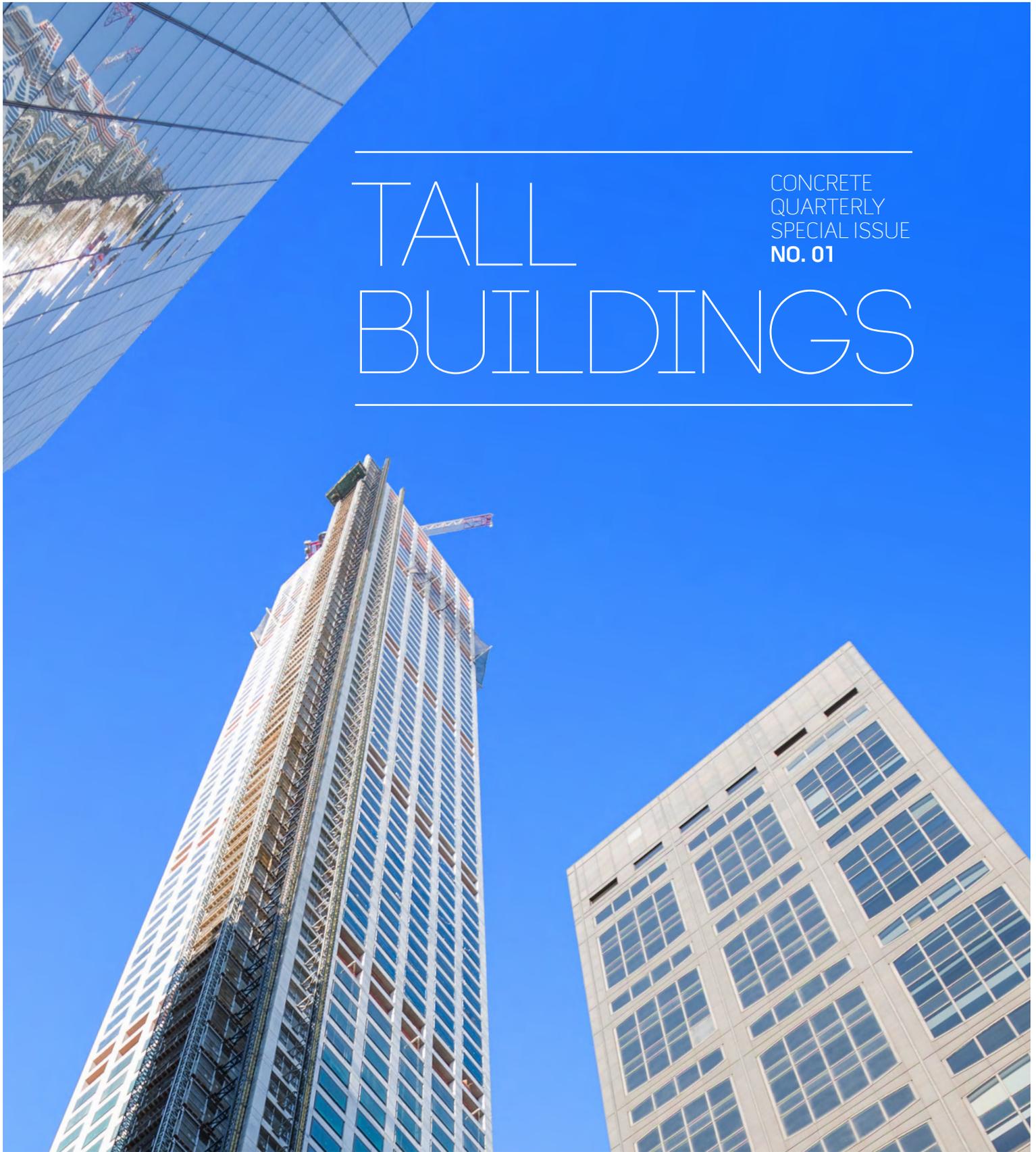


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# TALL BUILDINGS

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CONCRETE  
QUARTERLY  
SPECIAL ISSUE  
**NO. 01**



#### **MIGHTY MANHATTAN**

The stories behind two of the concrete giants redrawing the world's most famous skyline

#### **AS GOOD AS ITS WORD**

On site at Lexicon, the slender residential tower in the vanguard of London's high-rise revolution

#### **LOFTY AMBITIONS**

Expert guidance on the design strategies enabling ever higher, more sophisticated structures



NOW: AUTUMN 2015

## Concrete towers on the rise across London

Hundreds of concrete-framed towers are set to be added to the London skyline, as a high-rise residential boom takes place across the capital.

The annual London Tall Buildings Survey carried out in March by New London Architecture and GL Hearn revealed that 263 buildings over 20 storeys are now planned for the city, up from 236 in 2014. Of these, 80% have a mainly residential use.

"Most towers in London, under construction and planned, are concrete," says Bill Price, an expert in high-rise structural engineering at WSP Parsons Brinckerhoff. "The reason is that most are residential and concrete is currently the optimal material. Most use post-tensioned flat slabs, which minimises the floor-to-floor height, enabling more storeys. Concrete tends to be economically advantageous while better addressing acoustic separation, which is particularly important for residential."

Among the towers in the pipeline are 68-storey South Quay Plaza (below left) in London Docklands, designed by Foster + Partners, which won planning

approval in April and would be the UK's tallest residential building at 220m. It is unlikely to hold the title for long; construction is intended to start on Squire and Partners' 239m City Pride Tower (below centre) in Shoreditch by the end of the year. And Chinese developer Greenland has unveiled revised designs by HOK for Hertsmere House at West India Quay, a 67-storey tower that would stand at 242m – higher than its neighbour One Canada Square. WSP Parsons Brinckerhoff is the structural engineer on all three projects.

The high-rise trend in London is also causing a surge in demand for high-performance concrete. For example, One Blackfriars (below right) – one of a string of towers planned for Blackfriars Road, south of the Thames – is using a self-compacting concrete mix specified at C80/95, supplied by Tarmac and designed with specialist high-performance admixtures from CHRYSO. The 165m-high residential tower, designed by SimpsonHaugh and Partners, is due for completion in 2018.



## Vertical forest and 1WTC fly high at tall buildings awards

A variety of concrete towers – including a "vertical forest" and the tallest building in the US – led the way at the 2015 Council on Tall Buildings and Urban Habitat (CTBUH) Awards.

Bosco Verticale (pictured), a pair of towers in Milan that are covered in more than 700 trees and 16,000 other plants won the Best Tall Building Europe category. The 80m and 122m residential buildings, designed by Stefano Boeri, support this vegetation on a series of dramatic cantilevered prestressed-concrete balconies.

The Best Tall Building Americas was awarded to One World Trade Centre (page 6), Skidmore, Owings & Merrill's 541m-high Manhattan landmark, while the Asia & Australasia category was won by CapitaGreen, a sustainable office tower by Toyo Ito. The tower is the first in Singapore to use the ultra-high-strength Supercrete and has plants covering 55% of the facade.

The 10 Year Award, which recognises tall buildings that have proven to be valuable to their communities over a period of time, was awarded to the Turning Torso in Malmö, Sweden (see below).



THEN: AUTUMN 2004

### THE TURNING TORSO TURNS HEADS

Europe's tallest residential building wins over the Swedes ...

Santiago Calatrava's Turning Torso initially divided local opinion in Malmö. Based on a sculpture that explored the human body in motion, the structure is made of nine offset concrete cubes, clad in white aluminium and glass. The Swedish city had never seen anything like this twisted 190m residential tower – and neither had the rest of Europe. But as it rose rapidly over the harbour thanks to a number of innovations in concrete construction, its 152 luxury apartments began pre-selling just as fast. The local reception turned to one of "astonished delight", CQ reported.

Achieving structural stability and nullifying sway were challenges in the exposed coastal location, and one of the keys was the incorporation of reinforced tensioned "masts" with an internal diameter of 6m. The wall thickness of the in-situ concrete core was an immense 2.5m at the base.

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## Buildings with backbone

Welcome to a special issue of Concrete Quarterly, published to coincide with a boom in concrete tower construction in cities around the world. Concrete is overwhelmingly the construction material of choice for tall buildings, chosen for its strength, mass and durability – qualities that are enabling skyscrapers to reach ever greater heights and achieve ever more impressive technical feats.

For residential towers, concrete is the obvious solution, not only for the structural stability and flexibility it gives to thinner forms but to provide the necessary fire and acoustic separation. Lexicon in London's thriving Tech City demonstrates one elegant solution to the challenge of building high-rise homes, maximising usable space from a very small footprint. Office buildings too benefit from concrete's efficiency: at 240 Blackfriars, a speculatively built BREEAM Excellent commercial building, the switch from a steel to a post-tensioned concrete frame enabled the addition of two extra floors within the same overall height.

To help building designers get to grips with these techniques and more, The Concrete Centre and Fédération Internationale du Béton (fib) have published a comprehensive technical guide to the structural design of concrete tall buildings. Some of the content is picked up in our technical article on page 14, but you can purchase the full guide from [www.concretecentre.com/bookshop](http://www.concretecentre.com/bookshop).

**Jenny Burridge**

Head of structural engineering, The Concrete Centre

CONCRETE IS ENABLING SKYSCRAPERS TO ACHIEVE EVER MORE IMPRESSIVE TECHNICAL FEATS

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## DON'T MISS AN ISSUE

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**Innovation is our chemistry**



On the cover:

432 Park Avenue  
by Rafael Viñoly  
Architects. Photo:  
CIM Group and  
Macklowe Properties



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This Concrete Quarterly special issue was edited by Wordmule and designed by Nick Watts Design  
[wordmule.co.uk](http://wordmule.co.uk)  
[nickwattsdesign.co.uk](http://nickwattsdesign.co.uk)

# KING OF TECH CITY

Lexicon, London's latest residential tower, rises from a very small footprint to 36 storeys. Andy Pearson finds out how the designers made it stack up

"The client wanted a landmark residential building that could appeal to people working in London's tech industry," says Martin Grinnell, associate director at architect Skidmore Owings & Merrill (SOM). He's talking about Lexicon, a 36-storey tower of 146 apartments that is under construction close to Silicon Roundabout in the heart of the capital's Tech City. SOM's response to the brief is a futuristic skyscraper with a rakish cut-off top and an unusual parallelogram-shaped footprint.

Behind its fully glazed facade, this striking, slender building features a concrete core, concrete floorplates and a series of rectangular concrete columns that ring the perimeter of the floorplates. "We were keen to use a concrete structure for the columns and floor slabs, partly because of our confidence in using the material going up to that height and also because concrete has an inherent advantage in providing fire and acoustic separation between apartments," Grinnell says.

The additional mass provided by the concrete structure was also a key factor in its selection. For a 120m-high building, Lexicon has a very small footprint, which made wind resistance a major design consideration. "Because it is so slender, the same considerations of adding mass that you'd have on a much taller building come into play."

The tower's sleek profile also made the location of the concrete lift and stair core critical to ensure both structural stability and the efficient layout of apartments. "We didn't want to have to make the core walls so thick that they would reduce the size of the apartments or to have to accommodate a supporting structure that would affect the flexibility of the apartments' layout."

Early in the design process, SOM worked with structural engineer WSP to establish the best arrangement for the core. "Normally on residential towers you use a central core to give the perimeter to the apartments for views and daylight but on





#### OPPOSITE

The slender tower is parallelogram-shaped with an angled top to allow for open terraces

#### LEFT

Following the construction of the core, a second rig was used to build the perimeter columns and floorplates

#### RIGHT

The core was constructed at a rate of 3m a day

#### PROJECT TEAM

**Developer** Mount Anvil and Affinity Sutton joint venture  
**Architect** Skidmore Owings & Merrill  
**Main contractor** Mount Anvil  
**Structural engineer** WSP

this scheme we realised the best way of getting sufficient stability was to use the whole width of the building," says Grinnell.

To fully exploit the compact footprint, the tower's slender core has been positioned next to its western facade. It is linked by the apartments' floorplates and floor-height solid concrete "outrigger walls" on levels seven, 17 and 27 to two large "blade" columns positioned close to the eastern facade. In this way, it uses the entire width of the building to stiffen the structure to resist bending from wind loads. "If we had kept the core in the centre of the building, we'd have needed to incorporate shear walls or some other stability mechanism connected to the sides of building, which would have been disruptive to the residential layout," says Grinnell. "Instead, we were able to hide the blade columns and outrigger walls within party walls to minimise their impact," says Grinnell.

In addition to the outriggers, further mass has been added to the top of the structure by increasing the thickness of the floor slab at level 34 from 200mm to 750mm – this is also used as the base for mounting the building's maintenance crane.

For concrete contractor AJ Morrisroe & Sons, the tower's innovative structural solution demanded an equally inventive approach to its construction. First the building's concrete core was constructed using a slip-form rig. "Slip-form was used because the compact floorplates meant there would have been very little room to place the core shuttering between concrete pours," says Antony Blair, project manager and slip-form specialist for Morrisroe.

However, because the slip-formed core was designed to work in conjunction with the outrigger

columns it was potentially unstable until the superstructure was built. As a consequence, during the core's construction the contractor had to install a temporary bracing system of props inside the core to stiffen the walls.

Chasing the slip-form rig skywards was a second rig. This was used to construct the ring of perimeter columns, the parallelogram-shaped floorplates and to install the staircase inside the core. To improve productivity the floorplates were constructed in two parts. One half of the floorplate was cast first, allowing shuttering for the columns and walls to be erected, while on the other half, the floorplate falsework and reinforcement were being installed prior to casting. This system helped ensure the rig climbed upwards at the rate of one floor every six days.

The slip-formed core finishes at level 32. However, above level 28 construction of the floorplates became more complicated because the diagonal slice through the top of the building had to be accommodated. Here the apartments have the luxury of an open terrace with views over London, while the penthouse even includes a 2.5-storey winter garden. "A lot of complicated structural moves needed to be incorporated into these top levels including local transfer structures and the construction of additional columns to ensure the loads could pass straight down the main columns," says Grinnell.

The steel-framed winter garden is the only major structural element not to have been constructed from concrete. But by that height, it's safe to say that Lexicon's ingeniously designed concrete skeleton has already done its job.



## Race to the top

To meet a challenging construction programme, Morrisroe worked with Hanson Concrete to design the concrete mix for the slip-form rig to enable it climb more than 3m a day. Concrete was placed in the slip-form's shuttering in layers 300mm high. The concrete had to attain sufficient strength before the rig could be climbed. As winter closed in, temperatures started to drop and the concrete mix had to be adjusted. "We tested five different mixes to ensure we could continue to construct the core at the rate of 3m a day – we couldn't afford to have the 35 people working in the slip-form rig sitting around waiting for the concrete to set as that would have pushed up costs," says Morrisroe's Antony Blair.

The concrete used in the floorplates also had to be adjusted to increase its early-age strength. The perimeter protection screen used to construct these elements here was heavy; too heavy in fact to be supported by a single floorplate. Props were installed between the four floors directly beneath the rig to help spread its weight over multiple floors. "It meant that the concrete slab on each of the floors had to have achieved sufficient strength to allow it to take the load," says Blair. "We had to revisit the concrete mix several times in order to increase its setting rate to achieve the desired early-age strength. In the end we were completing a floor every six days, which meant we came in ahead of programme by about two weeks."

**Even now, more than a decade on, it is still hard to put into perspective the events of 11 September 2001 and the collapse of the twin towers of the World Trade Center. The world continues to follow a different course as a result of that day, and certainly the design of skyscrapers will never be quite the same again.**

But time has at least allowed for forensic analysis to establish how and why the towers collapsed, and for structural engineers the world over to consider how best to prevent a repeat of such a catastrophe. So when it came to constructing One World Trade Center, the design sprang not only from a terrible awareness of what could go wrong, but also from new knowledge and an implacable determination that design safety would not be found wanting. As Eduardo del Valle, design consultant for developer the New York Port Authority, puts it: "It may not be the tallest building in the world – but it is certainly the safest."

Not that 1WTC is small. While it may be dwarfed by the world-beating 830m Burj Khalifa in Dubai, it is at 541m (including mast) the tallest building in the US. Even without the mast, its 104 storeys, rising to 417m, would tower high above the tip of London's 306m Shard. All told they provide some 280,000m<sup>2</sup> of accommodation including 71 floors of office space, eight levels of services, a 15m-high lobby, a two-level observation deck, retail space and quite a bit more.

Square at the base, the building's corners taper until the floorplan becomes octagonal halfway up. This tapering continues until the floorplan is again square at the top, but now rotated 45° from the base. The eight elongated triangles of shining glass formed by this artful twist soar skywards with a kind of crystalline beauty – so that even in this city of skyscrapers, 1WTC stands out from the crowd.

Unsurprisingly perhaps, the structure is very different from those of the twin towers, which relied on external steel columns to create a structural "tube". In contrast, 1WTC's structure is unashamedly hybrid. A massive and super-strong concrete core rises all the way to the uppermost floors, and this is linked to a steel perimeter frame via steel beams spanning up to 14.3m to give column-free office space between core and facades. The immense strength of 1WTC's core means that the building is not reliant on its perimeter steel to anything like the same extent.

The tower does not rise from the exact site of the original buildings (the positions of which are now memorial gardens) but from a 62m<sup>2</sup> footprint nearby. It does, however, make use of the concrete groundworks that stabilised the site.

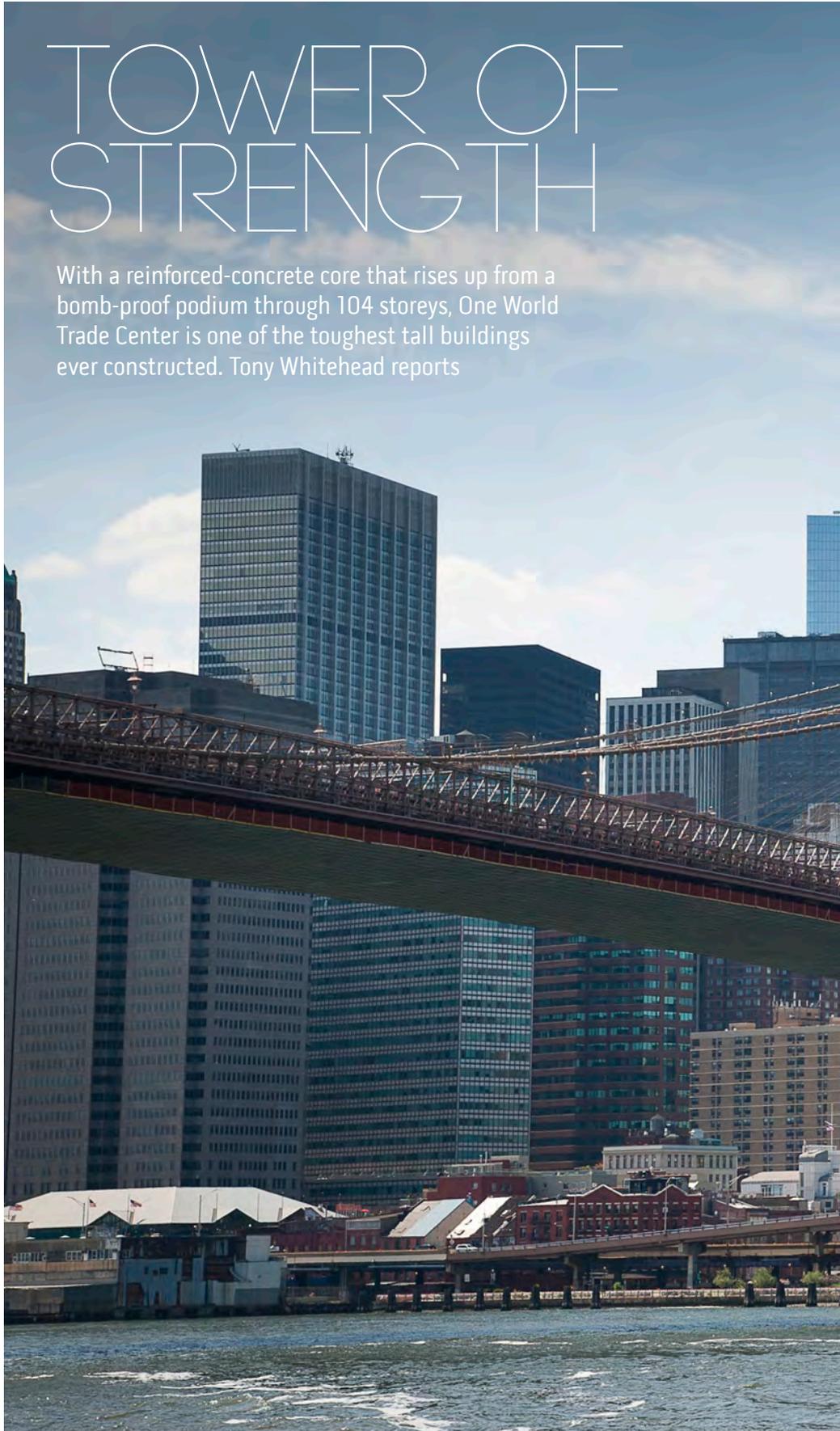
Notably these include a huge slurry wall which, together with a ground slab, protects the whole

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**UNUSUALLY, THE TOWER'S CURTAIN WALLING DOES NOT REACH GROUND LEVEL, OR EVEN CLOSE – RATHER IT SITS ATOP A 58M-HIGH CONCRETE PODIUM**

# TOWER OF STRENGTH

With a reinforced-concrete core that rises up from a bomb-proof podium through 104 storeys, One World Trade Center is one of the toughest tall buildings ever constructed. Tony Whitehead reports







area from the pressure of wet ground around the Hudson river. This had been formed by excavating a trench all around the site and then filling it with clay slurry to prevent it from collapsing under pressure from the surrounding ground. Reinforcement was then lowered in and the slurry displaced by pours of concrete.

Before work on the new tower began, this wall was reinforced by the addition of an adjacent concrete liner wall directly supporting the diaphragm slabs of the new building's subterranean levels. In this way, 1WTC's foundations laterally brace the slurry wall, creating a stable base from which to build.

As you might expect of such a tall building, the below-ground concrete is substantial. Long-span, deep, flat concrete slab construction up to 90cm thick is supported by composite beams, columns and supporting walls up to 1.8m thick. As well as bearing the weight of the tower above, this bulk also guards against the effects of a bomb like the one that exploded in the World Trade Center's underground parking area in 1993.

Unusually, the tower's curtain walling does not reach ground level, or even close – rather it sits atop a 58m-high concrete podium constructed from a lattice of steel column supports and thick reinforced concrete designed to defend the building from the blast of a street-level bomb. Within this podium is the building's lofty entrance plaza and four floors of plant and equipment.

Rising from the centre of the lobby is the core. Roughly square in plan and up to 33.5m wide at its base, it is this which provides the building's spine – its prime support for gravitational loads as well as its resistance to wind, seismic events and, of course, impact. It also contains all means of egress including heavily protected stairwells surrounded by 1m-thick concrete walls.

The core is formed from in-situ reinforced concrete and its structure is compartmentalised with internal supporting walls running in orthogonal directions. Over the access openings, walls are connected to each other using wide-flange steel link beams set into the concrete.

Below ground level and in the lower storeys the core is constructed using a specially developed 100MPa mix (see box, opposite), and had it not been for this the core's walls would have needed to be even thicker to achieve the required level of support for the building above. Even with the super-strong mix, the amount of reinforcement used in the core is impressive: below ground this amounts to 295 tonnes of reinforcement per 4m lift, and 218 tonnes per lift up to the 20th floor.

Within the concrete core zone, the floor system is an in-situ concrete beam and flat slab construction while the floor area outside the core is concrete on composite metal deck supported on steel beams and connected via shear connectors.

**LEFT**

The tower rests on a 58m-high concrete podium to protect against a street-level bomb

**OPPOSITE PAGE, TOP RIGHT**

In the lower storeys of the core, a super-strength 100MPa concrete mix is used

Both beams and the underside of the metal decking have been sprayed with a thick layer of concrete as fire protection.

With many concrete core buildings, the core rises ahead of other construction – the Shard being a case in point. But in New York they do things differently, apparently the result of the hybrid design, union rules and a certain amount of tradition. This means that a steel frame is erected throughout the whole floor, preceding the concrete core construction. The steel within the core area is primarily an erection system that becomes embedded in the concrete walls.

The core structure was constructed in four stages: steel framing, followed by metal deck and concrete outside the core, concrete core walls and concrete floor construction inside the core. A wide-flange ring beam was introduced at the outer face of the core in order to maintain a temporary gap between the floor system and the core wall, allowing for the raising of the forms. This system allowed the tower to rise by one floor every week.

By the time the 104th floor topped out, the superstructure had consumed 160,000m<sup>3</sup> of concrete. Hat trusses project in four directions from the top of the core to allow the perimeter steel to further benefit from the strength of the concrete spine.

Taking pride of place on New York's famous skyline, the completed tower represents the beacon of defiance and resilience it was always planned to be. Not the world's tallest, but thanks to all that concrete, quite probably the safest.

**This article first appeared in CQ 249, autumn 2014.**

#### PROJECT TEAM

**Architect** Skidmore, Owings & Merrill

**Structural engineer** WSP

**Contractor** Tishman Construction

**Concrete contractor** Collavino

Construction Co

**Concrete supplier** Eastern Concrete

Materials



Photos: Joe Woolhead, Nicola Evans

## One World Trade Center's remarkable recipe

The deployment of a massive concrete core to underwrite the structural safety of 1WTC demanded a lot of the concrete involved.

First and foremost, it had to be very strong: the 14,000psi mix used is equivalent to 100MPa. Dr Ahmad Rahimian, USA director of building structures with WSP, explains: "In any tall building, similar to the trunk of a tree, the requirement for structural strength increases at the lower floors relative to the upper levels due to accumulation of gravitational loads, as well as the effect of wind or seismic loads via the same concrete elements."

The 100MPa concrete mix – which 1WTC was the first building in New York to use on any scale – brought a number of advantages. The amount of material was reduced, making it an efficient use of resources, but also reducing the weight and gravitational load. Also, thicker concrete supporting walls were avoided, maximising the amount of lettable area in the building.

In addition to its huge strength, the designers wanted a low-carbon concrete mix that used less than 237kg of cement per m<sup>3</sup>. And it also had to remain workable for a two-hour window due to the time that it would spend in transport through New York and up to the tower's highest floors. This was potentially tricky, since high-strength concrete tends to cure faster than low-strength. In the event, however, the mix proved so workable that the concrete was pumped to the highest elevation to which concrete has ever been pumped in the Americas. What's more, this was accomplished with

a single pump that moved the concrete directly from the ground to the top storey.

There was also a strict requirement for controlling the heat of hydration. Rahimian says: "To reduce and slow this, industrial by-products such as slag and fly ash were used to replace more than 50% of the cement. This provided the additional benefit of lowering the carbon footprint and helping the project meet the anticipated LEED Gold standard."

Despite this, the sheer bulk of the concrete meant that temperature differentials across elements were potentially high, and could have caused cracking. To cope with this, some pours were performed in the cool of the night, and sometimes ice was added to the mix.

So what was the recipe that achieved such a remarkable combination of strength and workability? Per cubic metre, the 100MPa mix design included: 237kg of cement, 42kg of fly ash, 281kg of slag, BASF's Glenium high-range water-reducing admixtures, 19mm nominal aggregate, 3% air and a water/cement ratio of 0.3.

Mixes such as this could be game-changers in the design of tall buildings, according to Gary Graziano, vice president of sales and marketing for 1WTC's concrete supplier, Eastern Concrete Materials. "The future of high-rise construction will be high-strength, more durable, and more sustainable concrete. Only 15 years ago, 8,000psi concrete was considered high strength. Now most new projects have 10-14,000psi concrete as part of the design."



# A TALE OF TWO STOREYS

Andy Pearson reveals how AHMM and AKT2 increased their new London tower from 17 to 19 floors – without adding an inch to its height

**An 85m-high tower with a striking crystalline facade pierces the skyline just south of the Thames in Southwark. The faceted appearance of Allford Hall Monaghan Morris' 240 Blackfriars Road is designed to exploit views over the river to the City beyond, while reducing the tower's impact on its neighbours' access to daylight. But behind its glazed surface, a clever and highly efficient structural solution has played an equally important role in maximising values for developer Great Portland Estates.**

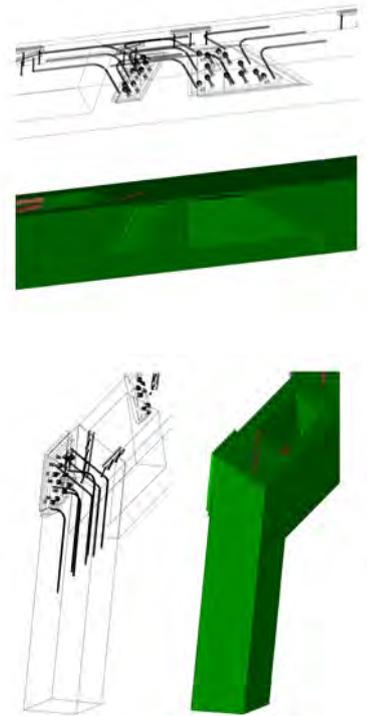
Concrete has been the key to making this new London landmark happen. The initial design was for a 12-storey, speculative office building supported on a conventional steel frame. That all changed, however, when a post-recession rethink by the developer prompted a request for an additional five storeys. AHMM and structural engineer AKT2 revisited the original structural proposition and found that, by replacing steel with a concrete-framed solution, they could do even better, adding a further two floors of offices. This increased the

total number to 19, without an increase in the tower's overall height.

The additional floors were made possible through the use of slender, 270mm-deep, post-tensioned concrete floor plates. "The building works harder because we can achieve the same 2.7m clear head-height with a minimum floor-slab thickness," says Haydn Thomas, associate at AHMM.

The parallelogram-shaped floor plates are supported on an in-situ concrete structural frame. This comprises a concrete core, positioned at the eastern edge of the floor plates, and a series of columns rising up through the building and around the rest of the perimeter. On the ground and first floors, where the base of the facade has been undercut on the north and west elevations, these perimeter columns are exposed as they rake outwards to overhang the pavement. "There is a lot of concrete that is not seen that is very efficient structurally," says Thomas. "Alongside that, we wanted to emphasise the beauty and simplicity of those bits of concrete that were exposed."

To ensure these 9m-high inclined columns achieved the "matt, paper-smooth" finish demanded by the architect, concrete contractor Byrne Bros cast each in a single pour. The size of the columns and the volume of concrete needed increased the hydrostatic pressures on



**FAR LEFT**

In-situ concrete columns flank the perimeter of the building

**LEFT**

The chamfered form is designed to maximise views across the Thames

**ABOVE**

The triple-height roof structure is formed from precast concrete beams

**ABOVE RIGHT**

A BIM model was used to work out the position of the fixings in the precast beams

**PROJECT TEAM**

**Architect** AHMM  
**Structural engineer** AKT2  
**Contractor** Mace  
**Concrete contractor** Byrne Bros

the formwork to such an extent that steel, rather than timber, had to be used. The inside face of the formwork was cleaned and shot-blasted to ensure the smooth finish. In addition, the contractor used self-compacting concrete, rather than risk having site operatives damage the surface using vibrating poker. The solution worked: "The quantity of concrete in the moulds was so great that it forced out every last bubble of air," says Thomas.

In addition to the columns, the floor plates are supported on an innovative, highly efficient, slip-formed concrete core structure at their eastern edge. Because this core is positioned off-centre, and since some of the facades are undercut at their base, the loads on it are uneven. However, rather than strengthen the core by increasing the amount of concrete and reinforcement in its walls, the engineers opted instead to pre-camber it, with the intention of making it lean away from the building. Then, as the office floors were added, their additional weight straightened the core little by little until it reached vertical with the completion of floor 19 – the slip-form core was jokingly referred to as "the banana" among the project team, says Thomas.

The core rises up from a basement structure that had been constructed well in advance of the superstructure works. The solution enabled any issues associated with the groundworks to be resolved without impacting the construction programme. It also allowed work on the superstructure to get underway quickly when the office market did eventually improve.

A laser point-cloud survey was carried out to check the accuracy of the basement before construction of the superstructure commenced; this also formed the basis of a BIM model of the building. BIM has

been used extensively on this project, and proved particularly useful for Byrne Bros when constructing its formwork: "They took the structural model and placed it inside their BIM formwork models to check there were no clashes," Thomas says.

BIM was also used to help precast the visual concrete elements on the triple-height top floor. The floor is topped by an inclined hybrid roof structure of exposed concrete and concealed steelwork. BIM enabled fixings for the steelwork and the cladding to be accurately positioned in the precast elements. "The structural gymnastics taking place inside the raking concrete roof beams is incredible, but the reality is that the concrete structure just looks effortless."

In addition to being structurally proficient, the fully glazed building also has impressive sustainability credentials. The original scheme was designed to achieve an Excellent rating under BREEAM 2008, but by the time the building was revisited, a more onerous version of the environmental assessment method had been published, requiring 25% lower emissions than Part L 2010. In addition to revamping the structure, the designers incorporated more efficient servicing, lighting and plant strategies to maintain the tower's Excellent rating under BREEAM 2011.

Thomas is pleased with the way the building's form and structure complement each other in a highly efficient, cost-effective solution. "We've ended up with something that has pure geometric forms for the columns; clean, flat, open floor plates; and a vertical core. That means the building not only works well now, but the legacy of this pure design is that it could easily be transformed for a different use in 20 or 30 years' time."

**This article first appeared in CQ 250, winter 2015.**



Photos: CIM Group and Macklowe Properties

# MANHATTAN SLIMLINE

Innovations in concrete frames have prompted a new wave of super-slim towers to rise over New York. Andy Pearson reports on the tallest yet

**432 Park Avenue is tall, very tall. In fact, at 425m, it is the third tallest building in the US and the tallest residential building, not just in New York but in the whole of the western hemisphere.**

Surprisingly, however, it is not the 96-storey building's height that is its most remarkable feature – what distinguishes 432 Park Avenue from most of Manhattan's skyscrapers is its slenderness. A tower is considered slender by New York's building codes when its ratio of height to its narrowest side is greater than 7:1. But this building is part of a new generation of super-slim towers currently rising over Manhattan, and has a footprint of just 28.5m in each direction, giving it a height-to-width ratio of 15:1, more than double the code definition.

Concrete is key to 432 Park Avenue, providing both structural strength and weight. "On slender and tall buildings, the weight of the structure is

very important," says Silvian Marcus, director of building structures at WSP Group, the structural engineer behind this and several other of Manhattan's super-slim towers. "You will never see a slender building with a steel structure – it will vibrate like a tuning fork because it doesn't have enough weight."

Crucially, concrete also allows the designers to maximise the floor area of the apartments and, ultimately, give developers CIM Group and Macklowe Properties the greatest return on their investment in this prime site. Addressing the unique structural challenges of slender towers without sacrificing sellable space is a key issue – particularly managing the building's response to the high winds circulating so far from the ground.

All tall buildings sway in the wind, but the height and slenderness of 432 Park Avenue increased the risk of excessive movement in the upper floors during relatively common wind events. The oscillation itself is not the problem – it's the change in speed that occupants will sense, just as passengers in a car feel its acceleration and deceleration. This is even less acceptable

for a residential building than for a commercial one, Marcus points out. "With an office, you can evacuate if there's a hurricane, but people have to feel safe in their homes regardless of the weather. It's impossible to stop the building moving but you can control the movement so the majority of people will not feel it."

To make the tower's structure stiff enough, WSP came up with an innovative structural solution based on two square concrete tubes placed on their ends, one inside the other. The smaller, inner tube is the building's 9m x 9m concrete core while the outer tube is formed by the tower's perimeter beam-and-column concrete frame. The two tubes are connected on every 12th floor to enable the entire structure to work as one. These stiffening beams are too big to be accommodated on the residential floors so they are in the plant rooms instead. "At each mechanical floor we have connections between the backbone and the outside tube," explains Marcus. The double-storey plant rooms play another key role to improve the building's aerodynamics – they are unglazed, allowing wind



#### ABOVE LEFT

432 Park Avenue is 425m tall and 28.5m wide, giving it a height-to-width ratio of 15:1

#### ABOVE

A CGI showing the tower's exposed concrete exterior. Insulation is placed on the interior face of the concrete, within the occupied space

#### PROJECT TEAM

**Architect** Rafael Viñoly Architects  
**Structural engineer** WSP Group  
**Contractor** Lend Lease  
**Concrete contractor** Rogers & Sons

## YOU WILL NEVER SEE A SLENDER BUILDING WITH A STEEL STRUCTURE – IT WILL VIBRATE LIKE A TUNING FORK BECAUSE IT DOESN'T HAVE ENOUGH WEIGHT

elevation to give residents those all-important views out. The frame structure also enabled the 250mm-thick concrete floor slabs spanning the 9.1m between the exterior and the tower's core to be constructed free from structural beams to give its occupants complete flexibility in how they configure their apartments.

With its 760mm-thick reinforced-concrete walls, the core is what Marcus refers to as "the building's backbone". Here, once again, the structural design has been developed to minimise the cross-sectional area and achieve the greatest possible floor area. Conventional floor-to-ceiling height for residential towers in New York is 12ft (3.7m), but at 432 Park Avenue it is 15ft 6in (4.7m). While the additional metre does add to the prestige of the apartments, more importantly it enabled the designers to add a second return to the core's access stairs to keep the core compact. "Adding a double loop to the stair gave us 250 square feet of additional space per floor," explains Marcus – a significant gain when multiplied over the tower's 89 floors.

Getting the concrete mix right was critical for the structure. The concrete needed to have a very high compressive strength of 16,100 pounds per square inch (111MPa); it also had to be white in colour to meet the demands of the architect. WSP considered using fly ash as a part-replacement for cement in the mixture but this addition would have coloured the concrete grey. In the end, the team replaced approximately half of the cement with metakaolin, a treated form of the clay mineral kaolinite, which increased the compressive strength of the concrete while lightening its colour. "We worked for almost a year to find the right mix," says Marcus.

The building's concrete structure was cast in-situ, the height of the building necessitating that the concrete be pumped upwards from the street. "If we'd have placed the concrete in a bucket and lifted it to the upper floors it would have set by the time we came to place it," Marcus points out, laughing.

With the structure complete, the engineers added more weight to the top of the building – 1,300 tonnes, in fact – to further limit the building's acceleration. This was in the form of two tuned mass dampers, located in the uppermost plant room on the 84th floor. Supported on diagonal springs, the concrete dampers work because their mass moves more slowly than the building sways, dampening its acceleration by 15%. "People want to feel they are living in a solid home, not in a boat," says Marcus. "Slender structures have such a small plan area, we had to mobilise everything possible to achieve that."

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## LOWDOWN New mixes for a new breed of towers



Tarmac recently commissioned a study to identify the savings that could be achieved in tall buildings through the specification of two high-performance concretes that both include specialised admixtures from CHRYSO. This was carried out at an elemental level, and for the overall build of the structural frame, applied to a real residential project. The mixes were Toproc Rapid high early strength concrete (HESC) and Topflow self-compacting concrete (SCC).

At an elemental level, the early strength gain of HESC led to programme savings by enabling quick rotation of formwork. Its high 28-day strength (typically 75MPa) also provided design savings by allowing reductions in wall and slab thickness, column size and/or reinforcement, while also increasing lettable floor area.

Topflow SCC can be placed in typically one-quarter of the time of a conventional mix, using one-third of the labour. In particular, this increases the speed of floor construction, resulting in significant programme and cost savings. These cost savings are shown below:

Element	Cost – Toproc Rapid HESC	Cost – Topflow SCC
Columns	-12.8%	+1.8%
Shear cores	-16.7%	+3.7%
RC slabs	-5.7%	-6.1%
PT slabs	-9.9%	n/a
Composite floors	n/a	-5.1%

Overall, the study found an 8.4% reduction in the construction cost of the building's structural frame. This was mainly due to lower material and labour costs when using Toproc Rapid HESC, and lower labour and plant costs when using Topflow SCC. Additional floor area also raised the sale price by £175,000. Other benefits included improved health and safety on site and reductions in truck movements and noise. Early engineering design including the ready-mix concrete supplier and admixture specialist has the potential to significantly save costs.

**TOP** World One in Mumbai, India, will be one of the world's tallest residential buildings at 442m. Its high-strength concrete superstructure uses admixtures from CHRYSO



# STRUCTURAL DESIGN OF TALL BUILDINGS

As towers continue to get higher, concrete plays an ever more vital role in their complex structural design. Gordon Clark and Andy Truby outline the key factors to consider

Building at height presents unique challenges both in terms of design and construction. For the structural engineer, the key factor is the relative magnitude of the lateral loadings (wind and seismic) when compared to the vertical loadings. The lateral loadings will almost certainly influence the size and strength of the structural elements.

The other issues that will influence the design of these structures include the requirements of the core, the distribution of services, the fire strategy, axial shortening and tolerances, and the dynamic behaviour of the building. There are also buildability factors to consider, such as floor construction time and hoisting of materials.

## Planning the core

The core of a tall building forms the spine for vertical transportation and services, but it is also probably the most fundamental structural element. There can be a wide choice of size and shape, dictated in part by the geometry of the building and the site. However the overriding factor is the lifts. It is essential that the lift strategy is well understood even at the early concept design stage. The number of lifts is primarily dictated by the occupancy of the building, which is in turn dictated by its use. Only once the number and size of the lifts has been established can the planning of the core begin.

The two key aspects of the core's structure are the strength of the concrete and the thickness of the walls. As buildings rise to extreme heights, the strength of concrete required at the base can be as high as C90/105, although for modest tall buildings a strength of around C50/60 is usually adequate.

Core walls will be sized to resist the applied loadings, and thicknesses can vary from 350mm to 600mm or more for buildings up to 200m tall. Such wall thicknesses can be unfamiliar to design

teams not used to working on tall buildings. It is therefore important for the structural engineer to make an early estimate of the wall thickness to allow the architectural planning to progress.

The core generally acts as a vertical cantilever taking both vertical and lateral loadings, with the outer columns supporting principally vertical loadings. When planning the core, the layout of columns should be configured so that the core supports a larger share of the vertical loading, as this helps to resist overturning from lateral loads. Spacing of columns away from the core should, therefore, ideally be maximised. The core may typically support about 60% of the vertical loading,

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STANDARDISATION OF ELEMENT DIMENSIONS AND EARLY-AGE STRENGTH GAIN OF THE CONCRETE MIX CAN HAVE A BIG INFLUENCE ON THE FLOOR-TO-FLOOR CYCLE TIME

**LEFT** The Shard at London Bridge, designed by Renzo Piano Workshop with WSP as structural engineer, is 310m tall and has a slip-formed core

with the columns supporting the remaining 40%. Figures 1 and 2 show a conventional core and one that uses mega columns.

### Fire considerations

Fire escape requirements must also be addressed early in the process. Key considerations include:

- Location, size and number of escape stairs
- Width and details for escape stairs
- Requirements for wet/dry risers
- Provision for firefighting lifts/shafts.

All of these factors have an impact on the space within the core and therefore must be given due consideration while planning the core layout.

### Wind and seismic effects

Where possible, the core should be placed close to the geometric wind centre or the seismic mass centre of the building, in both directions. Where this is not possible, the torsional or twisting loads on the core should be accurately determined and designed for. This can be particularly important for non-vertical or geometrically complex buildings.

For buildings over 250m, it is common to provide alternative structural stability systems such as bundled tubes, mega frames and outriggers. Such systems look to mobilise the full width of the building and use the perimeter columns to increase the restoring moments.

The lateral loads on tall buildings from both wind and seismic effects can be extreme and, combined with the vertical loads, govern the building's overturning moments. Factors such as topography and nearby buildings can cause significant localised increases in loads. Wind tunnel testing is often required to examine their effects.

One great advantage of concrete towers is that their inherent weight naturally enhances structural stability. This mass and the contiguous nature of the construction of concrete-framed towers also provide a greater degree of structural damping, dissipating cyclical sway from lateral forces.

### Flooring systems

Flooring systems are predominately either post-tensioned (PT) or reinforced-concrete flat slabs, or beam and slab. The use of precast or hybrid construction is becoming common because it enables shorter build programmes.

The use of PT slabs is often an advantage at height, as the reduction in slab thickness accumulated over many storeys can allow for an additional storey, thus providing greater occupancy and return on investment. Alternatively, reducing the overall height of the building can lead to significant cost savings in facade systems.

When designing the floors of a tall building, many skills from low-rise construction can be used. However, the floors may be required to resist very large lateral forces, which can require additional design load cases and further reinforcement details.

### Construction

It is important at the planning stage to consider buildability. Speed of construction is very important as clients want occupation to begin as quickly as possible to maximise return on investment. Standardisation of element dimensions and early-age strength gain of concrete can have a big influence on the floor-to-floor cycle. Cycle times of between five and seven days are typical for most tall buildings.

### Designing for movement

It is very important to consider tolerances and drift. A small deviation on each column can add up cumulatively to a major deviation. Lateral drift limitation would typically be about  $H/400$ , which for a 200m tower equates to 500mm. Differential shortening between columns and core walls should be considered as the permanent stresses in the core concrete are often less than those in the columns and this causes lateral movement.

It is usual for the cladding to follow the floor-by-floor construction upwards and the influence of shortening and changes in loading in the lower floors needs to be accommodated in the design of the facade systems. It is normal to install the facade from inside to avoid the need for external access systems but this requires careful specification and manufacture of the cladding.

The way that the building responds to wind also has to be considered as human perception of acceleration can cause discomfort, and damping should be examined. Current guidance recommends the acceleration limits of 10-15 milli-g



Photo: jufo87/Flickr

**ABOVE** At 180m, the Torre Cajasol in Seville is the tallest building in Andalusia. Completed earlier this year, its structure consists of a reinforced-concrete central core, 14 RC columns around the perimeter and RC slabs

for residential and 20-30 milli-g for offices.

Eccentric loading can be an added complexity. Some tall buildings are constructed out of plumb so that they straighten up when completed. However, predicting the effects of creep and shrinkage is difficult. The effect of time has been added as a key design criterion in the Model Code for Structural Concrete 2010 (see below).

### Holistic approach

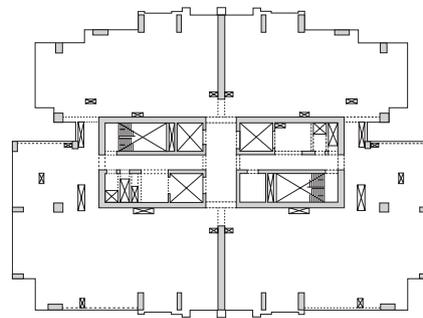
When setting out to design a tall building, it is clear that the structural engineer must work closely with the architect, the building services engineer and the lift, fire and facade specialists to establish the optimum solution. Tall buildings are monumental, and in many cases iconic, and their design needs the closest possible attention to ensure that they will serve our society in a sustainable way long into the future.

**Gordon Clark is president of fib and Andy Truby is chairman of fib Task Group 1.6 – Tall Buildings. This article first appeared in CQ 249, autumn 2014.**

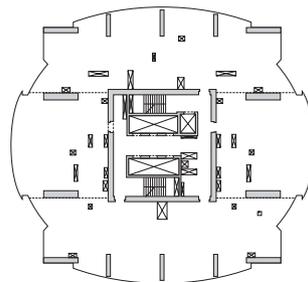
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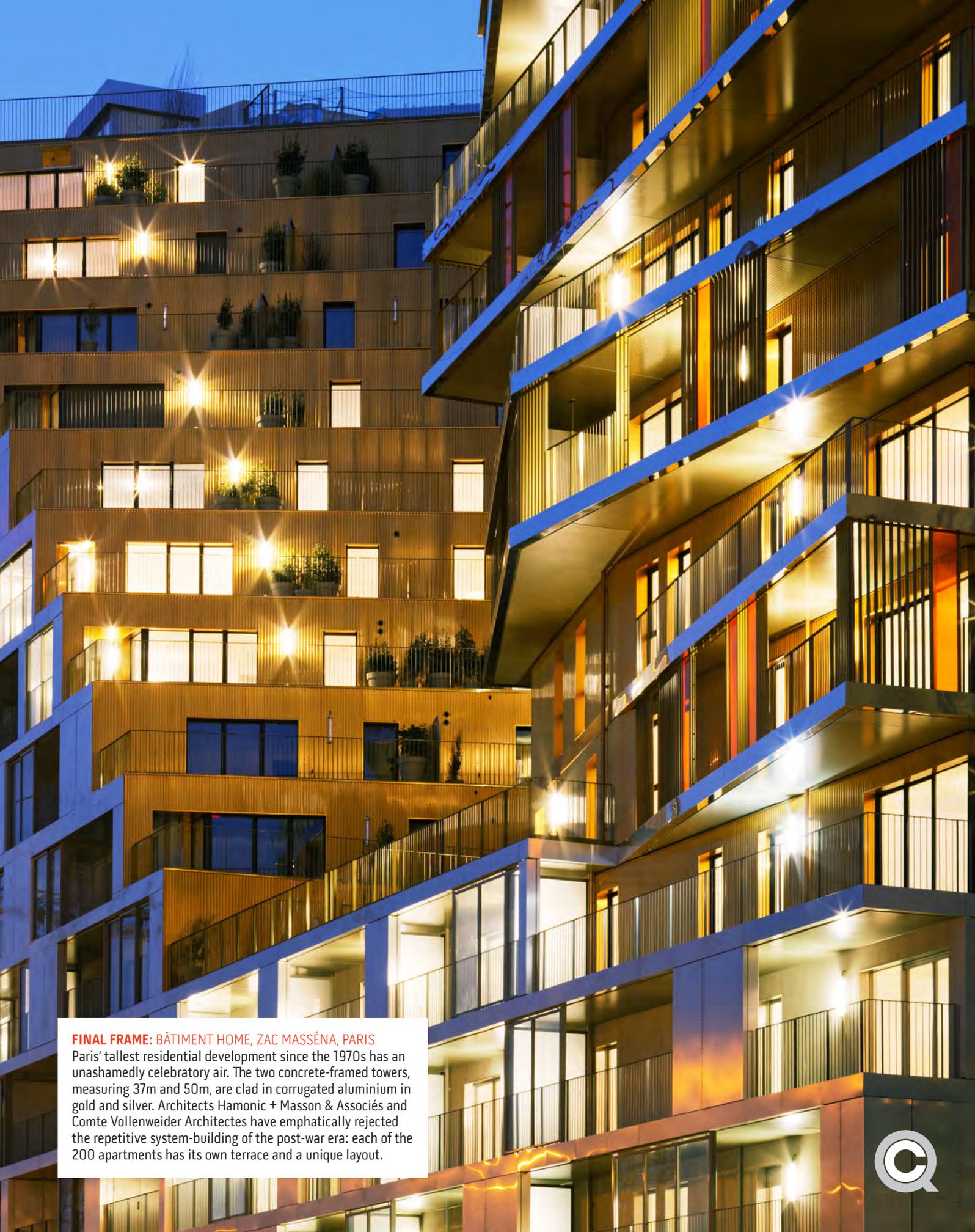
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**FIGURE 1:** PLAN OF A BUILDING WITH A CONVENTIONAL CORE, TYPICALLY USED IN BUILDINGS WITH UP TO 40 STOREYS



**FIGURE 2:** PLAN OF A BUILDING WITH MEGA COLUMNS, SUITABLE FOR BUILDINGS OF AROUND 50-60 STOREYS



**FINAL FRAME: BÂTIMENT HOME, ZAC MASSÉNA, PARIS**

Paris' tallest residential development since the 1970s has an unashamedly celebratory air. The two concrete-framed towers, measuring 37m and 50m, are clad in corrugated aluminium in gold and silver. Architects Hamonic + Masson & Associés and Comte Vollenweider Architectes have emphatically rejected the repetitive system-building of the post-war era: each of the 200 apartments has its own terrace and a unique layout.

