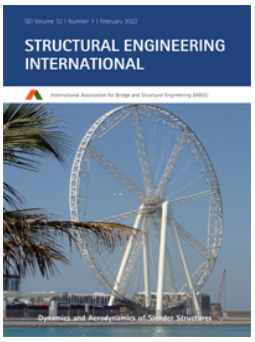

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Three Supertall Slender Towers in Midtown Manhattan

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Abstract

One Manhattan West (1MW), Two Manhattan West (2MW) and 35 Hudson Yards (35HY) are three slender supertall towers recently designed and engineered by the authors' company that rise above the underground train tracks approaching New York City's Penn Station on the west side of the island of Manhattan. Although the slender towers are neighbors and have similar heights and proportions, each tower resolves the constraints of the underlying tracks with unique structural approaches. The disparate below-ground conditions result in three distinct structural solutions that are all governed by the effects of the wind. All three towers were subjected to extensive wind tunnel testing programs in order to optimize their dynamic behavior. The structural system of 1MW is a reinforced concrete core and a perimeter steel moment frame. The site conditions prevent the perimeter of the 304-meter-tall tower from reaching the foundation. This challenge is addressed by sloping the perimeter columns to the core above the ground, thus making 1MW one of the slenderest structures in New York City. The structural system of 2MW consists of a central braced steel core with outrigger and belt trusses and a perimeter steel moment frame. Half of the core is undercut by train tracks; loads are strategically moved to the perimeter structure, which is tightly integrated with tracks below. 35HY is an all-concrete mixed-use tower where one of the main challenges was to align core wall and column placement with the spacing of the existing tracks below while trains continued to be operational.

Keywords: skyscraper; supertall; wind; overbuild; New York City; wind tunnel; occupant comfort

Introduction

Site

In the early 1900s, the Pennsylvania Railroad company dug the first tunnels under the Hudson River to bring rail service directly into New York City from the East Coast rail network to the west and south.[1] The tunnels emerge on the west side of Manhattan and cross the island below the surface, run under the New York Pennsylvania Station and continue under the East River to connect north to New England. For more than a century, a large tract of land west of Ninth Avenue remained unusable because it housed the tracks leading to the tunnels and a large parking rail yard. In addition, one of the approach ramps of the vehicular Lincoln Tunnel crosses the area in a North–South direction. In the early twenty-first century, a combination of real estate pressures, political will and advances in engineering made it possible to transform the western side of midtown Manhattan by bringing sustainable transit oriented development above this complex transportation infrastructure zone. The rights to develop the zones are split between two different companies. The rights to the portion between Ninth and Tenth Avenues were acquired by Brookfield Properties and is appropriately named Manhattan West. For this site, the train infrastructure below is largely running tracks where trains are operational 24 h per day and could not be interrupted. The stretch between Tenth Avenue and the West Side highway is developed by The Related Companies and is referred to as Hudson Yards. The majority of this area is covered by the large parking train yard for the Long Island Rail Road (LIRR) and Amtrak.

The authors' company has recently designed and engineered three of the towers at these two developments. One Manhattan West (1MW) is a 304 m tall, 70-story office tower. It is the first of the two primary towers that are part of a larger Manhattan West Development. It is located on the corner of Ninth Avenue and Thirty-Third Street (*Fig. 1*).[2] The sister tower of 1MW, Two Manhattan West (2MW) is a 62-story office tower standing 275 m above ground level. With three additional basement levels down to the tracks, it is freestanding for 293 m (*Fig. 2*).[3] Thirty-Five Hudson Yards (35HY) is a 72-story mixed use tower that rises 308 m above the lobby level and an additional 10 m above the railroad tracks and foundations.[4] The program consists of several restaurants, an Equinox fitness center and office levels at the base, Equinox hotel, and luxury residential condominiums above (*Fig. 3*).

Base Condition

All three skyscrapers face difficult challenges in reaching solid ground on which to place foundations, but their challenges are different because of dissimilar layouts of complex rail infrastructure below (*Fig. 4*).

1MW

At the site of 1MW, the tracks narrow in the zone between Ninth and Tenth Avenues. Thus there is a zone of 39 meters where the ground is unobstructed between the northernmost track and Thirty-Third Street, which bounds the site to the north. A Class A office tower, however, requires a minimum width of about 50–60 meters to be commercially viable. Thus, the available area of the building foundation is considerably smaller than the total footprint of the building. While the building's central core can be founded on rock, none of the perimeter columns on the south side could come down vertically to the ground. These constraints were addressed by sloping in the perimeter columns on the south to the central concrete core between Levels 2 and 6. This configuration would have created an unbalanced lateral system with considerable uplift on the north face. In order to balance the shear in the concrete core, the columns on the north face were also sloped into the central core. The result is a configuration where the central core is the only lateral system for the building between Level 2 and the foundation (*Fig. 5*).[5]

2MW

The site of 2MW does not contain an uninterrupted area at the foundation level large enough for the central core of a Class A office tower. Active train tracks pass under a significant portion of the tower footprint, undercutting half of the core. As a result, the design took an integrated approach, finding opportunities to bring perimeter columns down to terra firma between tracks and existing infrastructure. On the north side, openings had been left in the platform that cover train tracks in anticipation of the future tower. Kicker columns and a system of story-deep transfer trusses were provided to move loads to these access openings. The north line of core columns, which cannot continue to terra firma, is transferred within the lower mechanical zone and lobby both south to the centerline of the core columns (the northernmost extent of the core at track level) and north to the location of the platform access openings. These large diagonal members and the tie above the lobby act as part the outrigger trusses in the lower mechanical zone. On the south side, the columns slope at the base to the available location between the existing road bridge and train tracks (*Fig. 6*).

35HY

In the case of 35HY, the key component of efficiently building over a site consisting completely of railroad tracks is the vertical organization of the structural system to align with the existing infrastructure below. The location of 35HY on the Hudson Rail Yards site required the entire tower structure to be supported on 600 mm steel columns aligned between the tracks—the only building of the four planned towers in the Hudson Yards Development with no direct connection to terra firma.

The structural system of the Platform beneath 35HY consists of 1200 mm

Fig. 1: One Manhattan West (© Fadi Asmar | SOM)

Fig. 2: Two Manhattan West (© SOM)

Fig. 3: 35 Hudson Yards (© Dave Burk | SOM)

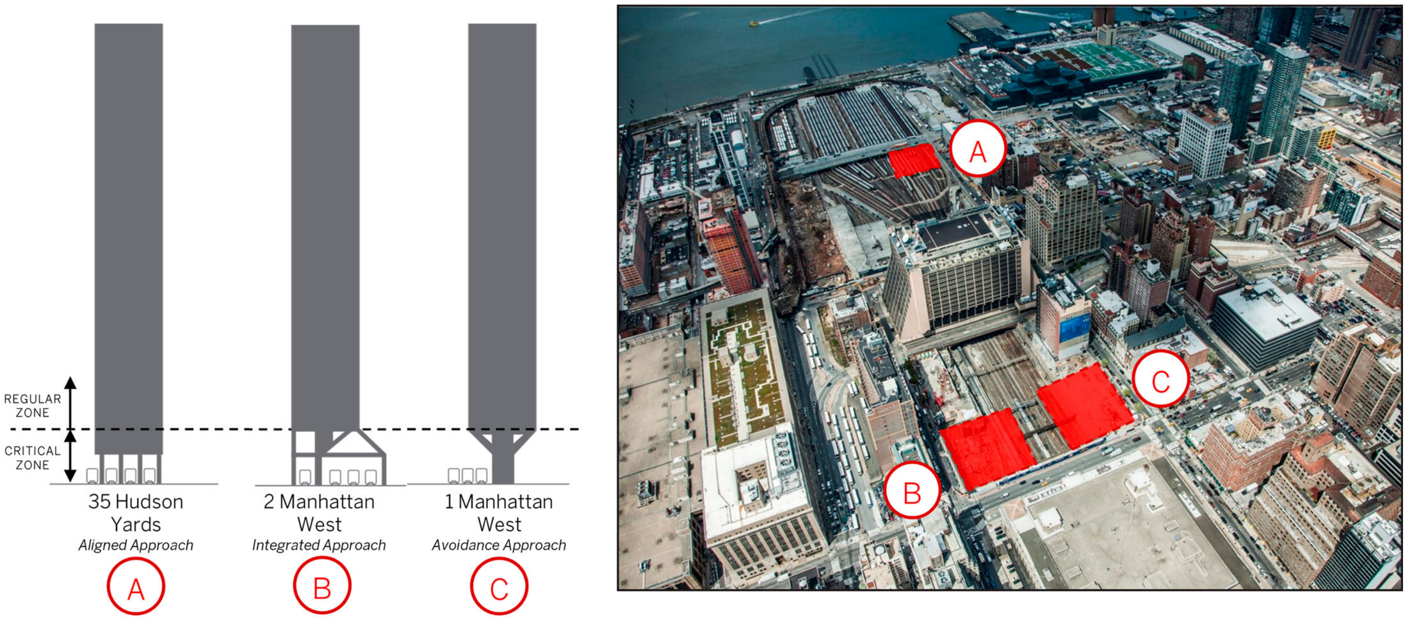

Fig. 4: Diagram of building strategies

steel moment frames with 600 mm solid steel columns in the North–South direction and steel braced frames in the East–West direction. The braced frame of the platform is organized so that vertical elements below reflect the organization of vertical elements above, ensuring a direct load path.

The primary core walls and hammerhead columns for the tower are placed along these E-W running lines to take advantage of the direct load path to the foundations. In the N-S direction, core walls are located along the lines of platform moment frames, and are designed to gradually shed their gravity and lateral loading to the adjacent core walls as they span 15 m (50 ft) from one support line to the next (*Fig. 7*).

Lateral System

1MW

The lateral system of 1MW is a central reinforced concrete core and perimeter moment frame with structural steel columns and beams. The exterior columns along the north, east and south "kick back" to the concrete core below Level 6. To enhance structural resilience, and reduce lateral drift, a perimeter belt truss is located at the top of the tower (*Fig. 8*).

2MW

The primary lateral system of 2MW is a structural steel braced core and perimeter moment frame. The core and perimeter are interconnected at two locations along the height of the building with outrigger and belt trusses above the lobby and at the top of the tower, which serve as the mechanical zones for the building.

The tower is split into two distinct zones. The typical zone above Level 6 consists of a braced core–outrigger system in the major (N-S) direction and an eccentric braced core in the E-W direction, allowing for coordination of elevator lobbies and MEP services. Below Level 6, the core transitions to half its depth to fit within the allowable structural zone between tracks, and is encased in concrete shear walls below ground level. The perimeter moment frame improves tower serviceability behavior under wind (*Fig. 9*).

35HY

Laid out and detailed to transition directly to the platform below, 35 HY resists lateral loads with a reinforced concrete core enhanced by a series of buttress walls that extend from the core out to the perimeter. Four

high-strength concrete buttress walls in the North–South direction and two walls in the East–West direction stiffen the central core, ending at staggered levels over the height of the tower.

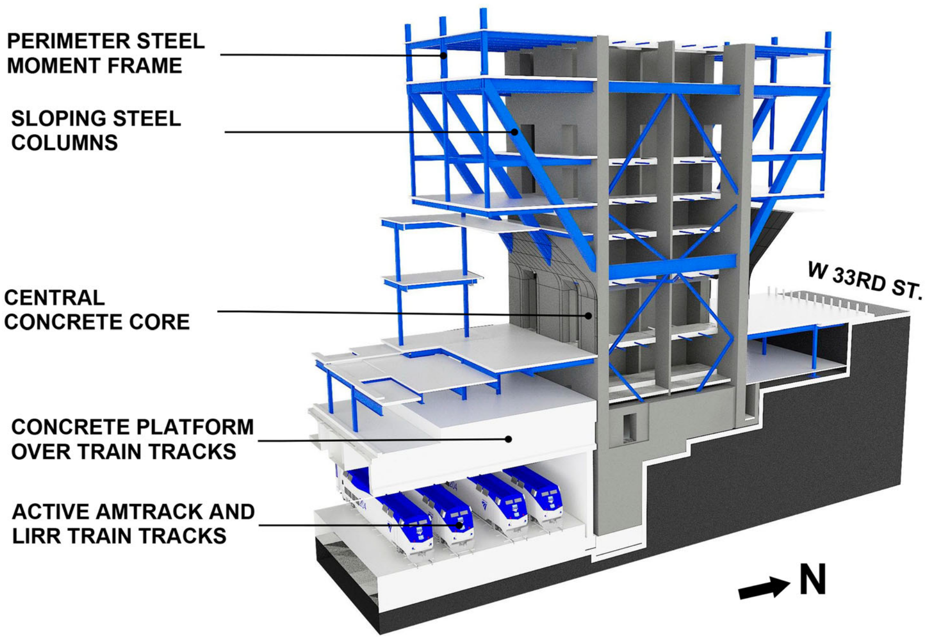

Fig. 5: 1MW perimeter column transition to core (© SOM)

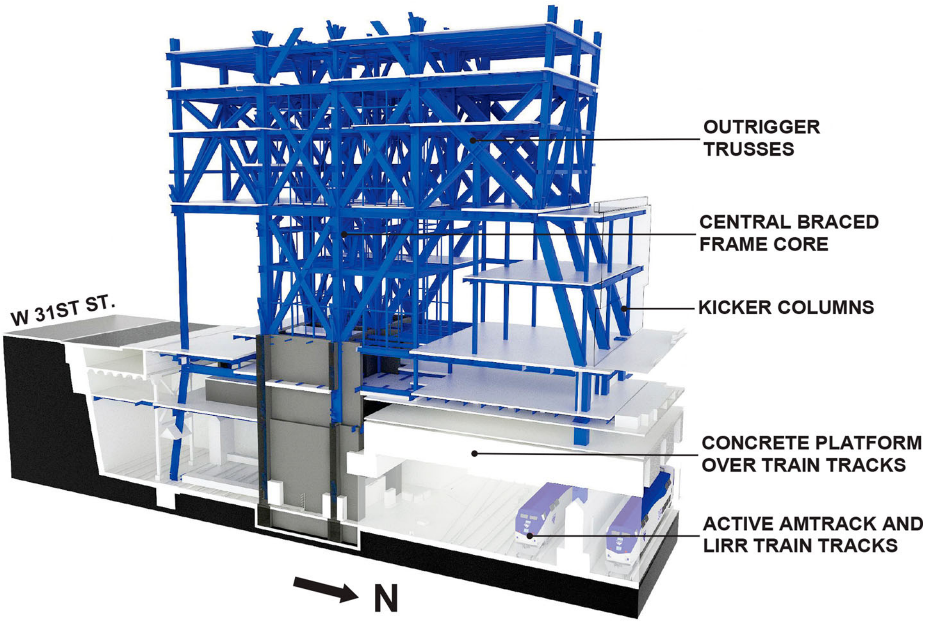

Fig. 6: 2MW core and perimeter column transfer structure

Hammerhead columns, placed at the end of each buttress wall, increase the overturning moment resistance and channel loads directly into steel platform columns and caissons. Reinforced concrete belt walls transfer perimeter gravity columns to major columns and hammerheads, further channeling load to the main support lines between the tracks below (*Fig. 10*).

Geometry and Aspect Ratio

The 1MW tower is rectangular in plan with the north, south and west faces rising vertically up from the ground. The east face bows out until the 16th floor and then tapers in uniformly to the roof. All four corners of the architectural façade have a rounded transition with a radius of 2720 mm. The envelope of the building meets the ground at a rectangle with dimensions 45.3 × 61 meters. However, the only portion of the structural system at ground level and down to the foundation is the reinforced concrete core with dimensions 20.0 × 40.0 meters, giving the tower a structural aspect ratio of 1:16.

2MW

Architecturally similar to 1MW, 2MW is also a tapered extrusion, rectangular in plan, with the north face gently sloping out to Level 17 then tapering back uniformly to the roof. The glazed exterior enclosures feature rounded corners. Due to the location of available touchdown points at track level, the north and south perimeter columns slope away from the tower at its base, slightly increasing the width of its footprint and resulting in an aspect ratio of 1:5.6.

35HY

The architectural massing of the tower was developed in concert with the placement of the primary vertical elements to conform to the limited support points between tracks. The tower floor plate is stepped in direct response to the changing architectural mixed-use functions. The retail and office podium, requiring the largest floor plates, continue up until Level 14, above that leaving an approximately 30.5 × 30.5 meter floor plate at the hotel floors up to Level 30. Starting at Level 32, the southwest corner of the floor plate is chamfered, creating a terrace. Every ten floors, corners are chamfered in succession in a counterclockwise manner to create a series of residential terraces. The overall aspect ratio of 35HY is 1:7.

Materials

1MW

In order to minimize the thickness of the concrete elements while preserving high stiffness, the project utilizes high-strength concrete with a standard 28 day compressive strength of 70 MPa up to Level 16 and 55 MPa in the walls above. The perimeter moment frame is composed of structural steel beams framing into structural steel columns, both utilizing rolled shapes. Late in the design process, rolled shapes as large as W14 × 873 in ASTM A913 Gr 70 steel with 482 MPa yield strength became available on the local market. Taking advantage of this, the design team optimized the column design and eliminated all plated columns on the project.[5]

2MW

To minimize gravity drift of the building due to the asymmetrically undercut core and to aid in "bridging" the large gap between available foundation space, an all-steel structural system was selected for 2MW. A concrete

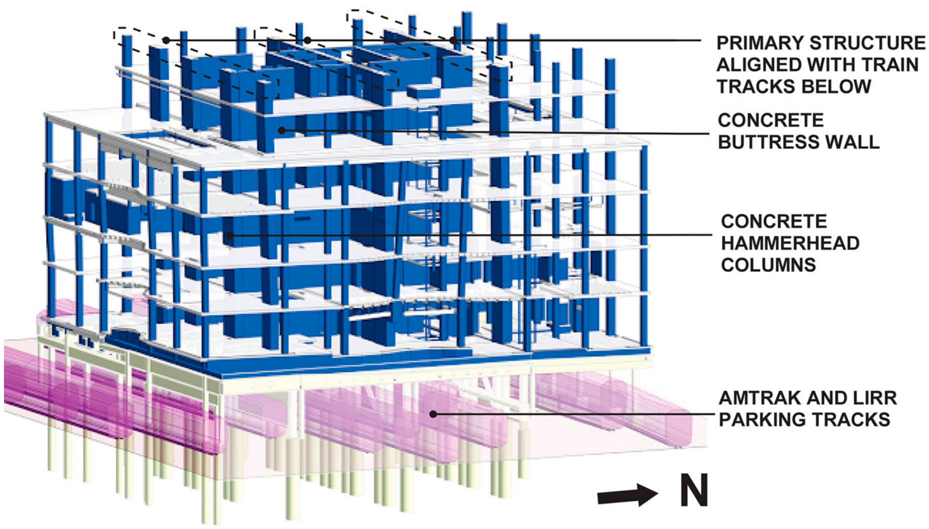

Fig. 7: Alignment with train parking tracks

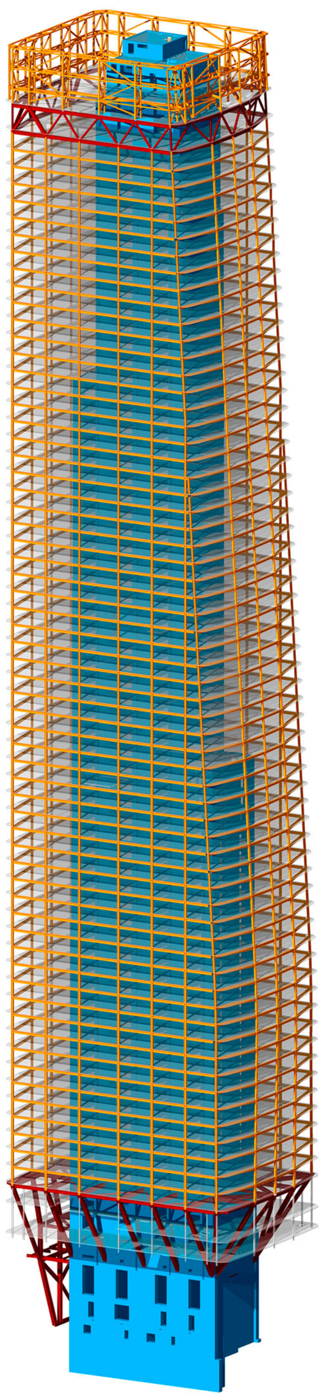

Fig. 8: 1MW structural system

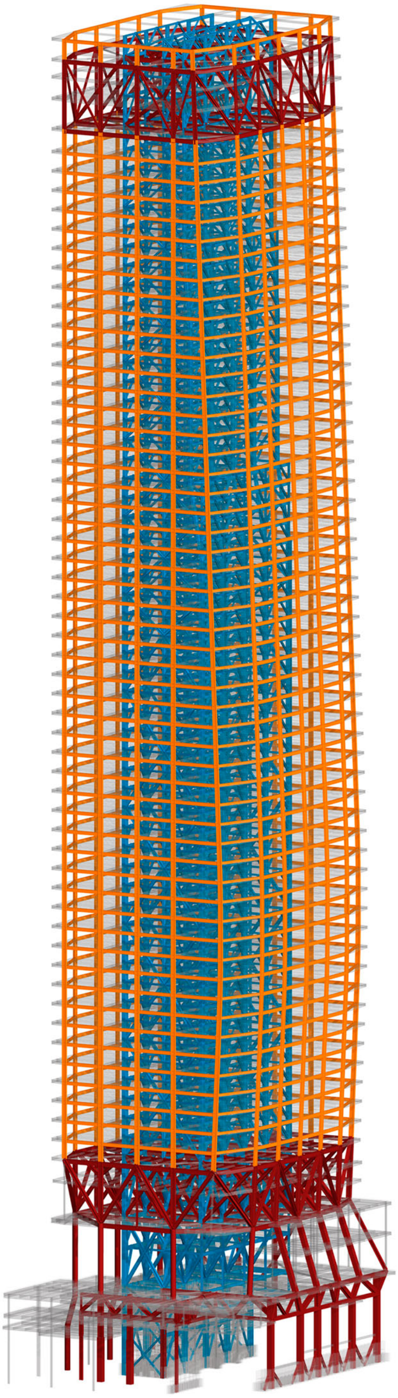

Fig. 9: 2MW structural system

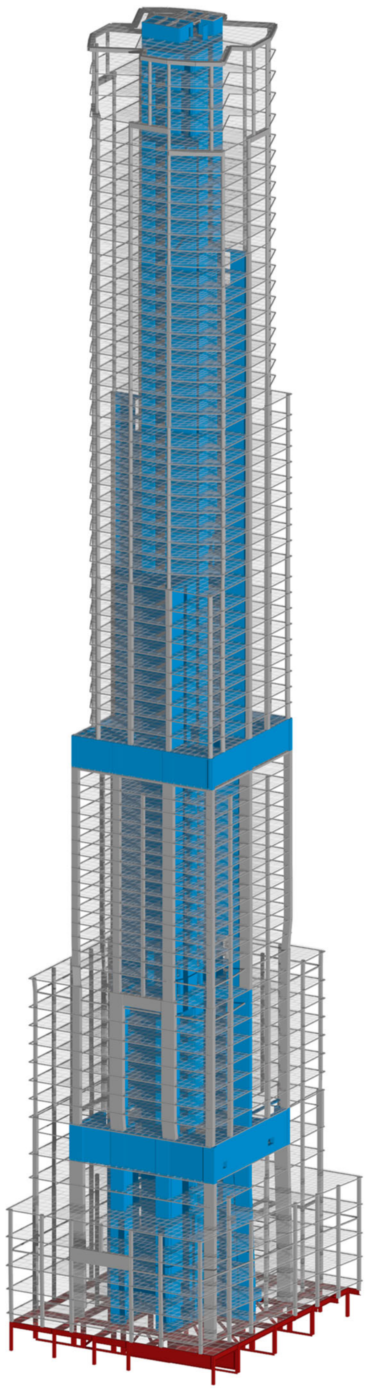

Fig. 10: 35HY structural system

core with a steel overhang above the undercut area was initially considered, but was eliminated due to increased gravity drift, connection intricacies at steel to concrete interface, and complexity of construction sequencing.

Due to the outrigger trusses at the top of the building, the perimeter columns of 2MW are generally stiffness-governed. However, A913 Gr 65 steel with 450 MPa yield strength is used where appropriate to avoid built-up or plated columns at the perimeter. The core utilizes large built-up columns, with sections weighing up to 5400 kg/m (3600 plf), and plates with A572 Gr 50 material properties are obtained in thicknesses up to 203 mm. Plates up to 152 mm with A572 Gr 65 are used for columns at the very base of the tower and in the transfer trusses.

These large, high-strength steel rolled sections and plates resulted in significant savings in fabrication. To limit the impact of the steel core columns on the architectural layout and elevator system, complex built-up shapes of 152 mm plates were initially required to provide the necessary tower stiffness. With the use of 203 mm A572 Gr 50 plates, essentially all of these complex shapes were simplified.

35HY

Concrete strengths at 35HY are varied over the height of the tower to lessen changes of stiffness due to setbacks or buttress wall drop-offs. Vertical elements at residential levels above Level 30 utilize 69 MPa concrete; hotel levels between Levels 15 and 30 are 82 MPa concrete; and mixed-use office and amenity space below Level 15 apply

96 MPa concrete. Targeted minimum modulus of elasticities of those high-strength concretes were specified to be provided from concrete mix design. Increasing building lateral stiffness while maintaining building mass lowers the natural period of a building, which generally results in reduction of overall wind-induced overturning moments and shear forces. Opting for high-strength concrete with its enhanced stiffness was beneficial in terms of resistance to wind loads. This allowed for reduced section size requirements, which lightened the loads on the platform and foundations, some of which were governed by compressive bearing capacity.

In addition to conventional rebar, high-strength large-diameter rebar (#14 and #18) was used throughout the project to allow for the prefabrication of column and wall cages. This significantly sped up the construction schedule allowing the contractor eventually to reach a two-day construction cycle on the upper levels.

Foundation & Uplift

The site of Manhattan West has hard sound rock (Class 1A) with 6435 kPa (60 tsf) capacity, and can be increased 10% for each 0.3 m (1 ft) of embedment in rock in excess of 0.3 m (1 ft), up to 12,870 kPa (120 tsf). As a result, 1MW and 2MW are able to use strip footings below the core walls and spread footings below the perimeter columns. This reduces excavation and the concrete used in the foundation, but also reduces the area available to place rock anchors to reduce uplift.

1MW experiences high uplift forces on the north and south sides of the core due to its high aspect ratio and large windsail area. A new ultrahigh-strength rock anchor was developed to fit within the core foundations. Each anchor consists of a group of three 75 mm diameter SAS Stressteel grade 150 anchors, 1034 MPa yield strength. The anchor's embedment depth ranges between 17 and 23 meters.

For 2MW, uplift is expected on the north and south column foundations as well as the south side of the core. The 3-bar type rock anchors are used under the core as well as the south mega columns, where the uplift forces are more significant, and more traditional 1-bar type rock anchors are used under the north columns.

The foundations beneath the 35HY tower and platform structure consist of 5 ft diameter caissons, which are embedded and sealed against a sound rock surface meeting the minimum requirements of New York City Building Code (NYCBC) Class 1c (Intermediate rock). The built-up solid steel columns of the platform are embedded down into the caissons.

Serviceability

Due to the height and slenderness, the design of all three towers required a comprehensive set of wind tunnel tests in order to determine the dynamic behavior and loads on the structures. In all three cases, the testing was performed by Rowan Williams Davies & Irwin Inc. (RWDI).

1MW

The reinforced concrete core of 1MW provides the majority of the stiffness of the tower. As described above, due to the constraints of the site, the perimeter steel moment frame does not reach the ground. Despite this, the perimeter frame contributes to the stiffness and serviceability of the tower. Finally, in order to enhance structural resilience and reduce lateral drift, a perimeter belt truss composed of structural steel rolled and built-up shapes is located at the top of the tower. A comprehensive wind tunnel testing regiment was implemented. Due to the phased construction approach for the overall development, and the knowledge that this was to be the first of multiple tall buildings in the vicinity, three separate configurations of the surrounding environment were studied (*Fig. 11*). Configuration 1 consisted of only 1MW and the existing midrise buildings on the block. Configuration 2 added 3MW which was under construction at the time. Finally, configuration 3 added 2MW, which was to be the final tower to be completed. All three configurations included the towers of the neighboring Hudson Yards development across Tenth Avenue to the west.

2MW

The steel core of 2MW results in a more flexible lateral system and less torsional resistance compared to 1MW's reinforced concrete core. During the initial wind tunnel studies, the structure exceeded recommended 10 year peak accelerations and torsional velocities. In response, the base of the core was encased in high-strength concrete to increase overall building stiffness, and the perimeter moment frame was fine tuned to help to meet both interstory drift and torsional velocity requirements.

At the time of wind tunnel testing for 2MW, the configuration of 1MW and the towers in the Hudson Yards development were more clearly defined. Therefore only one configuration was tested (*Fig. 12*).

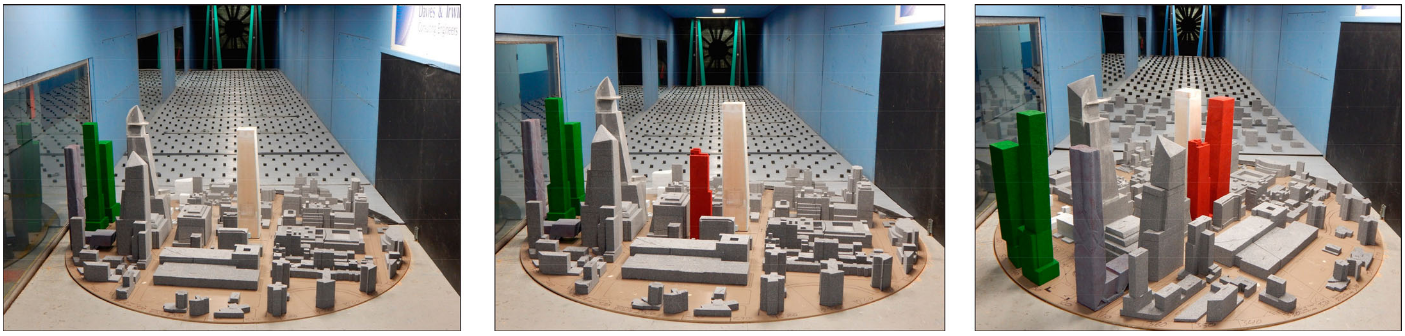

Fig. 11: Wind tunnel test models showing the three configurations tested for 1MW (© RWDI)

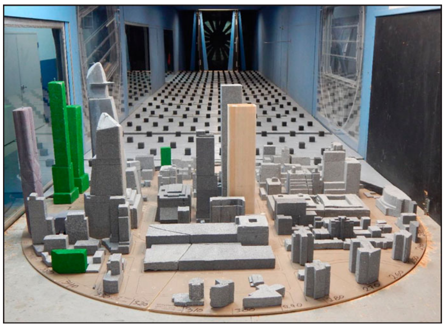

Fig. 12: Wind tunnel model for 2MW (© RWDI)

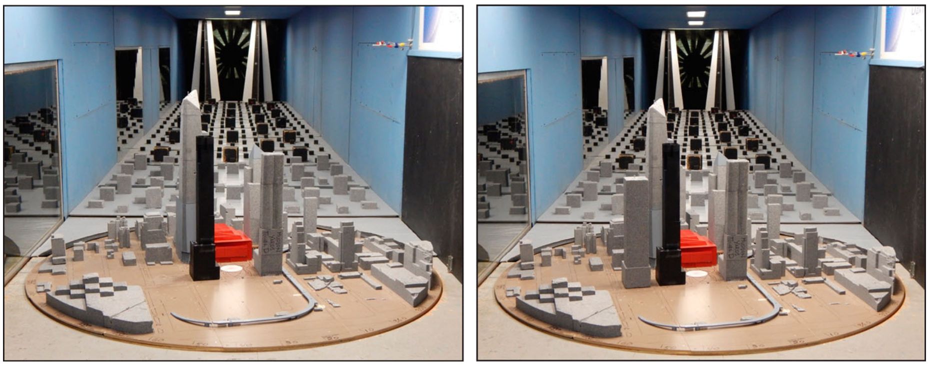

Fig. 13: Wind tunnel model for 35 HY showing the two configurations tested (© RWDI)

35HY

The evolving Hudson Yards development contributed to wind engineering challenges for 35HY. Wind tunnel testing for 35HY included two setups, Configuration 1 (C1) and Configuration 2 (C2): with and without the adjacent tower at 55 Hudson Yards, located directly across Thirty-Third Street (*Fig. 13*). The adjacency of the towers creates a tunnel effect to the north of 35HY. Higher wind speeds through the tunnel result in lower pressures on the north side of the building, inducing displacements in the North–South direction. This pressure imbalance is interpreted to create the higher cross-wind responses seen in C2. Loads from both wind tunnel test configurations were analyzed for structural design. In collaboration with the 35HY architectural team, chamfered corners and notches were introduced for the upper half of the tower, mitigating the shape effect and vortices of the previous iterations of tower form.

The lateral load resisting systems of the majority of slender tall buildings in zones of low seismicity are typically governed by serviceability criteria. The main component of serviceability that governs human comfort in tall buildings is the peak acceleration experienced by occupants due to dynamic movement of the structure. The acceleration is the value that governs human motion perception.[6] Additionally, the sensitivity of this perception varies depending on the level of activity and posture, thus the peak acceleration allowed for office and residential occupancies differ significantly, refer to *Figs. 14, 15 and 16*. Acceleration criteria for buildings at the 1-year return period is provided

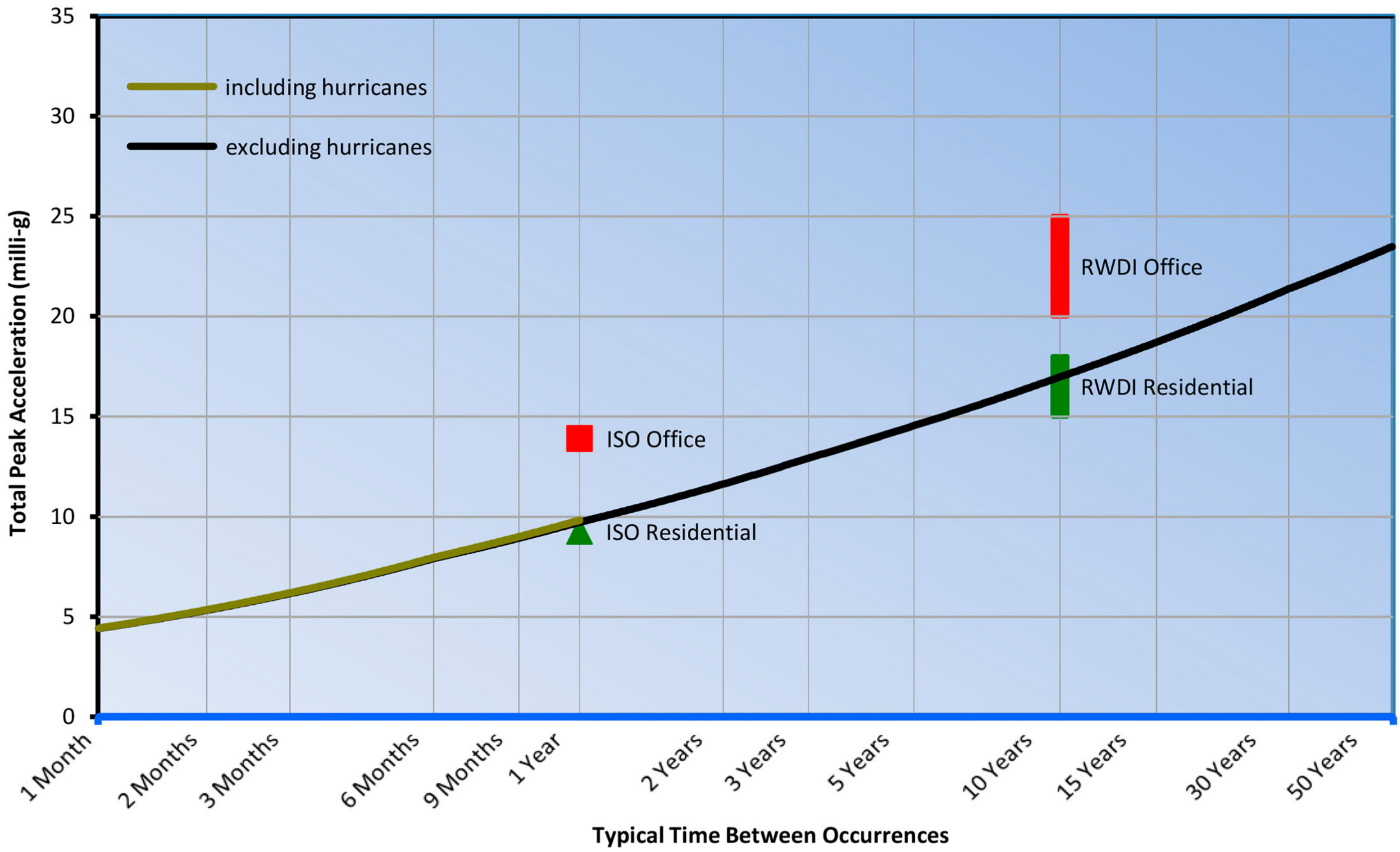

Fig. 14: 1MW peak acceleration wind tunnel results (© RWDI)

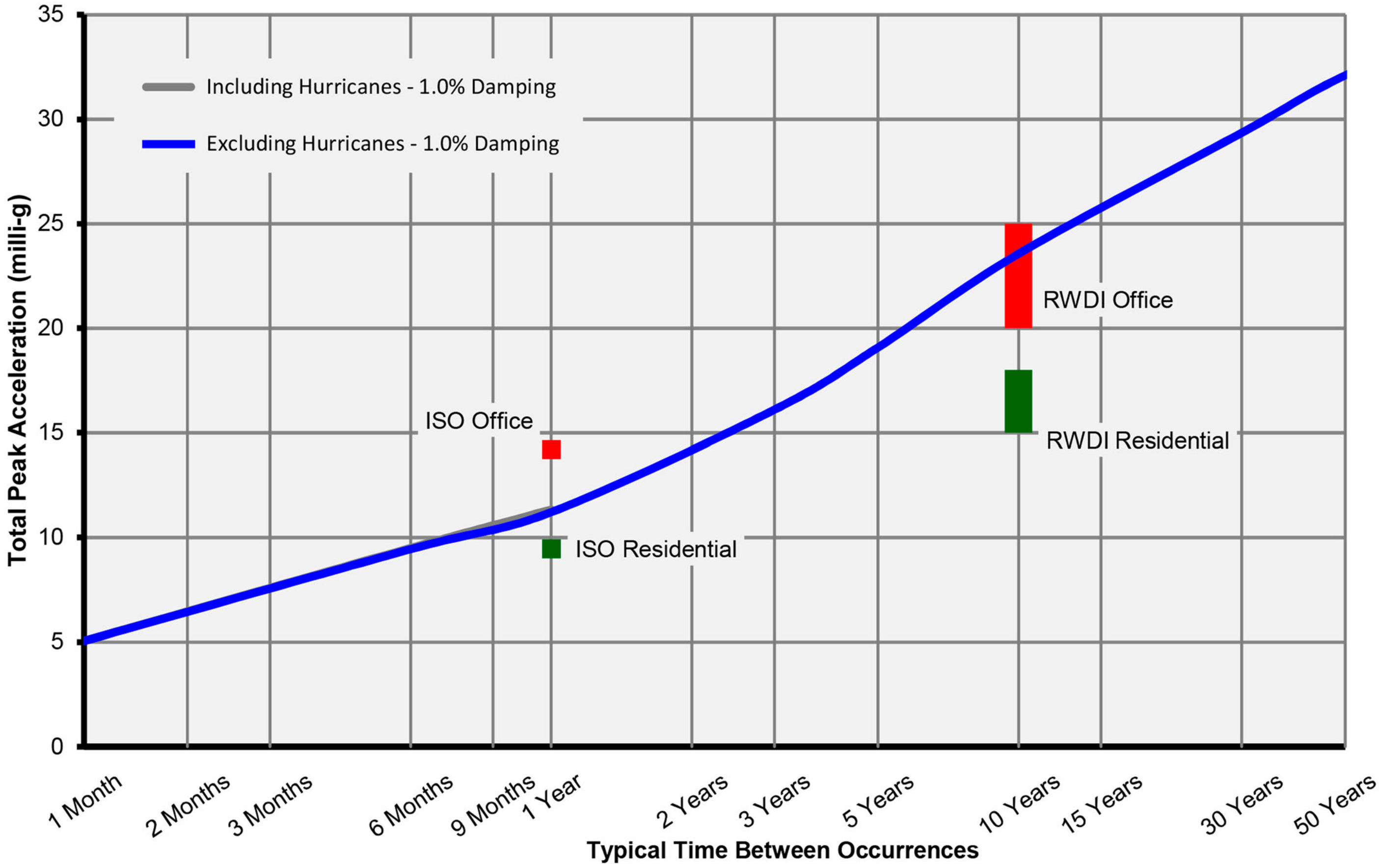

Fig. 15: 2MW peak acceleration wind tunnel results (© RWDI)

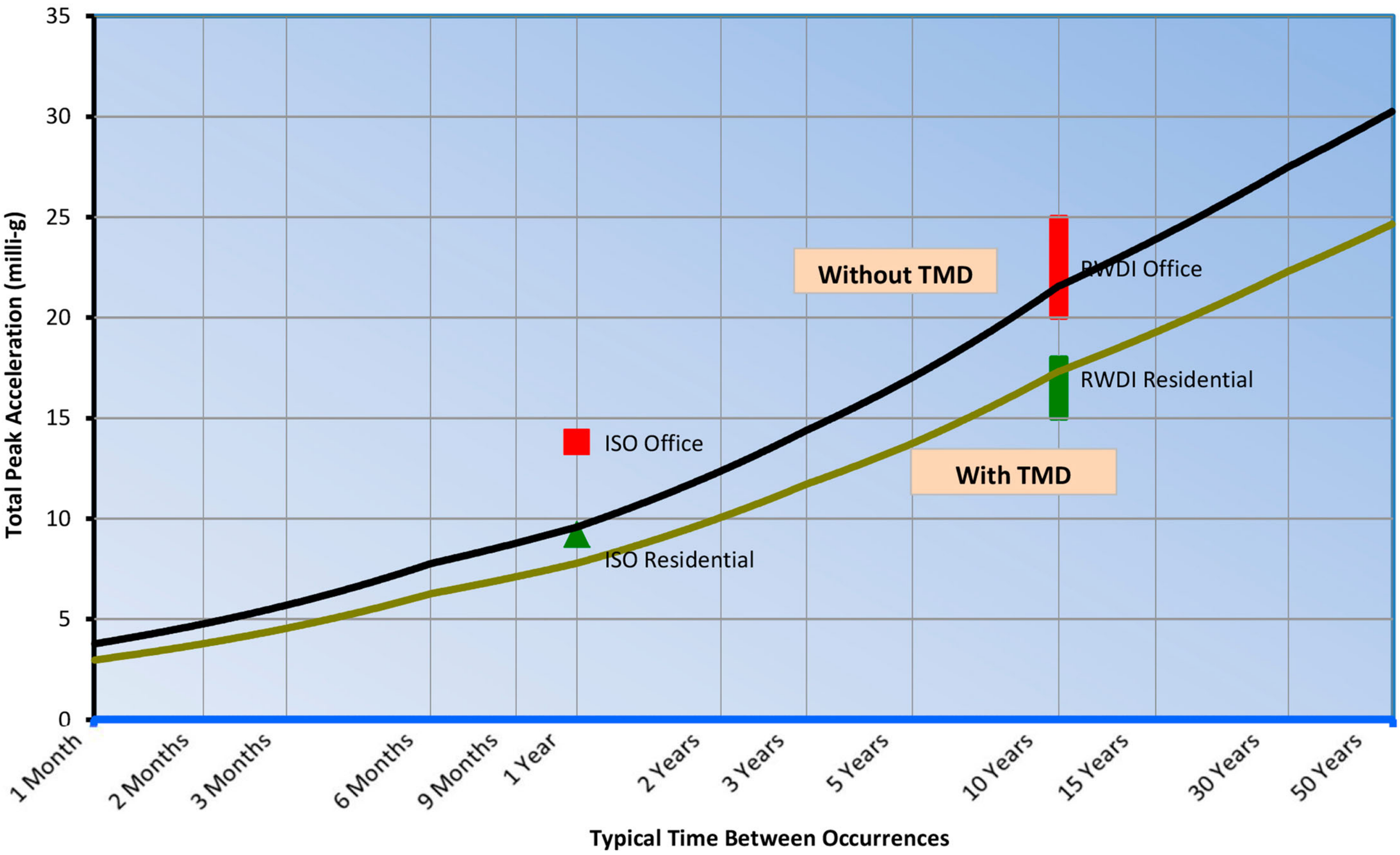

Fig. 16: 35HY peak acceleration wind tunnel results (© RWDI)

by the standard ISO 10137:2007 by the International Organization for Standardization (ISO).[7] The allowable acceleration for residential buildings is significantly more stringent than that for office buildings.

The primary building characteristics that affect the dynamic response are the building's geometry[8] and the inherent damping of the structure. The three buildings in this paper have three different structural systems, each with a distinct inherent damping characteristic. 2MW, an all-steel structure with the lowest damping, used a damping ratio of 1% for serviceability and 1.5% for strength. 1MW has a composite lateral load resisting system with a reinforced concrete core and steel perimeter moment frame. The concrete core provides a higher inherent damping and thus a damping ratio of 1.5% for serviceability and 2% for strength.

Concrete structures provide a higher degree of inherent damping within the structural system than steel structures, which was an advantage in the case of 35HY. The damping used for this tower was 1.75% for serviceability and 2% for strength design. However, due to the higher accelerations caused by Configuration C2 and to meet the strict criteria required for residential occupancy, 35 HY implemented a tuned mass damper to ensure occupant comfort. The function of the damper is to mitigate building accelerations. Building strength design and overall wind drift are all computed without the effects of the damper. The damper is a 520 metric ton horizontal double pendulum tuned mass damper. It is located on the roof level of the tower. A double pendulum was chosen to allow for decreased clearance requirements.

Concluding Remarks

Three supertall slender towers located in close proximity provide three distinct solutions to the challenge of designing tall buildings in a high wind environment. Each tower's structural system was optimized to respond to both the program and to address the challenges of their base conditions. 1MW is an office tower where only the core reaches the ground and thus a reinforced concrete core was chosen for its inherent stiffness and damping. 2MW is an office tower where the core is undercut, and the perimeter reaches the ground indirectly. Here, an all-steel structure was used in order to facilitate the transition to the foundations. 35HY is primarily a residential tower where strict acceleration criteria required the use of an all-concrete structural system that incorporated supplemental damping in the form of a tuned mass damper.

SEI Data Block

1MW
Owner:
Brookfield Properties
Structural Engineer:
Skidmore, Owings, & Merrill LLP
Architect:
Skidmore, Owings, & Merrill LLP
Construction Manager:
AECOM Tishman
Steel Fabricator:
Walter's Group International
Wind Tunnel Testing:
RWDI

Tower Height (m):	304
Steel Tower (t):	17,000
Steel Plaza (t):	1,700
Concrete (m^3):	50,000

SEI Data Block

2MW
Owner:
Brookfield Properties
Structural Engineer:
Skidmore, Owings, & Merrill
Architect:
Skidmore, Owings, & Merrill
Construction Manager:
AECOM Tishman
Steel Fabricator:
Walter's Group International
Wind Tunnel Testing:
RWDI

Tower Height (m):	275
Steel Tower (t):	35,000
Steel Base (t):	16,000

SEI Data Block

35HY
Owner:
The Related Companies
Structural Engineer:
Skidmore, Owings, & Merrill
Architect:
Skidmore, Owings, & Merrill with David Childs
Construction Manager:
AECOM Tishman
Concrete Contractor:
Roger & Sons
Wind Tunnel Testing:
RWDI

Tower Height (m):	308
Concrete (m^3):	50,000

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