EDUARDO TORROJA FOUNDATION

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One World Trade Centre, New York and The Shard, London.

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Bill Price is a Director of WSP, a global engineering, transport and environmental consultancy with over 14,000 employees worldwide. Most recently he has been the client Director for the Shard in London. Now almost complete this 310 metre building, designed by architect Renzo Piano, forms a new landmark in London. Bill has travelled extensively and spoken often about high rise buildings, sustainability, regeneration and the wider impacts of engineering.

Introduction

This paper follows the presentation given at the Eduardo Torrojo Colloquium in Madrid in November 2012. It describes some of the key features of both projects as they approach completion after several years in planning, design and construction. WSP is the structural engineer for both of these buildings.

Eduardo Torroja was a pioneer and innovator in engineering. He was passionate about collaboration with architects, knowledge sharing and pushing materials to their limits. The WSP engineering groups in the USA and UK follow similar principles and the realisation of high rise buildings calls for all these factors to be combined through dialogue and mutual technical support.

Obtaining permission from the New York Port Authority to deliver the presentation was a protracted process due to security and confidentiality concerns. The WSP team in New York was able to satisfy the client that the Foundation represented a special opportunity to begin to share knowledge and learning in the tradition of Eduardo Torroja established in the early to mid-part of the 20th century. The paper compares and contrasts One World Trade Center and particular aspects of the Shard.

Two Towers – Two Cities

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 541 metres (1776 ft) as a tribute to the "freedoms" emanating from the Declaration of Independence adopted in 1776. 1 WTC, with its main roof at 417 metres above ground, is designed to have the same height as the original towers.

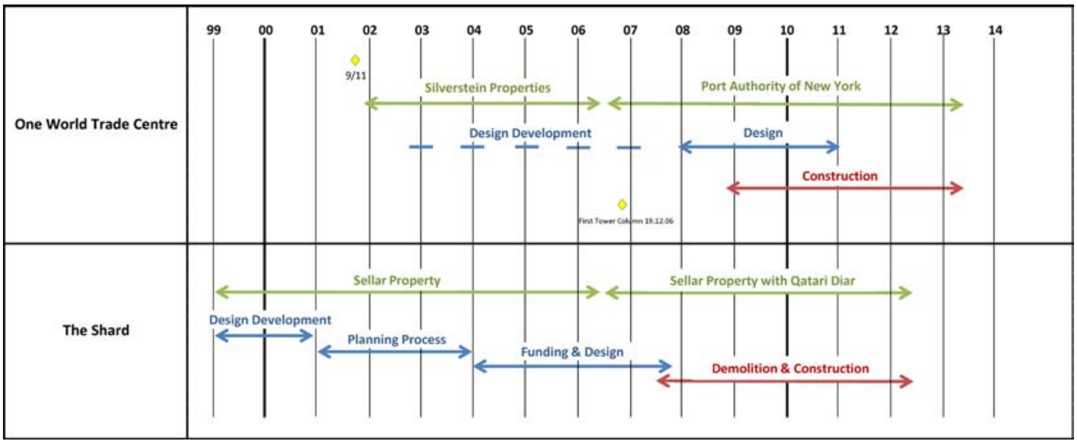
WSP Cantor Seinuk was commissioned by Silverstein Properties, the developer of the tower, as the structural engineer for the new One World Trade Center. In 2006, the Port Authority of New York and New Jersey, the owner of the Word Trade Center, took over the development of 1WTC as part of an agreement 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, embodied in 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 programme includes 300,000 m^2 of new construction above ground and 50,000 m^2 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 17 metre high lobby, tenant amenity spaces, a two-level observation deck at 379 metres above ground, a "sky" restaurant, parking, retail space and access to public transportation networks.



The Shard in London is in the fit-out stage. Completion of the 'shell and core' occurred in July 2012. At 310 metres the building is the tallest in Western Europe and has taken around 12 years to pass through design development, planning, funding, demolition of existing buildings and construction.

The tower is unusual in containing a mix of uses including commercial office, residential, hotel, retail, restaurant and public viewing at the top.

Particular challenges included the issues emanating from the building's close proximity to London Bridge Railway station and the tunnels for the Jubilee line and the congested urban location. The London developer Irvine Sellar has championed the project throughout and secured funding from Qatar prior to the start of construction. The overall investment in the 130,000m^2 development will approach £1bn (including 'The Place', a new 17 storey building beside the Shard, also designed by Renzo Piano) when complete.

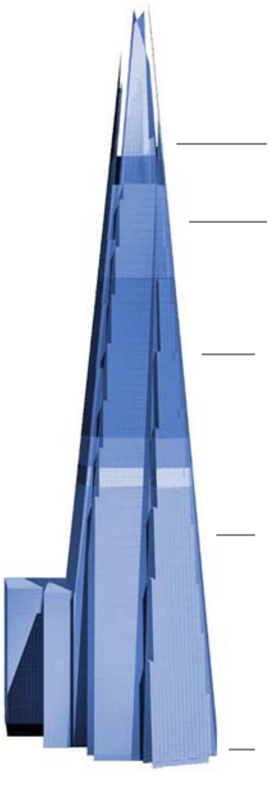
Building Geometry

The 1WTC building footprint above grade level starts with a 62.5 metre square plan. The office levels start 58 metres 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 44 metres, 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.

Above the main roof at elevation 417 metres, a 125-metre 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 23 metres below grade passing through four subterranean levels, where some of its structural components required repositioning to clear train tracks that pass under the building at the lowest basement level.



The mixed use of The Shard

The Shard building form is essentially a slender pyramid but rather than having 4 similar faces the external envelope comprises 18 separate 'shards'. At ground floor level the tower is around 90 metres by 70 metres. A concrete slip-formed core 19 metre by 19 metre extends from the ground through the commercial space to level 30 and then through 3 levels of restaurants at 31, 32 and 33. The core size reduces as it passes through 20 levels of hotel and reduces further through the 13 residential levels. The upper 60 metres of the tower are steel framed to accommodate the viewing gallery and spire.

The Spire of The Shard

Lateral Load Resisting System

The 1WTC tower is founded on Manhattan rock using spread and strip footings with bearing capacities of 6000 KN/m^2 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 26 metres 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 13.5 metres. 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 "bath tub" structure. The findings from this study are incorporated in the design of the below grade spaces common to multiple stakeholders on the site.

The tower structure comprises 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 vertical spine, providing support for gravitational loads as well as resistance to wind and seismic forces. It houses mechanical rooms and all means of access and egress. The core structure is compartmentalized with additional internal shear walls in orthogonal directions. The concrete strength ranges from 96 N/mm^2 to 55 N/mm^2 from the base to the top. The walls are connected to each other over the access openings using steel link beams embedded in 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 faces, forming a tube system.

Over 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 multi-level outrigger trusses in both orthogonal directions.

The Shard internal load system primarily comprises the concrete core. The large size of the core is due to the need for many lifts to serve the mix of uses. As a result it has been possible to use relatively thin walls ranging from 800mm at the base reducing to 600mm and then to 300mm near the top.

The dynamics of the building are controlled by the disposition of mass in differing framing systems. The commercial office space is steel framed with a floor to floor height of 3.65 metres. The hotel and residential levels are all concrete framed. The mass of this part of the structure helps to control lateral movement due to wind. A small 'hat truss' positioned in the upper plant room (levels 64 and 65) connects the core to perimeter columns. This further reduces acceleration to acceptable levels for residential use.

The building is supported on a piled raft positioned 15 metres below ground level. The 191 piles range from 1.5 to 1.8 metres in diameter and extend 50 metres through London Clay into dense sand.

Building Gravity System

The 1WTC floors within the concrete core zone are cast-in-place concrete beam and flat slab systems. The floor areas outside the core are concrete on composite metal deck supported on steel beams and connected via shear connectors acting as composite systems.

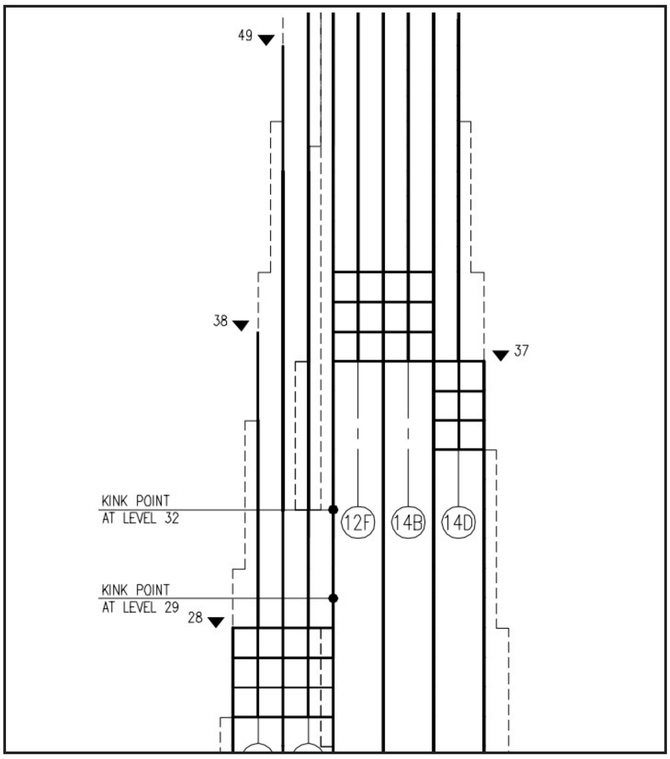
At 1WTC, as in recent hybrid projects such as 7WTC (2006) and One Bryant Park (2009), the construction is sequenced by first erecting an all steel framing system throughout each floor, both inside and outside of the core, followed by concrete core construction. The steel framing within the core is primarily 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 behaviour of the materials in the various structural systems..

1WTC, 3D analysis model

The Shard form of construction is extremely unusual and comprises a reinforced concrete frame (hotel and residential) above a steel framed office. The concrete core is continuous throughout.
The office levels comprise slender composite concrete floors on steel plate girders. Fabricated beams are 500mm deep and generate uniform zones for servicing and ceilings. Perimeter steelwork is particularly stiff in line with cladding design criteria. Perimeter columns are spaced at 12 and 6 metre centres.

The hotel and residential levels comprise post tensioned flat slab floors connected to perimeter concrete columns on a 3 metre grid.

The tapering geometry and multi-surface façade together with the reduction in perimeter column spacing with height required the introduction of local transfers at various levels. These transfers have been made within the floor thickness and are not expressed in the elevations



The Shard transfer structures

Axial Shortening

Axial shortening studies were performed for 1 WTC to identify the anticipated deformation of the concrete core walls 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 level 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 theoretically required or shimming in the field during erection or a combination of both.

The Shard axial shortening situation is different from 1 WTC. This is because the core is a continuous slip form (no steelwork embedded); the piled foundation behaves differently at the building perimeter than under the core and the upper reinforced concrete columns also behave differently from the steel columns beneath.

Calculations and experience indicated that the need for super-elevation of the core on a progressive basis amounting to around 30mm to accommodate concrete shrinkage and shortening under self-weight (100,000t approximately).

High Performance Concrete

The 1 WTC tower height and 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 96 N/mm^2 was utilized. For this project, 96 N/mm^2 concrete was introduced for the first time in New York City.

1WTC Construction, March 2010. Courtesy of Joe Woolhead, Silverstein Properties

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 96 N/mm^2, the modulus of elasticity of 48,000 N/mm^2 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. 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.

Concrete for the Shard ranges in strength from 80 to 40N/mm^2 and cement replacement occurs throughout. Super high strength mixes and enhanced elasticity have not been used and were not needed for the design solution adopted.

Codes and Standards

From the onset in New York, 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.

In London for the Shard British Standards are used. As usual for high rise design, however, there is value in considering how International and American codes compare. Further reviews with Eurocodes were also undertaken. Particular effort was put into the design for robustness and resilience. With the majority of design carried out post 9/11 it was possible to incorporate much of the thinking and design approach now regarded as necessary for such structures. The precise way in which the frame elements function with the core and floors remains confidential but a range of security scenarios have been investigated and modelled.

In addition, the performance of the building in fire and the phased evacuation strategies has been modelled by the WSP team.

Wind Tunnel Testing

The 1 WTC 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, 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, as per IBC 2003.

The Shard was also modelled by RWDI to generate data for the design of the core and perimeter frame.

1WTC Construction, June 2011. Courtesy of Joe Woolhead

This approach leads to economic design of the key elements whilst highlighting areas which need special attention. Results are also fed into the cladding design where significant cost savings are achieved over a 'standards and code' approach.

The tapering form, like 1 WTC, provides a relatively low centre of mass and inherent aerodynamic efficiency towards the top of the building.

Design Collaboration

`The design processes for tall buildings tend to be quite long and complex. Such buildings are expensive and require patience to secure planning and funding.

These circumstances demand strong leadership and commitment but they also need excellent teamwork and collaboration.

In London the relationship between WSP's structural engineers and Renzo Piano Building Workshop has been enjoyable, creative and mutually supportive. This has also been true of the client and contractor.

In New York, a long standing relationship of over 40 years continues between the WSP team and Architects SOM. Again, the process has been complex and protracted but the results are clear to see and the joint effort has been richly rewarded.

These are two good examples of engineer/architect collaboration and mutual respect promoted strongly by Eduardo Torroja during his working life and great achievements in Spain and beyond.

Summary

As of the end of 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 the creation of an iconic tower reaffirming the pre-eminence of New York City.

In London, the Shard has already become a new symbol for a leading world city and has received much praise from the political, property, planning and design community.

The hotel, viewing gallery and restaurants will be open in the spring of 2013 bringing new life to the area around London Bridge which is close to the City of London and St Paul's Cathedral.

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(Right) The Foundation panel prior to the presentation and discussion. From right to left: Pepa Cassinello, Juan A. Sandamera, José A. Torroja and Bill Price