Shard at London Bridge Tower

London's Tallest

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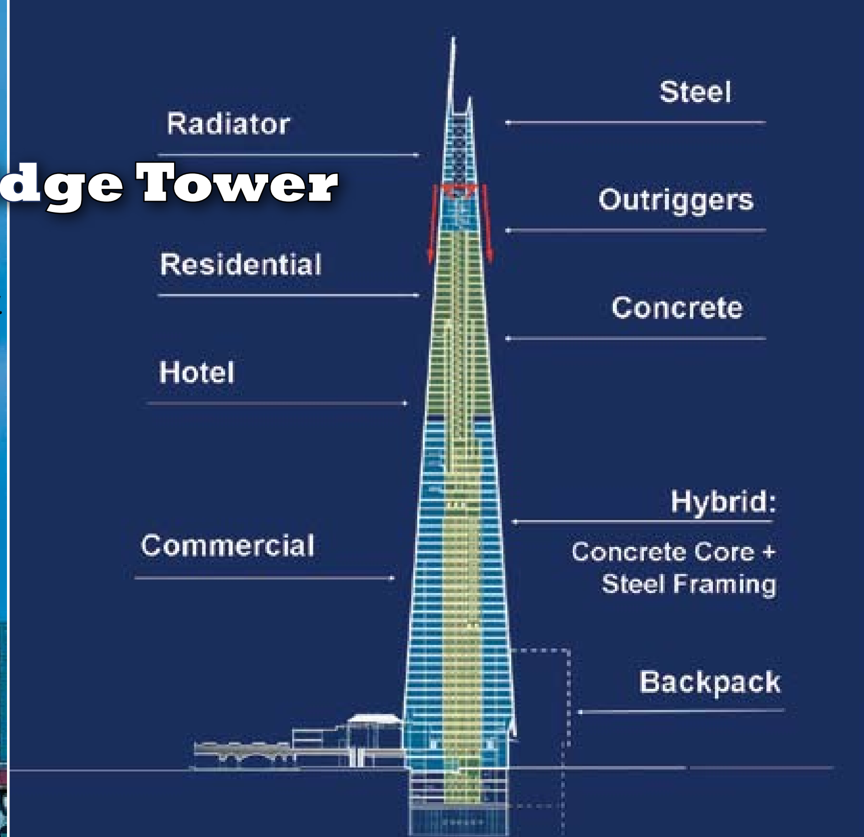

Figure 2 (above) Model of Shard Tower.

Figure 1 (left) Shard at London Bridge Tower; Courtesy of Hayes Davidson, Sellar Properties.

The iconic mixed use tower of "Shard" at London Bridge, when completed to a height of 310 meters (1017 feet), will become the tallest building in the Western Europe (*Figure 1*). A world-class building designed by Architect Renzo Piano Building Workshop, it will be constructed in an extremely complex urban environment. The project is currently underway and will be completed by 2012. It was designed to accommodate retail and office usages at the lower levels, hotel usage at the mid-height levels, and residential usage at the high-rise levels of the tower. In addition, it will accommodate parking, viewing galleries, mechanical/electrical/plumbing (MEP) systems, power plant facilities, and other ancillary facilities.

Geometry

"The shape of the tower is generous at the bottom without arrogantly touching the ground, and narrow at the top, disappearing in the air like a 16th century pinnacle or the mast top of a very tall ship," explained Renzo Piano, the project architect.

The tall, slender, multifaceted and tapered geometry of the tower, combined with multi-use programs at various heights, set the primary challenges for the structural design. The tapered geometry efficiently accommodates the various usages along its height: residential at the upper portion with smaller floor areas, hotel at the mid-height portion with average floor areas, and commercial at the low-rise portion with maximum floor areas, augmented by an extension to the building at the lower level, called "backpack", to further increase the commercial floor area (*Figures 2 and 3*). Fundamentally, the challenges were to create harmonious structural systems, while addressing the often conflicting requirements of multiple programs. This involved selecting the appropriate lateral load and gravity load bearing structural systems, while creating an economical and constructible design.

From the early stages of the design and conception, the intent has been to support the architect's inspiration and to use state-of-the-art structural engineering and construction techniques to design a building that optimizes every aspect of its structural design, from its foundations to its gravity and wind/seismic load resisting systems. The use of different structural materials at various zones of the tower will be geared to accommodate maximum conformance to the architectural and usability requirements, while addressing overall stability and performance.

Key features of the structural design include use of top-down basement construction for the main tower together with conventional bottom-up construction under the low-rise annex "backpack" portion of the building on the east side of the tower. This was done to increase the speed of construction and to minimize the ground movement around the site. Top-down construction is an alternate method of construction where, after installation of the load bearing elements such as diaphragm walls and piles, the basement floors are constructed as the excavation progresses from grade level down to the lowest basement level.

The Site and Foundation

The site is at the junction of St. Thomas Street and Joiner Street, adjacent to London Bridge Station. It is close to major railway infrastructure, including station platforms at the eastern and northeastern boundaries of the site. The running tunnels of London Underground's Jubilee Line between London Bridge and Bermondsey Stations exist at the northern boundary of the site. A major Victorian water main runs along the southern boundary of the site beneath St Thomas Street. The site is currently occupied by an existing building known as Southwark Towers, which has a loading dock to the west and an 'at grade' car park to the east.

The existing building is founded on piles, under-reamed within London Clay. Abandoned stair and vent shafts belonging to the London Underground also exist on site. Local geology consists of fill over drift deposits comprised of Alluvium and River Terrace Deposits, which overlay clays known in England as London Clay, Lambeth Group Clays, Thanet Sands, and chalk.

Due to the sensitivity of the adjacent infrastructure, the main focus of the new foundation design was to minimize the ground movement during construction, while working through the existing piles and other obstructions. A foundation system consisting of a perimeter secant pile wall, comprised of 900-millimeter (3-foot) diameter piles and 1500-millimeter (4.9-foot) diameter bored piles 50 meters (164 feet) deep, using a top-down construction methodology, was proposed.

A finite element analysis of the soil and structure was performed to assess the effect of the demolition of Southwark Towers, the installation of the perimeter basement walls, the excavation for the basement, and the reapplication of loads to the new piles from the tower. The results of these analyses indicate that the movement of the adjacent infrastructure will be within acceptable limits. However, the adjacent structures will be monitored during the construction.

The basement is three stories deep. Ground levels B1 and B2 were designed as reinforced concrete flat slabs with drop panels supported on concrete columns or plunge columns that will be positioned during the top-down construction operation. Plunge columns are structural steel members embedded in freshly poured concrete piles that act as structural columns. The reinforced concrete mat was designed to be 1.5 meters (4.9 feet) to 3 meters (9.8 feet) deep, depending on the location of the supporting load. The new piles will be placed between the anticipated positions of the existing piles and their under-reams (enlarged bases), where possible.

Superstructure

After studying several structural system options, a hybrid structural form was found to be the most adaptive structural solution for the project. To maximize the number of floors within the restricted height of the tower, while providing the most suitable system for various uses within the building, a combination of composite steel frames and post-tensioned concrete floors was chosen. This system will have the added advantage of improving the dynamic performance of the tower in response to wind loads. At the lower retail and office levels above ground, composite steel framing (Levels 3 to 39) was designed for spans of up to 15 meters (50 feet) from the perimeter to the concrete cores (*Figure 4*). At the upper hotel and residential levels, 200-millimeter (8-inch) thick post-tensioned concrete slabs (Levels 40 to 72) were designed for spans of up to 9 meters (30 feet) from the perimeter to the concrete core. These post-tensioned slabs will provide the maximum number of floors within the limit of the building height, as well as providing the required acoustic separation between the residential levels.

Figure 3: Courtesy of Renzo Piano Building Workshop.

The added mass and damping characteristics of the concrete floors will have the added benefit of providing an enhanced dynamic performance of the building, thus eliminating the need for any supplementary damping devices. Slabs within the core will be normal weight concrete designed for lift construction.

Typical floor beams at the office levels will be 500-millimeter (20-inch) deep built-up members, with flange and web plates sized to provide the required strength and stiffness. The use of fabricated steel beams will make optimum use of the available structure zones within the ceiling depth, and will maximize the allowable size of service penetrations. The architectural design required the junction between the floor plate and the cladding to have the least depth to allow daylight penetration. As a result, the spandrel beam depths were minimized using compact plate girders.

Three locations at the perimeter on each office floor were designated as winter gardens where the steel frame will be exposed. At these areas, the steelwork was detailed as architectural exposed steel and the floor slabs were detailed with "Luxcrete" type glass lenses set into the pre-cast slab units.

The upper floors of the tower, including the higher levels of the hotel and residential floors, will be constructed using post-tensioned (PT) floor slabs with a story height of 3.1 meters (10.2 feet). Post-tensioned slabs were chosen to minimize construction depth of the floor system, and thus the story height. The spans were reduced by the introduction of intermediate columns that will rise from the stepped back core wall.

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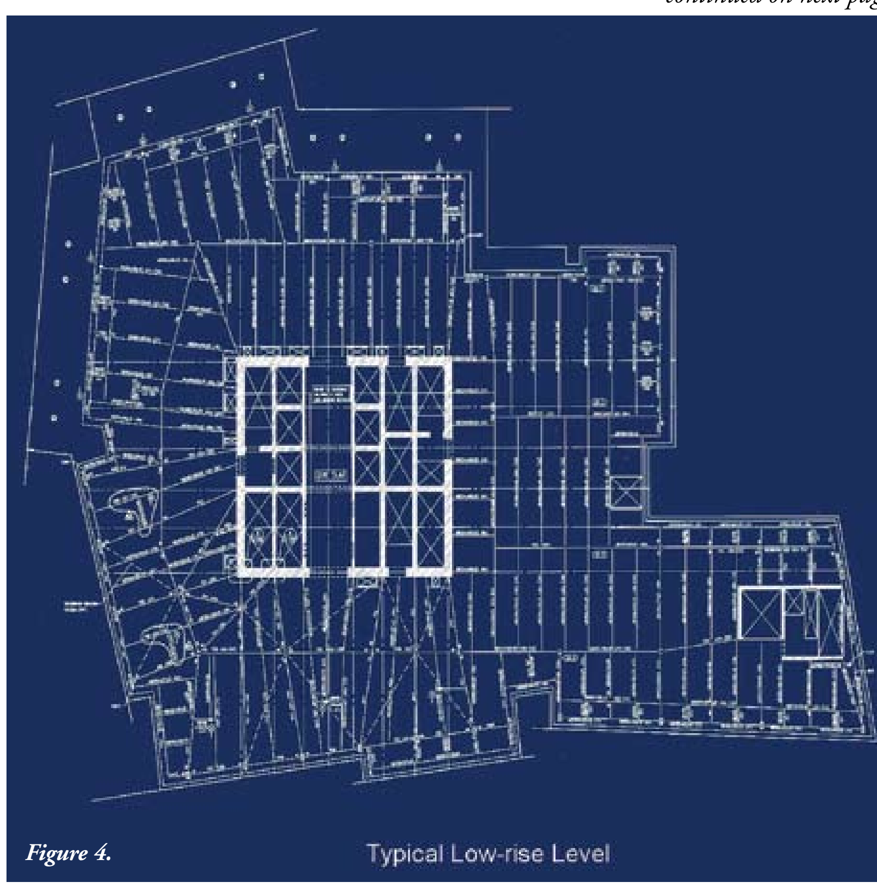

Figure 4.

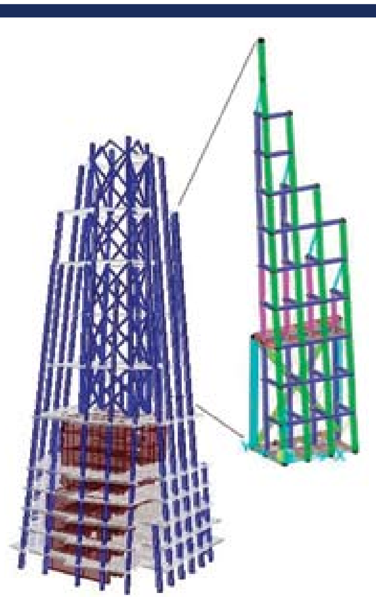

Figure 5.

The first four floors of the hotel will consist of a steel floor system with a story height of 3.65 meters (12 feet). It will accommodate the realignment of the upper tower columns with the office floors using a steel Vierendeel Truss system, which is a multistory grid of closely spaced moment frames.

However, the flexibility of the Vierendeel system produces an uneven axial deformation for the perimeter columns. This needed to be considered in the design of the floor framing system, especially for the post-tensioned floor system. Staged construction analyses were performed to assess the differential movement of the columns in order to adequately reinforce the slabs.

At the top 60 meters (197 feet) of the tower above the residential space, structural steel framing will be used to house the heat rejection plant. This part of the building is known as the "Radiator". The Radiator framing will consist of a central braced steel mast supporting the steel framed plant access decks (*Figure 5*). The top of the central mast will support a building maintenance crane unit.

At the very top of the tower, cladding will extend upward expressing extruded sheets of glass called "Shards" that will taper into the sky. Structural grids using a series of vertical trusses will provide the stability for the Shards (*Figure 5*). In order to reduce the visual impact of the truss bracing members behind the glass panels, the bracing members were designed using 25-millimeter (1-inch) rod elements.

The perimeter columns were designed so that their sizes and spacings will reduce with height, adding to the impression of an increasingly refined structure tapering and disappearing into the sky. The spacing of these columns will be 6 meters (19.7 feet) at the base and office levels, 3 meters (9.8 feet) at the hotel and apartment levels, and 1.5 meters (4.9 feet) at the Radiator levels. The transitions are made by sets of Vierendeel grids at various locations along the height of the tower.

A-frame transfer systems will be used at the junction of the tower and the Backpack structure to increase the column spacing, thereby creating an open-office space at the lower levels. Perimeter columns at the lower steel levels will be rectangular steel tubes and will be fire protected with an epoxy-based intumescent fireproofing material at public areas. Columns also will be filled with concrete to enhance their robustness.

High-strength concrete in the range of 65-80 Megapascal (9,500-11,500 psi) will be used for the reinforced concrete columns at the upper hotel and residential levels in order to minimize their dimensions. The concrete slab strength at these levels will be adjusted to 50-60 Megapascal (7,200-8,700 psi) in order to address the strength at the column slab joint where it passes through the slab.

The sloping nature of the building geometry, combined with the sudden variation in floor plate dimensions, created scenarios where the inclined perimeter columns were required to realign themsleves at some locations by further sloping the columns in the *opposite* direction. This generated horizontal push and pull forces in the floor diaphragms that needed to be resolved by the building's central core wall.

The tower's lateral stability will be provided primarily by center core shear walls acting as the main spine of the tower (*Figures 6a and 6b*). The core stiffness will be augmented by wing shear walls at the hotel and residential levels, as well as by outrigger hat trusses within the upper plant levels (*Figure 2, page 42*). This enhancement to the stiffness was solely designed to improve the serviceability performance of the tower under wind loads. Consequently, there was no requirement to fire-protect the hat truss steelwork. Most of the MEP risers will be placed outside the concrete core in 'soft' areas; therefore, the duct penetrations and access ways into the core will be avoided. Like many high-rise mixed use towers, the vertical transportation design was intricate with the presence of a mid-height tower sky lobby that required transfer walls and girders within the core walls. In addition, a secondary core was designed within the "Backpack" low rise extension to minimize the torsional load on the tower core.

Three-dimensional finite element computer modeling was used to evaluate the performance of the structure under wind and seismic loads. Dynamic analyses were performed to evaluate the building frequencies and mode shapes. The results were used in conjunction with High-Frequency Force Balance HFFB wind tunnel testing, which was performed by the Rowan Williams Davies & Irwin Inc. (RWDI) Wind Tunnel Laboratory, to determine the building's wind-induced accelerations, parameters that are required to evaluate occupant comfort levels.

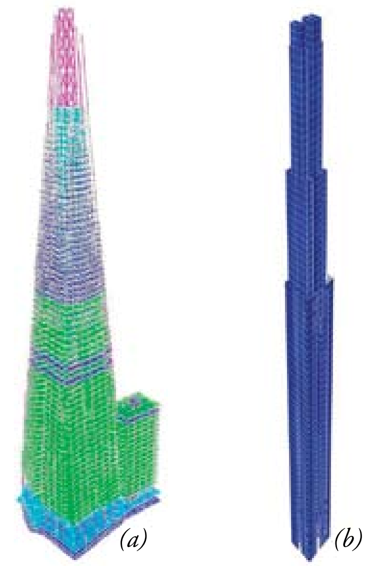

Figure 6.

Additional wind tunnel tests were performed in order to provide more detailed information for the design of the Radiator framing and for the trusses supporting the cladding panels.

The slender and tapered geometry of the tower, combined with its height and mixed usage, provided numerous challenges, as well as opportunities in the design of the structure. It was through a collaborative effort with the architect, other consultants, and stakeholders that the challenges were met and the opportunities were fully explored and utilized.▪

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