

Title: **Steel-Concrete-Steel: Unique Hybrids at London Tallest**

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## Steel-Concrete-Steel: Unique Hybrids at London Tallest

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### Biography

Kamran Moazami works between London, New York and the Middle East, ensuring that clients involved in high rise developments derive the full benefit of WSP Cantor Seinuk's internationally renowned, specialist expertise in tall building design.

The director of WSP Cantor Seinuk received his BSCE, MSCE from Columbia University and professional engineering licence in New York, USA. At this point, Kamran focused on specialising in the design of skyscrapers, mostly in New York, where he was responsible for projects including 7 World Trade Centre, 101 West End Avenue, Manhattan Mall and the Trump Riverside project. In 1989 he set up Cantor Seinuk's London office and in 2000 successfully merged with multidisciplinary property and environmental specialists, WSP Group plc, and has been involved in over 10 million square feet of mostly high-rise construction throughout the UK including London Bridge Tower (Shard of Glass), Barclays Bank Headquarters, Castle House and one Blackfriars in London, Beetham Tower in Birmingham, the Manchester Hilton and West Central in Leeds. In recent years he has worked increasingly in the Middle East, exporting his expertise to this new and rapidly growing market, with projects such as Kuwait United Tower and Al Asima tower, residential towers of the Burj Dubai and EO Tower Dubai.

Kamran Moazami will primarily discuss some of the innovative solutions which have enabled the distinctive architecture appropriate to the different uses of the Shard of Glass building, achieving flexibility to meet the needs of the building's various tenants and providing maximum efficiency to help ensure the project's commercial success.

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## Abstract

This paper presents the structural engineering design approach used to create the iconic tower named the ‘Shard at London Bridge’ (Architect: Renzo Piano Building Workshop). At a height of 1016 feet (310 metres), it will become the tallest building in Europe. It will be a world class building constructed in an extremely complex urban environment designed to accommodate retail, offices, viewing galleries, hotel and residential accommodation together with the associated plant rooms and MEP systems, parking and other ancillary facilities. From the early stages of the design and conception, the intention was to maintain the architectural inspiration and use state of the art structural engineering tools and techniques to engineer a building that optimizes every aspect of its structure from the foundation system, to the gravity supporting and lateral bracing systems. The use of different structural materials at various levels is geared toward use and space requirements and to assist in the overall stability system.

**Keywords:** Europe Tallest, Foundation System, Gravity Support, Lateral Bracing, Materials

## Introduction

Throughout the design process the goal has been to deliver an elegant, structurally efficient building suitable for a highly significant landmark development in one of the world’s major capital cities. Key features of the structural design included utilization of top down basement construction for the main tower together with bottom up construction for the lower portion of the building on the east side of the tower (known as the Backpack), to increase the speed of construction and minimize the ground movement around the site.

A combination of composite steel frames and post tensioned concrete floors have been chosen to best suit the various designated uses of the different parts of the building, in order to maximize the number of floors and to enhance the dynamic performance of the building in terms of lateral acceleration.

The lateral stability system is based on a vertical spine consisting of a cantilevered concrete shear wall core stiffened by an outrigger hat truss at high level engaging the perimeter columns of the building. A robust, highly compact core has been developed to suit vertical movement through the building and to provide the best possible net to gross ratio. Optimized perimeter column locations transfer with height, from 6m spacing at the base, to 3m, to 1.5m at the very top. All vertical column transfers were optimized and achieved with no loss of space. Perimeter columns are transferred using either a load sharing steel girder transfer system or A frames at the intersection of the Backpack and the tower. Interior columns are strategically positioned to land on a discontinued lower concrete core wall.

## The Site

The site is at the junction of St. Thomas Street and Joiner Street, and is adjacent to London Bridge Station. It is therefore close to major railway infrastructure

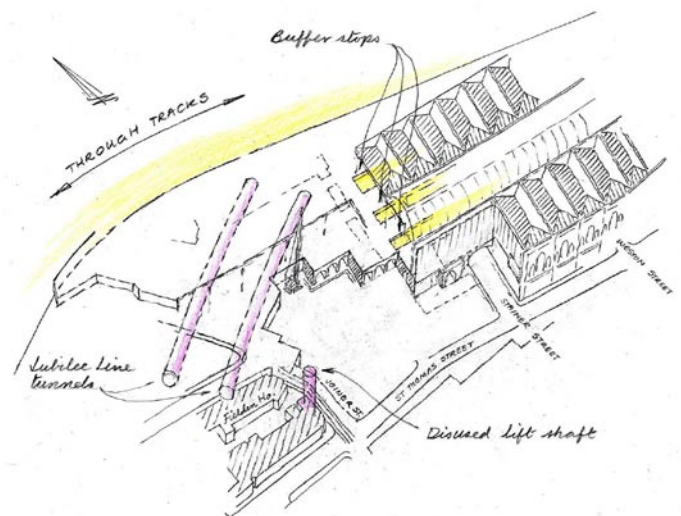


Figure 1, Site Constraint

including station platforms on the eastern and north eastern boundaries of the site. The running tunnels of London Underground’s Jubilee Line between London Bridge and Bermondsey stations are within 5 to 10 metres of the northern boundary of the site. A major Victorian water main also 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 the

London Clay. Disused stair and vent shafts belonging to London Underground also exist on site. Local geology consists of made ground over drift deposits comprising Alluvium and River Terrace Deposits which overlie London Clay, Lambeth Group Clays, Thanet Sands and chalk. Perched water tables are present at various levels. Contamination associated with railway use is expected.

### Foundations and basement construction

Due to the strategic location of the building and the sensitivity of the adjacent infrastructure the main focus of the foundation design was to minimize the ground movement during construction, to deal with the existing Southwark Towers piles and other obstructions, and to provide support for the building's gravity and lateral loads.

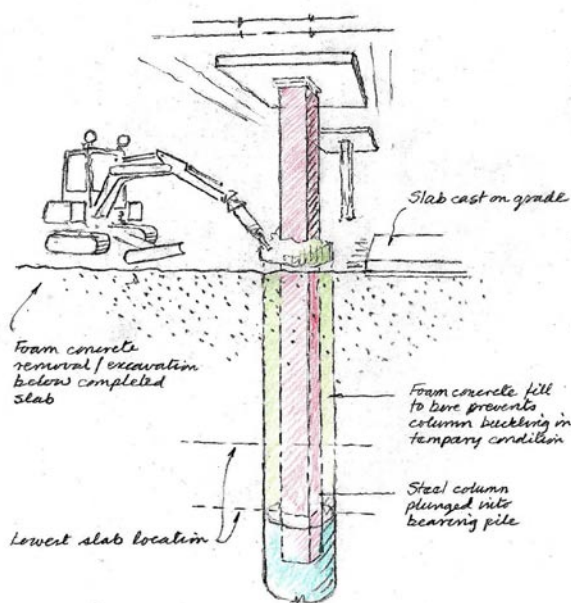


Figure 2, Top Down Construction

A foundation system consisting of a perimeter hard-hard secant pile wall, comprising 900mm diameter piles at 700mm centre to centre spacings, 1500mm diameter bored piles and a top down construction methodology is proposed to deal with the site conditions. With a 1 to 200 vertical tolerance and maximum 75mm plan tolerance, piles will remain secanted into the London Clay and will provide groundwater cut off during the construction.

A number of perimeter columns land directly on top of the secant pile wall, with service point loads up to 20MN at 6m centres. Therefore, in these locations, the secant pile wall becomes a load bearing element with male piles extending about 50m below ground level. The capping beam ensures adequate spread of the point loads into the male piles.

Long term water ingress due to seepage is dealt with by providing under slab drainage allowing the water to be collected and pumped away. The basement slab is

however designed to resist heave pressures from the unloaded clay.

Ground movement will occur due to unloading the soils during demolition, excavation of the basement and re-loading the sub-strata during construction of the new tower. A finite element analysis of the soil and soil structure interaction was performed to assess the effect of the demolition of Southwark Towers, installation of the perimeter basement walls, excavation for the basement and the reapplication of load to the new piles from the tower. The results of these analyses indicate that the movement of the adjacent infrastructure will be within the acceptable limits. However, the adjacent structures will be monitored during the construction to ensure the validity of complex calculations. A zone of influence has been established to determine which adjacent structures will need to be monitored during the demolition and construction.

The basement is three storeys deep. Ground, levels B1 and B2 are designed as reinforced concrete flat slabs with drop panels supported on concrete columns or plunge columns positioned during the top down construction. The ground floor slab is designed for temporary loads to deal with the construction activities on the congested site.

The reinforced concrete mat at the foundation level B3 is 3 metres deep below the main core, 2 metres deep below the Backpack core and 1.5 metres deep elsewhere. The mat is analyzed taking into account mat/pile interaction using RAM Concept and SAFE finite element computer programs to arrive at an optimized foundation solution with the minimum number of piles.

The Southwark Towers is supported on under-reamed pile foundations. Location and length of these piles have been obtained from construction drawings produced for the existing building. These piles will form significant obstructions during piling operations. The new piles are placed between the anticipated positions of existing piles and their under-reams where possible. Reanalysis of the mat will probably be required once the existing mat is excavated and 'as built' locations of the existing piles are surveyed. A degree of flexibility in the design of the foundation has therefore been assumed to allow for the relocation of the piles during construction. Where existing piles cannot be avoided, piles will be de-bonded and extracted or rock augered and drilled out.

The service loads on the columns are up to 21MN and as such, piled/barrette foundations are the only suitable foundation solution. One and a half metre diameter bored piles extending about 50 metres bgl down to Thanet Sands will provide the required capacity. The design of the piles is governed by the structural capacity rather than the geotechnical properties of the ground.

A number of additional piles are provided for the temporary support of some plunged columns and to deal with the tower crane loads.

Piles are base grouted to stiffen the sand which will be loosened by the drilling operation and to reduce settlement.

### Superstructure gravity framing

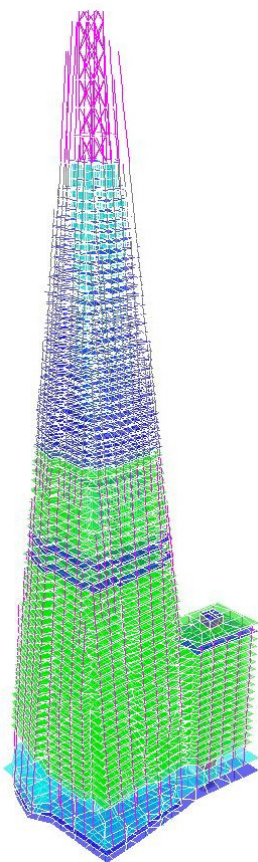


Figure 3, Finite Element  
3D Model

After several iterations of the lateral and gravity analysis a hybrid form of construction was found to be the most suitable structural solution for the project. At lower retail and office levels above ground, composite steel framing (level 3 to 39) provide spans of up to 15 metres from the perimeter to concrete cores. At the upper hotel and residential levels 200mm post tensioned slabs (level 40 to 72) are designed to span up to 9 metres from perimeter to core and to provide the maximum number of floors as well as providing the required acoustic separation between the residential levels.

The added mass and damping characteristics of concrete floors has the added benefit of providing enhanced dynamic performance of the building eliminating the need for any damping device. Slabs within the core are normal weight concrete designed for lift construction and lobby loads.

Steel framing with building services passing through the beams is the most appropriate form of construction for the office, retail and the majority of the public spaces. Steel framing is also used in the lowest floor levels of the hotel from 37th to 40th floor where

edge transfer beams are required to transfer loads from columns at 3m centres to office floor columns at 6m centres.

Office floor slabs consist of lightweight concrete on re-entrant metal deck giving a 130mm total depth working compositely with fabricated steel beams. To reduce the noise and vibration generated from the mechanical plant, the thickness of concrete slabs above and below the plant rooms is increased to 225mm normal weight concrete on metal deck.

Beams are 500mm deep, with flange and web plate sizes adjusted to provide the required strength and stiffness. The use of fabricated beams makes optimum use of the available structure zone and maximizes the allowable size of service penetrations.

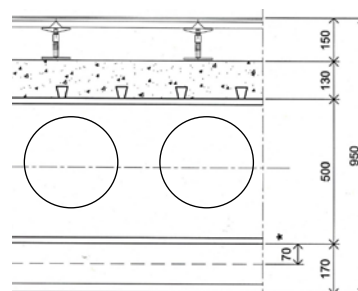


Figure 4. Floor Construction

In a number of cases the top flange is raised above slab soffit level. This is necessary above restaurant kitchens, where additional headroom is needed, and in certain transfer locations where services need to pass under the beams rather than through holes in the webs.

Outside the cores, because of raised floor construction, the upper level floor slabs are not power floated. The use of cambers to individual beams and girders will provide a near level condition under dead loads due to self-weight of steel members, plus the weight of slabs and deck. Steel beams, girders and the metal deck are designed so that they can be constructed without the need for temporary propping.

Design criteria for vibration are based on standards set out in the UK Steel Construction Institute's technical literature '*Design Guide on the Vibration of Floors*.' The response factor R for general office classification where spans are less than 12m is limited to 8, the natural frequency for individual beams is limited to 4.0 Hz and the system natural frequency is limited to 3.5 Hz. For longer spans, the natural frequency of the individual members is limited to 3.5 Hz for individual beams and 3 Hz for the system. However, the response factor R is still limited to 8.

The junction between the floor plate and cladding is shallow to allow daylight penetration and therefore the spandrel beam depths are minimized using compact plate girders. Three locations at the perimeter on each office floor plate are designated as winter gardens. Here the steel frame is exposed and the steelwork is detailed appropriately as architectural exposed steel. The floors



within the winter gardens are detailed with “Luxcrete” type glass lenses set into pre-cast slab units.

The floor plates of the lower four levels of the hotel are steel framed with a storey height of 3.65m. Downstand edge beams on all four levels act as load sharing systems transferring load from the perimeter columns spaced at 3m centres to perimeter columns below spaced at 6m centres. For acoustic reasons, the slabs on these floors are increased to 140mm overall depth, using normal weight concrete.

Higher levels in the hotel are constructed using post tensioned (PT) floor slabs with a storey height of 3.1m (Figure 5).

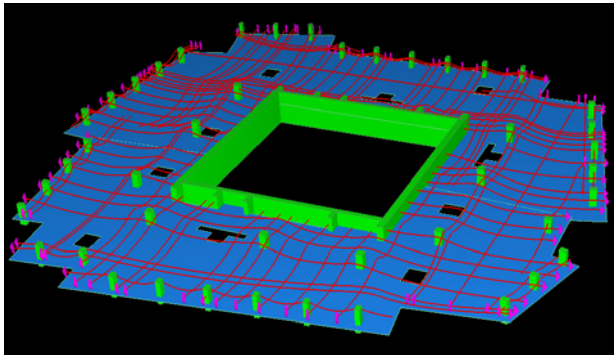


Figure 5. Post-tensioned slabs

PT has been chosen to minimize construction depth and storey height, to provide good acoustic separation and to provide floors with flat soffits. The spans are reduced by the introduction of intermediate columns which spring off the stepped back core and by the use of wing walls located between service risers and projecting from the main core. As in the office levels below, the intermediate columns drop off when the floor span is reduced by the taper of the building's outline. In some cases an architectural need to remove a column required an increase in slab thickness from 200mm to 250mm over part of the floor.

The apartment levels, high level plant room and high level viewing galleries are also post tension slab construction, with spans reduced by the introduction of intermediate columns which spring off the stepped back core: the approach is similar to the approach adopted for the hotel levels.

One major challenge in the design of the PT floor plates was the presence of “softer” perimeter columns. These columns are transferred at the lower levels 37 to 40 by a load sharing beam system therefore settling more than the supporting columns (see Figure 7). Staged construction analyses were performed to assess the differential settlements of these “softer” columns in order to adequately reinforce the slabs.

At the top 60 meters of the building where the

building footprint cannot accommodate usable residential space, structural steel is used to house the heat rejection plant – this part of the building is known as the Radiator. The Radiator framing consists of a central braced steel mast supporting steel framed plant access decks (Figure 6a).

The very top of the central mast supports the building maintenance crane unit. The tops of the cladding surface facets, called the Shards, are braced by vertical trusses (Figure 6b). Diagonal truss members are designed as Macalloy bars in order to reduce visual impact.

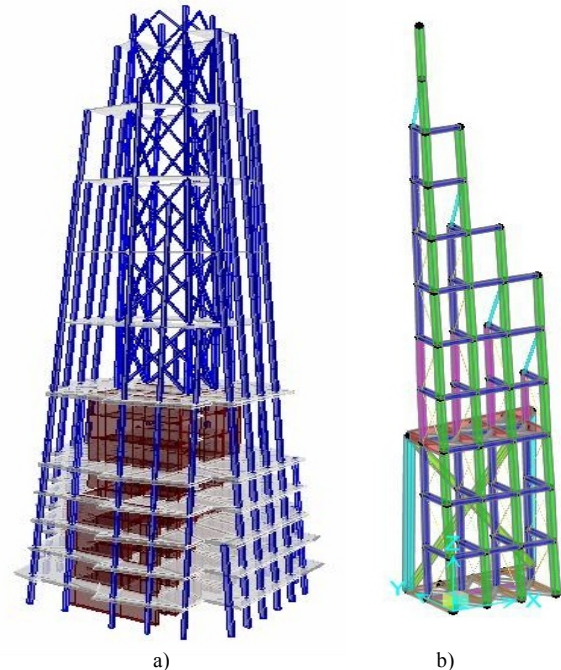


Figure 6 – Radiator Framing

### Perimeter Columns and Transfer systems

Building perimeter columns are designed so that their weight, size and spacing reduce with height adding to the impression of increasingly delicate structure tapering into the sky. The spacing of these columns is 6 metres on centre at the base and offices, 3 metres at hotel and apartment levels and 1.5 metres at Radiator levels. The system requires the use of sets of load sharing beams at various locations in the elevation.

Transfer systems are also required to minimize the edge beam cantilever lengths where the tapered outline of the Shards truncates the inclined perimeter columns (Fig. 7).

Transfer vertical trusses or A frames are used at the junction of the tower and the Backpack structure to increase the column spacing in order to create open office space at lower levels (Figure 7 and 8).

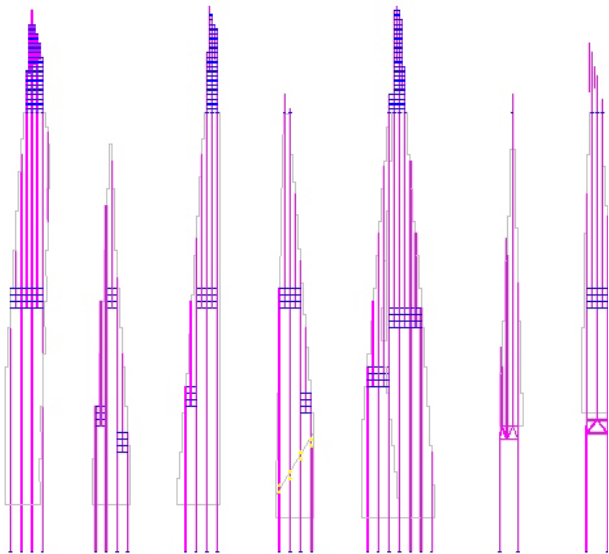


Figure 7. Perimeter Column Transfer

Perimeter columns in the lower steel levels are rectangular steel tubes and fire protected with epoxy based intumescent at public areas. Columns are also filled with concrete to enhance their robustness.

High strength (C65/80) reinforced concrete columns are used in the concrete levels from 40 to 50 in order to minimize their size. The grade of concrete slabs at these levels is also increased to C50/60 in order to avoid a weak layer at the slab column junctions.

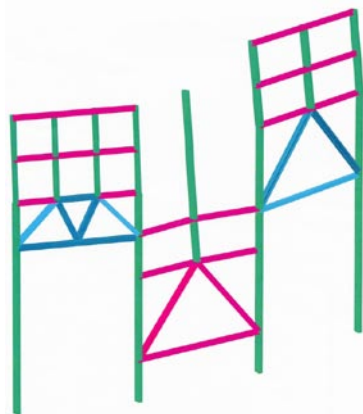


Figure 8. Column Transfer at Backpack

One major challenge in the design of the PT floor plates was the presence of “softer” perimeter columns. These columns are transferred at the lower levels 37 to 40 by a load sharing beam system therefore settling more than the supporting columns (see Figure 7). Staged construction analyses were performed to assess the differential settlements of these “softer” columns in order to adequately reinforce the slabs.

In certain locations - particularly on Shard 14, on the southern side of the building - the inclined perimeter columns step back towards the core so that they do not land outside the building footprint at ground level. The resulting changes of direction generate substantial horizontal push and pull forces; these forces are taken back to the cross walls in the core by diagonal steel floor framing (Figure 9).

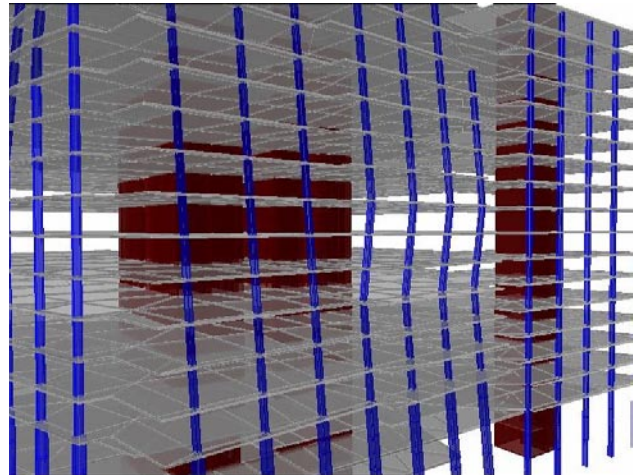


Figure 9. Column Setback – Shard 14

Various other horizontal forces are generated at different levels and locations due to the various columns that change direction from inclined to vertical.

#### Lateral Stability system

The lateral stability system is a slip or jump formed core acting as a vertical cantilever and stiffened by using wing walls in both the hotels and apartment levels and by a hat truss within the upper plant levels. The concrete core provides the primary lateral load resisting system. The core layout is efficient in order to meet the net to gross target. Most of the risers are placed outside the concrete core in ‘soft’ areas and therefore dedicated access ways within the hard core are not required; and the difficulties of getting ducts out of the core into the floor voids are avoided. Like many high-rise mixed use towers, the vertical transportation design is complex. Nevertheless, the layout of the main structural walls within the core, both in the north-south and in the east-west direction, is simplified as far as possible. One major transfer occurs through levels 34 to 37.

A secondary core within the Backpack ensures that there is no tendency for the building to twist due to wind loads on the lower section.

Outrigger struts forming a hat truss rise diagonally within the upper plant levels to engage the perimeter columns (level 66-67). This enhancement to the stiffness of the building is used to improve the serviceability performance only; it is not needed for strength purposes.

Consequently there is no requirement to fire protect the hat truss steelwork.

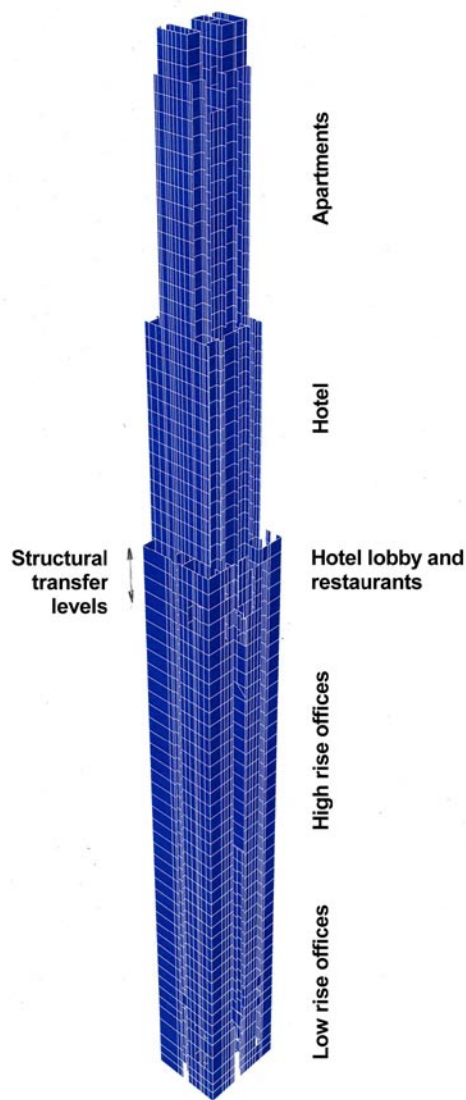


Figure 10. Concrete Core

Three-dimensional finite element computer modeling is return which is the acceptable limit for the residential towers and therefore, as mentioned above, a tuned mass damper or slush damper was not required.

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