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The Rise of One World Trade Center

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Abstract

One World Trade Center (1WTC) totaling 3.5 mil square feet of area is the tallest of the four buildings planned as part of the World Trade Center Reconstruction at Lower Manhattan in New York City. Currently it is the tallest building in the Western Hemisphere with an overall height of 1776 ft. (541m) to the top of the spire.

The 1WTC structural and life safety design set a new standard for design of tall buildings in the aftermath of the September 11 collapse. The unique site condition with existing infrastructure also added additional challenges for the design and construction team.

Keywords: Reconstruction; Super-Tall; World Trade Center; WTC Complex

One World Trade Center (1WTC), is the tallest of the four buildings planned as part of the Ground Zero reconstruction master plan for lower Manhattan. It is also the tallest building in the Western Hemisphere, as well as the third tallest building in the world.

The setting for the building is the World Trade Center Memorial Complex which occupies several city blocks from Fulton Street on its north end to Liberty Street on the south, with the West Side Highway and the future Fulton Street Transportation Hub marking its western and eastern boundaries. The master plan places the Memorial space, delineated by a tree-lined, landscaped plaza containing the Memorial reflecting pools, as the centerpiece of the expansive site, while the surrounding structures occupy the perimeter and define the site as a cultural, transportation and commercial hub. One World Trade Center uniquely emerges as a soaring expression of the resilient and the irrepressible nature of New York City and a physical representation of our nation's most noble achievements. (See Figure 1)

In keeping with the master plan, 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. The addition of a 408 feet (125 meter) tall spire rising from the main roof completes the tower as it soars to the symbolic height of 1776 ft. (See Figure 2)

Figure 2. View of 1 World Trade Center Across the Hudson River (Source: WSP Group)

Originally commissioned by Silverstein Properties, the developer of the tower, the project transitioned to the owner of the World Trade Center, the Port Authority of New York and New Jersey, who took over the development of 1WTC in 2006 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 from the consequences of the attack and the need for mitigation strategies to be implemented for future high-rise buildings. Intensive private and public funded studies were conducted for years after 9/11. All of which were culminated in the reports issued by the National Institute of Standards and Technology (NIST) in September 2005, highlighting the lessons learned and suggesting guidelines to be implemented in future codes and standards for high-rise buildings.

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. The design team clearly understood that the task of developing the design would mean traversing uncharted waters. Careful consideration of all aspects of the plan remained a critical component throughout the project as every design solution would have to be meticulously reviewed and supported by a multitude of rigorous analyses and design procedures.

Along with the entire project team, we were profoundly aware, on a daily basis, of the importance of the challenges and responsibilities entrusted to us and were keenly aware that the design of this tower would have the potential to set a standard for future tall buildings.

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 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 meter) above ground, a "sky" restaurant, parking, retail, and access to public transportation networks.

Building Geometry

The building footprint above grade level starts with a 205 feet (62.5 m) square plan. The office levels start 190 ft. (58m) above ground level, 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 again forms a square but with reduced dimension of 145 feet (44 meters), and 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. (See Figure 3)

The tapering of the building geometry not only accommodates the project gross area requirement, it also creates an aerodynamic shape that reduces the wind effect on the tower (see Figure 4). Generally, tall building designs in New York City, is governed by wind load, thus the tower shape has an innate positive effect on the building performance under wind loading.

Figure 1. World Trade Center Complex (Source: Silverstein Properties)

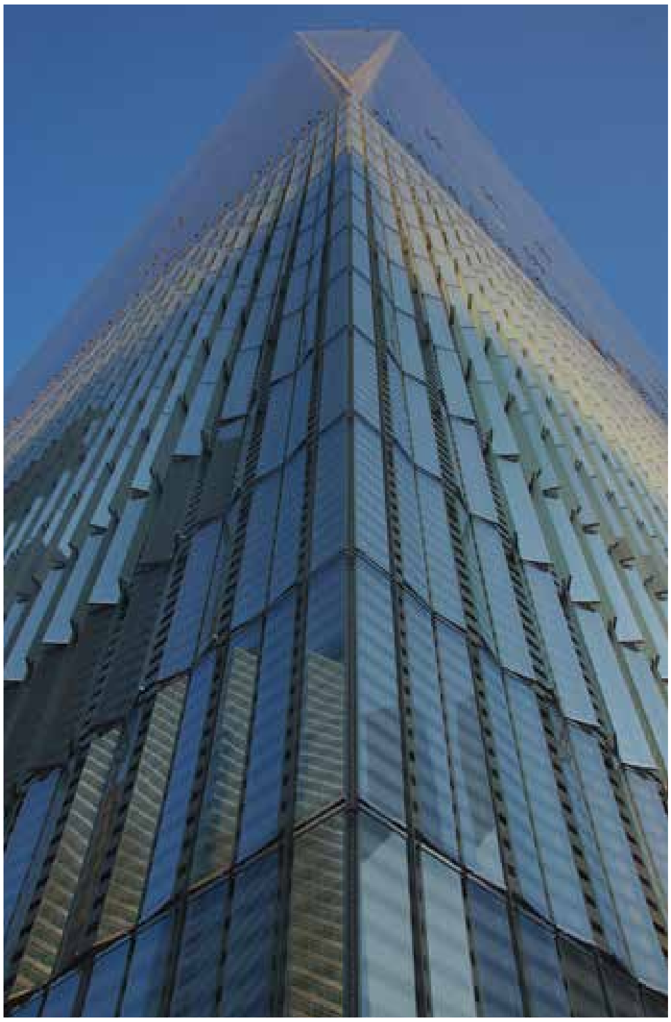

Figure 3. View of Chamfered Corner (Source: WSP Group)

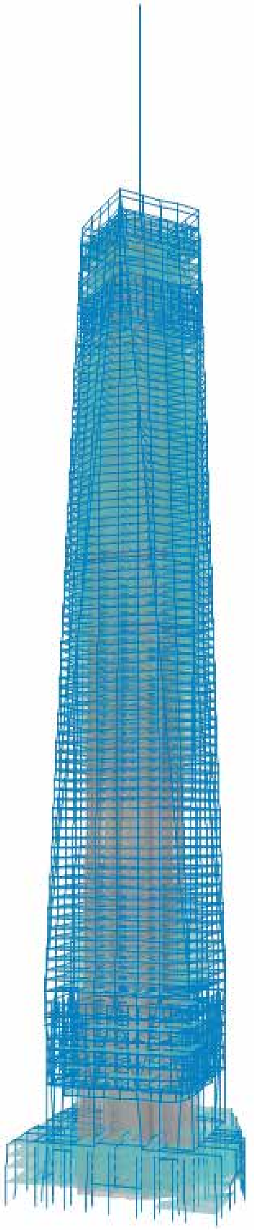

Figure 4. 3D Analysis Model (Source: WSP Group)

Above the main roof at an elevation of 1,368 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, connected to the spire via a series of cables and supported by the main roof framing.

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 pass under the building at the lowest basement level. The below grade space extends beyond the footprint of the tower providing a multitude of functional and access spaces.

Lateral Load Resisting System

The tower foundation as well as the extended below grade structure, are 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 of up to 114 tons per square foot. Rock anchors / tie downs extending 80 ft. 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 ft. This is a result of the optimization process undertaken early on during the design phase, aimed at addressing the security and constructability requirements of the project.

As part of the World Trade Center site recovery, the Port Authority of NY & NJ installed temporary tie-backs in all existing slurry walls that surround the World Trade Center site. This was necessary in order to stabilize the original underground slurry wall construction, the so called "bathtub" walls, after the collapse of the below grade structure. As a parallel assignment to the design of 1WTC, was the commission to conduct an overall study of the World Trade Center site "bathtub" stability. 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 to meet the structural, security and program requirements. The existing slurry walls are reinforced by the addition of a liner wall directly supporting the slabs below grade. 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. Considering the fact that 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 were introduced and integrated into the permanent structure, bridging over the train tracks. Permanent and temporary steel framing was used for temporary support of the existing slab.

Due to the high-level structural demands at a major transfer area, #20 rebars along with fully grouted posttension reinforcement were used to strengthen the transfer elements while minimizing the reinforcing congestion. 3D drawings were developed to assist the contractors during shop drawing production and construction. 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. The core is approximately square in footprint with a depth of about 110 feet at the base; which is large enough to be its own building. It houses mechanical rooms and all means of egress. The core structure is compartmentalized with additional internal shear walls in orthogonal directions.

The dimensions of the core wall, with thicknesses up to 4 feet 6inches and higher at some locations, vary along the height of the tower at appropriate intervals. The concrete strength ranges from 14,000 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. (See Figure 5)

Along the height of the tower, the antiprism 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.

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. The column-free floor system spans between the core and the perimeter steel moment frame to accommodate tenant usage flexibility and construction efficiency.

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 steel framing. Subsequently, steel framing is constructed around the constructed core. In New York City, however, historically this approach has not been available to the construction community. Therefore, 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 steel framing: metal deck and concrete outside the core, concrete core shear wall, and concrete floor construction inside the core. To facilitate the raising of the forms for the core walls, a ring beam is 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. The construction sequencing was a critical aspect in the design of the structure 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, 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 such as the shortening of steel and concrete as a result of elastic, creep, and shrinkage effects over time.

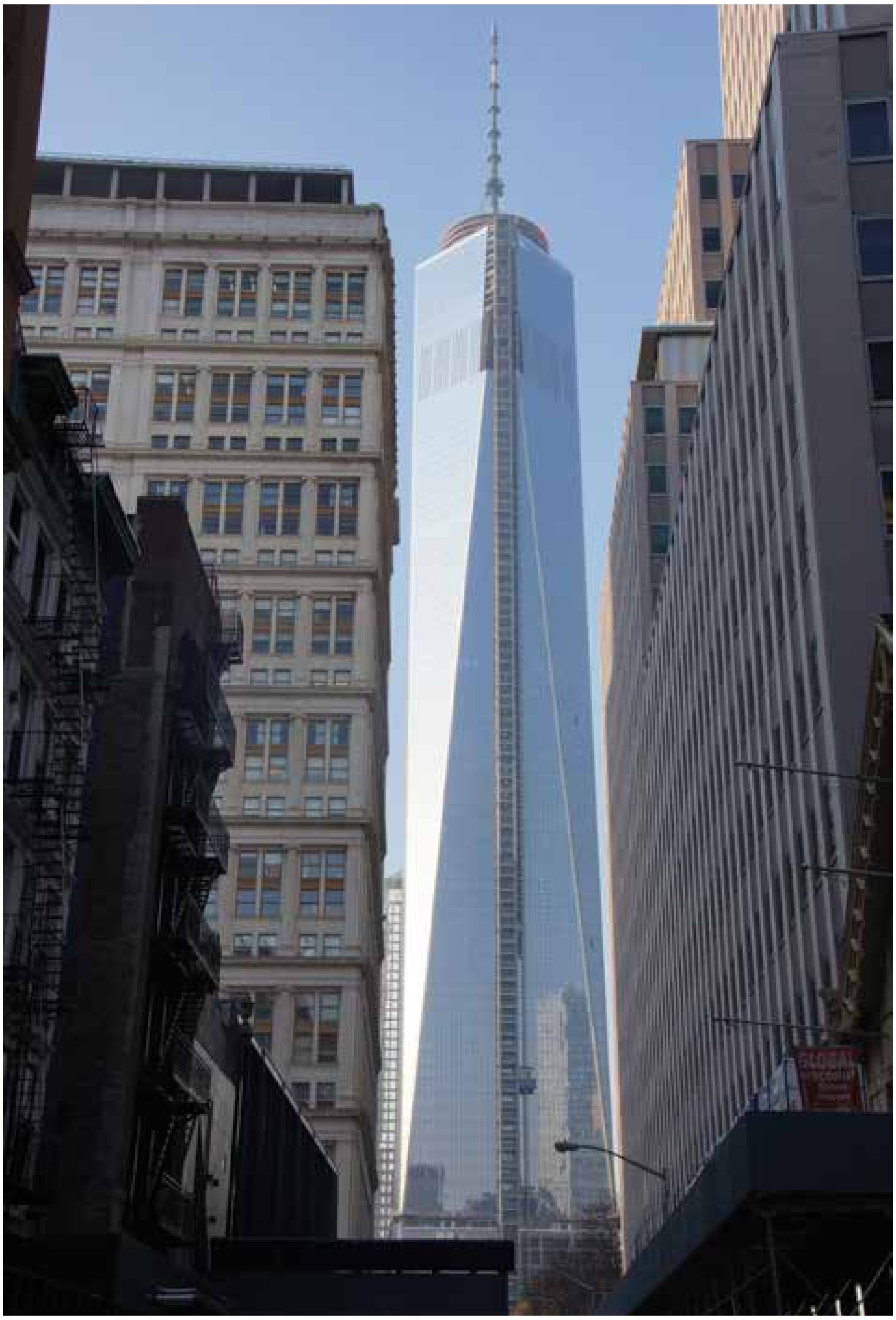

Figure 5. Street View of 1 World Trade Center (Source: WSP Group)

Axial Shortening

Axial shortening studies were performed to identify the anticipated deformation of the concrete core wall and perimeter steel framing during and post construction. The elastic shortening of the steel erection columns at the core before encasement had to be carefully considered. The contractor was advised of the anticipated axial shortening, based on which the project shortening compensation program was generated. 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. In general, at the upper levels, the perimeter steel framing would have to be super-elevated for an amount higher than the concrete core so that during erection the floors would slope contrary to the direction of shortening and by the end of construction they would level out.

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 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 IBC 2003 structural provisions were adopted with respect to wind and seismic loading. 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 these enhancements. The latest edition of AISC and ACI codes were adopted, particularly those regarding ductile design of the moment frame connections. In 2008, while the building was already under construction, the New York City Building Code adopted a modified version of IBC 2003. (See Figure 6)

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 Aeroelastic tests were performed at the RWDI 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 with different surrounding scenarios, considering that Towers 2, 3 & 4 may or may not be completed at the time of completion of 1WTC. 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.

Other wind tunnel tests were also performed to determine the wind effect on cladding and mechanical system performance as well as the Aeroelastic effect of the Spire at the roof of the tower. (See Figure 7)

Summary

As of mid-2015 construction of the tower is complete and tenants gradually occupy the building (see Figure 8). The One World Trade Center tower incorporates numerous innovative engineering solutions, some of which were presented here. If we could go back and change anything it would be the circumstances under which we were granted the design of this remarkable structure. 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 the creation of an iconic tower reaffirming the preeminence of New York City.

Figure 6. One World Trade Center During Construction (Source: WSP Group)

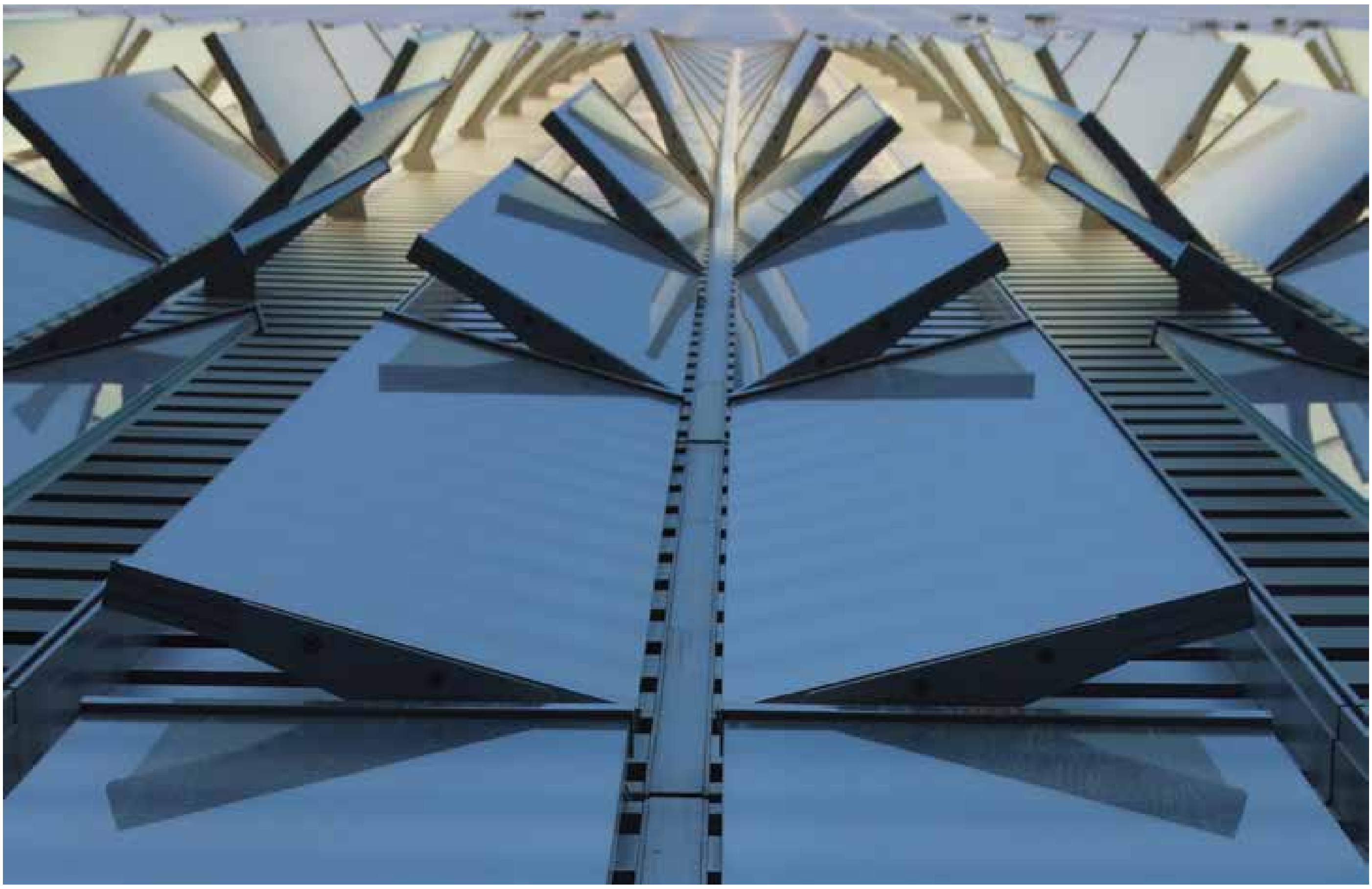

Figure 7. Tower Cladding at Base (Source: WSP Group)

Figure 8. View of 1 World Trade Center and the Brooklyn Bridge from the East River (Source: WSP Group)