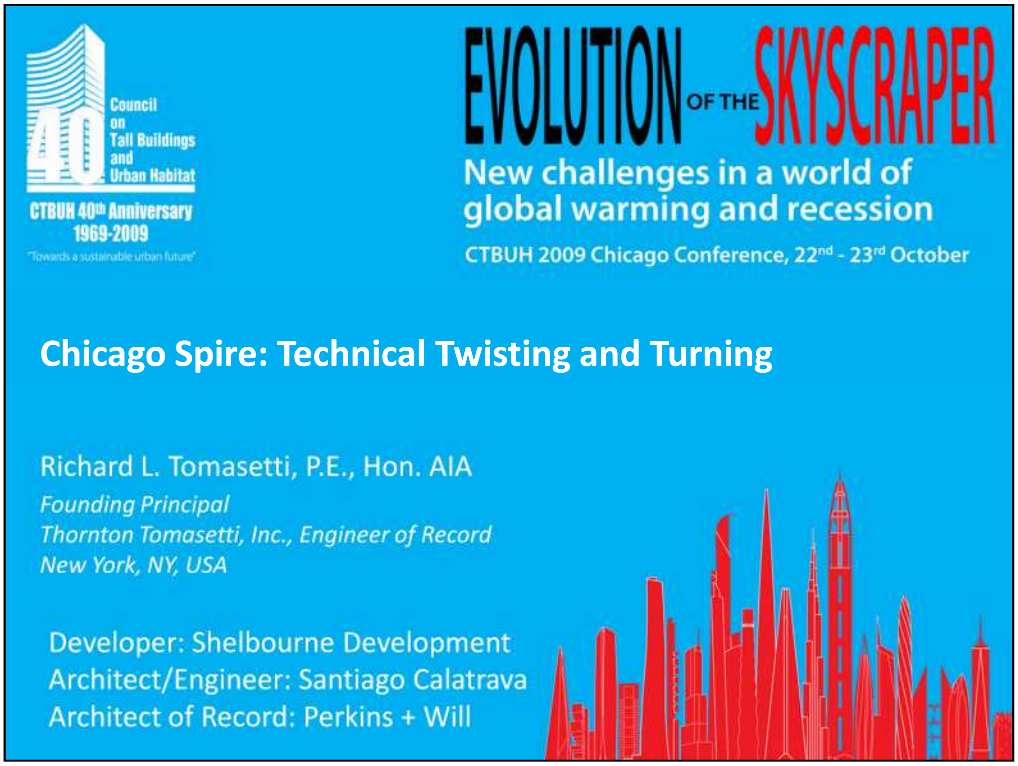


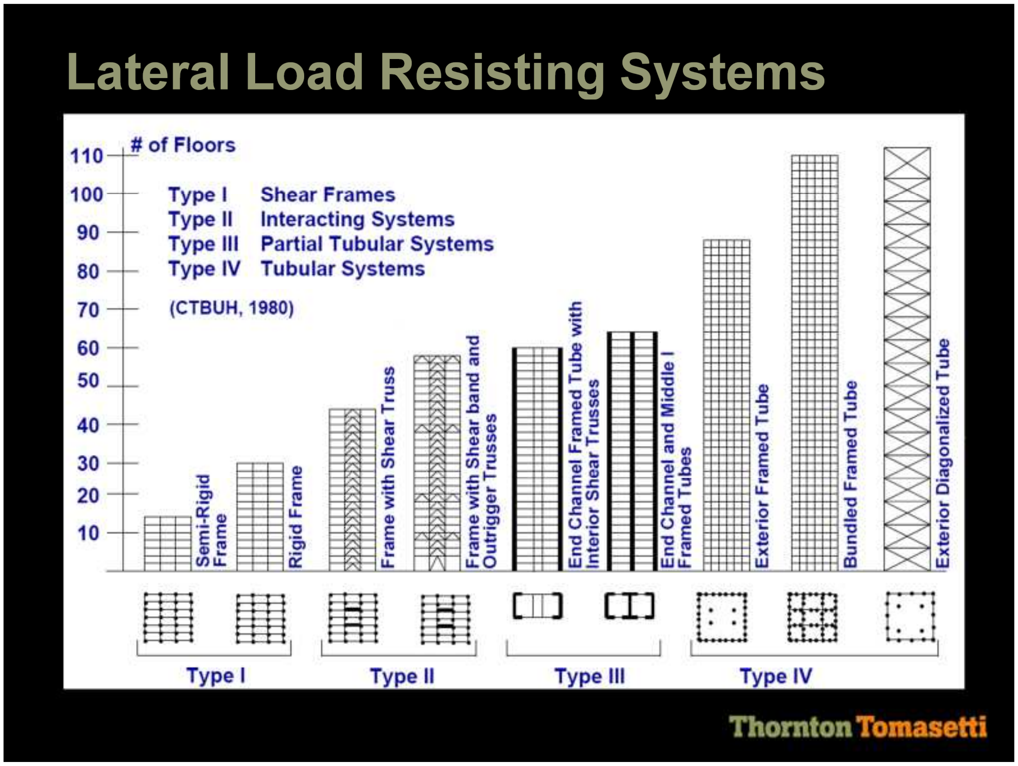
SUMMARY OF REMARKS

It is a pleasure working on this project with Garrett Kellerher of Shelbourne Development; Santiago Calatrava, the Architect and Engineer and Pascal Guignard of his structural engineering department; and Perkins+Will, the Architect of Record. Thornton Tomasetti is the Structural Engineer of Record and I want to acknowledge managing principals Joe Burns and Tom Scarangello as well as David Mc Lean, Garret Brown, Nicholas Steele, Suzanne Provanzana and their support staff in our Chicago and New York offices for their intelligent work on this project. In addition, thanks to all the consultants on the design and construction team for making our work possible.

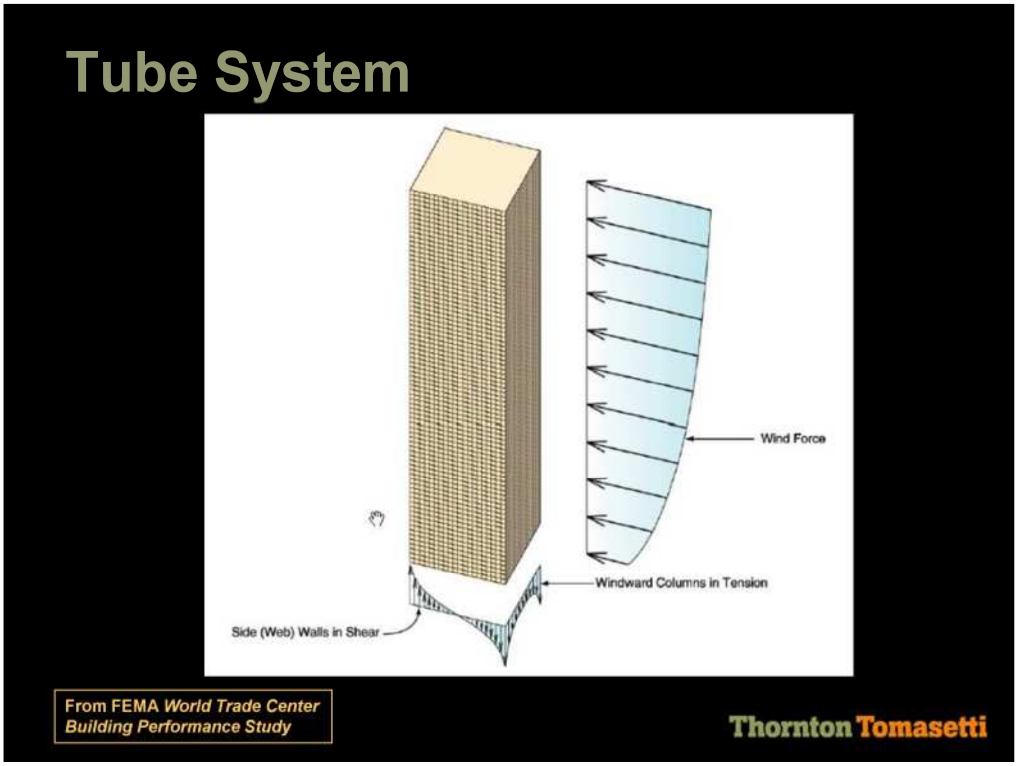
The Santiago Calatrava's Spire is 2000 ft. (600m) tall, and its circular, twisting and tapering geometry reduces accelerations and wind loads. Yet it has a very straightforward primary structural system. It represents a significant evolution of the integration of architecture and engineering in the design of tall buildings. This presentation will focus on some of the innovative structural design and analysis techniques developed for this project, which I believe will be of interest to design professionals and the building industry for future projects.

BUT FIRST SOME HISTORY

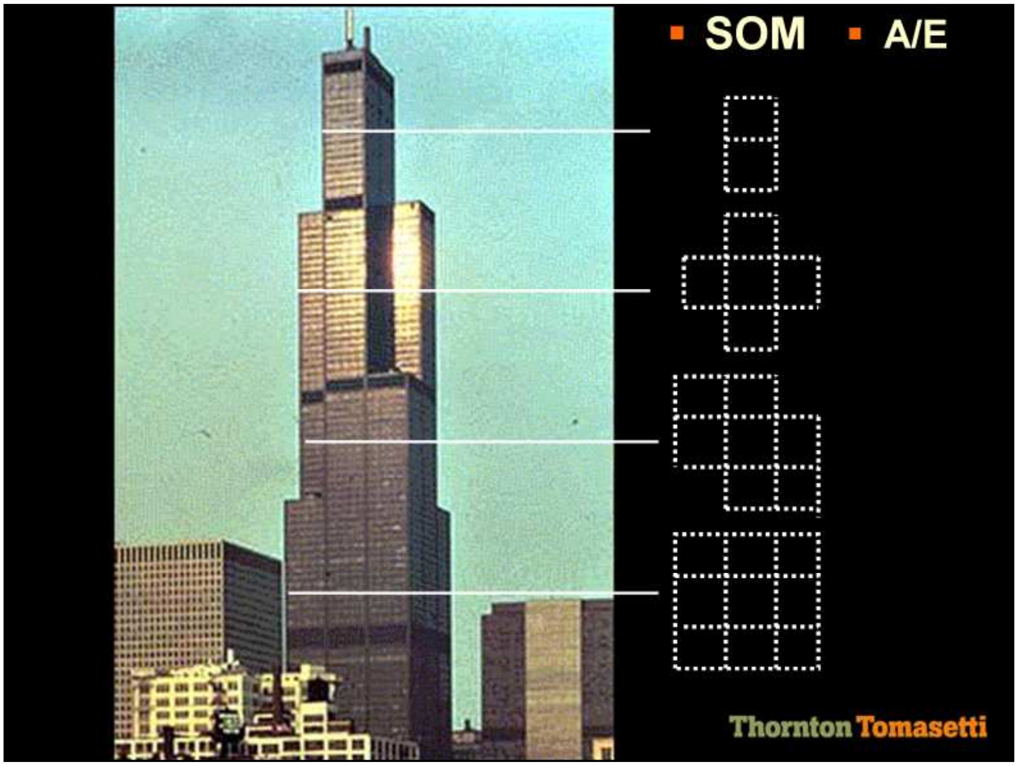
The quest for geometries that minimize forces has been with us for a very long time. Gaudi tried to eliminate the horizontal hoop stresses typical of church domes by using tapered "spires." But his circular, tapered, rough geometry also minimized the effects of wind, although not as critical on mid-rise buildings.



In the ’70s and ’80s, based on the work of Fazlur Khan, CTBUH classified high-rise structural systems based on their efficiency for increasing heights. The emphasis then was on steel structures. Since then, concrete has also become popular because of its added mass and damping, and higher strength concrete reduces column size and increases stiffness. The emphasis was also on tubular systems for very tall buildings. Note the Type II outrigger system was shown only for 50- to 60-story buildings. (Today it is used on much taller buildings.) The exterior framed and bundled tubes have very close perimeter column spacing and activate all of the columns in resisting lateral loads. It also minimizes or eliminates bracing in the core. The outrigger system permits much larger perimeter column spacing (and views), but it adds bracing to the core as the outriggers penetrate it. It typically does not activate all of the perimeter columns in resisting lateral loads.



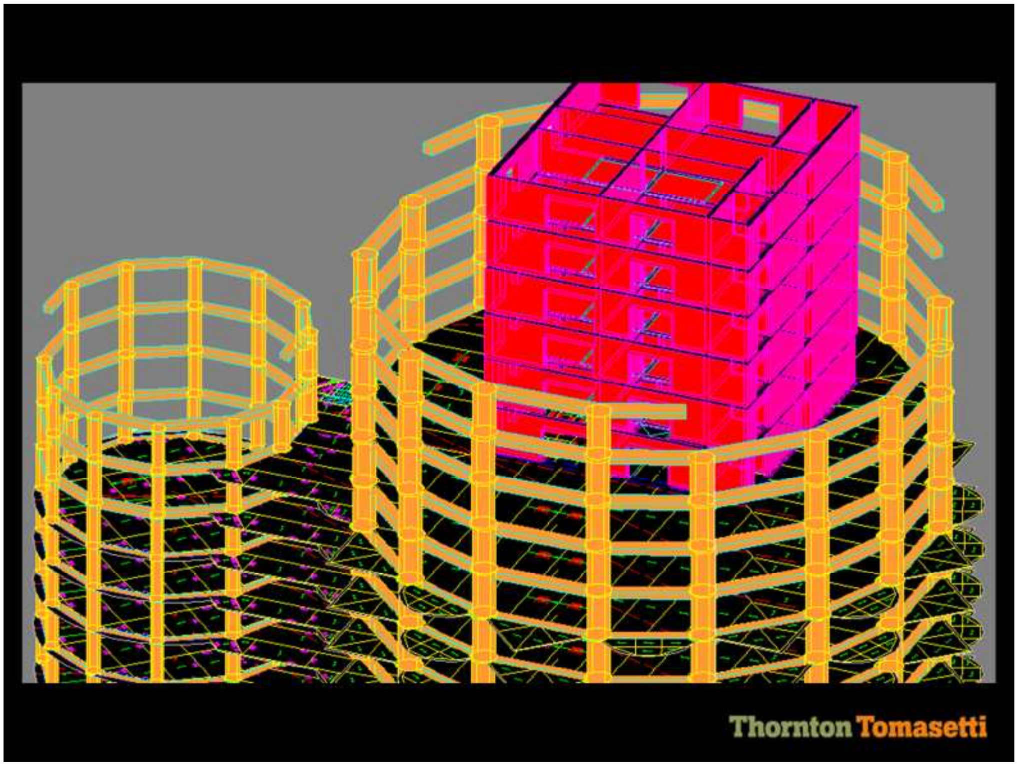
As shown, all perimeter columns participate in resisting lateral loads, and the tube also has significant structural redundancy, which contributed to the excellent performance of the World Trade Center towers in New York City during the tragic attack on September 11, 2001.



Chicago went one step further and higher with the bundled tube of the Sears Tower. But still, column spacing was only 15 ft. center to center, which was generous for steel tubes that more typically have column spacing at 10 feet or less.

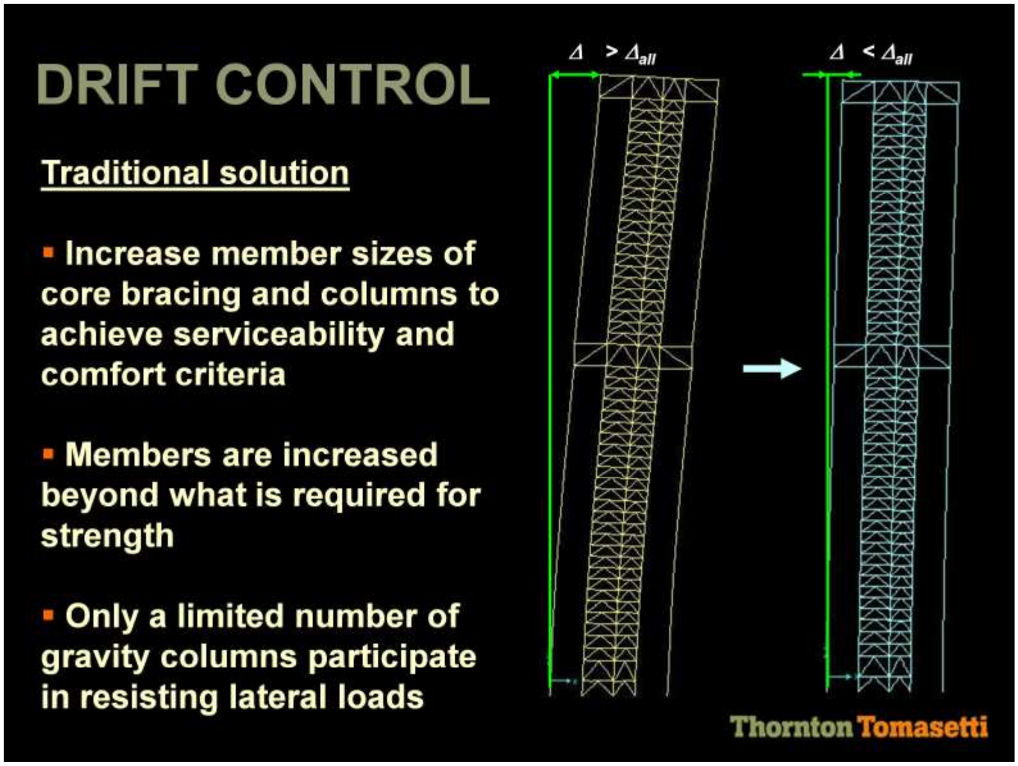
But even before Sears Tower, Chicago's John Hancock Building used a diagonalized tube to increase exterior column spacing and views. It is interesting to note that the diagonals resist both lateral and gravity loads. One might think of this building as the start of the exterior diagrid systems being used today.

More recently, concrete primary structural systems have been used for very tall buildings. Petronas Towers in Kuala Lumpur has a concrete core and a circular rigid perimeter concrete frame that provides partial tube behavior with large column spacing. Two outrigger levels help tie the core to the frame.



Accelerations are minimized due to increased mass and high internal critical damping properties of concrete framing (typically 2% vs. 1%). High strength concrete also results in higher stiffness. No mass dampers were needed.

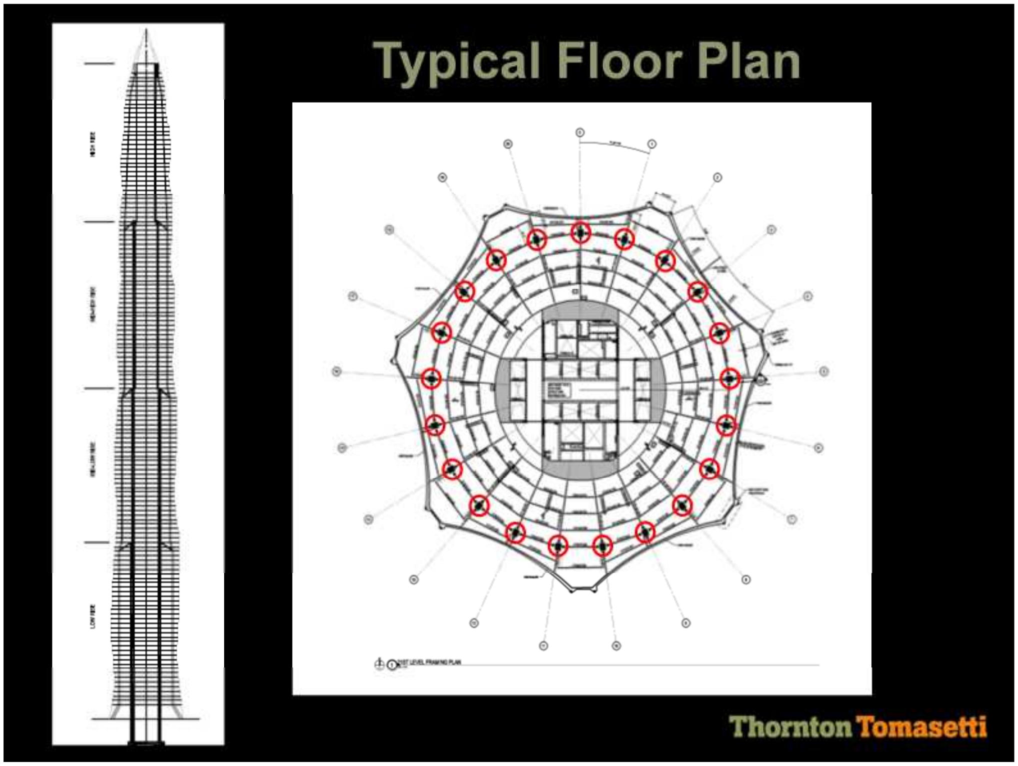
Outriggers were used on the New York Times Building in New York to provide large perimeter column spacing.



Instead of the traditional solution, some of the bracing in the core at the outrigger levels were eliminated and replaced with light weigh cross bracing on the outside of the building.

This resulted in an interesting integration of architecture and engineering that resulted in the structural efficiency of activating all perimeter columns in resisting lateral loads while providing more space in the core.

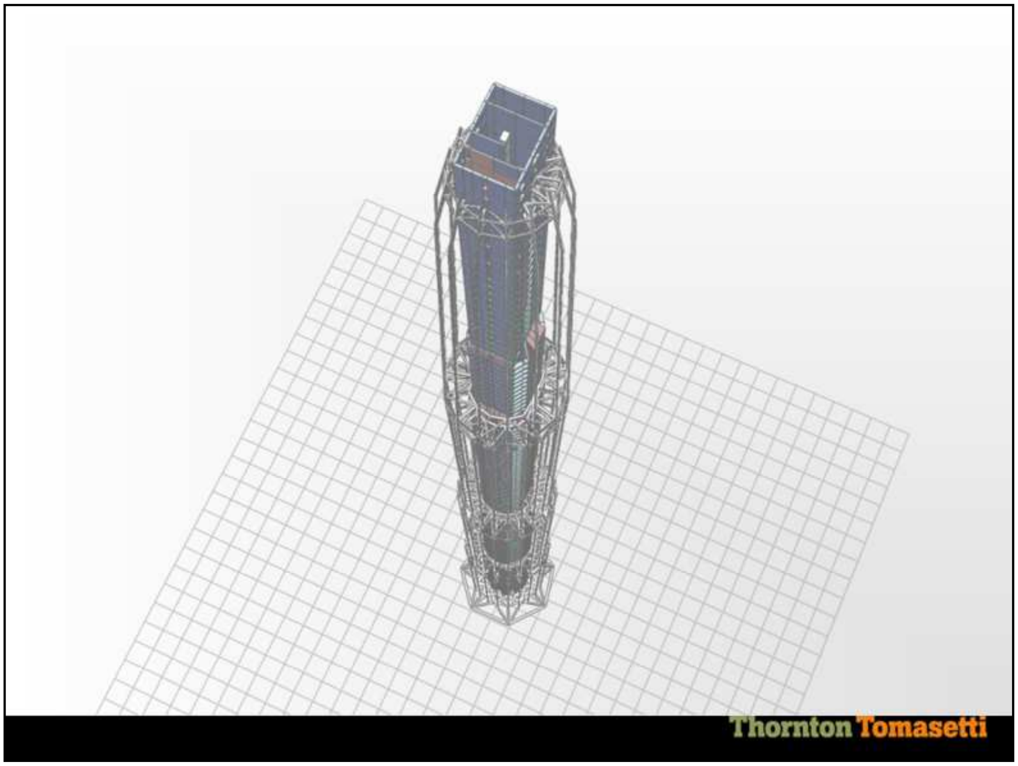
The evolution of these previous structures provides a background for the development of the structural design for Santiago Calatrava's Spire.



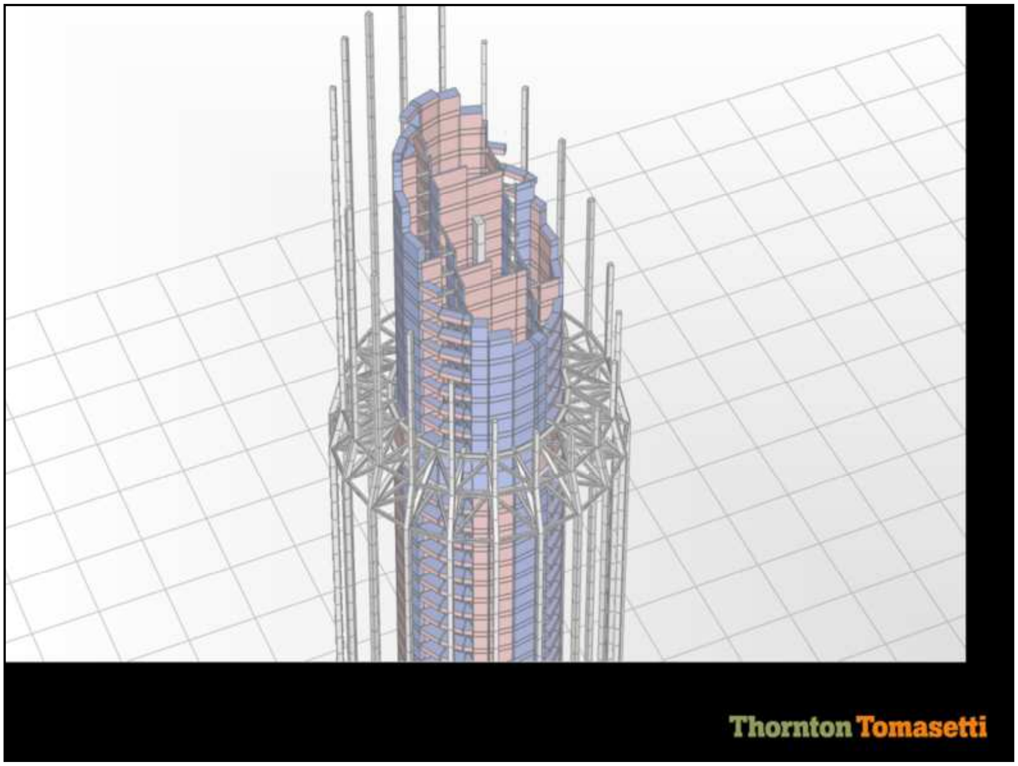
It has a high strength (110 MPa, 16,000psi and E=49,500 MPa) concrete core with steel perimeter columns at a large spacing. Chicago is a leader in building concrete core/steel frame buildings, making the Spire the right type of construction for its environment. The floors are typical steel floor design composite with the concrete slab. The columns are moderate strength (Fy=42 or 50 ksi) and are solid built-up plate members, which maximize floor space.

The twisting geometry is accomplished by the cantilever floors being incrementally rotated at each level. The vertical support structure is essentially straight for most of the height of the building.

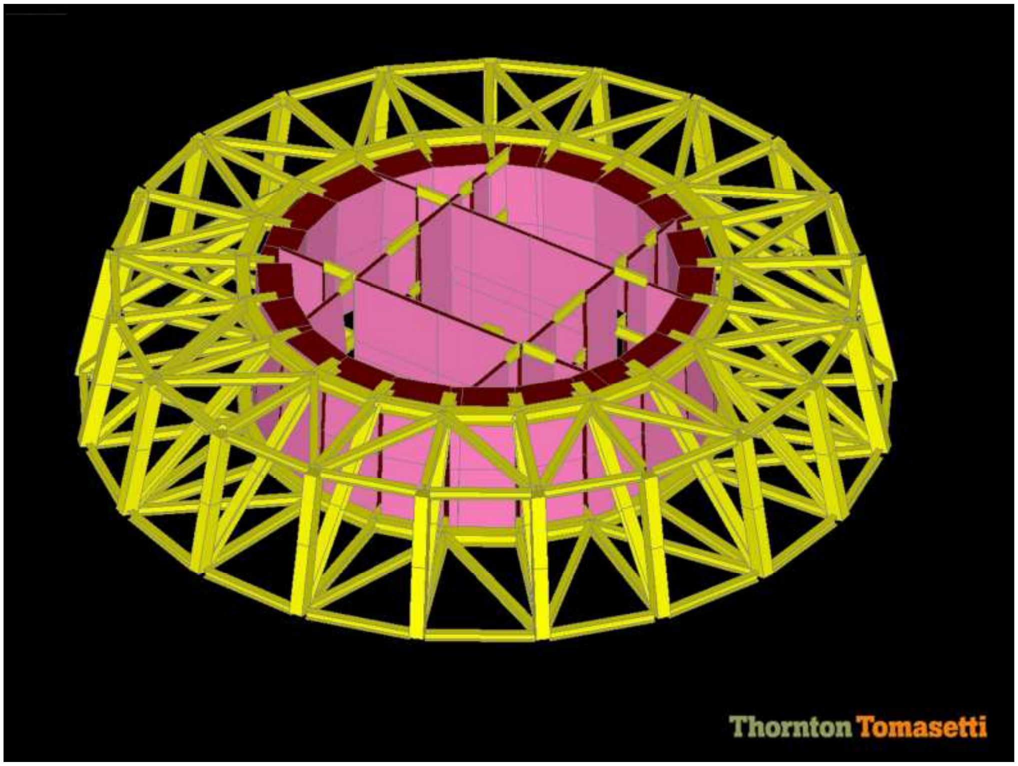
Note the twist and taper, which minimizes wind forces and accelerations.



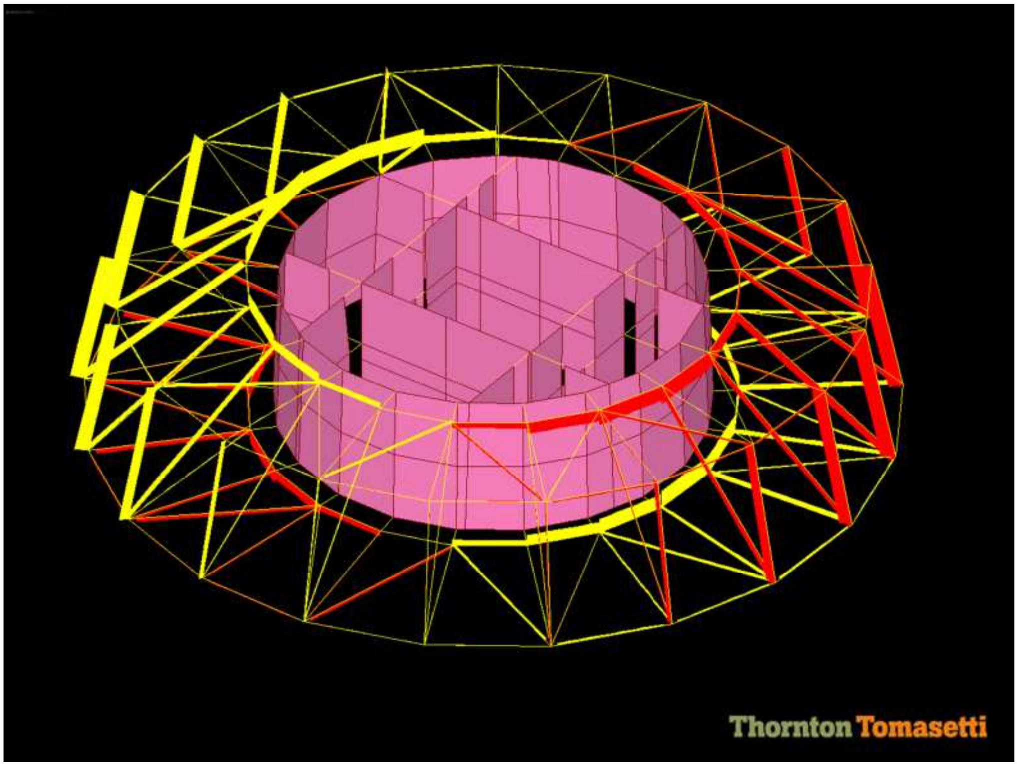
Circular steel outriggers activate wind load resistance from all perimeter columns.



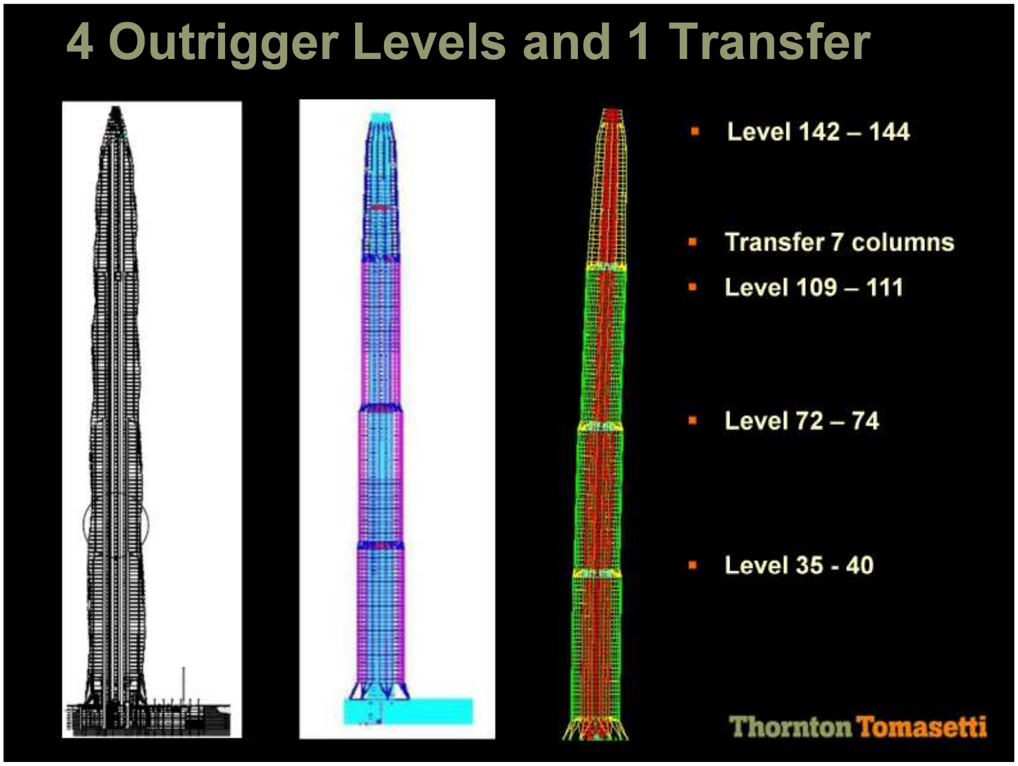
Note that every column is “picked-up” by the outriggers, resulting in both structural efficiency and structural redundancy.



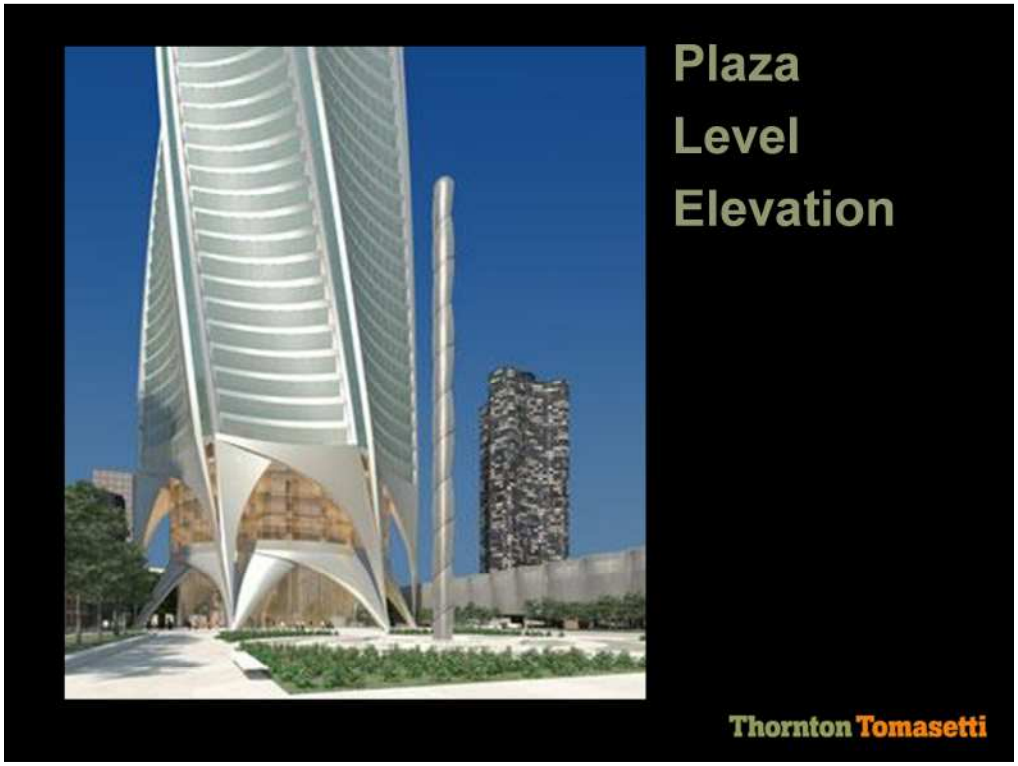
Note that outriggers do not penetrate the core, maximizing space and minimizing interference with mechanical and electrical equipment. The circular steel outriggers are designed to act like a tight sleeve around the core. This is accomplished through the use of an inner circular tension or compression ring, depending on wind direction.



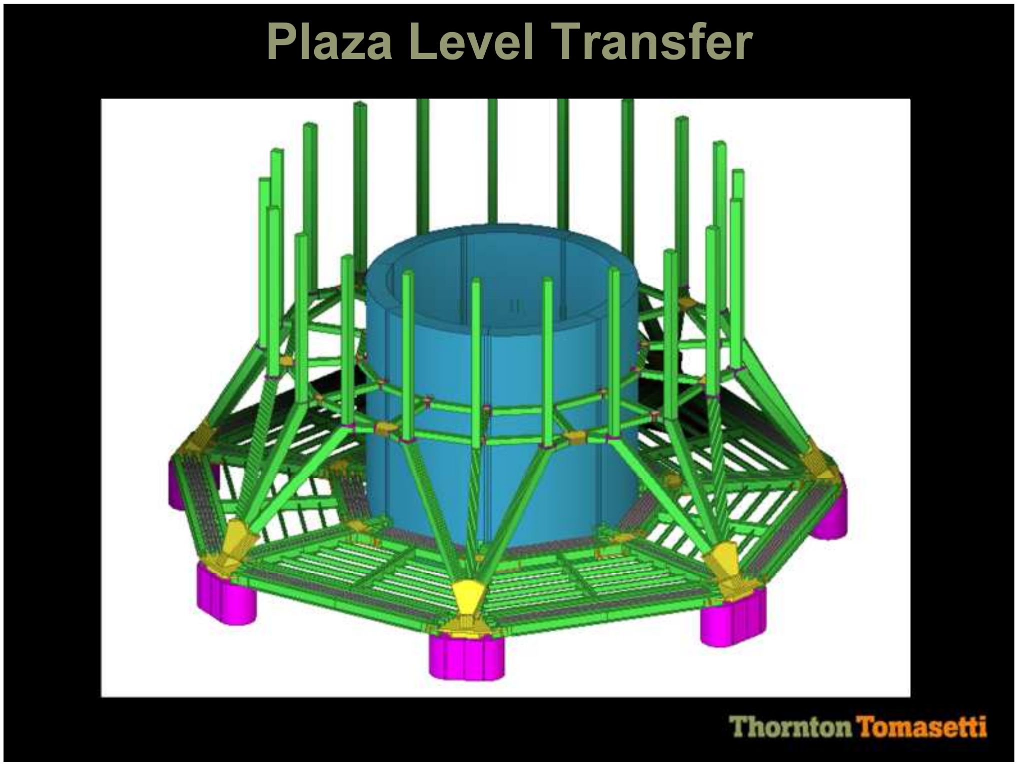
In this structural analysis graphic, red or yellow indicates tension or compression in the outrigger members, showing the entire outrigger activated for any wind direction, thus activating all perimeter columns.



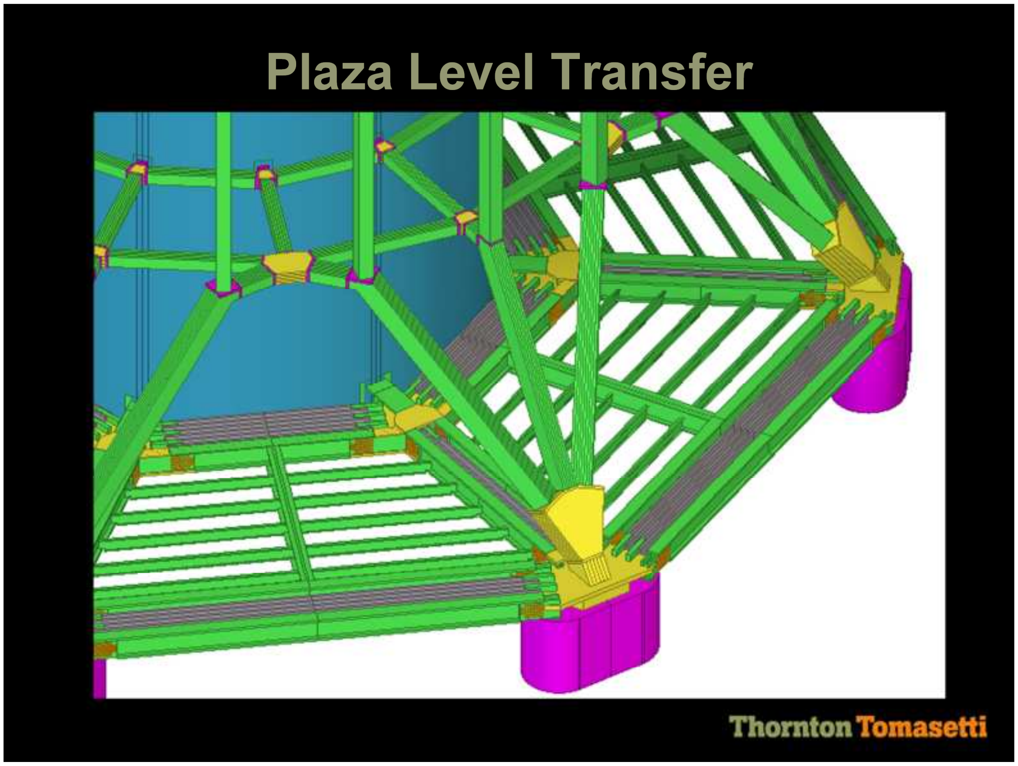
With the concrete core and the efficiency of the circular outriggers, we get a tube-like deflection of the building. This minimizes relative horizontal floor-to-floor deflections, helping with curtain wall installation and performance.



At the plaza level, Dr. Calatrava designed a wonderful open lobby and entrance area by transferring 21 perimeter columns in two directions to seven caisson foundations.



This motivated an innovative design for a structurally redundant transfer grid of two dimensionally slopped columns and tension and compression rings.

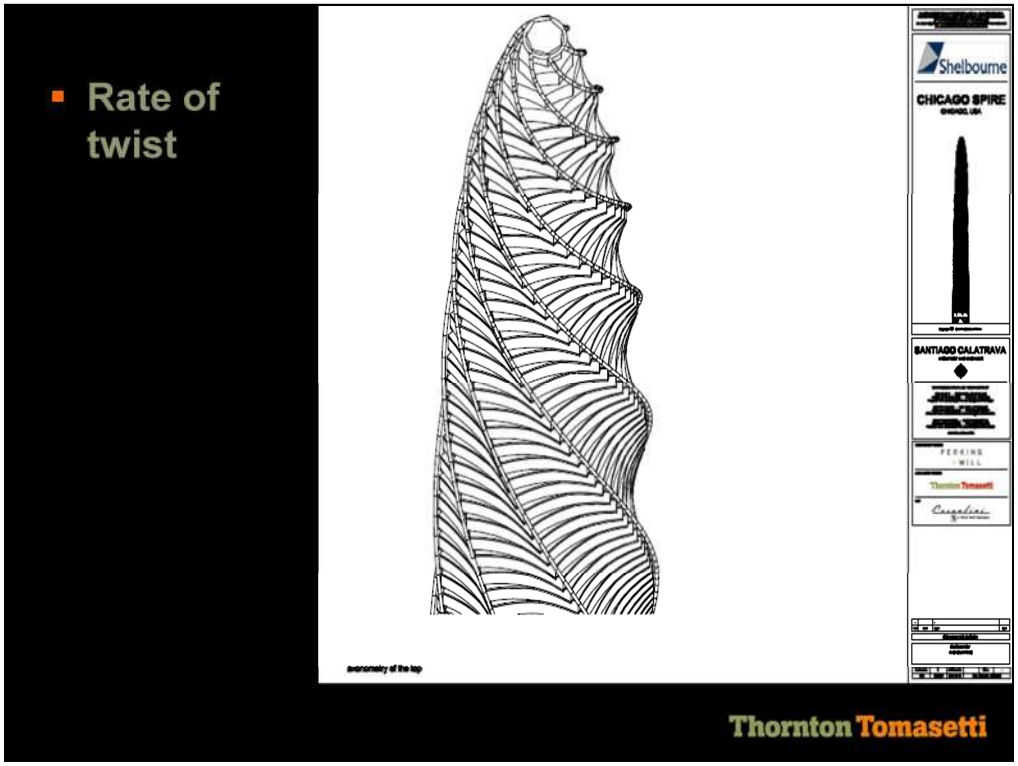


Together with uniquely designed welded steel connections, the building space at the lower levels was maximized.

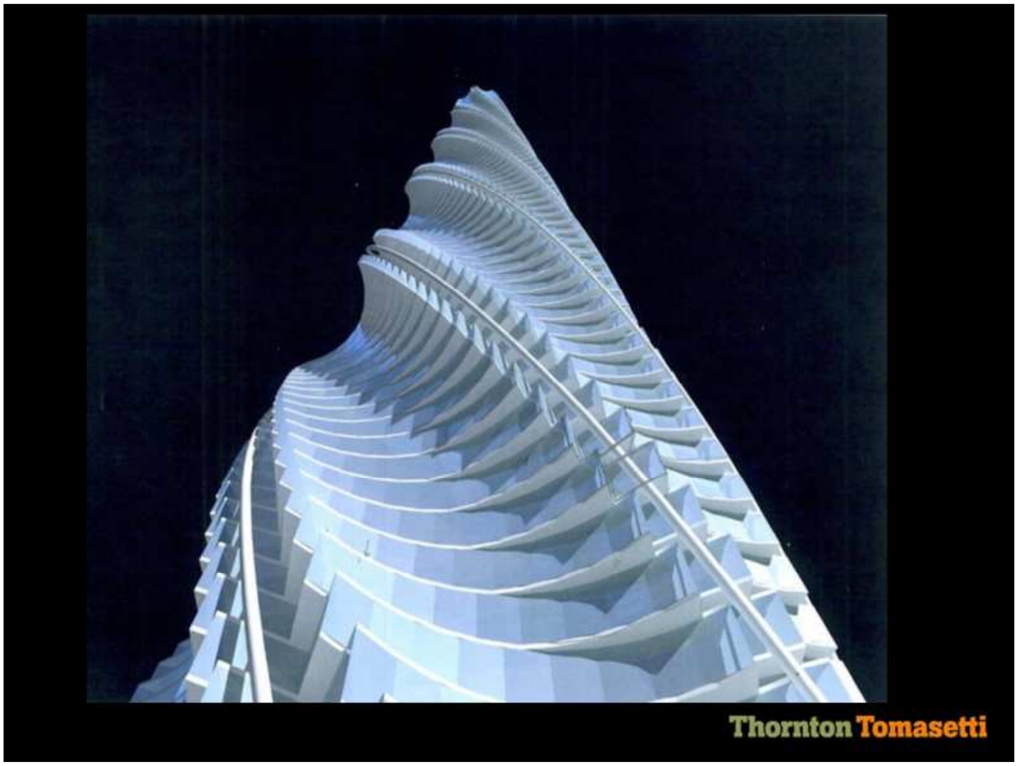
Wind Tunnel Testing

- RWDI, WIND ENGINEERING CONSULTANTS

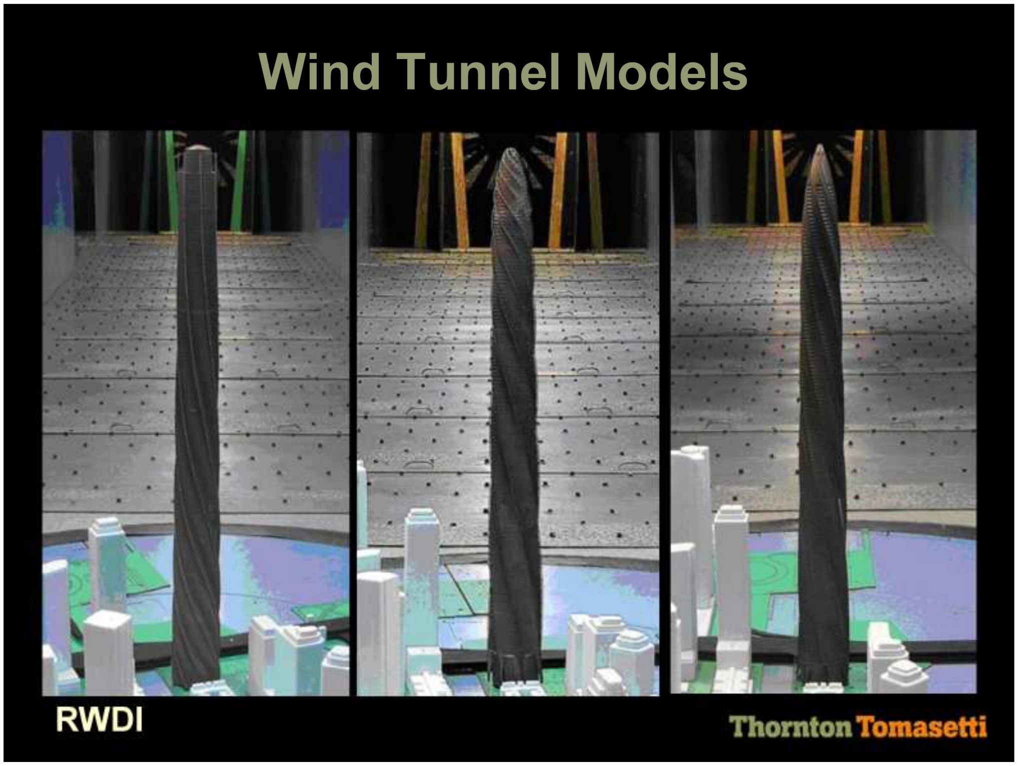
Thornton Tomasetti



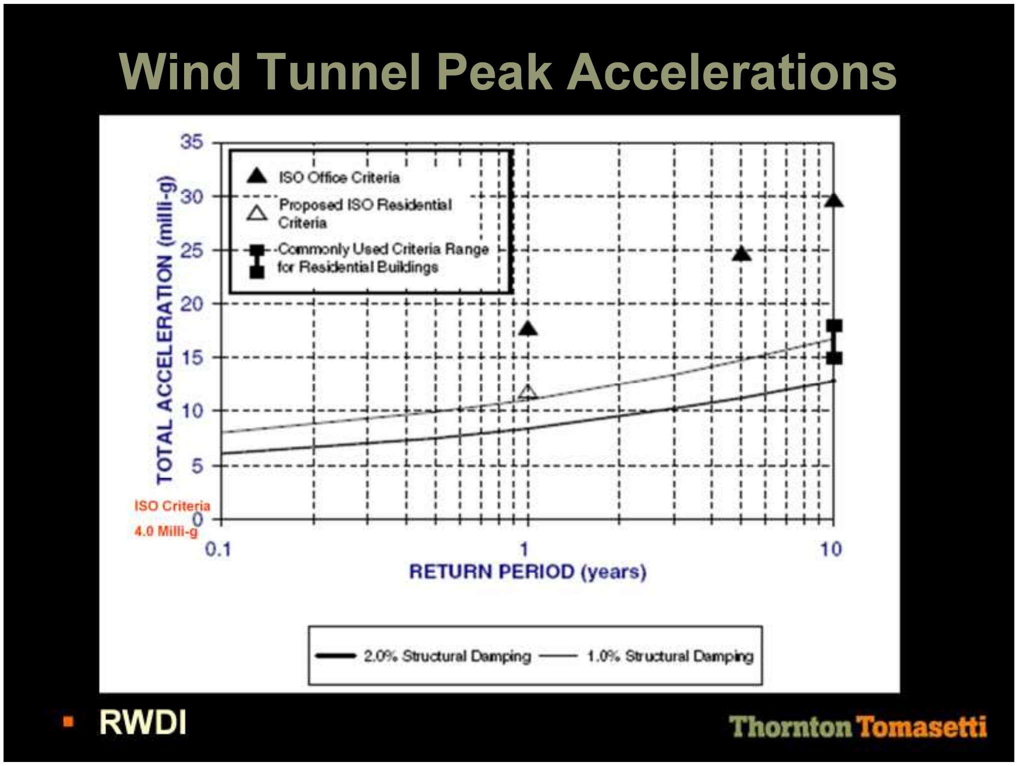
The rate of twist and taper effects the wind response of the building, as well as circular and scalloped floor plate geometry. All help to reduce forces and accelerations.



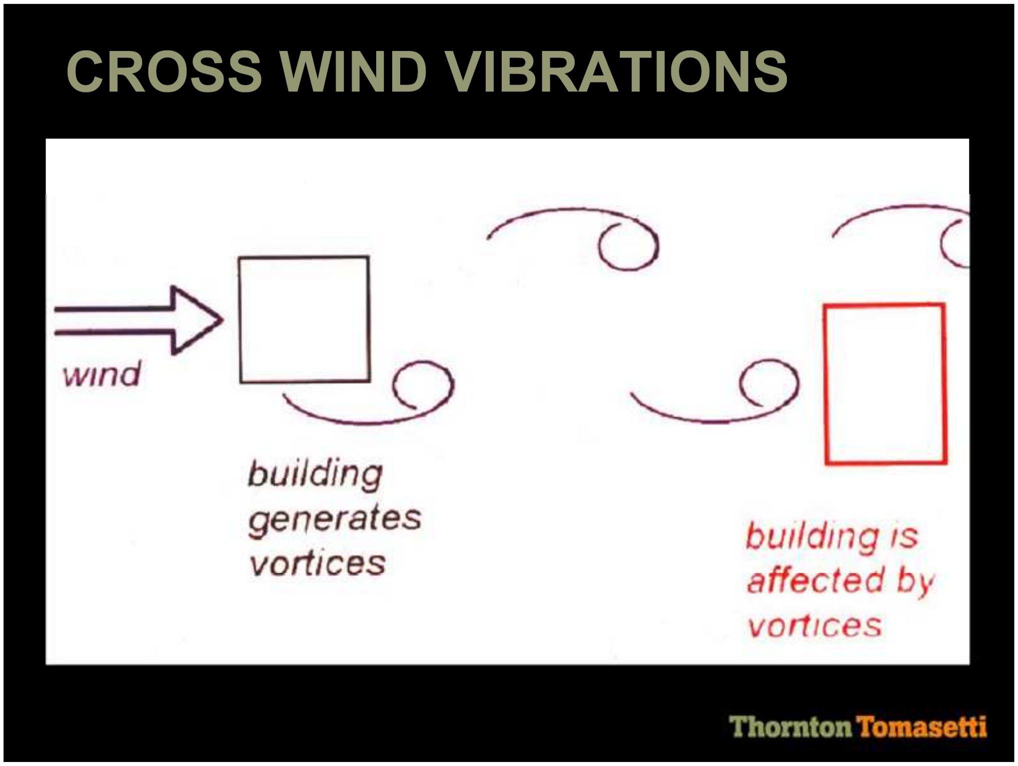
Typical expression of twist shown on earlier design.



Three different geometries developed by Santiago Calatrava during the design process were tested by our wind consultants, RWDI. Tests methods included High Frequency Force Balance (HFFB), High Frequency Pressure Integration (HFPI) and Aeroelastic (on the final model). For all three designs, base moments were about 75% lower than required by the Chicago Building Code. Accelerations were significantly lower for the second and third models: 20% lower for the 10-year return period wind. Accelerations were also 40% lower for the 1-month return period. This is significant because the accelerations for the 1-year and 1-month return periods seemed high for their frequency of recurrence.



Note acceptable levels of acceleration at top occupied floor at the 10-year return period, which is typically used for comfort criteria (1.5% to 1% damping was used for behavior at 10-year and lower wind speeds). But accelerations were 11 milli-g and 8 milli-g for the 1-year and 0.1-year (1 month) return periods. This seemed high, especially when compared to the ISO human perception threshold criteria of 4.0 milli-g.



Why? For this high 18-second period building, we are getting vortex shedding contributing to resonance at lower than normal speeds.

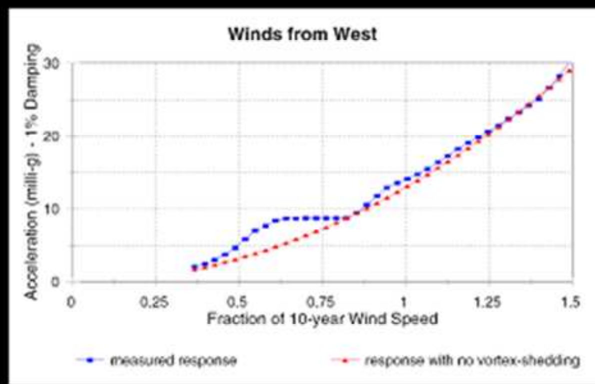
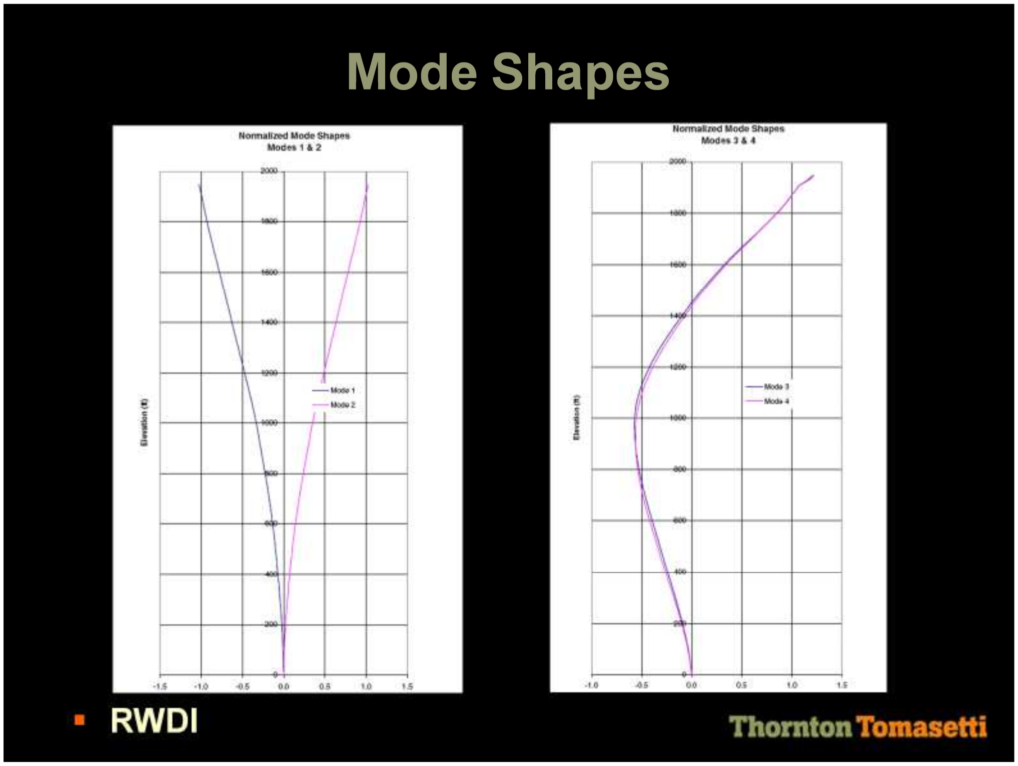
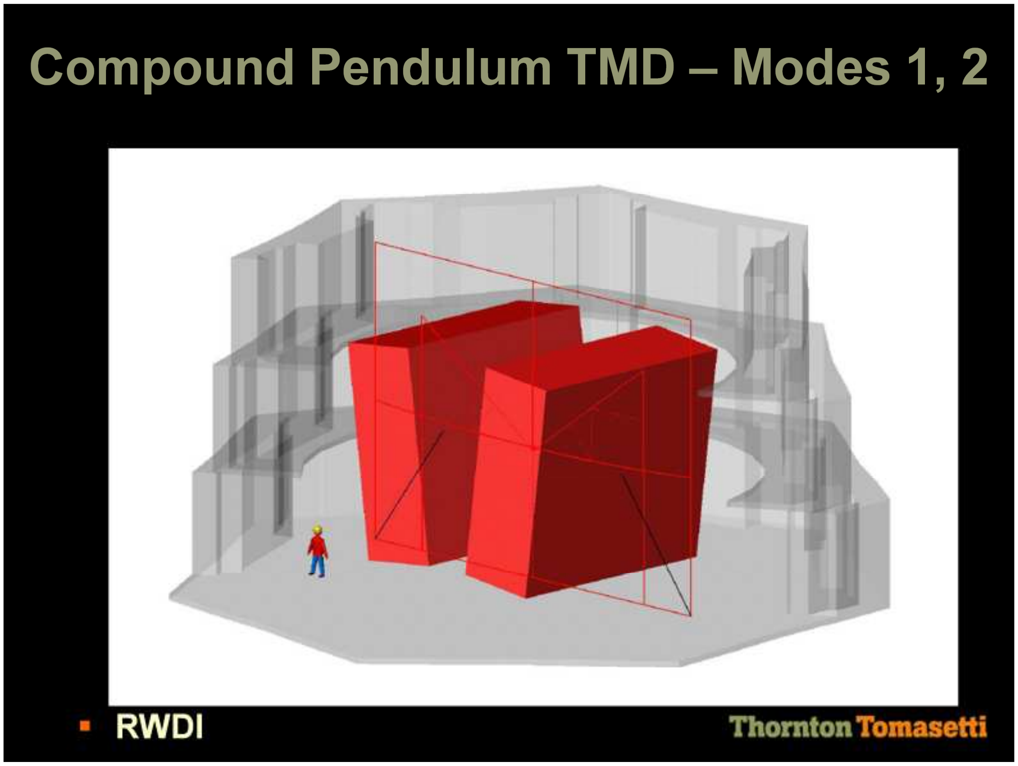


Figure 3 - Total Acceleration at Level 141 versus Wind Speed for Winds Approaching from the West

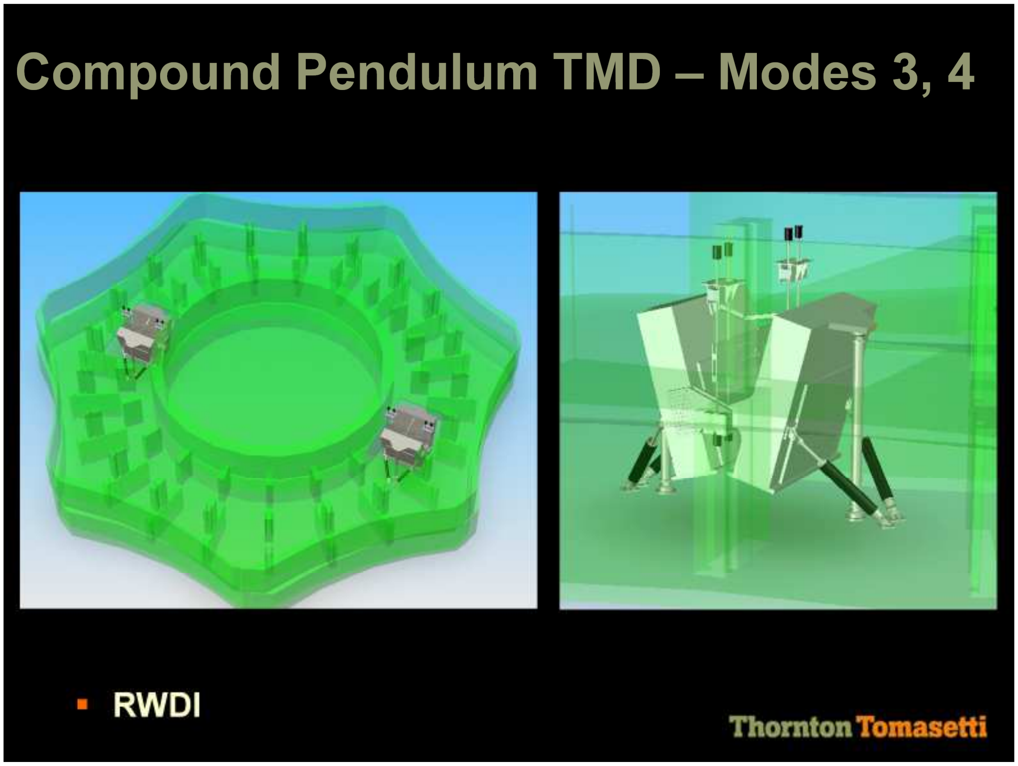
Note the increase of accelerations due to vortex shedding in the range of 50% to 75% of the 10-year wind speed.
The 1-month and 1-year wind speeds are in this range.



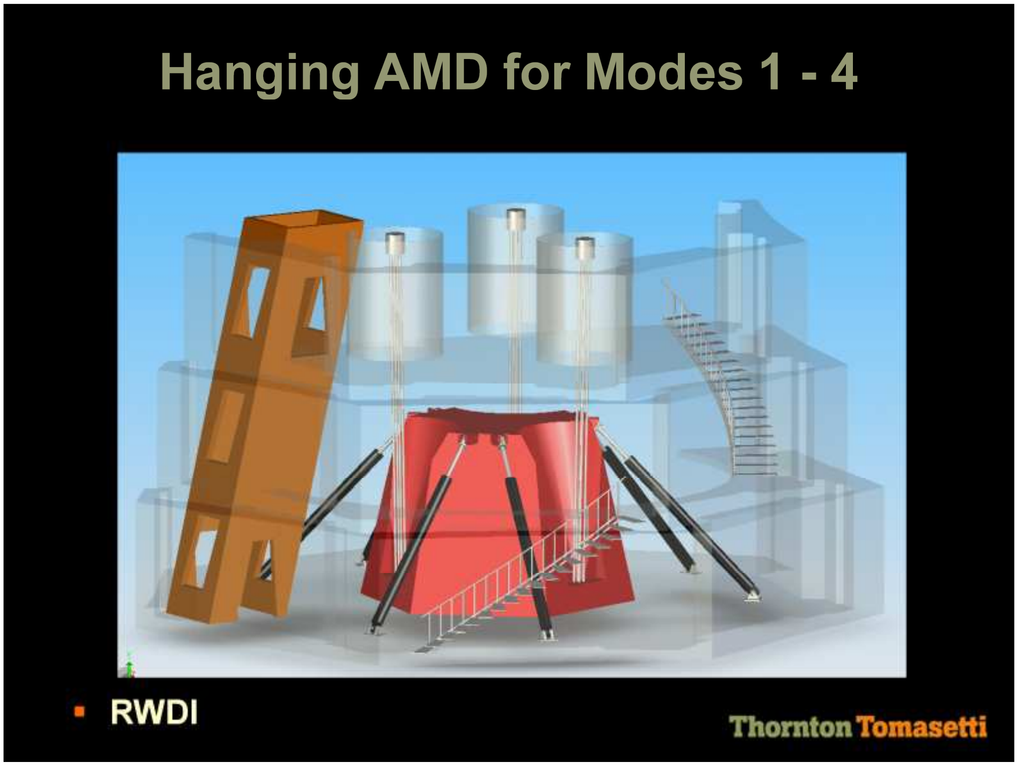
Also, because of the large fundamental period of 18 seconds (1st and 2nd modes in x and y directions), the 2nd and 3rd modes were contributing about 20% to 30% to the accelerations of all the models tested. Why? The 2nd and 3rd modes have periods of about 5 seconds, which is typical of the first mode of buildings about 50 stories high.



Because of the above discussions, to insure building comfort, this building required additional damping for the 1-month and 1-year return periods and not, as is more typical, the 10-year return period. Passive tuned mass dampers (TMD) can only be tuned to one period at a time, but would have to be tuned to the period of the 1st and 2nd modes as well as the period of the 2nd and 3rd modes. Because of space restrictions, this would require a compound pendulum TMD at the top of the building and…..



…two others at another location. The TMD for modes 3 and 4 had to be located in two areas and could not be placed at the ideal location of the top of the building due to space requirements.



Therefore it was decided to use a computer controlled active mass damper (AMD), which can be tuned to multiple modes and located in one area at the top of the building. This is the most efficient, space saving and cost-effective solution. This will be the largest AMD ever used in a building.

What does 5, 10 or 15 milli-g feel like?

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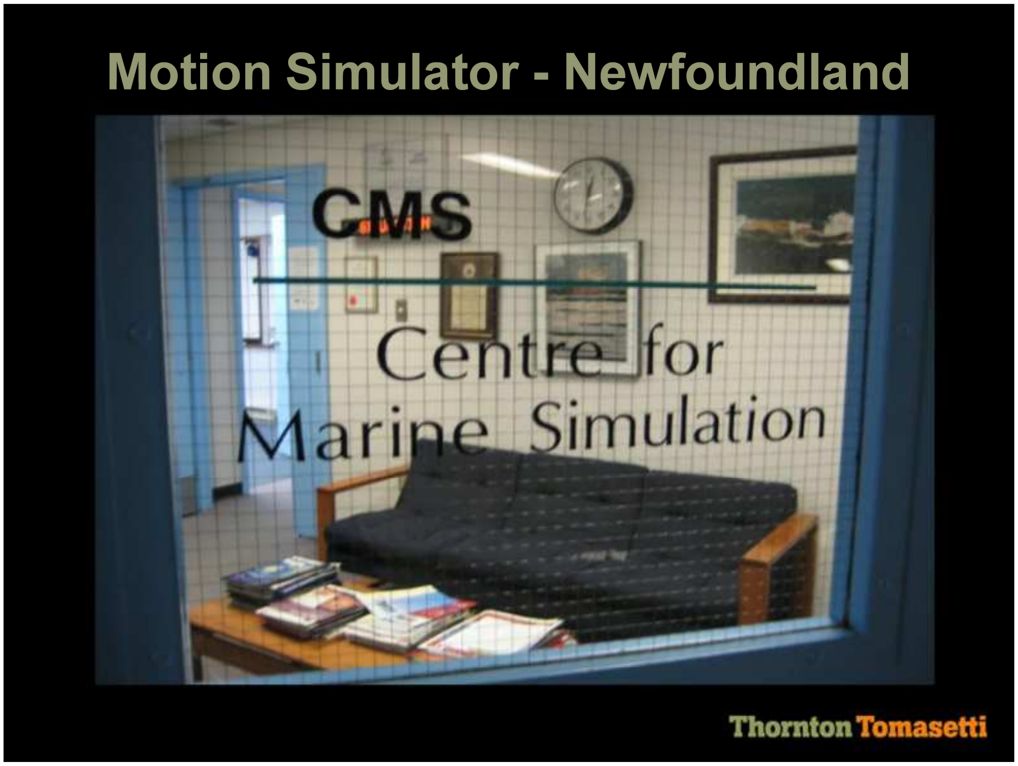

To confirm the perception of the 1-month and 1-year return accelerations with and without additional damping, a motion simulation was developed by our wind consultants, RWDI.

This was conducted with a ship motion simulator.

This is the first time that I know of that this was done to study building motions and included both acceleration and visual simulations.

Note the Chicago skyline.

Note typical residential setting.

Occupant Acceleration Perception

Chicago Spire Motion Simulator Scenario List

Scenario	Floor	Return Period	AMD active
1	70/105/140	0.1	Y
2	70/105/140	0.3	Y
3	70/105/140	1.0	Y
4	140	1.0	Y
5	140	0.1/0.3/1.0	N
6	140	0.1/0.3/1.0	Y
7	140	0.1	N/Y/N
8	140	0.3	N/Y/N
9	140	1.0	N/Y/N
10	70	0.1	N/Y/N
11	70	0.3	N/Y/N
12	70	1.0	N/Y/N
13	140	1/3/10	Y
14	70	1/3/10	Y

- RWDI

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Numerous scenarios were tested with and without the AMD with representatives of the client present. The AMD simulations provided additional damping of 3.1% in modes 1,2 and 3.2% in modes 2 and 3. The test confirmed the wind study analysis and all participants agreed that with the AMD the motion of the tower was virtually imperceptible.

Foundations and Basement

- STS / AECOM, GEOTECHNICAL CONSULTANTS

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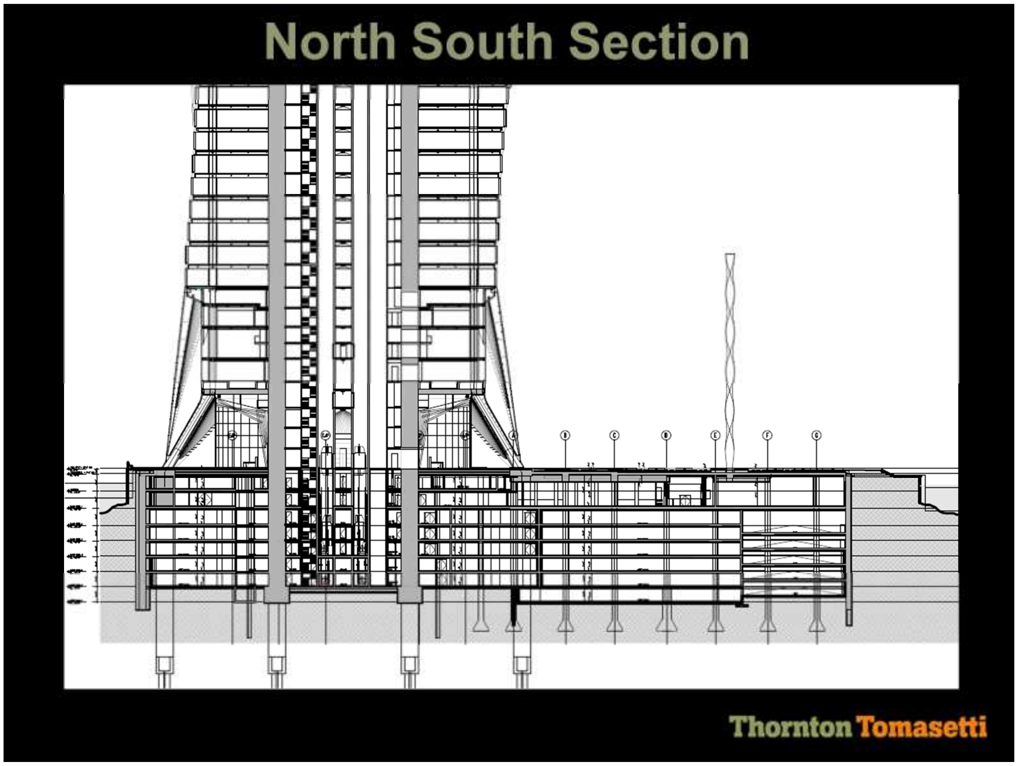
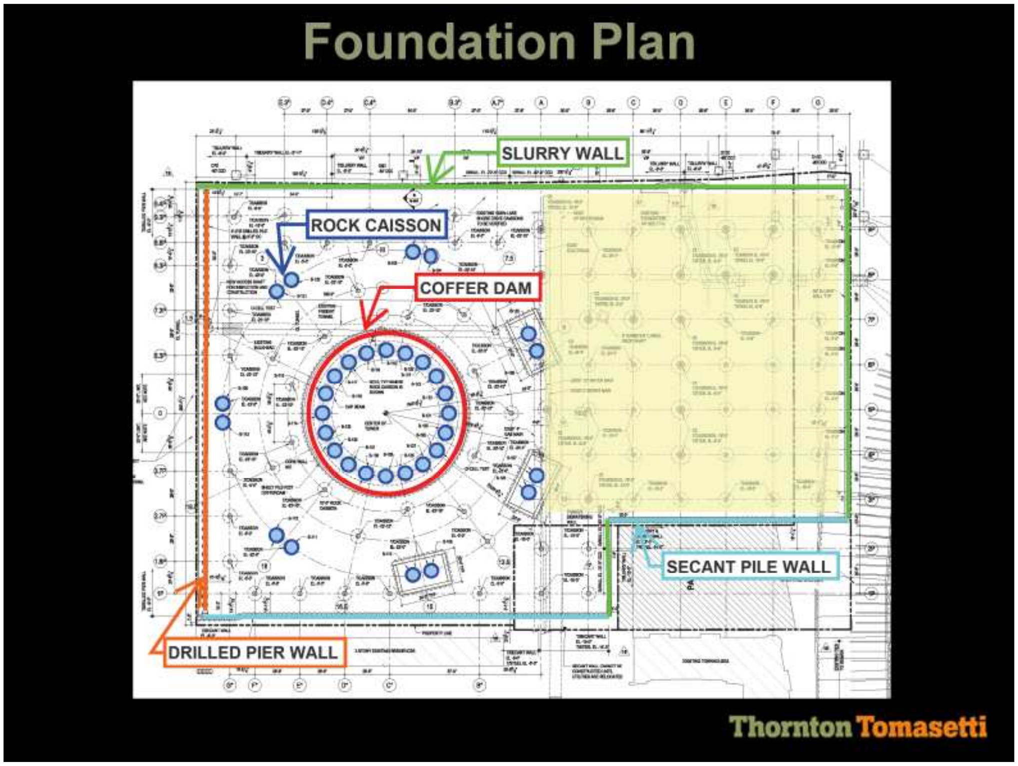
The building is at the northern bank of the Chicago River's inlet from Lake Michigan.

It is surrounded by water on the north and south, condominiums on the west and Lake Shore Drive on the east. It would not be possible to use temporary perimeter wall support systems such as rock or soil anchors. Cross lot bracing would cause unacceptable wall movements and site interference. Therefore top down construction will be used.



The seven/eight basement/parking levels will be the deepest basement level ever excavated in Chicago. The tower will be supported on deep rock socketed caissons, and the podium and garage will be supported on belled caissons bearing on hardpan.



To allow for such deep excavation, permanent earth retention was provided by slurry and secant/drilled pile walls, braced by floor slabs at each level during the top down construction and permanently. Top down construction methods will be used in all basement areas outside the cofferdam, wherein bottom-up construction will used to allow for construction of the core and superstructure while the basements are constructed. The tower is supported with 10-ft. diameter rock caissons – 34 total, 20 at base of cofferdam, 78 feet below grade. Osterberg load tests were used to confirm a record high bearing pressure of 300 tsf (27.7 MPa). Bearing pressure for belled caissons on hardpan is 20 tsf.

Top Down Construction

Why Basement Parking ?

- Planning requirements favor below grade parking
- Provides at grade space for public Plaza
- The building superstructure and shape

Why Top Down Construction ?

- Economical Way to brace deep perimeter basement walls
- A 414’ x 275’ x 75’ “Bath Tub” is difficult to cross brace
- Sequenced excavation minimizes foundation wall movements impact on the neighboring structures

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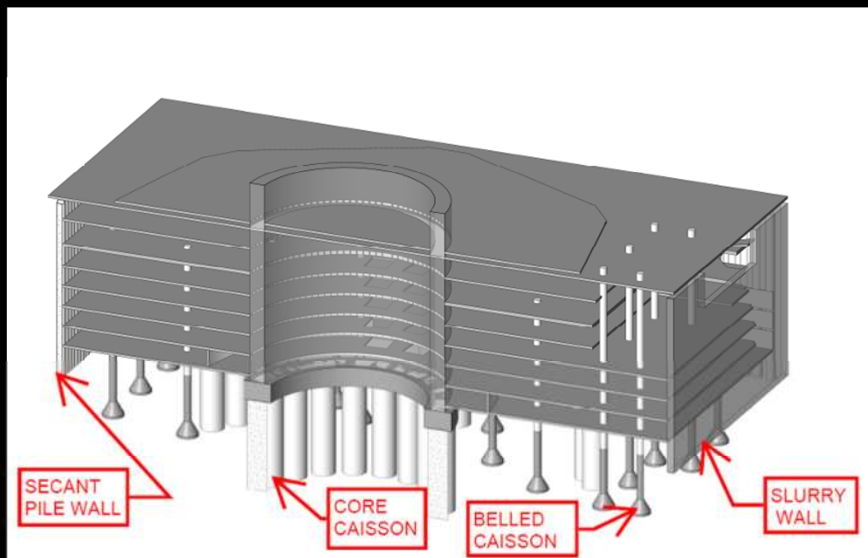
Revit Model of Spire below grade



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Slurry Wall Construction

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Secant Pile Wall Construction

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Cofferdam, Core Rock Caissons

- 100 FT. DIAMETER, CONCRETE WHALERS

Rock Caisson Construction

300 Tons/Sq.ft

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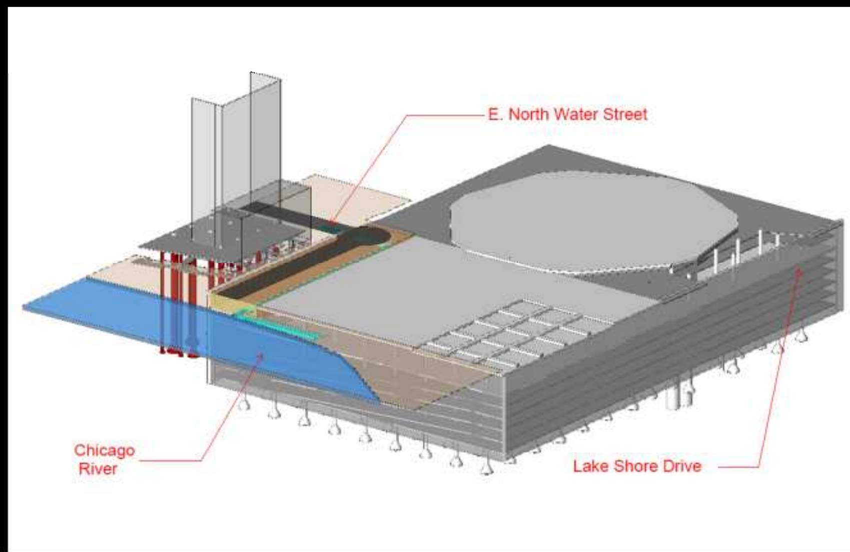
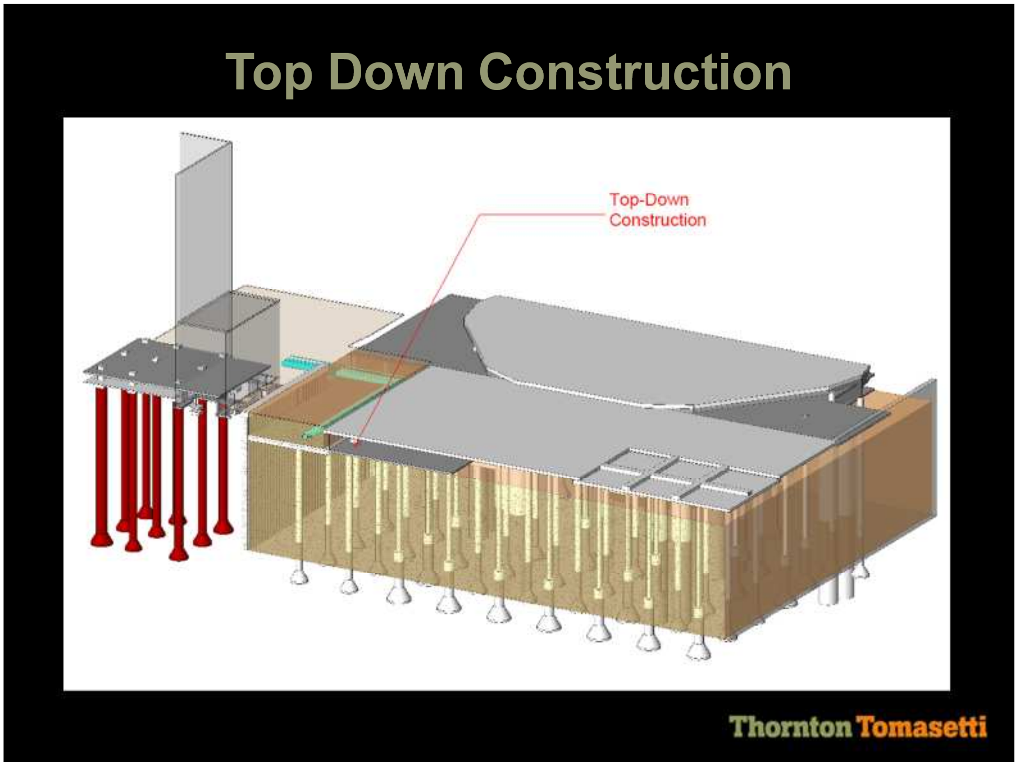
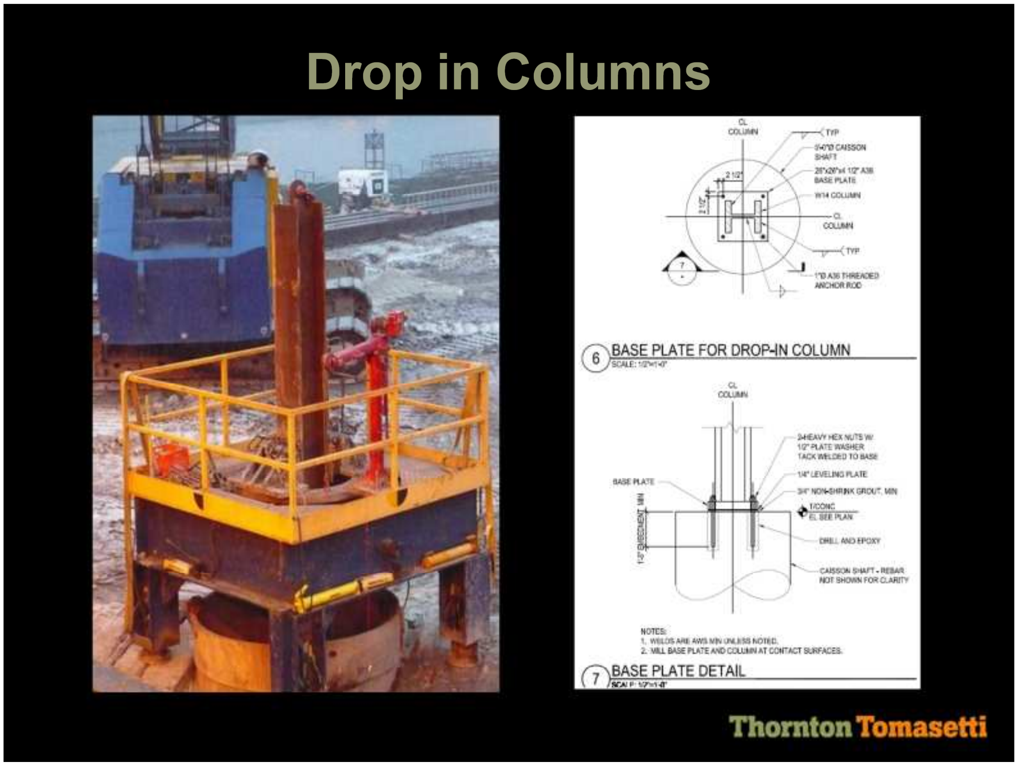
Top Down Construction



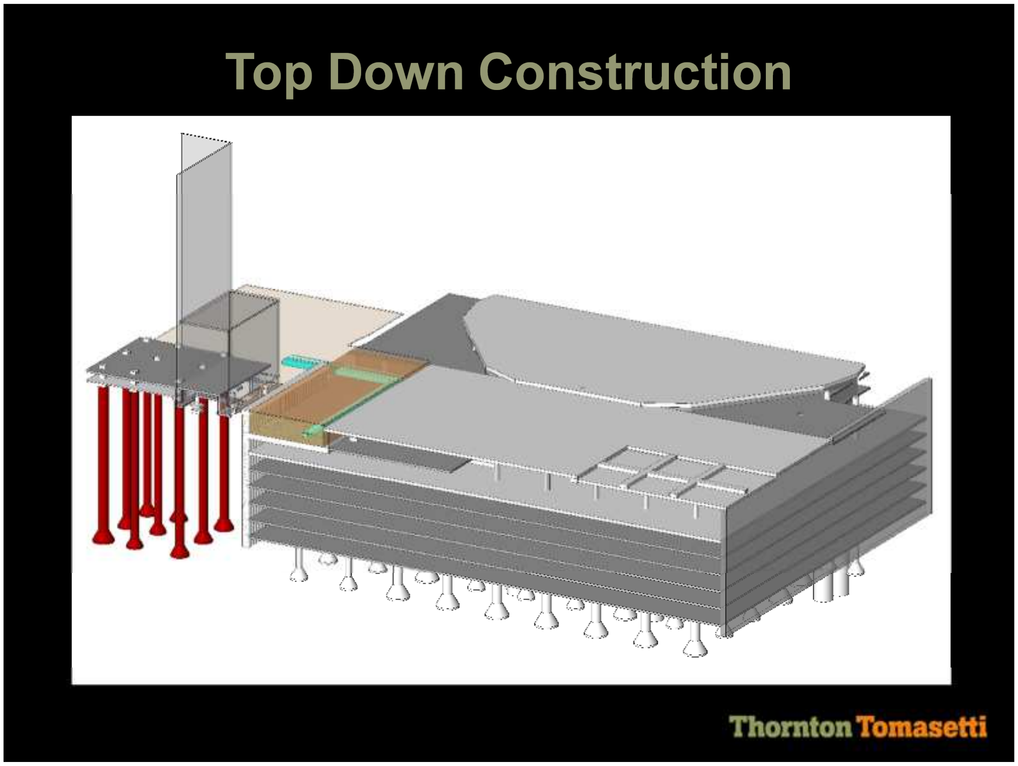
Note existing building on east.



After caissons are in, first slab at grade level is poured using soil as the form. Next, holes in slab allow excavation below to permit construction of next lower slab. Then process continues to lowest level.



Note that the upper part of many belled caissons used a steel drop-in column surrounded by temporary concrete that will be removed later to maximize basement space.



Completed simulation.

Current condition of the site with all perimeter wall, cofferdam and caissons completed and ready to start simultaneous top down construction of basements and bottom up construction of core and superstructure.

A significant evolution of skyscraper architecture and engineering will make a significant contribution to the skyline of Chicago.