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Engineering Tall in Historic Cities: The Shard


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Kamran Moazami
With over 33 years of structural engineering experience, Kamran works between the United Kingdom and United States, ensuring that clients involved in property development derive the full benefit of WSP's internationally renowned, specialist expertise in structural engineering.

Kamran received his BSCE and MSCE from Columbia University and his professional engineering licences in New York. In 1989 he set up WSP Cantor Seinuk's London office and since then has been involved in more than 20 million square feet of mostly specialist structures throughout the United Kingdom. He has also been involved in masterplanning and development of such prestigious projects as Canary Wharf, Wood Wharf and Bishopsgate Good's Yard.

Ron Slade
Ron received his BSc in Civil Engineering at City University, London and became a chartered member of the Institution of Structural Engineers in 1971, when he was awarded the Institution's A. E. Wynn prize. He was first appointed as a director in 1982.

Ron has special expertise in construction forms and methodologies and materials use. He has been involved in a wide range of jobs in various sectors, on both new-build and refurbishment projects. Over the past 13 years, Ron has specialized in high-rise construction. His recent work includes concept design for several London projects, including both the Shard and the Place at London Bridge, and the Milton Court development, which incorporates the Guildhall School of Music and Drama.

Ron has published papers in The Structural Engineer, Civil Engineering and elsewhere and chairs WSP's Technical Strategy Group for structural engineering for the advancement of technical knowledge and design skills.

Can historic cities preserve their character and identity while embracing the modern tall building phenomenon? Two engineering-team leaders behind the Shard discuss the creative solutions needed to insert a massive project into the dense historic and infrastructural fabric of London.

The Shard and The Place at London Bridge (see Figure 1), projects by developer Sellar Properties / Qatari Diar and architect Renzo Piano, demonstrate the special challenges faced by engineers and architects to preserve and develop the character of historic cities, while properly embracing the tall building phenomenon. Both buildings work within the ancient street pattern of Southwark and demonstrate how modern development can add new life to an area without destroying the local environment. Southwark, like other parts of London, suffered heavy damage during the Second World War, but retained its historic street layout. In fact, the shape of The Shard site was created by bombing during the war.

The site was redeveloped in 1975 by the construction of a rather insensitive, inward-looking building, but now, with the help of far-sighted designers, the new buildings are on the verge of changing the whole area into an iconic part of London, adding to the rich texture of the neighborhood, rather than detracting from it. It was no accident that Renzo Piano acknowledged the history of London and the local area in his planning submission by referring to the influence of 17th-century church and cathedral spires.

One of the key challenges of building tall in historic cities is keeping streetscapes permeable and delicate. Certainly, tall buildings require large cores and huge columns to take lateral and gravity forces, but they must also respect people and public spaces at street level. Historically architectural development has not paid sufficient attention to the interface of tall buildings and life at ground level. Now it is generally accepted by the best designers that the effect at street level is equally as important as the impact on the skyline, and is critical to a project's integration into the culture and lifeblood of a city.

In recent decades, the planet has urbanized on an unprecedented scale. We need to create cities that can cope with these demographic changes and accommodate the inevitable pressure on transport, energy, water, and living spaces. In an age when more than half the world's population lives in cities, there is more demand than ever for space. Tall buildings offer the most efficient use of land; building up, rather than out, must be part of the solution. It is part of the responsibility of engineers to design the structure of tall buildings so that they meet the various needs


Figure 1. The Shard & The Place at London Bridge. © Sailko

Figure 2. The Shard – winter garden. © Renzo Piano Building Workshop

Figure 3. Existing and new piles at the Shard. © WSP

of the urban population in a flexible and responsible way. Consequently, the challenges for the engineer are numerous.

The Right Streetscape

In the past, street design has not been a priority for all stakeholders – the net result is that tall buildings have been planted on sites without due regard for their surroundings. By engaging in a different approach, through an evolving and collaborative process with professional designers and enlightened key stakeholders, a robust and respectful result is achievable. Analyzing different street typologies and public realm treatments and assessing capacity for pedestrians, public transport, and traffic now contributes to balanced streetscapes, in terms of movement and the psychological perception of tall buildings.

The concept of the "vertical city" is gaining acceptance, resulting in more mixed-use tall buildings in recent years. The Shard recognized that tall buildings need to deliver places that people enjoy for living, leisure, and shopping, as well as for working. The wider economic, social, and environmental benefits of tall buildings set in a good public realm is beyond question. A well-positioned tall building has a regenerative effect on its surroundings.

In some instances, the streetscape can be taken into the buildings. At the Shard, each office floor is provided with three winter gardens in order to improve the environment for tenants. These spaces are outside the double-glazed part of the façade, but within the outer single-glazed skin. Ventilation allows fresh air into these spaces, and the steelwork detailing is visually enhanced and left on view (see Figure 2).

By breaking away from the standard, risk-averse approach to design, and instead following a rational and creative process, we can achieve high-quality places that embrace modern tall building design. This leads to large buildings that sit comfortably alongside buildings from different ages. Instead of dominating historical cities, they will complement and contribute to the development of our cities in a way that preserves and enhances urban character. In well-considered schemes, all applicable engineering disciplines will have studied traffic and pedestrian flows, wind comfort, and the permeability of structures at ground level.

Dealing with a Spider's Web of Existing Underground Infrastructure

Unlike building on clean sites in suburban areas, building on historic inner city sites often has inherited complexities that must be considered. New development is constrained by a spider's web of ground-level and underground infrastructure, which presents enormous challenges to the designer.

The Shard foundations in London were affected by the piles left in the ground from Southwark Towers, a 26-story reinforced concrete building constructed in the 1970s. This building had no significant basement, and was supported on under-reamed piles founded in the London clay. They extended only a few meters below The Shard basement slab, and so could not be reused to provide vertical support for the new building. It was not economical to remove the old piles, so the new piles were designed to pass between the old ones and their under-reams (see Figure 3).

Existing piles were not the only constraint to be dealt with at the Shard. Other existing infrastructure in the vicinity included London Underground's Jubilee line tunnels, which were about 5–10 meters from the northwestern corner of the Shard basement, a disused stair shaft inside the site, a disused lift shaft straddling the boundary, and a ventilation shaft to the west, in Joiner Street. The adjacent streets also contained the usual sewers, Victorian water mains, and other utilities.

Creating good-sized floor plates in the tower called for some clever structural solutions and meant building as close as possible to the underground infrastructure. Limiting ground movement was critical to protect London Underground's assets and to ensure no damage occurred to the water main. Therefore, 3D finite element analysis was used to predict potential ground movement and convince the statutory bodies that it was safe to work within sensitive close-proximity zones.

Movement monitoring, vibration, groundwater mitigation and possible re-use of old piles were taken into account in the design of the Place as well as the Shard. These factors affect many other developments in London and elsewhere.

Made ground	+4.7 m OD to 0.0 m OD
River Terrace Gravel	0.0 m OD to -6.0 m OD
London Clay	-6.0 m OD to -27.0 m OD
Lambeth Group Clay (cohesive soil)	-27.0 m OD to -39.0 m OD
Lambeth Group Sand (granular soil)	-39 m OD to -45.0 m OD
Thanet Sands	-45 m OD to -57.5 m OD
Chalk	below -57.5 m OD

Table 1. Ground configuration at The Place site.

Navigating Around Sensitive Buried Secrets

The potential presence of archaeological artifacts also complicates building tall in historic cities. Excavations have to be painstakingly inspected by archaeology teams, and the unpredictable nature of archaeological excavation poses a big risk to the program.

Smaller buildings covered the site for The Place at London Bridge Quarter, and Roman remains had been left undisturbed. The time needed for the archaeological dig threatened to delay construction in the ground. Engineers knew that time lost in the ground is rarely recovered. In the interest of minimizing risk to program, the team responded through the rather drastic measure of reducing the depth of the basement by one level.

How could the team deal with losing a whole basement in a project of this scale? In some ways, the answer was Building Information Management (BIM). The software and techniques were used to adjust plant positions and to package the plant rooms more efficiently, resulting in reduced excavation and construction costs, and program risks.

As well as reducing the size of the basement, the Place team also had to find a construction methodology that would minimize delay. Top-down construction was the answer to this challenge, enabling work to progress above ground while the basements were constructed below ground.

Top-down construction is essentially a time-saving methodology, wherein construction takes place from the ground level downwards, rather than excavating to the bottom of the basement and working up. At The Place, 500-by-500-millimeter steel columns were lowered or "plunged" from ground level through empty pile bores into freshly poured concrete. The ground level slab was then cast on grade. Once it had gained strength, the slab was capable of propping the perimeter embedded walls and could be supported on the plunge columns, allowing excavation to commence below the slab.

Through top-down construction, the risks posed by archaeological works to the program were circumvented. This enabled the superstructure and basement works to proceed simultaneously (see Figure 4). The archaeological work, essential to our understanding of historical cities, was completed without compromising the job.

The team selected 1.2- and 1.5-meter diameter rotary bored piles founded in the top of the Thanet Sands to support the very large concentrated loads.

Ground conditions at The Place are typical of inner-city development sites, consisting of made ground over natural strata (see Table 1). The areas to be piled were tackled initially by the archaeologists. When their work was complete, the pits were backfilled and piling could begin.

The basement perimeter was piled first, and plunge columns were used to support the core and top-down slabs. There was so little room on the southeastern side of the site that a single 2.4-meter diameter pile was needed to support the load, rather than a more typical

Figure 4. Top down construction at The Shard. © WSP

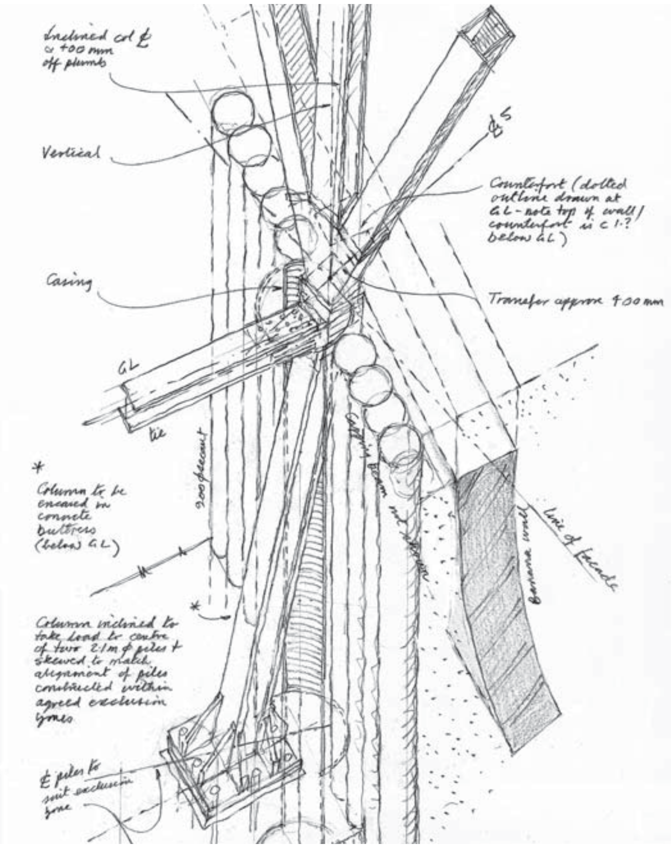

Figure 5. Avoiding the historic banana dock wall in London's Docklands. © WSP

Figure 6. The Place – raking columns and corbel. © WSP

group of three 1.2-meter diameter piles spaced three meters apart, which would have taken more space in this narrow corner of the building. By agreement with London Underground, the pile was formed only 1.5 meters from the Jubilee Line tunnel wall. Piles close to the underground infrastructure were sleeved to minimize ground movement. Because the piles were so close to sensitive underground tunnels, best practice soil-structure analysis was carried out to fully explore likely ground movements and convince the guardians of the assets that ground movements could be properly controlled. Further confidence was provided by real-time monitoring of the surrounding area.

Twin cores were "jump-started," borrowing a technique pioneered on The Shard. Jump-starting counters the costs inherent in building to reasonable programs on confined and constrained sites in historic city centers. In effect, the cores were also built top-down, and therefore the superstructure could move ahead without waiting for the basement "bathtub" to be completed.

Similarly at the Shard, the slip form was set up at the second basement level, and while the core was being built upwards, basement construction continued beneath. At one stage, the plunge columns beneath the core were supporting 23 stories to Level 21. The lowest parts of the core walls were cast using self-compacting concrete, pumped from the base of the shutters, up to the underside of the previously cast concrete.

The foundation piles, constructed in similar strata as the nearby Place, were bored up to 1.8 meters diameter, using standard auger rigs, to a depth of up to 53 meters from ground level. The piles were cased through the alluvium and gravels, and bentonite was used to support the bores in the water-bearing Lambeth Group beds and Thanet Sands.

A pile test, in accordance with the Institution of Civil Engineers (ICE) specification for Piling and Embedded Retaining Walls (ICE 2007) was conducted in the early stages of the piling program, and the results were used to justify a factor of safety of 2.25. A vertical tolerance of 1:200 was specified for the secant piles in order to ensure that they remained interlocked for the full depth of the basement – 98% of the piles achieved this tolerance.

Many of the bearing piles inside the basement perimeter contained plunge columns to support the core, superstructure columns, and upper basement slabs. They were installed using a hydraulically controlled, laser-guided rig specially developed for the project. The plunge columns achieved a vertical accuracy of 1:400, and the tops were within ±15 millimeters of the specified positions.

All these measures are necessary consequences of building in historic cities. Other examples include building transfer bridges over archaeologically important structures to leave them in place and undamaged for the benefit of future generations. This approach was taken to protect the Grade 1-listed dock wall at Canary Wharf, where transfer structures were built to divert load to safe positions on either side of the wall, or building columns were sloped to avoid the wall completely (see Figure 5).

> “The Shard foundations in London were affected by the piles left in the ground from Southwark Towers, a 26-story reinforced concrete building constructed in the 1970s.”

More Plot Constraints at The Place

In historic city settings, designers and engineers of tall buildings often need to cope with highly constrained footprints.

At The Place, not nearly as tall as The Shard at 17 stories, it was nevertheless necessary to cantilever the frame outwards from the ground level perimeter by up to 12 meters, in order to maximize the available air space while leaving the underground infrastructure unaffected. Here, rather than opting for a typical space-hogging two-story high transfer structure, the structural engineer developed corbel arrangements to transfer the loads to ground more efficiently.

Raking columns extend from the cores to the façades, at Level 3 to Levels 11 and 12 and are tied back to the cores with specially designed beams (see Figure 6). A strong, triangulated structure was created, with the lower floors suspended from the nodes where the raking columns meet the façade. This form of construction required the use of extensive temporary works to support the lower parts of the frame while the corbel arrangements were being erected.

The Place's constrained site also required cantilevering over the bus station next to the building, so again temporary works had to be located skillfully to keep the service operational. To add to the pressure, the bus station had to be clear of temporary works in time for the 2012 Olympics – all part of building in a vibrant, historic city!

One of the most unusual aspects of The Place is the fact that the cores are subject to permanent unidirectional lateral loading. This is because the building and associated cantilevers are asymmetrical, and the building pulls to the east. The cores are more heavily reinforced and have thicker walls than would otherwise be required, to provide sufficient stiffness. The cores were built with a "pre-set," a lean toward the west, and were gradually pulled vertical as the building was constructed.

As the frame was built, the loadings on the cores and individual steel members gradually increased. WSP had to calculate the movement of the building and predict its impact on construction. Pre-sets were built into the frame so that floors were eventually level.

> "The lower level floors were framed in steel to suit large spans, while in the upper levels, the spans are smaller, and post-tensioned concrete was more suitable. Spans were sufficiently short in the top few concrete floors to allow the use of normal reinforced concrete construction."

Figure 7. Steel framed structure above the residential levels. © Terri Meyer Boake

More Plot Constraints at The Shard

At The Shard, the vision of a "vertical city" within a constrained area set into ancient street patterns inspired the tapered shape of the building. The engineering design needed to bring this to reality. Large floor plates were preferred for offices because of their suitability for commercial operations. Intermediate levels were allocated to restaurants, and the luxury ShangriLa hotel, which required a corridor near the core and suites around the perimeter. Very large floor plates would not have been suitable for the hotel because each room required a view. Exclusive residential apartments were positioned at the top of the building, occupying entire floor plates in most cases, and in some cases two floors.

The vision to create this mixed-use vertical city and desire for the tapered shape informed the choice of material and structural system. At the Shard, the lower level floors were framed in steel to suit large spans, while in the upper levels, the spans are smaller, and post-tensioned concrete was more suitable. Spans were sufficiently short in the top few concrete floors to allow the use of normal reinforced concrete construction. The spire was framed in steel for ease of construction (see Figure 7).

To create extra space in a constrained site, at the Shard's upper levels there was no need for a large ceiling void, because the services routes were above the corridor around the core. A 200-millimeter thick post-tensioned flat slab reduced the structural depth and this, together with shallower finishes in the upper levels, reduced the floor-to-floor height by 550 millimeters, compared to the composite steel floors in the office levels. This allowed two floors to be added without changing the height of the building. The thicker, normal-weight concrete slabs in the upper levels provided additional mass, as well as the necessary acoustic separation between hotel and apartment floors.

Creative engineering can maintain strength and mitigate the horizontal forces due to wind. By using concrete at the upper levels for the Shard, additional structural damping was delivered. Wind-induced horizontal accelerations in the apartments were limited to 0.015 m/s^2 during a 10-year storm, following guidance published by the Council on Tall Buildings and Urban Habitat. In early designs, the structure was conceived as steel throughout the full height, but the low damping of the steelwork required the use of a tuned mass damper. Removing the tuned mass damper from the design saved money and weight, while releasing a further two floors of useful space. In some ways, it was counter-intuitive that concrete near the top of the building improved the dynamics. However, the relatively small area of the upper floors led to only a small increase in mass, and the additional damping inherent in the concrete-framed upper stories provided adequate compensation.

Constructing the spire at the very top of the Shard while 120,000 people per day were using the London Bridge station at its feet presented a considerable challenge. The steel frame was more than 60 meters tall, and there was no lay-down space at ground level to

Figure 8. Installing the steel spire. © Mace

assemble structural elements. The spire was therefore designed so that it could be fabricated in modules; each module was the maximum size that could be transported by road and lifted by the tower crane. Because the spire contained the viewing gallery, the structural engineer worked closely with the steel fabricator to ensure that there was no reduction in aesthetic quality by using modular construction (see Figure 8).

A trial assembly of the spire was carried out at the fabricator's yard in order to ensure the modules could be erected rapidly and safely when they arrived on site.

Modern Modeling Techniques Allow Historic Cities to Enjoy the Juxtaposition of Old and New

Computer modeling plays a central role in enabling the realization of complex projects. Computer analysis enabled the structural engineer to demonstrate to London Underground that it was safe to build within its usual 3-meter exclusion zone while working on The Place at London Bridge.

The biggest ground movement predicted was only 4 to 5 millimeters on some of the assets. With this reassurance, London Underground was prepared to allow construction firm Mace to work within 1.5 meters of the sensitive Northern Line escalators. Work was constantly monitored for movement using real-time techniques. At The Place, the asymmetrical nature of the loads called for non-linear analysis to understand the direction and power of the forces in the building, and to develop an efficient structural design.

Another aspect of designing any tall building in a prominent city like London is the higher risk of extreme events. To fully assess a building's structural performance in an extreme event, a non-linear geometric/material properties analysis is required. Non-linear analysis was pioneered by WSP immediately after the World Trade Center attack in 2001 and was used to understand the disproportionate collapse of tall structures. This has helped engineers design more resilient buildings, and is now widely used for designing complex tall structures. These analyses provide a better understanding of structural behavior and allow appropriate design to be carried out.

As well as being a core method used in overcoming construction conflicts and constraints, BIM has a strong commercial role to play. Sellar Property Group/Qatari Diar wanted to use BIM on The Place to help streamline its construction and operation. WSP worked with Mace specialist contractors and the client facility managers to enable BIM to be part of the construction process as well as facility management (FM), making the design and delivery of the project more efficient, and saving an estimated 10% on build costs and on-going FM costs.

BIM was key to the process of removing a basement level at The Place, in order to save time and reduce program risk around archaeological work. This was achieved by modeling the plant and packaging it more efficiently. Without BIM, the developers would not have had the confidence to proceed with this approach.

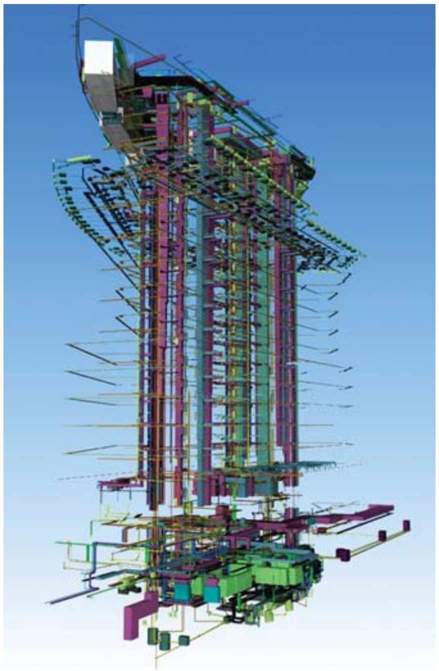

Figure 9. BIM used to position utilities and services routes for The Place. © WSP

BIM was also useful as a tool when Mace discovered a hitherto-unknown shaft in the way of the secant wall at The Place. The shaft turned out to be a forgotten entrance to the old City & South London Underground line. BIM enabled a rapid redesign of the secant wall and associated structure and plant layout.

Using BIM also made it easier to position openings for utilities and services (see Figure 9). Sellar/Qatari Diar had an agreement with Mace that no holes over 150 millimeters in diameter would be cut in the structure after the concrete had been cast; using BIM helped eliminate new hole cutting.

For historic cities to grow and develop, and to be leaders on the world stage, they must embrace social and cultural shifts and welcome the opportunities that tall buildings provide. The benefits of modern modeling techniques such as BIM, fused with the creativity of tall building specialists, drive developers to overcome significant economic and physical challenges that are inherent in the fabric of historic cities. As demonstrated here, these challenges are not insurmountable. ■

For more information on The Shard see the Talking Tall data box on page 57.