used expressions. While 'envelope' originally referred to aircraft performance limits, and 'box' to the boundaries of a nine-dot puzzle, these days both phrases could easily relate to building design and construction. Digital modeling, designing, detailing and fabrication tools developed in recent years have made unusual shapes and complex geometries practical to construct, if not necessarily the most economical solutions. Current and planned cutting-edge buildings are indeed pushing building envelopes to new shapes, and those shapes are often far from boxy. As composer Cole Porter named his song, "*Anything Goes.*"

In the world of tall towers, does anything goes still apply? On one hand, big buildings have big budgets and the potential for economies of scale: research and testing for determining performance of a cutting-edge technology may be too great a cost for a small project, and small production runs may result in high unit costs, but the reverse is true for a mega project. For a large building, it can make sense to create and dedicate a factory to manufacture a custom design, where the performance payoff is great enough. On the other hand, size and scale pose their own challenges, including the need to consider four non-negotiable conditions: gravity load, wind behavior, earthquake response and geometric limitations. One or more conditions can govern building structural design, based on the direction of the overall building concept. Rather than 'anything goes,' a better, if less catchy phrase might be 'any goal by taking the right direction.' Key decisions make the difference between theoretically possible but unaffordable concept sketches and practical, affordable completed buildings. Identifying key decisions early and finalizing them as a collaborative process within the ownership/design/construction team is essential, as will be shown through case histories of contemporary projects.

Let's start with gravity, a constant and ubiquitous effect that cannot be ignored. What if we actually push the (building) envelope over, literally, by building on a slant? Gravity creates a tower overturning moment with zero story shear force. The 26-story, 374-ft (114 m) mirror-image Puerta de Europa towers in Madrid, Spain designed by Philip Johnson/John Burgee and engineer Leslie E. Robertson Associates and completed in 1996, lean toward each other by 15 degrees from vertical. The concept is visually simple: the side elevation of each tower is a parallelogram with the outer edge of the roof almost over the inner edge at the ground. See Figure 1. In theory a building of uniform density could simply balance its weight on that inner corner. In practice balancing a building on a fulcrum leaves no reserve against additional moments from wind or earthquakes. Directing load to such a balance point would also be difficult, as floors in tall narrow buildings typically span from perimeter columns to a central core, which is needed anyway for vertical circulation and services (elevators and stairs, water, power and telecom risers). Even for a core located near the inside bottom corner to fit vertically within the parallelogram shape, gravity loads will not conveniently flow to the inside corner. In theory a core could resist the overturning moment, but it would be impractically costly

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**Figure 1.** Puerta de Europa Elevation. Credit: Royal Production, Philip John/Alan Ritchie Architects.

for a gravity overturning moment many times greater than the wind overturning moment. Connecting the outer sloping face to the core where they meet at the roof uses geometry to advantage, creating a tall, stiff triangle against overturning. Triangulation, however, is only a partial solution to the challenge due to load reversal and strain effects.

The outer sloping face columns could cycle between tension and compression from minor lateral loads, complicating determination of effective stiffness and splice designs. Construction-phase strains are also complicated: overturning effects deform the entire building as upper levels are built, potentially pulling lower floors out of alignment, but the triangulation achieved at the top could lock in misalignments whether intentional or not. Long-term strains in central core concrete will occur from shrinkage as its relative humidity approaches that of conditioned air in the building, and from creep under sustained load such as dead load, a continued increase in strain over time that gradually slows years after construction. Where compressive stress varies due to flexure, creep will exaggerate core curvature and upper floor displacements.

The engineer's solution to all these concerns was post-tensioning, running high strength tendons along the outer sloping face from a 15,400 ton (14,000 tonne) counterweight below grade to jacking points at the roof level. Tensioning the tendons compresses the outer face columns, keeping joints in contact for maximum stiffness. As the outer face columns shorten from induced compressive strain, the horizontal component of that movement draws the roof level and core top sideways, creating a righting moment that offsets base overturning and minimizes stress differences across the core and resulting deformations from differences in creep. While not supertall buildings, the Puerta de Europa towers illustrate the complex and subtle ways that arbitrary forms can affect building strength and behavior, the value of strategic decisions to provide effective solutions to such challenges and the cost premiums associated with unusual designs.

Another visually dramatic building design with both gravity and seismic challenges is the CCTV Headquarters building in Beijing, China. The design by Rem Koolhass of the firm Office of Metropolitan Architecture (OMA) was engineered by Arup. Two towers sloping six degrees are joined at the base by a building extension forming an L in plan. The towers are also joined at the upper floors by an opposite L in plan as separate cantilevers meet at a right angle to form a bent torsional tube. See Figures 2(a) and 2(b).

At 49 stories and 768 ft (234 m) in height the building is not a supertall tower, but presents numerous design challenges. Its large cantilevers mean that balancing gravity loads about a tower edge is not remotely possible. Gravity overturning must be resisted by the structure. The designers chose to develop maximum stiffness by bracing

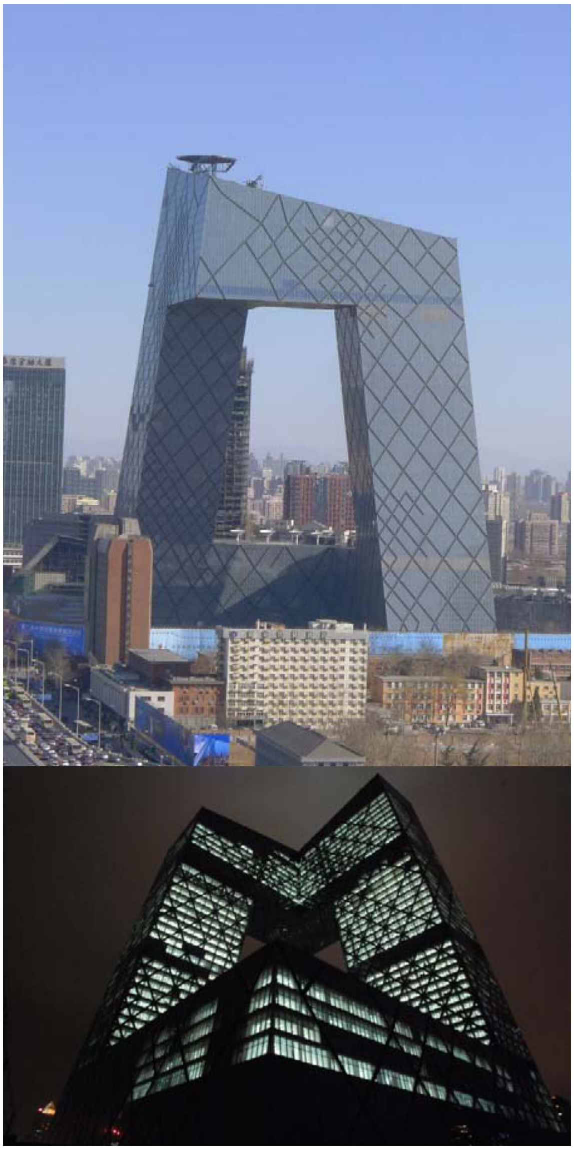


**Figure 2.** CCTV Headquarters in Beigjing, China by day and night.

the building perimeter to create a continuous tube that runs seamlessly from base to towers to cantilevers. Using the full tower width maximizes stiffness against overturning, and running the bracing continuously around building corners creates a closed tube shape that is very stiff against torsion. This was more efficient and effective than relying on slender internal cores and separate cantilever framing. The ability to resist lateral loads by a combination of moment and torsion is also beneficial when considering the eccentric seismic and wind load distributions that result from the unique building shape. Required strength is provided at critical points in the continuous tube by locally adding structural materials, inserting additional brace members at the most highly stressed corners at half the usual spacing and opening up brace spacing at the least stressed locations. The braces can be seen in the night photo and are expressed on the façade in the day photo. The continuous tube approach did not address all challenges, as transfer truss systems were inserted in each tower to support upper floor vertical gravity columns that would be interrupted by the sloping faces below.

The continuous tube of steel bracing addressed deflection concerns both during construction and over the building's life. The structure is stiff enough that construction-phase deformations were manageably small, and steel does not creep or shrink, so additional dead load deflections would not occur once construction was completed. Acceptable seismic behavior was verified by advanced analyses, a form of performance based design. CCTV Headquarters inevitably inspires the reaction, "Wow, how did they do that?" The short answer is lots of analysis and lots of structural material.

Unusual perimeter geometry is the central idea behind Aqua Tower in Chicago, Illinois, USA. Conventional concrete columns and flat plate floors nine inches (229 mm) thick support typical rectangular floor plans 16,000 $ft^2$ (1490 $m^2$) in area. What makes the 88-story, 874-ft (266 m) tower unique is its exterior balconies. Studio/Gang/Architects designed balconies with curved edges that vary from story to story and along each floor level to create a surprisingly flowing, organic visual effect evoking a rippled surface. See Figures 3(a) and 3(b).

The challenge for structural engineer Magnusson Klemencic Associates and contractor James McHugh Construction Company was to make construction of these balconies practical and efficient. The projections of up to 12 ft (3.7 m) were cantilevered as extensions of the main floor slab, but tapered to reduce weigh at the tip and enhance drainage. The free-form curves were transferred from the design drawings onto a uniform width band of perimeter formwork sized to fit the largest balcony plus working room. The slab perimeter was established by a flexible edge forming angle, fixed to a different location on every floor based on working points set out with remarkable accuracy by a computerized surveying system. See Figure 3(c). The process went so smoothly that a three-day production cycle was typically met. This was an example of the ability for modern documentation and production methods to efficiently construct seemingly complex geometric variations.

Taller towers tend to have less extreme architectural moves. Larger costs are associated with larger scales, and this applies to the premium for special features as well. Even so, there are plenty of challenges to address in modern high-rise designs. At 1483 ft (452 m) the Cesar Pelli design of the Petronas Towers in Kuala Lumpur, Malaysia was the tallest building in the world upon completion in 1998. To control costs the design was developed in collaboration with engineers Thornton Tomasetti with structural efficiency in mind, but it still posed both subtle and obvious challenges. A subtle gravity issue was

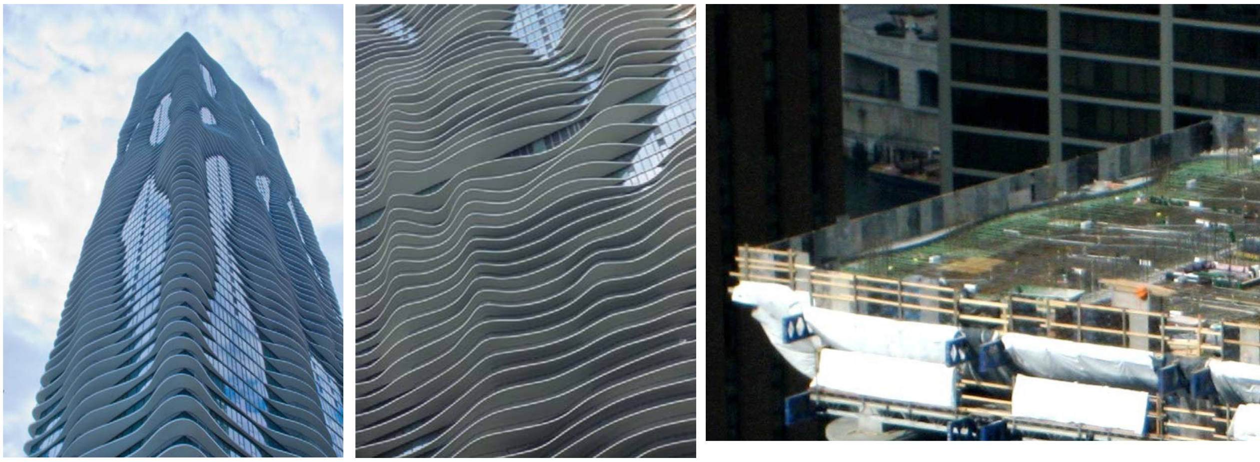


**Figure 3.** Aqua Tower, Chicago uses continuously varying balcony dimensions to create an organic ripple effect from a curved edge form. Credits: Matthew Huizinga, Steve Rohr, Jonathan Block, Thornton Tomasetti.

**Figure 4.** Petronas Towers, Malaysia. Credit: Michael Goodman.

the presence of large setbacks at levels 60, 73, 82 and 84M3. See Figure 4. Column offsets would conventionally be provided by transfer girders, but the extra story height needed to fit such girders would conflict with the uniform heights needed for the double deck elevator system, which provided remarkably compact cores. The solution was to slope the columns radially inward over several stories below each setback. See Figure 5. The column kinks create symmetrical horizontal thrusts resolved by radial and hoop reinforcement.

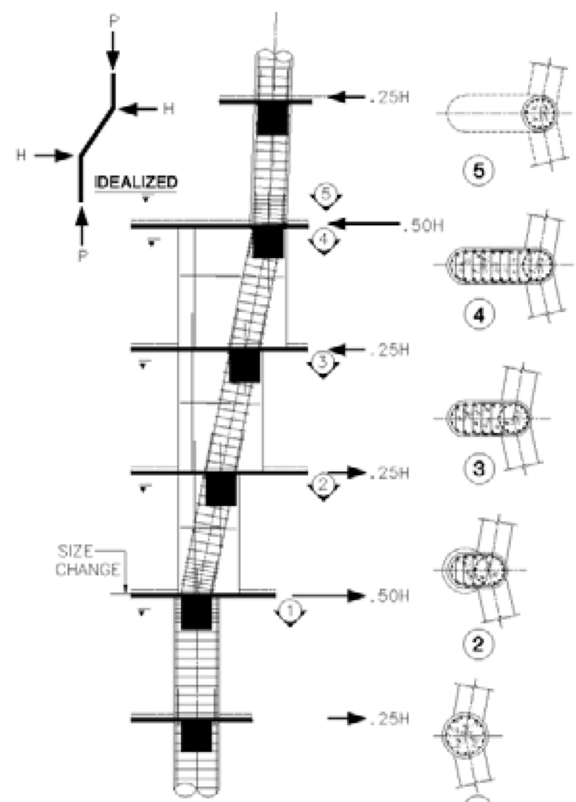



**Figure 5.** Sloped column.

For tall, slender towers crosswind response can be a

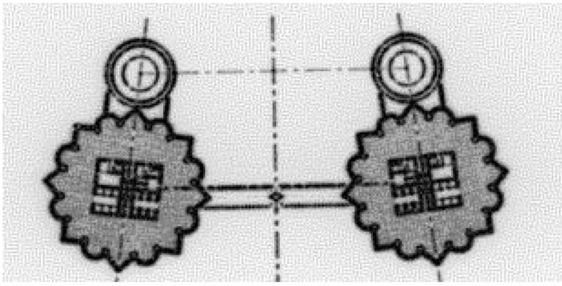


**Figure 6.** Point and Arc plans.

**Figure 7.** Bridge leg bearing.

significant issue due to vortex shedding behavior. This is particularly true when two similar towers are in close proximity, as vortices shed by an upwind tower will naturally excite the downwind tower. The highly articulated façade of these buildings, alternating eight points and eight arcs on each floor plan, naturally suppressed vortex formation and minimized wind interaction between the towers. See Figure 6. The compact cores visible in the plans resist about half the overturning forces, with perimeter moment frames fit below the points and arcs resisting the other half. It helps that Kuala Lumpur has a mild wind environment.

Geometric requirements were important when developing the skybridge design. Sloping legs were determined to be sufficiently flexible that the cost of leg pins at the arch crown was avoided, while a vertical pin and slide bearings form an arch crown turntable that allows for bridge deck rotation from towers leaning perpendicular to the bridge axis. Bridge end bearings permit in-out sliding to allow for towers moving in opposite directions, and plan rotation to work with the turntable, while bearings at leg tips allow for rotation in multiple axes when the towers 'dance' differently. See Figure 7. Bridge deck framing is also capable of spanning without arch support, but with large deformations, as a disproportionate collapse control measure.

Lateral forces dominate design of vertical superall towers. At Taipei 101 in Taipei, Taiwan, a record breaker in 2004 at 1666 ft (508 m), the design by C.Y. Lee & Associates evokes tiered pagodas and upward-opening flowers. See Figure 8. While most of the tower is composed of eight eight-story gradually flaring modules, the variation is small enough that wind behavior is comparable to a tower of uniform width. This can result in large crosswind excitation forces, as the long periods and large floor plan dimensions of supertall towers can lead to resonance with vortex induced oscillations at typhoon wind speeds. The most effective way to reduce these forces is to disrupt the formation of vortices along building corners. On this project, wind tunnel testing showed that double-notched corners would be more effective than chamfered or rounded corners of comparable size. See Figures 9, 10. The double notched configuration also provides 12 corner office locations per floor, a real estate benefit. A publicly visible tuned mass damper at the observation deck further reduces building movements for occupant comfort in windy conditions.

**Figure 8.** Taipei 101 shows tapering modules. Credit: Dugald Mackay courtesy C. Y. Lee & Associates.

Even with vortex-disrupting corner shapes and supple-

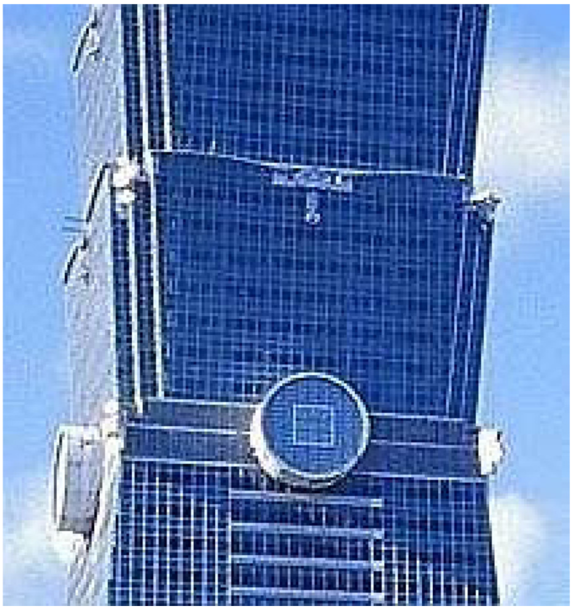


**Figure 9.** Double notched corners reduce vortex shedding.

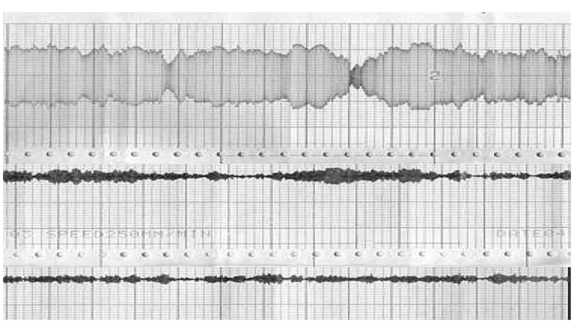


**Figure 10.** Aeroelastic model traces show dramatic base moment reduction from square corners (top) to double notches with low and higher damping (middle and lower).

mental damping, substantial overturning stiffness and strength is required to resist the lateral loads on this tall, narrow building. Engineers Thornton Tomasetti and Evergreen provided stiffness and strength by a steel-braced core and outrigger system, as local construction practice supported steel framing and its lesser building mass reduces seismic demand. For economical stiffness enhancement the core and outrigger columns consist of steel boxes filled with stiff high strength concrete for most of their height. Frequent outriggers coincide with refuge/mechanical floors to maximize overall efficiency. See Figure 11. Outrigger columns, which carry all perimeter gravity loads, run vertically and are located within the narrower floor plan as following the upper façade slopes and setbacks was determined to be impractical. The columns flare at the base. Perimeter steel moment frames do follow the sloping upper façade planes, both providing the special moment frames of the tower's dual system and transferring the gravity loads of individual

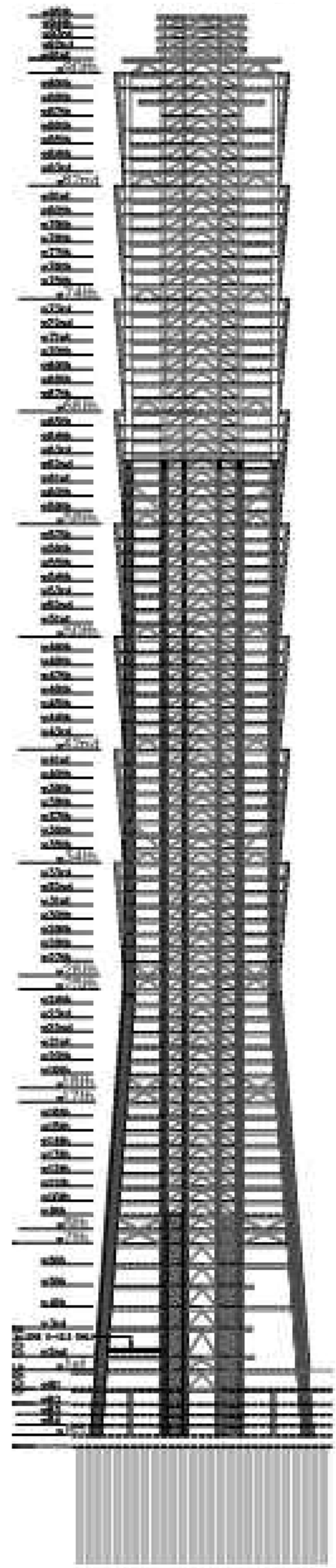


**Figure 11.** Taipei 101 braced core and outrigger system with concrete filled box columns shown shaded.

floors to outrigger columns through setback trusses. Those moment frames and ductile reduced-beam-section details on braced core coupling beams provide a dual system for seismic performance. Taipei 101 exemplifies ways that unusual features are addressed through creative shaping and innovative structural design.

A new supertall tower rising on a windy coastal site is the 1972 ft (600 m) Incheon 151 in Incheon, South Korea. The John Portman & Associates design is based on mirrored triangular extrusions with facing truncated peaks. Engineer Thornton Tomasetti linked the two vertical elements by rigid skybridges to form a stiff ladder. Although wind will flow through the slot between the towers, sharp building corners could be a source of troublesome vortex shedding for some directions. Aerodynamic alternatives such as rounding or roughening the corners were inconsistent with the aesthetic intent. The solution was to maintain the knife-edge corners, but suppress vortex formation by bleeding air through slots adjacent to the corner. See Figure 12.

**Figure 12.** Incheon 151 in South Korea uses slots to disrupt vortex formation. Credit: John Portman & Associates.

Wind, earthquake and geometry all play a role in the design of Shanghai Tower in Shanghai, China by Gensler. The competition-winning, 2073 ft (632 m) design is based on a rounded triangular perimeter plan that turns and shrinks as it rises. The building envelope shape offers significant benefits for wind behavior. For wind coming from any direction, both taper and twist make the tower look different at different heights, disrupting organized vortex shedding. See Figure 13(a). In fact this phenomenon was extensively studied in wind tunnels and the degree of wind effect for different amounts of twist over

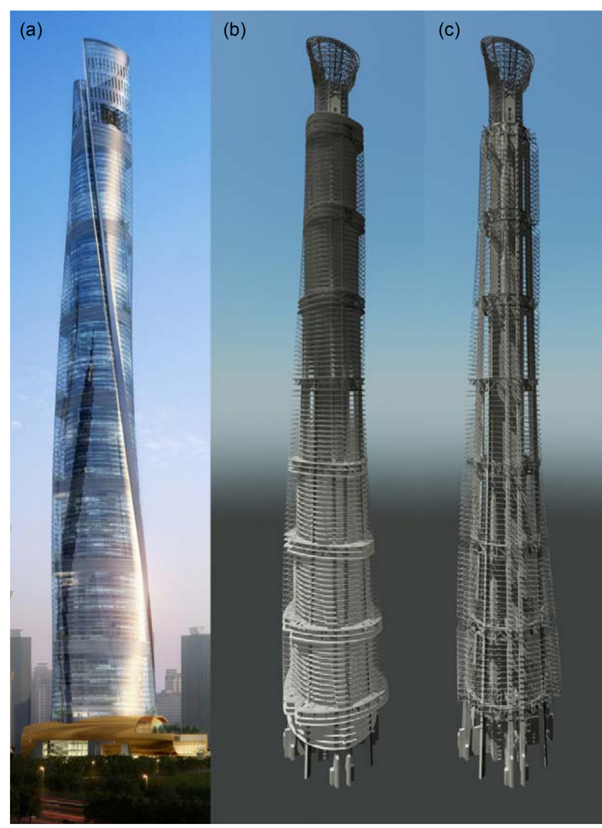



**Figure 13. (a)** Shanghai Tower rendering shows a skin based on a tapering twisting triangular plan as indicated by the visible groove, **(b)** REVIT model shows stacks of circular floor plates by tiers separated by extended mechanical and atrium floors, **(c)** REVIT model without floors shows structural system of core, outriggers, belts and sloping super columns. Credit: Gensler/Thornton Tomasetti.

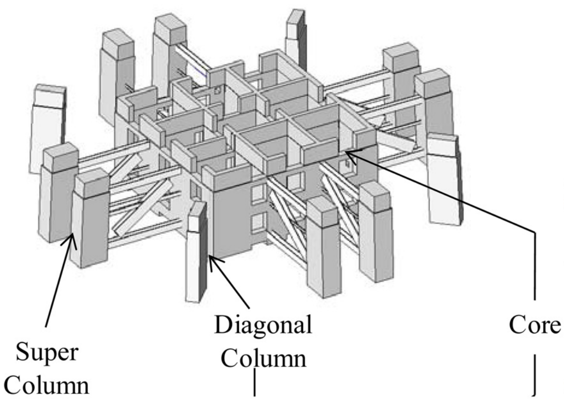



**Figure 14.** Outriggers align with inner core walls to suit circular floor plans.

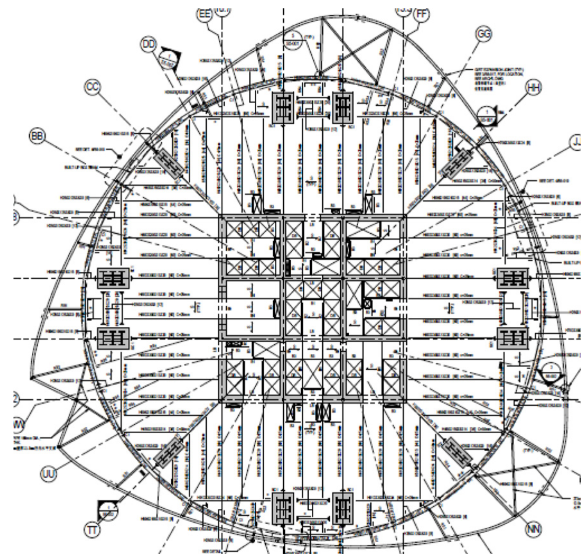
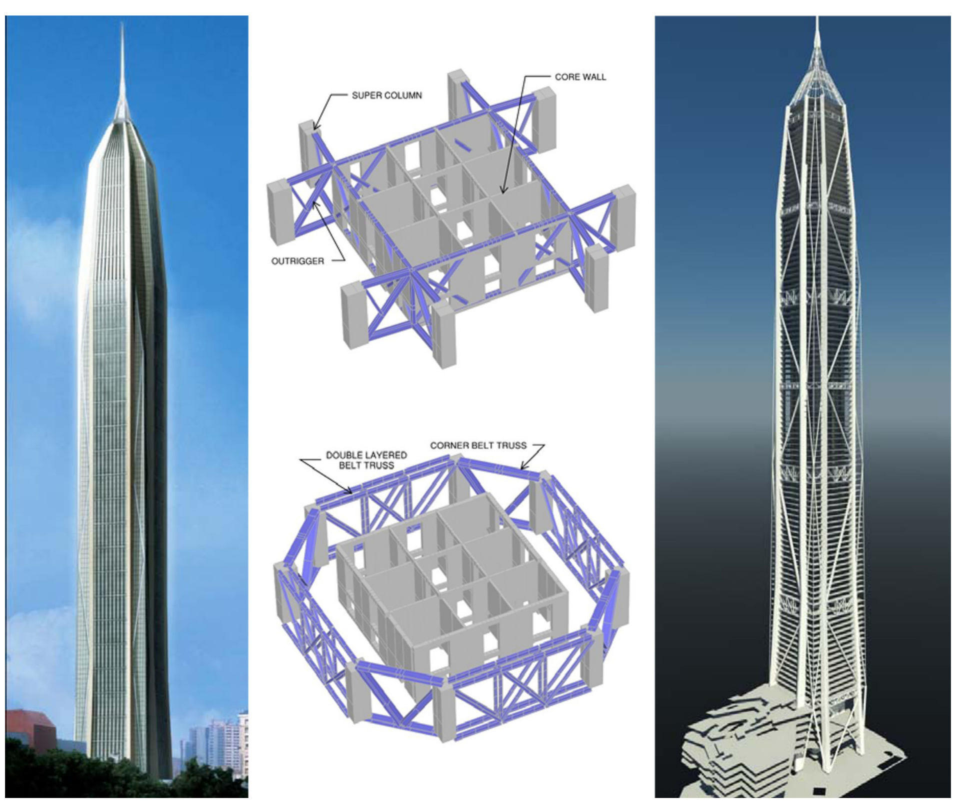


**Figure 15.** Typical floor plan showing circular floor plate and curved pipe girt for the rounded triangular plan of the outer skin.

tower height was considered when finalizing the design.

Gravity design, lateral resistance and stiffness, and construction practicality were considered simultaneously by structural engineer Thornton Tomasetti. Following the swirling skin with floor plates and framing would require continuous complex changes in formwork at great cost. The design solution that simplified construction while providing dramatically tall atriums on multiple levels, a desirable amenity, was to separate skin geometry from floor geometry. The internal construction is a series of stacked circular steel-framed floors, with a conventional curtain wall enclosure, changing diameter only at the refuge/mechanical levels visible in the model. See Figure 13(b). At those levels steel truss outriggers link composite core walls to composite perimeter super columns aligned with core inner walls. The columns symmetrically and gradually tilt in as they rise to avoid offsets or kinks in the load path. See Figures 13(c) and 14. Seismic resistance is addressed by performance based design,




**Figures 16**(left), **17**(top), **18**(bottom), **19**(right). Ping An rendering showing notched corners, core and outrigger arrangement, belt truss, and mirrored bracing pattern. Credits: KPF, all others Thornton Tomasetti.

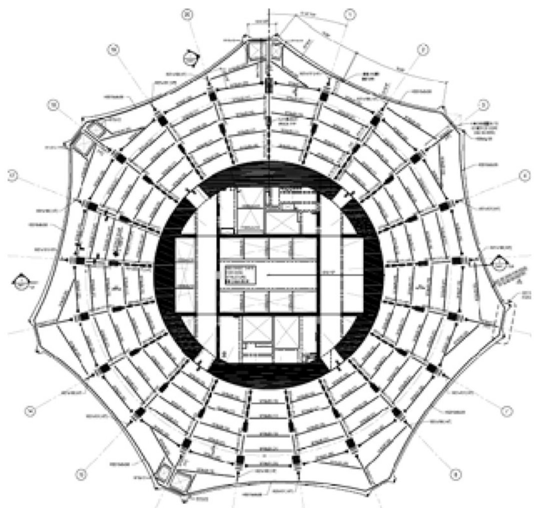
using advanced analysis to confirm satisfactory behavior of the structural frame under different earthquake scenarios.

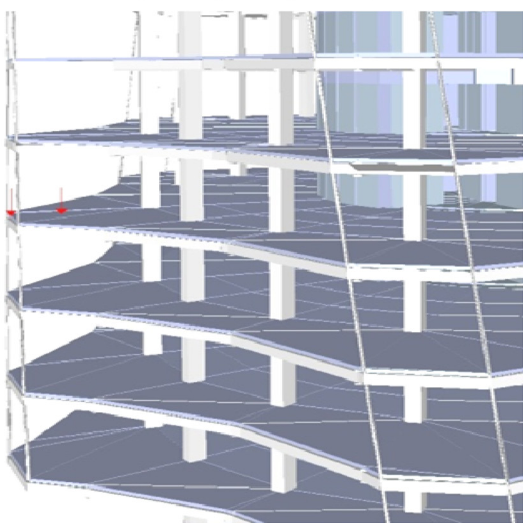
The continually varying geometry of the swirling outer skin is provided separately from the cylindrical internal building. A horizontal circular pipe at each level is the girt that supports outer curtain wall panels. The girt is bent to establish the skin geometry. Wind and seismic loads perpendicular to the skin are resisted by horizontal radial pipe spokes framing back to the edge of each inner floor level. Wind and seismic loads along the skin are resisted by horizontal bracing and by guided keeper blocks at the three points on each floor where the outer girt touches the inner floor. Several load paths are provided along the perimeter so that girts can incorporate expansion joints to accommodate thermal movements in event of a localized fire. See Figure 15.

Skin and girt gravity loads are carried by nearly vertical tension rods that follow the skin swirl, suspending up to 15 stories of cumulative weight from cantilevered mechanical floor framing above. A large-travel horizontal expansion joint just above each mechanical floor allows for the effects of multiple stories of thermal strain, long-term super column creep and shrinkage and transient strains from wind and seismic overturning forces. Building construction is currently well underway.

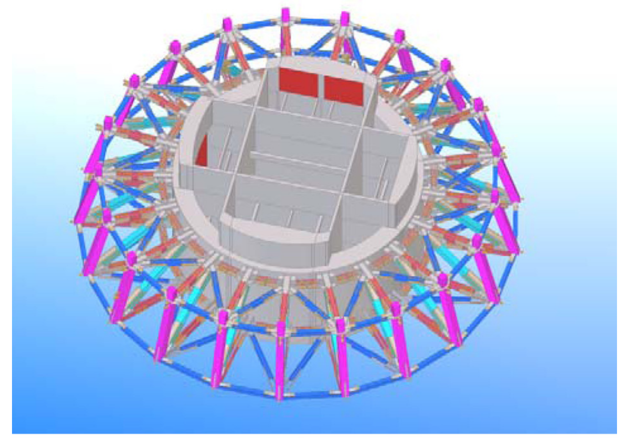
Soon after expert panel review and approval of the Shanghai Tower structural design, work began on Ping An International Finance Center in Shenzhen, China. This Kohn Pedersen Fox design, engineered by Thornton Tomasetti, is of similar height at 2164 ft (660 m) but quite difference in appearance. As another tall, slender tower close to a typhoon coast, wind behavior was an important aspect of the design. The square floor plan has been modified by double notched corners which disrupt vortex formation, and also visually define the paired super columns that occur near each corner. As the main building faces and corresponding super columns gently slope inward, the cantilevered corner between each super column pair gradually diminishes and then vanishes. See Figure 16. To efficiently maximize building strength and stiffness, a nine-cell concrete shear wall core has embedded steel members to reduce wall thickness and provide direct connections of outriggers and braces. Steel truss outriggers aligned with core outer walls occur at multiple levels to engage the corner super columns. See Figure 17. Belt trusses deliver gravity loads from secondary columns to the super columns, and act with the super columns to form a perimeter frame as part of a dual system for seismic resistance. See Figure 18. Reflecting China code changes coming into force at the time, the secondary system was required to provide at least a certain percentage of full building lateral stiffness, as well as a minimum percentage of required lateral strength. To meet this stiffness requirement, diagonal braces are provided along each building face, forming zigzag patterns

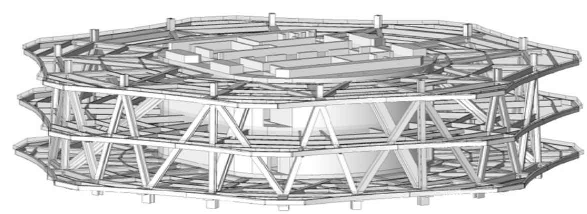
**Figure 20.** Chicago Spire rendering. Credit: courtesy of Shelbourne Development/Santiago Calatrava.

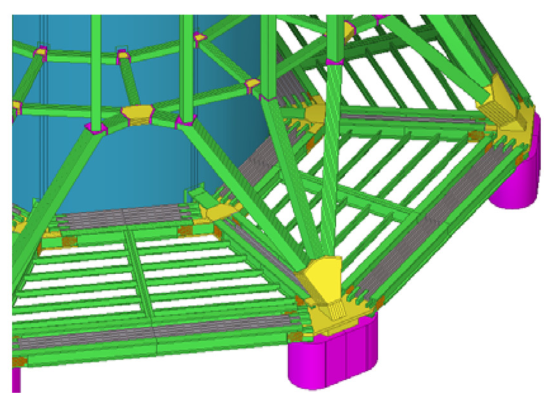




**Figures 21**(planL39), **22**(model). showing vertical columns behind flutes.







**Figures 23**(top)**, 24**(middle)**, 25**(bottom)**.** Radial trusses for outrigger level, outrigger and column transition level, lobby transition level.

as they run column to column between sets of belt trusses. The presence of diagonal (not X) bracing introduces a subtle gravity behavioral issue: steep, nearly vertical braces will attract axial compression as gravity loads shorten the columns to which they connect. The horizontal component of that axial force will tend to generate lateral deformations between floors if not addressed thoughtfully. If all braces at a floor were to slope the same way when viewed in elevation, then the effect would twist the building. To avoid this result, braces are arranged in a mirror image pattern to each side of each corner, resulting in diagonally opposite corners trying to push outward at belt truss levels. See Figure 19. Floors at these levels are designed to resist the outward forces. The Ping An International Finance Center is currently under construction.

The effects of gravity from different choices of column alignment led to key design decisions for the Chicago Spire, a 2000 ft (610 m) Santiago Calatrava design that was to become the tallest building in North America. The tower would be based a circular floor plan with seven notches. At upper floors, plan diameters would diminish in size and notches shift in location, creating flutes spiraling around the building. See Figure 20. Wind effects would be reduced by tower taper and spiral flutes and spirals, which all serve to disrupt organized vortex shedding. The geometry, however, brought other challenges. Floors span radially outward from a central concrete core. If perimeter columns were to follow the flute spirals, they would all be leaning the same way and gravity load would cause building twist about the vertical axis. In theory the core could resist such torsion. The cost to do so and the construction complications to anticipate and compensate for the resulting deformations made this ap-

**Figure 26.** Kingdom Tower rendering. Credit Adrian Smith + Gordon Gill Architecture.

proach impractical. Instead, engineer Thornton Tomasetti proposed to pull the perimeter columns inward enough to run vertically, clear of the flutes, and frame slab tips between flutes as cantilevers. See Figures 21, 22. Moving perimeter columns inward reduced the total lever arm available to resist overturning, so four sets of outriggers would engage all columns through radial steel framing. See Figure 23. At upper floors where reduced diameter would result in close column spacing, the same trusswork was used to transition from 21 to 14 perimeter columns. See Figure 24. To visually open up the ground floor lobby level, steel trusswork transitions from 21 columns to support points, with outward radial thrusts from the splayed legs resisted by redundant sets of circumferential ties. See Figure 25. The Chicago Spire shows that complex geometric moves can be provided within supertall building designs, with a corresponding complexity in structural framing.

Kingdom Tower, currently being designed for Jeddah, Saudi Arabia, will be the world's tallest building by a wide margin based on its 3280 ft (1000-plus m) proposed height. Adrian Smith + Gordon Gill Architecture intentionally avoided adding complexity to a project where height alone will be a major challenge. Effective strategies from previous supertall towers were adopted, starting with a tapered three-wing shape that minimizes

**Figure 27.** Wuhan Greenland Center rendering.

vortex shedding excitation and maximizes base width to resist overturning moment. The three-wing or tripod approach provides very efficient lateral resistance by using walls along each wing as webs and perpendicular crosswalls and end walls as flanges. Engineers Thornton Tomasetti fine-tuned the structural system to avoid any need for outriggers or transfer girders. Vertical alignment is maintained at walls that serve as both columns and shear resisting elements. End walls slope inward uniformly for simpler forming and a uniform load path. The three tower wing-end slopes are intentionally slightly different,

**Figure 28.** Wuhan Greenland top detail showing tripod feature and rounded wing tips. Both credits Adrian Smith + Gordon Gill Architecture.

so the pinnacle that results from building taper has geometry with interesting visual complexity. See Figure 26. Concrete formed in a silo system is planned for pinnacle construction to óbenefit from the experience gained on lower floors rather than switching to steel framing.

Wuhan Greenland Center in Wuhan, China is also by Adrian Smith + Gordon Gill Architecture and engineers Thornton Tomasetti. At 119 stories and 1988 ft (606 m) it is slightly more than half the height of Kingdom Tower. Size does matter in design decisions: while it has a three-wing plan like the previous project for excellent structural efficiency, it does not steadily flare out. See Figure 27. Since overturning demand is smaller, other shaping options were practical to consider. The tower top, while lofty, is also at a more manageable height, so a creative tripod feature is being provided to cap a special rooftop space. See Figure 28. A much more subtle issue is geometric, the curvature of the plan ends. An aesthetic goal is smoothly rounded wing tips, rather than having facets from flat glass panels. Curved glass is prohibitively expensive if hot formed, but gentle curvature can be economically provided if cold bent by pulling flat panels down to non-planar support points during field installation. The key is limiting the curvature required. Thornton Tomasetti building skin specialists worked with the architect to establish acceptable curvature limits and recommend geometric parameters for wing tips to stay within those limits.

## 2. Conclusion

Is it 'anything goes' in modern high rise buildings? The answer is, perhaps unsurprisingly, 'It depends.' Is there extra money in the construction budget and extra time in the schedule? Unconventional designs involve unconventional costs and construction schedules. Is the environment severe or moderate? Extreme wind conditions and high seismicity must be respected. An unusual feature used at one site may result in very different structural demands and cost premiums in other locations. What is the scale? Size does matter; just as there are different leg-to-body proportions for ants and elephants, one cannot simply double building dimensions without making other adjustments as well. This does not prohibit unusual design features from supertall towers, it just means that any such features must be carefully and thoroughly considered before adoption. With an appropriate budget, schedule and design approach, the sky is the limit!