Introduction
In order to regenerate London Bridge Quarter, Irvine Sellar and Renzo Piano set out a vision of a new, architecturally-outstanding building designed to feature high-quality commercial, residential and public spaces. The Shard is the realisation of this vision, a 306m high, internationally-recognised symbol (Figure 1). The skill and collaboration of the engineers, architects and contractors was paramount in overcoming the engineering challenges and site/budget constraints to ensure that this ambitious tower, situated in one of London’s busiest commuter interchanges, became reality.

The Shard is designed to welcome more
than 8000 workers, residents and hotel guests each day, and more than 1M visitors each year. It is a vertical city comprising 25 storeys of offices, three levels of restaurants, 18 storeys of hotel and 13 floors of apartments. At the top is a 65m tall steel and glass spire, disappearing into the sky, where carefully detailed steel surrounds visitors as they appreciate views over London.

The development promoted sustainable travel by including just 48 car-parking spaces and included a major refurbishment of the adjacent London Bridge station. The team, client and Southwark Council also put together a vocational programme associated with the project to create local employment and apprenticeships.

Site history
The Shard occupies a site adjacent to London Bridge station, on the south side of the River Thames (Figure 2a, 2b). It is on the corner of St Thomas Street and Joiner Street, in an area which was occupied from Roman times until the 19th century by small-scale buildings and narrow roads. Then, in 1836, the London to Greenwich Railway (the first railway into the capital) built a terminus at London Bridge. There was rapid expansion of the station, and by 1893 it occupied an area over 300m long and 130m wide. The Shard site was used by a succession of railway buildings, including offices, a hotel and a Royal Mail depot.

In addition to the mainline railway, London Underground built a Northern Line station at London Bridge. This was also altered considerably over the years, leaving disused lift and stair shafts on the Shard site. Other developments included the Jubilee Line (extended to London Bridge early in 2000) and a busy bus station. Approx. 54M passengers use the various modes of transport at London Bridge station each year, and the presence of this public transport hub is one of the reasons that the Shard was granted planning permission. During WWII the site was bombed heavily, destroying an irregular-shaped corner of the station (Figure 3). The site was redeveloped in the 1970s, when Price Waterhouse Coopers built a 26-storey headquarters, named Southwark Towers. This building had a reinforced concrete frame and was supported on under-reamed bored piles, founded in the London clay. It had a swimming pool at ground floor level, but no basement.

Southwark Towers was Y-shaped in plan, and the three wings allowed large amounts of natural light into the offices. However, the wings were narrow and so the lettable area was low: 19 800m² in total. By comparison, the office floors of the Shard – from level 04 to level 28 – provide 55 800m² net.

The area has a geology typical of this part of London (Figure 4). Chalk is present at depth, overlain by Thanet sands and then the Lambeth Group beds. Above these is London clay, and then layers of river terrace gravels and alluvium (the area was once part of the River Thames). The water table is at the top of the gravel – around 4m below ground level – and the high permeability of this stratum presented the greatest challenge for keeping the basement dry. Water is also present in the sands and the Lambeth Group, requiring the piles to be constructed under bentonite.

A series of small faults cross the site from north to south, resulting in the base of the London clay and the strata beneath being 5m lower on the east of the site than on the west. The faults have not moved since the end of the last Ice Age, and so their only effect was to make the eastern piles a few metres deeper.

Architectural concept
The architect’s first meeting with the client took place in Berlin on 30 May 2000 and the idea of a vertical city was conceived on that day (Figure 5). The tower would be built in Southwark, over London Bridge Station – its shape influenced by the arrangement of the railway tracks on the ground and by images of the soaring spires that once were a striking part of the ancient skyline of London (Figure 6).

Early research by the architectural team from the Renzo Piano Building Workshop (RPBW) included viewing the urban landscape from the top of Southwark Towers. RPBW’s architects were struck by the view of a river of water (the Thames) and a river of steel (the railway tracks). The project then began to take shape, by reference to the movement and scale of these ‘rivers’, by the inspiration of 17th Century landscapes and through a belief that the idea of a tall, mixed-use tower was an idea fully compatible with urban regeneration and living in the city. The architects decided to taper the building and make it ‘disappear into the sky’. They felt that the approach in London should not replicate solutions adopted in other cities such as New York. As they put it:

‘New York has a completely different urban context to London. In New York you have an extrusion of vertical towers, like trees in a dense forest. London is completely different: dense, even chaotic at times and largely
mid to low rise, especially south of the river. Designing a very tall building for London demanded a completely different approach. The site Sellar had acquired for the project was complex. Small, with an irregular shape, it perched on top of London Bridge Station. The fact that a site for a building existed there at all was because a bomb had destroyed part of the train station during the Second World War, creating a space for the construction of an unsightly tower in the early 1970s."

RPBW also convinced the planners that the existing Transport for London (TfL) bus station with its 15 bus stands, located in front of the entrance to the Shard, should rotate to align with the train tracks and move to the north to create clear sight lines from the train station through to the London Bridge river crossing. With this move they were able to create a small but important piazza between the Shard and the Place; a sister development immediately to the west by the same client and design team.

The next step was to combine this irregular site and the idea of the building tapering towards the top, with the concept of ‘shards’ – planes of façade – which did not touch one another. This was a device to fragment the scale of the building and reflect the light in an unpredictable manner, diminishing the presence of the tower against the sky. So, from a very early stage, a glass façade was chosen to give the best chance of achieving – in the architect’s words – ‘an incorporeal, crystalline effect that would play with the light and the mood of the weather.

The tapered shape suited the various intended uses, both in terms of elevation and area. Apartments were positioned at the top where floor plates are small, the hotel is at mid-height where all rooms would have a view over London, and commercial space is in the lower third of the building where floor plates are large. From ground level to level 16, the office floor plates are further extended by a ‘backpack’ on the east side – this helped to ensure that the Shard extended to the site boundary on every elevation.

**Concept**

The proposed building and its architecture made a great deal of sense from an engineering point of view. The taper minimised the effect of wind load at high level and lowered the centre of gravity, providing useful benefits for building dynamics. There was something satisfying about designing a building which was elegant, which did not rely on structural gimmickry to sell itself, and which was essentially ‘the right way up.’ (It was no accident that the Egyptians built the pyramids with the pointy bit upwards!) Early designs envisaged an all-steel framed building, stiffened by steel outriggers that connected sizeable internal columns with the core. In addition, there was a need for a tuned mass damper at high level.

WSP’s preferred solution for commercial
buildings has usually been compositely designed permanent metal deck slabs on steel frames. Building services shared the ceiling void with the downstand beams; with lateral distribution provided through holes in the beam webs. Conversely, experience on residential towers and hotels, was that designs based on thin fully bonded post-tensioned (PT) flat plate floors were the most economic and most likely to maximise the number of floors for a given height. For example, in the Marriott hotel at West India Quay (completed in 2003), the services distribution was confined to the corridor near the core, where the ceiling could be lower. In the hotel rooms there was virtually no ceiling void at all. Therefore a ‘mixed structure’ was developed for the ‘mixed use’ Shard, with steel in the lower, office levels and concrete for the hotel and the residences at the top (Figure 7). Concrete construction – PT for larger spans and reinforced concrete for smaller spans – saved 550mm of height per floor compared to a steel solution, allowing two more floors in the available height. Finally, it made good sense to revert to steel for the spire.

Hybrid construction in tall buildings is unusual in the UK, but the engineers were able to draw on the experience of colleagues in New York who had successfully designed the fiercely complicated AOL Time Warner building using a combination of frame types. For the Shard, many column arrangements were investigated, always with the aim of minimising the number of internal columns and, where possible, landing these columns on core walls at levels where lifts dropped off. Careful analysis of the distribution of mass, stiffness and damping within the building demonstrated that all the normal design criteria, such as displacement, inter-storey drift, period and acceleration, could be achieved without a tuned mass damper. This reduced costs significantly and freed up two more floors for lettable area. Other issues solved at conceptual design stage included:

- **Grid:** firstly, for the steel framed floors, it became obvious that the beam arrangement was simplest if the beams were set orthogonally to the shards (façade planes) rather than being arranged at right angles to the core walls. Secondly, the perimeter spans reduced from 6m in the steel floors to 3m in the concrete floors and again to 1.5m at the top of the spire.
- **Transfers:** a number of strategies were employed to make these as efficient as possible. The change in perimeter column spacing from 6m to 3m was achieved using vierendeel trusses (discussed in more detail later). At the junction of the main tower with the backpack (the extension of the office space which is 19 storeys high), the column spacing was widened to 12m in order to avoid a ‘wall of columns’ interrupting the office spaces. Here, simple (but very large) trusses were used.
- **Landing the columns at ground level:** after much debate, the simplicity of direct lines was preferred both aesthetically and economically to earlier cranked, Y-shaped perimeter columns.

**Enabling works, interfaces and authorities**

Before work on the Shard could begin, it was necessary to carry out a number of enabling works. The 1970s development of the site included not only Southwark Towers but also structures serving the railway and bus stations. Southwark Towers itself had to be demolished. 95% of the waste produced during demolition was recycled.

The most difficult incursion into the site was a spiral concrete ramp that provided access from street level to the railway loading bay. Before the ramp could be demolished, a new ramp was needed in another location. Fortunately there was a space between the railway tracks and St Thomas Street, to the east of the site, which was used as a car park for the signalmen. The arches adjacent to the façade wall were demolished in this area and a new reinforced concrete ramp was provided in the gap. Piled buttress walls were provided at each end of the gap in order to resist the lateral thrust from adjacent arches, but no other new foundations were needed: the existing arch footings were reused.

A larger area of arches was demolished at the entrance to the ramp, in order to allow a turning space for large vehicles, and this area was covered by a new concrete deck. Vehicle blockers, operated from the station control room, were provided at the base of the ramp in order to increase security in the station. The existing masonry façade wall adjacent to the street was out of plumb by up to 200mm and since the wall had to be retained, a system of concrete waling beams was installed to ensure that it remained stable. An access road to the signal box was maintained throughout construction of the ramp, and a new car park was provided for the signalmen within the arches under the tracks.

Other works included: a new electricity substation; a new support frame for one of the columns of the listed train shed roof; alterations to the bus station and its roof; and a replacement footbridge to maintain access to Guy’s Hospital. On the western side of the site, part of the frame of Southwark Towers also supported the bus station, in a complex arrangement that also incorporated at least two earlier structural systems. The substructure of the Shard cut through this area, and so it was necessary to introduce yet another level of support. The area was so complicated that it became known as the ‘Bermuda Triangle’ because of the view that engineers entering it might never be seen again! Ironically, most of the Shard enabling works have been removed in Network Rail’s redevelopment of London Bridge station for their Thameslink project.

**Robustness, stability, wind and sway**

The Shard was designated as a class 3 building to Approved Document A and as such, a systematic risk assessment was carried out to take into account normal and abnormal hazards.

In addition, as a class 3 building it was necessary to meet all the requirements of
a class 2 building. The regulation required the engineers to follow BS 5950-1 for: details of vertical and horizontal ties; the design approach required for checking the integrity of the building following removal of vertical members and for the design of key elements. The design also took into account the Institution of Structural Engineers’ report Safety in tall buildings and other buildings with large occupancy. This gave recommendations regarding: the design of robust structures; alternative load paths; the use of elements with robust, ductile and energy-absorbing properties; and the provision of strong, ductile connections.

Risk assessment
‘Normal’ hazards were those that could, in theory, apply to any building. They included earthquakes, hurricanes or tornados, deflagration (gas or dust explosion) and explosions caused by terrorism. The latter was not in the scope of Part A3 and required consultation with security experts and specialist advice with regard to blast loading. Measures taken to mitigate this hazard are not disclosed.

‘Abnormal’ hazards were particular to the locations of individual buildings, and included avalanche, ice flows, landslip and scour. The majority of these hazards were not applicable. However, train impact was considered because of the building’s proximity to the platforms at London Bridge station. Subsequently, the position of some columns was refined, in order to locate them outside the overrun impact zone defined in Railway Group Standard GI/RT 7016. With the new station this risk disappears altogether because the tracks are further away.

Mitigation measures were taken for each identified risk. In order to maximise robustness, perimeter columns in certain areas were designed as grout-filled steel tubes. In addition, load-sharing systems were used extensively. A large measure of robustness was afforded by the concrete core (particularly in comparison to a steel core) which also provided secure emergency exit routes.

Other measures included vertical and horizontal ties to meet the requirements of BS 5950-1, key elements designed to resist the effect of localised accidental loading and certain column removal scenarios. The latter was assessed by an alternative load path procedure, using 3D nonlinear dynamic finite element analysis. Different columns were removed from the model in turn and an envelope of beam reaction forces derived. These figures were then used to check the members, connections, composite floor slabs and other structural elements in the emergency scenarios.

Stability and core
The Shard gains its lateral stability from the central core, which is cantilevered from basement level. Lateral forces are transferred to the ground floor slab and from there to the basement perimeter wall. Push-pull forces in the core continue down to the piles and the basement raft slab.

Due to the height and mixed-use nature of the tower, there are 21 lift and stair shafts in the core at ground level. The number of shafts gradually reduces with height in order to maximise the net lettable area of the floor plates. In order to achieve maximum efficiency some shafts are shared by lifts at different levels, separated by slabs capable of withstanding buff er forces. There are lift shafts on the north side of the core up to level 28, but in between, the space is opened out and used for toilets. Three levels of shaft walls above level 28 are designed as a grillage (or ‘egg crate’) to transfer the stability forces to other walls in the core (Figure 9).

The size of the core is sufficient to provide the strength needed for the building. However, as the number of lift shafts reduces with height, a number of strategies are adopted for maximising its inertia and therefore its stiffness. The cross-walls are extended outside the main perimeter in...
Concrete was pumped to the top of the building while the crane was moved and there was no need to halt concreting operations. The crane therefore rose with the slip forming, such that they were able to carry not only the weight of the slip but also the tower crane. The crane was able to carry not only the slip forming the core using a Schwing pump capable of producing an outlet pressure of 24MPa. The contractors made frequent adjustments to the concrete mix to allow for different wind, temperature and weather conditions. They guided the slip using GPS technology, which gave more consistent results than alternative laser systems. The specified tolerance of ±25mm was achieved.

Wind tunnel
Lateral forces applied to the core were obtained through wind tunnel tests, carried out by Rowan Williams Davies & Irwin Inc. (RWDI) in Toronto. The high-frequency force balance technique was used. An essentially rigid 1:400 scale model was connected to its base by a system of springs. The stiffness of the springs was chosen to allow for the model with appropriate lateral and torsional fundamental frequencies based on computer model calculations. The forces at the base of the model were measured using load cells and the full-scale values were determined by calculation, using an overall damping ratio of 1.5%. The model was mounted on a turntable and 36 wind directions were tested. Sensitivity checks were carried out by varying the damping ratio and the natural frequencies. Wind pressures on the cladding were determined using a second model containing 800 pressure taps. A larger (1:150) scale model with 123 pressure taps was used to investigate the loads on the top section of the building (the Spire). A fourth series of wind tunnel tests was carried out in order to investigate pedestrian comfort and the wind speeds at ground level.

Basement
Being surrounded by roads, utilities and railway infrastructure meant that the design and construction of the substructure was both challenging and critical to the programme. The team discussed methods to achieve time and cost savings in the construction of the core, basement and piled raft. The result was top-down construction for the basement, including the first major core construction top-down in the world.

The scheme comprised steel plunge pile columns to support the core and the floor slabs, and a carefully optimised piled raft, 3m deep below the core and 1.5m deep elsewhere. This was relatively shallow for a building of this size (Figure 12). Sustainability played a strong role in the design decisions made. Minimising the thickness of the raft reduced the amount of excavation required and the quantity of fill removed. This, in turn, allowed a more efficient secant pile wall design because its vertical span was reduced. The use of ground granulated blast furnace slag eliminated nearly 800t of carbon in the raft slab. It also reduced absolute and differential temperatures during the curing of the concrete, minimising the risk of cracking.

A secant pile wall was designed for the three-storey basement in order to retain the ground and minimise movement in surrounding assets, while also preventing water ingress. The male piles were 1000mm in diameter, spaced at 1500mm centres and approximately 53m deep, bearing in the Thanet sands. The female piles, at 960mm diameter, formed a cut-off to the ground water in the London clay approximately a metre below the underside of the raft slab. In order to demonstrate that a factor of safety of 2.25 would be suitable for pile design, a 50MN pile loading test was carried out by Beadman et al. This was believed to be the biggest pile test carried out to date in the UK. A
capping beam, between 1.2m and 2m deep was provided on top of the piled wall in order to connect the secant piles and distribute the load from the inclined external columns. The main bearing piles supporting the raft were 1800mm diameter where plunge columns were required, and 1500mm elsewhere. They were of a similar depth to the male piles in the secant wall. Southwark Towers was piled, with under-reamed piles approximately 20m deep. The piles were not deep enough to be reused and their removal would have been prohibitively expensive and time-consuming. However, it was possible to cut through the unreinforced under-reams. The engineers positioned the new piles between the existing piles and in line with the core walls so that the plunge columns would not protrude into the lift shafts (Figure 13). The only record information available was a microfiche of the pile layout which was scanned, scaled, rotated and stretched to match known points on the survey. The accuracy of this operation could not be verified until demolition of Southwark Towers and subsequent probing was complete. It was therefore good news when the investigative results were received, and it was found that they were in good agreement with the approximations made previously. Very little adjustment was needed to an already complex scheme. The sequence of top-down construction (Figure 14) was as follows:

- Bearing piles were bored from ground level and steel plunge columns installed.
- The raft slab was installed in a single 5500m³ pour taking 32 hours. Up to this point, all loads were carried on the secant wall and the piles containing plunge columns. Subsequently, the other piles and bearing pressures under the raft slab, were also mobilised.
- The core walls in the basement were then completed using self-compacting concrete pumped from the base of the shutters. This rendered the plunge columns redundant, but they were, of course, left in place.

Extremely tight tolerances (±10mm in position and ±1-400 vertically) were required on the plunge columns to ensure that the 1000kg/m sections stayed within the finished core walls.

- The ground slab was cast on a slip membrane so that blinding concrete did not adhere to the underside.
- Excavation of two levels of basement then took place beneath the ground floor slab (Figure 15).
- The slipform was set up at level B2 on the plunge columns.
- Meanwhile, the slab for level B2 was cast. Excavation continued beneath B2 to formation level.
- The slipform was not allowed to climb above level 21 while the core was supported on plunge columns only. Excavation was completed to underside of raft level.

The raft slab was as follows:

- The sequence of top-down construction already complex scheme. Very little adjustment was needed to an investigative results were received, and it was found that they were in good agreement with the measured results. It was therefore good news when the movement assessment and monitoring exercise of the site to ensure that demolition of Southwark Towers, construction of the basement and erection of the tower did not adversely affect the surrounding structures. The zone of influence of the works extended to a radius of approximately 90m, and encompassed the Jubilee Line tunnels, Guy’s Hospital, several major utilities, London Bridge bus and train stations, and the station’s extensive network of Victorian masonry arches. The computer models showed that the movements in the tunnels were expected to be less than 5mm, with less than 25mm movement in the arches. Automatic monitoring stations (15 in total) were set up, with readings collected from over 900 targets in the vicinity of the Shard. Reports were made available via the internet and by text message. The team can take pride in the fact that movements during construction were all within the predicted ranges.

Floors

As mentioned previously, the floor framing in the Shard was altered with height: the office levels were designed in steel, while the hotel and residences were framed in concrete (Figure 16a and b). In fact the transition did not exactly match the change of use; steel construction was continued up to level 40 — six floors above the lowest part of the hotel. The reason for this mismatch was related to the span between perimeter columns and the low allowable deflections of the glass façades. The composite edge beams achieved the required performance with a span of 6m but in the concrete levels, the maximum perimeter column spacing was 3m because downstand beams were not preferred — they would not permit table forms to be removed easily. Transfer structures were needed in order to achieve the reduction in spacing, and these took the form of three-storey high vierendeel frames at the top of the steel levels (i.e. from level 37 to level 40 (Figure 17)). It was not desirable to reduce the column spacing lower down the building, because the view from the restaurants and the hotel lobby (levels 31 to 36) would have been impaired. The restaurants and hotel lobby were designed with three-storey high spaces, and open views were understandably seen as very important from these levels. (Later in the project, the hotel was reduced to two storeys, but the change came too late to redesign the vierendeel frames).

From the outside, the Shard appears to have an uninterrupted taper from base to tip. However, the architectural and engineering design includes subtle measures to increase...
the lettable floor area. In some parts of the office levels, the perimeter columns rise vertically for several floors before adopting the general 6° slope. In one location their slope is actually reversed for a number of levels. At the column ‘kink points’ substantial horizontal forces are generated, which are transferred via steel struts and ties, back to the core.

The 200mm thick, normal-weight PT slabs in the hotel and residential levels provide acoustic separation between floors. Less stringent standards apply to offices, and here the 130mm thick, lightweight concrete slabs on top of the beams are sufficient. Thicker slabs are provided above and below plant rooms and in the steel-framed parts of the hotel. One floor supports an electrical substation, and the slabs above and below incorporate 6mm thick steel plates to eliminate electromagnetic interference. All steel beams are fabricated plate girders, mostly 500mm deep. Web thicknesses and flange sizes are tailored to provide the strength and stiffness required for each beam — which saved hundreds of tons of steel compared to using standard rolled sections.

Standard 300mm diameter holes, on a regular pattern, are provided through the webs, allowing building services to be installed in straight and level runs, easing installation and avoiding the need for endless bends in the pipes (Figure 18). This meant that the majority of the services could be prefabricated, minimising the number of operatives on site. Some heavily-loaded primary beams are 650mm deep. For these beams, the top flange is set level with the top of the concrete slab. The bottom flange matches the other beams to maintain a constant ceiling zone. Edge beams are shallower (350mm) in order to create a ‘thin edge to the frame near the glass façade’. A unique prefabricated edge detail was provided to the steel floors, with steel tubes installed on a plate to enable immediate installation of safety barriers to the perimeter of the building (Figure 19).

It was necessary to calculate axial shortening effects in order to ensure that the frame of the building achieved the correct levels on completion. Steel elements shortened elastically, but shortening of the concrete core and columns also depended on creep and shrinkage effects. The situation was further complicated by the change from steel columns to concrete.
Project focus
The Shard

Spire
The ‘spire’ is the 60m tall pinnacle at top of the tower, containing the public viewing gallery (Figure 20). The architect’s vision to ‘allow the building to merge into the sky’ is achieved by gradually reducing the density of the structure at the top of the building. The concrete core stops at level 72 and continues as a steel mast. The solid floors are replaced by open grids and the shards stop at different levels. The steelwork is visible and carefully detailed to provide an aesthetically outstanding structure. At the same time, it is designed to be constructed safely, 300m above ground in the middle of Central London.

The spire comprises a central steel mast to provide stability, floor plates every third level and the ‘shards’ themselves (shaped pieces of façade which terminate in jagged points and give the building its name). The structure is open to the elements and in addition to the viewing gallery, contains plant and building maintenance units. The shards themselves extend past the top floor plate by up to 18m and are supported by cantilevering trusses. The compression booms are restrained by U-frame action from the trusses acting together with the frames in the plane of the façade.

The wind tunnel test on the spire checked the structure for any resonant or ‘galloping’ effects from wind gusts. It also showed that despite being 300m above ground level, the average wind load on the shards is 1.5kN/m², with peaks around the edges of 2.25kN/m². The biggest challenge in designing the spire was to ensure that it could be built safely and quickly at height. In order to achieve this, the entire structure was split into modules that conformed to two constraints. Firstly, each module weighed less than 8t (the lifting capacity of the crane) and secondly, it was small enough to be brought to London from Yorkshire without police escort.

Each module was designed to be pre-fabricated in steelwork subcontractor Severfield Reeve’s factory and to be self-stable so it could be lifted without temporary bracing. Edge beams were fabricated channels, so that when one module was bolted to its neighbour, the appearance was of an I-beam. Building the spire in modules rather than ‘piece-small’ minimised both the number of crane lifts and the number of connections to be made in situ, at extreme height. The whole spire was modelled using Tekla 3D software, and the model was used to illustrate site method statements as well as to produce fabrication drawings. A trial

“The architect’s vision is achieved by gradually reducing the density of the structure”
assembly was carried out in three 20m lifts at the fabricator’s works. This process allowed the final assembly to be refined, with great benefits for speed and safety of site construction (Figure 21). In order to build the spire, a novel crane strategy was employed. Using the crane mounted on the core, a tower crane was erected on a bracket attached to the perimeter columns at level 54 of the building. The crane was stabilised using struts tied to the core at level 72. This crane was used to dismantle the crane on the core and to lift in the steel modules and façade panels (Figure 22). The sequencing and logistics around demounting the cranes was even more complex. After the spire structure was complete, the tower crane installed a recovery crane at level 72. The tower crane contained hydraulic legs, enabling it to dismantle itself to a large extent. The recovery crane at level 72 then removed the remainder of the tower crane. A small ‘spider crane’ removed the recovery crane, before it was itself dismantled and taken to ground level using the goods lift.

Considering that 70% of crane time was lost due to inclement weather and that there were significant risks in working at this height, the modular system was a remarkably efficient and safe way of assembling the UK’s highest pieces of steel and glass.

**Fire**

WSP was appointed to provide structural fire engineering services, to ensure that the passive fire protection of the structure was cost-effective. Fire is a significant safety issue in any building but especially so in tall towers. As buildings get taller it takes longer for occupants to escape and it also becomes more difficult for fire fighters to tackle any fire. One of the main functional requirements of the Building Regulations is that the structure remains stable for a reasonable period, so that occupants can escape the building and emergency services can extinguish the blaze in relative safety. A prescriptive method, based on a standard fire and tests carried out on isolated structural elements, is often adopted. However, this is inefficient and so the issue was addressed through the adoption of a performance-based approach to determine the fire resistance requirements of each element of the structure.

A number of scenarios were considered, covering a range of localised and more widespread fires. These included:

- Fire resistance ratings for the external columns at the bottom of the structure were determined using external flaming calculations to BS EN 1991-1-2
- Internal columns were protected using fire board. Due to their critical nature, a prescriptive approach was used for these elements
- Computer models of the steel floors covered the entire structure over a number of levels. These were used to determine the behaviour of the floor plates in a fire, and typically allowed secondary beams to remain unprotected. Primary beams, non-composite beams and beams providing restraint to columns, were protected using intumescent paint
- Fire resistance ratings for the transfer structures over the backpack/tower interface were determined from the effects of severe and highly localised fires. It was important to limit the temperature of the transfer structures during any fire
- A qualitative assessment was made of the likely performance in
The different structural fire engineering approaches ensured that the functional requirements of the regulations were not only met but often exceeded. Significant savings in structural fire protection costs were made.

**Façades, lifts and MEP**

**Façade**

The façade of the building was recognised as its most distinctive feature. The architect desired a very clear (or ‘white’) appearance, without the common green tinge that is often seen — and so a low-iron glass was specified. Triple-glazed panels were produced, with a single skin on the outside and a sealed double-glazed unit inside. The shards were extended beyond the edges of the floor plates as ‘wing walls’, providing additional visual definition to the separate façade planes.

The outer cavity is 300mm wide and is ventilated at each floor level. When the air in the cavity is heated by the sun, it rises and exits through the vent at the top of the panel, drawing cool air in at the bottom (Figure 23). In addition, the cavity contains a roller blind, operated by the building management system (BMS), to further reduce solar gain. Users of the Shard can lift a blind to see the view, but after a short time the BMS lowers it again.

The office floors each contain three ‘winter gardens,’ separated by glazed panels from the rest of the office, with special ceilings incorporating exposed structure. It is possible to open the outer façade slightly in the winter gardens in order to admit fresh
“From the outside, the Shard appears to have an uninterrupted taper from base to tip”

air, although the opening mechanism is connected to the BMS. If the temperature is too low, or the wind speed is too high, the window cannot be opened.

The double-glazed units can be opened to clean the outer cavity, and to maintain the blinds. Due to the façade sloping at about 6° to the vertical, the glazing can only be opened a short way and special three-legged stepladders are provided for maintenance.

External cleaning is carried out from building maintenance units (BMUs). Eight are provided at level 29, four more at level 75 and one at level 87 – the highest floor in the building. The highest BMU is similar to a crane, and has a jib long enough to lift material from street level (although in normal circumstances the goods lifts would be used). The BMUs have arms with multiple joints, allowing them to reach all parts of the façade and, when they are not in use, to be stored in compact garages.

Façade panel replacement is carried out from inside the building, using the same manipulator that was used in the original construction. A small number of panels, such as those in the wing walls, are replaced from the outside using the BMUs.

Lifts

Most of the Shard’s vertical transportation is carried out by double-decker lifts in the main core. People wishing to reach an even-numbered office floor travel in the bottom part of the lift car, while those wanting to reach an odd-numbered floor travel in the top. Similarly, visitors to the restaurants share a double-decker lift with viewing gallery guests.

The lift arrangement is optimised in order to reduce the size of the core while still taking people to the correct floors as rapidly as possible. This optimisation is the reason that a visit to the viewing gallery involves a change of lift at level 34: the lower lift is in a part of the core that stops part way up the building. Efficiency is also gained by using the same shaft for different lifts at different levels.

Unusually, the lifts are used for escape in fires. The shafts and the power supplies are protected and the lifts operate in a special evacuation mode. Occupants walk down the
stairs to pre-determined muster levels, from where the lift conveys them to ground level without stopping. This approach, agreed with the Building Control authorities, was deemed to be safer than requiring everyone to walk down the stairs – although this method of escape is also possible.

**MEP**

The Shard contains plant rooms in the basement, at levels 29-30 and at levels 66-67. There are external plant areas on the roof of the backpack, and a small amount of plant in the spire. Risers are accommodated outside the core, in order to avoid multiple penetrations through core walls, and to provide good maintenance access to the services.

In order to achieve maximum efficiency, combined heating, cooling and power plants are used. The basement also contains a mechanical car stacker, providing space for 48 cars. The building achieved a BREEAM 'excellent' rating.

**Public realm and station**

Planning permission for the Shard required a number of section 106 works to be carried out. These included improvements to St Thomas Street and other highways near the building, and major improvement works to London Bridge station. The station had last been renovated in the 1970s, at which time the concourse was provided with a space frame roof incorporating pyramidal glass rooflights. Although the roof structure was advanced for its time – it was analysed by computer, with a high degree of optimisation of member sizes – by the late 1990s it was showing its age. The concourse was small and gloomy and the view of the trains was blocked by retail units.

The Shard team designed a new glazed roof and entrance façade for the station concourse. Retail units are now in the Shard, the trains are visible from the concourse and the overall effect is much lighter, more spacious and inviting (Figure 24).

The roof comprises a grillage of steel box-section beams, joined using fully-welded connections in order to achieve the robustness required by Network Rail. The webs of the sections are extended below the lower flange, in order to echo the shape of the Shard columns. Purlins, comprising pairs of steel flats, span between the main beams and support the glass.

The roof is supported on its southern edge by, and gains its lateral stability from, the Shard. Additional vertical support is provided by circular section steel columns. Most of these are founded on the masonry walls that support the arches below the concourse.

Transfer beams under the finishes ensure that the arches themselves are not loaded by the columns. The remaining columns pass through openings in the arches to foundations at ground level. Further improvements are planned as part of Network Rail's London Bridge Station Redevelopment.

**Conclusion**

The Shard is one of London’s most ambitious and distinctive buildings (Figure 25). A decade of planning, design and execution overcame many design and engineering challenges without compromising the client’s and architects’ vision, and succeeded in difficult economic times. This is testament to the strong relationships between team members which resulted in an efficient and sustainable structure, with maximum floor area, sensitive and exciting public spaces and proud and satisfied stakeholders.

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**Project focus**

The Shard

**References**

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**Client**

Sellar Property on behalf of LBQ Ltd

**Architect**

Renzo Piano Building Workshop with Adamson Associates

**Building services engineers**

Arup

**Main contractor**

Mace

**Steelwork subcontractor**

Severfield Reeve

**Concrete subcontractor**

Byrne Brothers

**Piling subcontractor**

Stent Foundations

**Glazing subcontractor**

Scheldebouw