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The New Supers: Super-Slender Towers of New York

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Abstract

432 Park Avenue, the MoMA Tower and Steinway Tower at 111 West 57th Street are the first of a new generation of supertall buildings in New York City. 432 Park Avenue will stand as the tallest residential building in the Western Hemisphere; MoMA Tower will be fully supported at 1050 feet despite its lack of vertical architectural lines; and 111 West 57th Street will break the record for the world's most slender skyscraper. With limited horizontal space and increasing demand for high-end residential real estate, the sky is the city's next frontier. In a climate such as this, engineers are constantly challenged to pioneer the technical advances that make these structures possible.

Keywords: 111 West 57th Street; 432 Park Avenue; MoMA Tower; New York; Super-Slender Towers; WSP

New York City, by definition, is synonymous with the description of a "skyscraper city." Manhattan has historically held an impressive track record of world record-breaking tall towers. The historic architectural treasures that hold their place of honor in the skyline are still admired today as beautiful and venerable landmarks. We must not lose sight however, of the fact that the innovations that made them possible were, in their own era, no less wondrous than the amazement we experience today as we watch the newest iconic structures rising up in the very birthplace of the skyscraper.

One by one, each new structural accomplishment of the past advanced the practice and possibilities in tall building design. Considered one of the world's most iconic buildings of its time, the 1902 Flatiron building was one of the tallest in the city at 21 stories made possible by the shift to steel-skeleton construction. A decade later, the Woolworth Building, completed in 1913, rose 57 stories to 792 feet (241 meters). The Chrysler Building became the tallest structure in the world at 1,046 feet (319 meters) until it was surpassed 11 months later by the 1931 Empire State Building that boasted 102 Stories, a 1,250-foot (380-meter) roof height, and reached 1,454 feet (443 meters) with its spire. The Empire State Building held on to the title of the world's tallest building for nearly 40 years until 1970. The World Trade Center Twin Towers 1,368-foot (417-meter) roof height surpassed that of the reigning Empire State Building and attained the title of tallest building in the world. It was a source of pride for New York City until the tragic events of September 11, 2001. Completed in 2014, One World Trade Center brought back record breaking heights to New York City and signaled its resurgence after the attacks of 9/11.

In keeping with the master plan for the rebuilding of the World Trade Center, the overall height of the tower from the ground level to the top of the spire reaches 1,776 feet (541 meters) as a tribute to the "freedoms" emanating from the Declaration of Independence adopted in 1776. One World Trade Center, with its main roof at 1,368 feet (417 meters) above ground, is designed to have the same height as the original towers. The addition of a 408-foot (125-meter) tall spire rising from the main roof completes the tower as it soars to its symbolic height of 1,776 feet (Figure 1).

It is interesting to note that surprisingly, whereas New York City, which in the last century was the place where tall building design got its start, experienced a lull in record breaking supertall and megatall building construction after 9/11 as compared to other parts of the world. Still, at the behest of market trends for prestigious addresses and the excitement of architectural possibilities, the construction of these new icons are radically changing the familiar skyline of the city and satiating a thirst for the new, the exhilarating and the structurally challenging.

When land is scarce, height and panoramic views evoke glamour and prestige, and buyers are willing – even desirous of living and working in the clouds, developers are encouraged to break through the skyline with iconic towers like those currently appearing over the New York skyline.

The financial viability of building ever taller towers on relatively miniscule footprints is a direct result of the high value of dense urban sites combined with the demand for space in an environment of limited horizontal availability. This is particularly true in a market like Manhattan that draws upon the entire world for its clientele. New York City's new supertall residential buildings in particular, reflect a desire to live in lavish signature "architectural brushstrokes" in the sky with easy access to the richness of the surrounding attractions. In a climate such as this, engineers are constantly challenged to pioneer the technical advances that make these structures possible.

In a competitive real-estate environment, the end user seeks not only luxurious finishes, but the ultimate luxury of the feeling of expansive spaces with expansive views and the flexibility of configuring spaces that provide the freedom of achieving highly personalized living quarters. The structural engineer will have to contend with the market demand for column free spaces, highly articulated architecture and the desire for views unobstructed by structural elements. In addition, the engineer will have to define a structural system that will control the building acceleration, the dynamic motions imposed primarily by wind forces to achieve an acceptable level of occupant comfort. All these go beyond code safety provisions for integrity inclusive seismic loads and/or special safety requirements. The combination of these and additional constraints present increasingly complex challenges when determining the most cost-effective and efficient structural solutions.

As noted by Taranath (2009), the practice of engineering has seen rapid changes in recent years. For decades, the architect's aesthetic vision had to be "edited" by the structural engineer in a process that intended to achieve an efficient structural solution that would result in the least amount of imposition on the architectural intent. In fact, these challenges faced by the engineer over the years has resulted in the development of innovations in structural systems and building materials that have changed the architect-engineer dynamic, increasingly allowing the architect to go taller and express his/her creative vision with less and less "editing" of the aesthetic imposed by the practical aspects of achieving efficient structural systems and the limits of the laws of physics.

In this atmosphere of advances and innovation in building design and construction, a new vernacular between the architect and structural engineer has emerged. These innovations and analytical advances have set architecture free of structural restraints in which the final scheme may well depend on how best it can maximize the space utilization. The "structural efficiency first" model that was typical of the International Style has morphed into a new and much more complex quest. The engineer's judgment, experience and talent play a much greater role in optimizing the structural efficiency of a building. As a result, the practice of structural design has become as much an art as a science.

In response to the above, as architects reach ever higher into the horizon designing soaring vertical towers, the engineer must be prepared to address the resulting challenges, particularly those presented by dynamic movement. The main factors influencing dynamic movements are the building's rigidity expressed by the structural "period", the mass of the structure and the geometrical characteristics that allow fluidity in wind passage as well as the incorporation of auxiliary damping systems.

Of the three buildings being presented as examples in this paper, each demonstrates a methodological approach to how the architectural vision and the constraints of the building site dictate the dynamics of the structural design process. 432 Park Avenue,

Figure 1. View of One World Trade Center from the East River (Source: WSP Group)

Figure 2. 432 Park Avenue, 2015 (Source: CIM Group and Macklowe Properties)

Steinway Tower (111 West 57th Street) and Tower Verre, also known as the MoMA Tower, are optimized for the maximum fulfillment of usage needs by capitalizing on structural efficiencies that determine the unique structural system employed in each.

432 Park Avenue

Standing at 1,397 feet (426 meters) tall, 432 Park Avenue is currently the tallest residential structure in the Western Hemisphere and the third tallest in the United States, boasting the highest roof in New York City. At the same time, the building's base is only 93'6", giving it a slenderness ratio of 1:15 (Figure 2).

Figure 3. 432 Park Avenue during construction (Source: WSP Group)

The structural rigidity was achieved thanks to a robust core measuring about 30 feet by 30 feet that houses the elevators, stairs and mechanical spaces as well as a perimeter tubular frame composed of columns and perimeter beams. The two main components are connected five times throughout the height of the building. At the connecting levels, double open floors are created, thereby minimizing the vortex forces inherent to the wind flow.

A double tuned mass damper located at the building's top controls the accelerations to the level of the premier quality structures in the world. Using the highest strength concrete of 14,000 psi (100 MPa) facilitated minimizing the column sizes and their intrusion into the usable livable area. Thus, at the end of the day, despite height and slenderness challenges, spaces free of columns are achieved on every single level of the building.

The building is expected to be LEED certified, integrating energy efficiency and renewable energy technologies (Figure 3).

Tower Verre - MOMA Tower

To see the Museum of Modern Art's latest art exhibit, you need only look to the neighboring building 53 West 53rd Street. Currently under construction in the excavations and foundation stage, the spectacular 76-story, 1,050-foot (320-meter) MoMA Tower, coined "53W53", will house 140 luxury condominiums and three floors of gallery space for the museum. In mid-2018, the building is scheduled to open its doors to residents, who will choose from a variety of 1 to 5 bedroom apartments, with the largest being a 7,892-square-foot duplex penthouse. Those with north-facing apartments will enjoy unobstructed views of Central Park, thanks to the building's height, which makes it the fourth-tallest residential tower in New York City (Figure 4).

The MoMA Tower concept hatched in 2007, when the MoMA sold the 17,000-square-foot vacant lot next to the museum to Hines Properties. The deal was a win-win for the developer and the museum, since the new building will include 36,000 square feet of gallery space, and the museum's prestige will attract high-end residents.

To the MoMA, it was important that the new tower stay true to its trade: modern art. According to the New York Times, the museum even required veto power over the selected architect as part of its real estate deal with Hines. For this tall task, Hines selected Jean Nouvel, the Pritzker Prize-laureate. The French architect submitted two designs for the super tall, super slender structure, one more conservative and one more structurally daring. In the past, a developer might have chosen the conservative model, opting for practicality and cost-effectiveness. Now, in the age of skyscraper resurgence and the knowledge that efficient, cost-effective structural solutions were accessible, Hines chose the edgier design, intending to make an iconic splash on the New York City skyline (Figure 5).

Nouvel's avant-garde design features "randomly" patterned diagonal members, known as diagrids, which taper to form a glass-like spire. Each floor's plan will vary, as the tower's tapering effect will make each floor approximately two feet smaller than the next. The 2nd and 5th levels are designed to connect to the existing museum, with amenities on the 6th and 7th floors and residential condominiums starting on the 9th floor.

The complexity of the tower's design is rivaled only by the complexity of the structural engineering required to make it both

Figure 4. Rendering of MoMA Tower, 53 West 53rd Street (Source: Ateliers Jean Nouvel)

Figure 5. Model of the upper portion of MoMA Tower (Source: WSP Group)

economically feasible and structurally sound while maintaining its ultra-luxurious aesthetic and interiors. The structural engineering team designed Nouvel's signature concrete diagrids, which will be connected by 24-inch-deep spandrel beams. The engineers determined which diagrids would be load-bearing and which would be purely aesthetic in nature creating a harmonious overall flow. In order to maximize the space, the core housing the elevator and stairs is totally eccentric to the plate.

In addition, the team designed a single outrigger system between the 35th and 37th floors. The use of outriggers has been a popular strategy in supertall buildings since the 1980s, though the general concept has been used in design for millennia, dating back to Polynesian boats. As supertall buildings grew in demand, engineers began to choose outrigger systems. An outrigger system stabilizes and strengthens a building by connecting the building's core to the outer columns of the building thereby improving the structure's stiffness by as much as 15%.

From a structural standpoint, the space constraints of the museum were particularly challenging since the lower floors require unobstructed gallery space but also carry the weight of the supertall structure. The team solved this problem by designing a series of comprehensive and massive steel truss transfers on the 6th and 7th floors that pick-up the superstructure interior concrete columns, the East shear wall core, and hung interior columns that could not penetrate the museum space. This allowed for only two interior columns in the South section of the building. Similarly, the engineers designed the condominiums on the 26th floor and up without interior columns, maximizing the flexibility of interior layouts. To do this, the team supplemented the lateral resistance system of the structure with concrete shear wall cores surrounding the elevator shaft and egress stairs.

Unlike most buildings, the MoMA Tower has no vertical façade lines. The diagrid elements are the major factor in supporting the vertical weight as well as providing the lateral stability for this building, which has a slenderness ratio of 1:12. Meticulous details were created for the rebar connections in the inclined elements to the point where an actual one-to-one model was produced to test the constructability of the joints. Where the reinforcing intersects, a steel "glob" was introduced, an element never before used in concrete construction. The 12-inch-thick concrete floors introduce another element that maximizes the floor height at 11 feet (3.4 meters). Above the 76th floor the concrete is substituted by steel construction.

To accommodate the need to achieve the sloping peak at the top of the building, a prefabricated steel structure will be hoisted atop the 76th floor, since it was determined that continuing to form the angular concrete contours in place at the top would be too expensive. This design technique allows for easier construction of the top of the structure and its sharply sloped, shard-like tip (Figure 6). Due to the slenderness ratio of the building and the reduced massing at the top of its tapered shape, the structure houses a Tuned Mass Damper (TMD) at the 74th level, which stabilizes the building acceleration to top

Figure 7. Rendering of 111 West 57th Street (Source: SHoP Architects)

level industry standards. Due to its unique size and shape, the 450-ton TMD was custom designed as a pendulum TMD.

Steinway Tower, 111 West 57th Street

Part of the impetus for 111 West 57th Street, with its world-record breaking slenderness ratio of 1:24-plus, results from the opportunities presented by exorbitant New York City land values, scarce availability of land on which to build and ample demand in the high-end residential market, providing economic viability for this luxurious skyscraper on a miniscule footprint.

Located at the historic Steinway Building, 111 West 57th involves the renovation of the existing landmarked Steinway Building with the addition of a residential concrete tower above. The new 94-story tower will reach a height of 1,428 feet at the top. With a width of 58'-9", the slenderness ratio of the building is actually 1:24.3 (Figure 7).

Besides the code stability requirements of a building of this height and slenderness, the dynamic movements and motion perception of occupants had to be addressed as one of the most critical challenges. In addition, the reduction of the structural elements impact on the already limited usable space was a paramount priority in the structural design solution selected for the building. The challenges created by the height-to-width ratio were further augmented by the developer's requirement that all of the luxury apartments in the building have a commanding view of Central Park. In order for to achieve this goal, the apartment occupying the lowest floor had to rise above buildings that would otherwise interrupt park views. As a result, the first apartment level is situated at the 20th floor.

Typically, a residential structure would be braced with apartment floor slabs starting from the lowest floors of the building. In the case of 111 West 57th Street however, the structural team was faced with the additional complication of stabilizing the lower floors and managing the considerable building loads without the inherent advantages produced by the typical floor slabs. The structural solution involved adding beams at intervals of every 3 floors in order to overcome this formidable challenge.

The new residential tower is conventional reinforced cast in-place concrete of 14,000 psi strength together with built-up steel members consisting of welded plates to minimize the size of the structural elements.

As a result of the reduced floor plate the structural system is formed by just two exterior walls located at the east and west façade connected to the side core in the shape of an 'H' with two connectors. At the south end, in order to maximize the space, two vertical columns were eliminated and a 6-foot-wide flat beam was introduced. Four outrigger walls are added at the mechanical floors to augment the general structural stiffness. To control the motion/acceleration of this super slender tower, an 800-ton Tuned Mass Damper is being employed and after extensive testing, three open floors will provide an improved acceleration by as much as 12 percent.

Conclusion

432 Park Avenue, the MoMA Tower and Steinway Tower are truly pioneers on New York City's next new frontier: the sky. As these case studies show, we are at the forefront of creating a new breed of iconic buildings that challenge perceptions about what is possible in engineering and construction. Super-slender towers are in many ways a perfect embodiment of global aesthetic trends and market influences. Their form is driven by exorbitant city-center land values, scarce availability and very high demand, the combination of which makes it economically viable to create these luxurious skyscrapers on miniscule footprints. This presents many challenges for the integrated design team. As structural engineers, we must work within physical constraints, but also economic ones – our solutions stem just as much from the need to maximize useable space on these super-prime sites and create stunning uninterrupted views as they do from the need to control wind movement.

For each of these three buildings, the structural engineering team overcame specific challenges and designed solutions to meet the architect and developers' visions. At 432 Park, they engineered a building without interior columns, notwithstanding its status as the tallest residential building in the Western Hemisphere. In the MoMA Tower, despite the fact that the building is characterized by an architectural style articulated with no vertical lines, an efficient and elegant structural solution was achieved to support the 1050 foot sculptural tower. For 111 West 57th Street, the team broke the record for the world's most slender building, designing one of the city's tallest buildings on a plot of land only 60 feet wide. Each of these engineering feats are paving the way for the newest class of super tall, super slender buildings in New York City.

In a densely populated city of over 8 million residents, the limited availability of space has made vertical expansion not only economically viable, but necessary for growth. The desire for ever-taller buildings continues around the world, but New York is proving that it still has the power to push the boundaries and inspire new feats. It is our hope that developers and designers around the world will find as much inspiration in this new generation of skyscrapers as they did in the icons of the last century.