The most highly anticipated American skyscraper in recent history, One World Trade Center comes together in the context of past tragedy, present demands and future expectations for tall buildings.

Rising to the TOP

BY AHMAD RAHIMIAN, S.E., P.E., PH.D., AND YORAM EILON, P.E.

FOR SOME WHO VISITED the massive hole that was left in Lower Manhattan and the nation's heart following the events of September 11, 2001, it was likely difficult to imagine that the area would eventually be the home of the nation's tallest building. For others, there may have never been any doubt that it would.

For more than 12 years, however you thought the redevelopment of Ground Zero would happen, its largest, most symbolic and most prominent piece is now in place.

One World Trade Center (1WTC), the tallest of four high-rises planned as part of the Ground Zero reconstruction master plan for lower Manhattan, was officially declared by the Council on Tall Buildings and Urban Habitat (CTBUH) to be the tallest building in North America; it will likely be the third-tallest building in the world upon completion.

In keeping with Daniel Libeskind's master plan, the overall height of the tower from the ground level to the top of the spire reaches 1,776 ft, in reference to the year of the nation's founding, though the main roof is designed to have the same height as the original WTC towers (1,368 ft). The addition of a 408-ft-tall spire rising from the main roof (mounted atop a reinforced concrete mat directly supported by the tower's concrete core) brings the tower to its symbolic full height, and a multilayer circular lattice ring atop the main roof, which provides support for the spire, allegorically recalls the torch held by the Statue of Liberty.

A New Standard

The symbolic and high-profile nature of the building created a wide range of challenges and opportunities, and the structural considerations were equally immense. The collapse of the Twin Towers in 2001 created a major debate in engineering communities worldwide with respect to the appropriate lessons to be learned from the consequences of the attack and the need for mitigation strategies to be implemented for future high-rise buildings. The design team, faced with numerous and unique challenges—paramount among them being security issues—was expected to meet or exceed future codes and standards that had not yet been published. We were also keenly aware that the design of this tower would perhaps set a standard for future tall buildings, inspiring us to think beyond the conventional techniques of tall building design.

WSP Cantor Seinuk

1WTC's program includes 3 million sq. ft of new construction above ground and 500,000 sq. ft of subterranean space.

The framing system uses approximately 45,000 tons of structural steel.

The overall height of the tower (including the spire) is 1,776 ft, though the main roof will have the same height as the original WTC towers (1,368 ft).

1WTC's program includes 3 million sq. ft of new construction above ground and 500,000 sq. ft of subterranean space. The tower consists of 71 levels of office space, eight levels of MEP space, a 50-ft-tall lobby, tenant amenity spaces, a two-level observation deck at the 1,269-ft point, a "sky" restaurant, parking, retail space and access to public transportation networks. The tower structure extends 70 ft below grade passing through four subterranean levels where some of its structural components required repositioning to clear the PATH train tracks that cross the building at the lowest basement level. All of this space is framed with approximately 45,000 tons of structural steel in total.

The building footprint above grade level starts with a 205-ft square plan. The office levels start 190 ft above grade, stacked over four levels of mechanical space above the main lobby. The four corners of the tower are gradually "cut away," sloping gently from the first office level inward until, at the roof, the floor plan

Ahmad Rahimian (ahmad.rahimian@wspgroup.com) is director of building structures and **Yoram Eilon** (yoram.eilon@wspgroup.com) is vice president of building structures, both with WSP Cantor Seinuk.

A completed rendering of 1 WTC (far left) and other buildings at the Ground Zero site in Lower Manhattan, at night...

dimensions again square off at 145 ft on a side, now rotated 45° from the base quadrangle. The elevation is transformed into eight tall isosceles triangles forming an elongated square antiprism frustum. At mid-height of the tower, the floor plan forms an equilateral octagon. The tapering of the building geometry not only accommodates the project's gross area requirement but also creates an aerodynamic shape that reduces the wind effect on the tower. Since tall building design in New York is usually governed by wind load, the tower shape has an innate positive effect on the building performance under wind loading.

On the Right PATH

The tower's foundation and below-grade structure are founded on Manhattan bedrock using spread and strip footings with bearing capacities of 60 tons per sq. ft or better. Due to space constraints such as the proximity of the existing train lines, it was necessary to excavate deeper into the rock at select locations in order to achieve a higher bearing capacity of up to 114 tons per sq. ft. Rock anchors/tie downs extending 80 ft into the rock were installed to resist the overturning effect from extreme wind events.

PATH commuter trains run through the western portion of the "Bathtub" (an excavation down to the bedrock, surrounded by slurry walls, that was built to keep water out of the subterranean levels of the original WTC). As it was essential to keep the PATH trains operational during the construction process, 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 structure, bridging over the train tracks, and permanent and temporary steel framing was used for temporary support of the slab while some of the tower columns were transferred away from 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 surrounded by steel floor framing and 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,

...and during the day. 1 WTC's elevation is transformed into eight tall isosceles triangles forming an elongated square antiprism frustum.

➤ The building is now officially the tallest in North America.

providing support for gravity loads as well as resistance to wind and seismic forces. The core is approximately square in footprint with a depth of about 110 ft at the base—large enough to be its own building; it houses mechanical rooms and all means of egress. The walls are connected to each other over the access openings using steel wide-flange link beams developed into the concrete shear 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.

The tower's antiprism geometry creates unique structural conditions along its height, 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, composed of built-up box sections, in both orthogonal directions. Taken together, the perimeter and core systems make 1WTC safer than either system could make it on its own, thanks to the redundancy they provide to one another.


WSP Cantor Seinuk

Defying Gravity

The floor system within the concrete core zone is a formed cast-in-place concrete beam and flat slab system, while the floor area outside the core is concrete on composite metal deck supported on steel beams and connected via shear connectors. The column-free floor system spans between the core and the perimeter steel moment frame (with a maximum span of 47 ft) for construction efficiency and maximum flexibility of tenant use.

One of the most common approaches to hybrid construction is having the concrete core constructed using jump-forms or slip-forms, independent of and ahead of the steel framing. Subsequently, steel framing is constructed around the advancing constructed core. In New York City, however, this approach has generally not been available to the construction community until recently. 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 that is embedded in the concrete core walls. The construction of the structure was staged in four highly orchestrated sequences of steel framing, metal deck and concrete outside the core, concrete core shear wall and concrete floor construction inside the core. A wide-flange ring beam is introduced at


WSP Cantor Seinuk

➤ The building is designed for wind storms with 1,000-year return periods, per IBC 2003.

The structural system at the base of the tower.

the outer face of the core in order to maintain a temporary gap between the floor system and the core wall allowing for the raising of the forms. The total lag for the entire sequences is about eight to 12 floors. The construction sequencing was a critical aspect of the structure's design as it would affect the connection approach and details between various elements, especially at the interface between the concrete core walls and adjacent areas. It would also affect the nature of axial shortening of the tower as well as the method of computation and the construction compensation. Axial shortening becomes more important in hybrid structures due to the differing natures of the materials' behavior, such as the shortening of steel and concrete as a result of elastic, creep and shrinkage effects over time.

Axial shortening studies were performed to identify the anticipated deformation of the concrete core wall and perimeter steel framing during and following 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 center concrete 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.

Correct Code

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, acknowledging that it was essential to design this building with the most advanced standard available at the time, the IBC 2003 structural provisions were adopted with respect to wind and seismic loading (and were selected knowing they would be the basis for the new version of *New York City Building Code*). With respect to structural integrity, hardening and structural redundancy, the U.S. Government Standards such as GSA, DOD and FEMA were used as references for further enhancements. In addition, the latest edition of AISC and ACI codes, standards and specifications 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, taking into consideration New York's local wind 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 aeroelastic tests were performed at the Rowan Williams Davies & Irwin wind tunnel facilities at different stages of the design; the aerodynamic and aeroelastic effects of the spire were also considered. Wind tunnel tests were performed, including the surroundings effect, in view of the likelihood that Towers 2, 3 and 4 may or may not be completed at the time of 1WTC's completion. The acceleration results at the highest occupied level meets the criteria of human comfort for office buildings, and the structure is also designed for wind storms with 1,000-year return periods, per IBC 2003.

As of December 2013, construction of 1WTC was complete, though it isn't scheduled to open until later this year. The tower incorporates numerous innovative engineering solutions, some of which were presented here. If we could to go back and change anything, it would be the circumstances under which we were invited to engineer this symbolic building. That said, 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 with a resolute focus on the goal of creating an iconic tower reaffirming the preeminence of Lower Manhattan and the resiliency of the country's spirit and ingenuity. ■

Owner
Port Authority of New York and New Jersey

Owner's Representative
STV Construction, New York

Architect
Skidmore, Owings and Merrill, New York

Structural Engineer
WSP Cantor Seinuk, New York
SBP, New York (Spire)

Construction Manager
Tishman Construction Company, New York

Steel Team

Fabricators
MRP, LLC, South Plainfield, N.J.
(AISC Member/AISC Certified Fabricator)
Banker Steel Company, LLC, Lynchburg, Va.,
(AISC Member/AISC Certified Fabricator)

Detailers
Dowco Consultants, Ltd., Mississauga, Ontario, and Surrey, British Columbia (AISC Member)
Automated Steel Detailing Associates, Ltd., Toronto (AISC Member)