The Rise of One World Trade Center

By Ahmad Rahimian, Ph.D., P.E., S.E. and Yoram Eilon, P.E.

One World Trade Center (1WTC), currently under construction, is the tallest of the four buildings planned as part of the Ground Zero reconstruction master plan for lower Manhattan. It will also be the tallest building in the Western Hemisphere upon completion in 2013.

The overall height of the tower from the ground level to the top of the spire reaches 1776 feet (541 meters) as a tribute to the "freedoms" emanating from the Declaration of Independence adopted in 1776. 1WTC, with its main roof at 1368 feet (417 meters) above ground, is designed to have the same height as the original towers.

WSP Cantor Seinuk was commissioned by Silverstein Properties, the developer of the tower, as the structural engineer for the new One World Trade Center. In 2006, the Port Authority of New York and New Jersey, the owner of the World Trade Center, took over the development of 1WTC as part of an agreement with Silverstein Properties.

The collapse of the Twin Towers on September 11, 2001 created a major debate in engineering communities worldwide with respect to the appropriate lessons to be learned and the need for mitigation strategies. Intensive studies were conducted for years after 9/11, including reports issued by the National Institute of Standards and Technology (NIST) in September, 2005, suggesting guidelines to be implemented in future standards.

The design team, faced with numerous and unique challenges, paramount among them being security-related issues, was charged with the design of 1WTC and expected to meet or exceed future codes and standards that had not yet been published.

For obvious reasons, many of the specific technical solutions and details will remain confidential.

One World Trade Center's program includes 3.0 million square feet of new construction above ground and 500,000 square feet of construction of new subterranean levels. The tower consists of 71 levels of office space, and eight levels of MEP space. It also includes a 50-foot high lobby, tenant amenity spaces, a two-level observation deck at 1,242 feet (379 meters) above ground, a "sky" restaurant, parking, retail space and access to public transportation networks.

Building Geometry

The building footprint above grade level starts with a 205-foot (62.5-meter) square plan. The office levels start 190 feet (58meters) above ground level, stacked over four levels of mechanical space above the main lobby. The four corners of the tower slope gently from the first office level inward until, at the roof, the floor plan again forms a square, but with a reduced dimension of 145 feet (44 meters), rotated 45 degrees from the base quadrangle. The elevation is formed by eight tall isosceles triangles creating an elongated Square Antiprism Frustum. At mid height of the tower, the floor plan forms an equilateral Octagon.

The tapering of the building geometry reduces the wind effect on the tower. Generally, tall building designs in New York City are governed by wind loads; however, this tower shape has an innate positive effect on the building performance under wind loading.

World Trade Center by day. Courtesy of Silverstein Properties.

Above the main roof at elevation 1368 feet (417 meters), a 408-foot (125-meter) tall spire is designed to be mounted atop a thick reinforced concrete mat directly supported by the tower's concrete core. Additional supports are provided via a multilayer circular lattice ring above the main roof, that are connected to the spire via a series of cables and supported by the main roof framing.

The tower structure extends 70 feet below grade passing through four subterranean levels, where some of its structural components required repositioning to clear the Path train tracks that pass under the building at the lowest basement level.

Lateral Load Resisting System

The tower foundation is founded on Manhattan rock using spread and strip footings with bearing capacities of 60 tons per square foot or better. At selected locations, due to space constraints such as the proximity of the existing and operating train lines, it was necessary to excavate deeper into the rock in order to achieve a higher bearing capacity. Rock anchor tie downs extending 80 feet into the rock were installed to resist the overturning effect from extreme wind events.

The below grade structure entails long span deep flat slab construction supported by reinforced concrete and composite columns spanning an average of 40 feet. WSP Cantor Seinuk was also commissioned to conduct an overall study of the stability of the World Trade Center site foundation wall and subterranean diaphragm slabs, the so called "bathtub" structure. The result of this study is incorporated into the design of the below grade spaces common to multiple stakeholders on the site. It required the introduction of auxiliary shear walls at below grade levels, positioned in strategic locations. The original slurry walls are reinforced by the addition of a liner wall directly supporting the below grade slabs. The below grade floor slabs are also designed to laterally brace the slurry walls as part of the long term "bathtub" stabilization strategy.

The New Jersey Path Trains run through the West Bathtub where 1WTC is located. It was essential to keep the Path trains operational during the construction process; therefore, the constructability strategies became a primary consideration in the design of the below grade structure. Temporary structural steel framing was introduced and integrated into the permanent structure, bridging over the train tracks. The tower stability system, although enhanced by the below grade structure, was designed to be self-sufficient.

The tower structure is comprised of a "hybrid" system combining a robust concrete core with a perimeter ductile steel moment frame. The reinforced concrete core wall system at the center of the tower acts as the main spine of the tower, providing support for gravitational loads as well as resistance to wind and seismic forces. It houses mechanical rooms and all means of egress. The core structure is compartmentalized with additional internal shear walls in orthogonal directions.

The concrete strength ranges from 14,000 pounds per square inch (psi) to 8,000 psi from the base to the top. The walls are connected to each other over the access openings using steel link beams embedded into the concrete walls.

A ductile perimeter moment frame system is introduced for redundancy and to further enhance the overall building performance under lateral wind and seismic loads. The perimeter moment frame wraps around all vertical and sloped perimeters, forming a tube system.

Along the height of the tower, the tapering multifaceted geometry creates unique structural conditions which necessitated the design and fabrication of special nodal elements using relatively large plating with significant capacity for load transfer.

For further enhancement of the lateral load resisting system, the concrete core at the upper mechanical levels is connected to the perimeter columns via a series of multilevel outrigger trusses in both orthogonal directions.

3D analysis model. Courtesy of WSP Cantor Seinuk.

Building Gravity System

The floor system within the concrete core zone is a cast-in-place concrete beam and flat slab system. The floor area outside the core is concrete on composite metal deck supported on steel beams and connected via shear connectors acting as a composite system. At 1WTC, as in recent hybrid projects such as 7WTC (2006) and One Bryant Park (2009), the construction is sequenced by first erecting an all steel framing system throughout the floor, both inside and outside of the core, preceding the concrete core construction. The steel framing within the core is primarily an erection system which is embedded in the concrete core walls. The construction of the structure is staged in four highly orchestrated installation sequences of 1) steel framing, 2) metal deck and concrete outside the core, 3) concrete core shear wall, and 4) concrete floor construction inside the core. To facilitate the raising of the forms for the core walls, a ring beam was introduced at the outer face of the core in order to maintain a temporary gap between the floor system and the core wall allowing the forms to pass through. The total lag for the entire sequence is between 8 to 12 floors. Axial shortening, a consideration that must be accounted for in tall buildings, becomes even more important in hybrid structures due to the differing natures of the materials' behavior.

Axial Shortening

Axial shortening studies were performed to identify the anticipated deformation of the concrete core wall and perimeter steel framing during and after construction. The elastic shortening of the steel erection columns at the core before encasement had to be carefully considered. The goal was that at the end of construction, the floors would be leveled and positioned at the theoretical elevations. In order to compensate for the shortening, the contractor could adjust the elevations of perimeter steel columns and the concrete core walls by super-elevating them to differing degrees. For the structural steel, this could be achieved by either fabricating the columns longer than the theoretical, shimming in the field during erection or a combination of both.

High Performance Concrete

The tower height and its slenderness imposed stringent demands on the overall strength and stiffness of the structure. In order to meet those demands in an economical way, high strength concrete of up to 14,000 psi was

Construction, March 2010. Courtesy of Joe Woolhead of Silverstein Properties.

utilized. For this project, 14,000 psi concrete was introduced for the first time in New York City.

Research and experience have shown that a modulus of elasticity higher than values suggested by the American Concrete Institute (ACI) building code can be achieved by producing a high performance mix design specific to the project and site. Therefore, in addition to the strength, the modulus of elasticity of concrete was specified as a dual requirement. For 14,000 and 12,000 psi, the modulus of elasticity of 7,000,000 psi was specified.

This contributes to the stiffness of the tower core wall, without the premium of specifying a higher concrete strength or increasing the thickness of the walls. The high strength concrete used for the thick concrete walls, defined as mass concrete, required a particular concrete mix to meet the most stringent of demands. To reduce and slow the heat of hydration, industrial by-products such as slag and fly ash were used to replace more than 50% of the cement content. This provided the additional benefit of helping the project meet the anticipated LEED Gold Standard.

Codes and Standards

From the onset, one of the main challenges was the selection of appropriate codes and standards for the design of the structure. The latest edition of the New York City Building Code at the time, which was based on the 1968 code with amendments, was used as the primary design code in combination with the Port Authority's design guidelines. However, appreciating that it was essential to design this building with the most advanced standards available at the time, the *International Building Code* (IBC) 2003 structural provisions were adopted with respect to wind and seismic loading. The latest editions of the American Institute of Steel Construction (AISC) and ACI codes were adopted, particularly those regarding ductile design of the moment frame connections.

Wind Tunnel Testing

The structure has been designed for wind load requirements of IBC 2003, with due consideration of the New York City local wind climate conditions. In addition, a series of wind tunnel tests were performed to ascertain a more accurate measurement of wind loading and wind response of the tower with respect to hurricane wind load effects and human comfort criteria. High Frequency Force Balance (HFFB) and

Construction, June 2011. Courtesy of Joe Woolhead.

Aeroelastic tests, that are prevalent methods of wind tunnel testing for tall buildings to obtain overall wind loads and responses such as accelerations, were performed at the Rowan Williams Davies and Irwin Inc. (RWDI) wind tunnel facilities in Canada at different stages of the design. The aerodynamic and aeroelastic effects of the spire were also considered. The acceleration results at the highest occupied level meets the criteria of human comfort for office buildings. The structure is also designed for wind storms with a 1000 year return period, per IBC 2003.

Summary

As of mid-2012, construction of the tower has reached above the 100th floor and soared above the height of the Empire State Building. Completion of construction through the main roof is anticipated for first half of 2013. The design and construction of this project is the result of a relentless collaborative effort between numerous design and construction teams over a period of several years, resulting in creating an iconic tower reaffirming the preeminence of New York City.▪

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