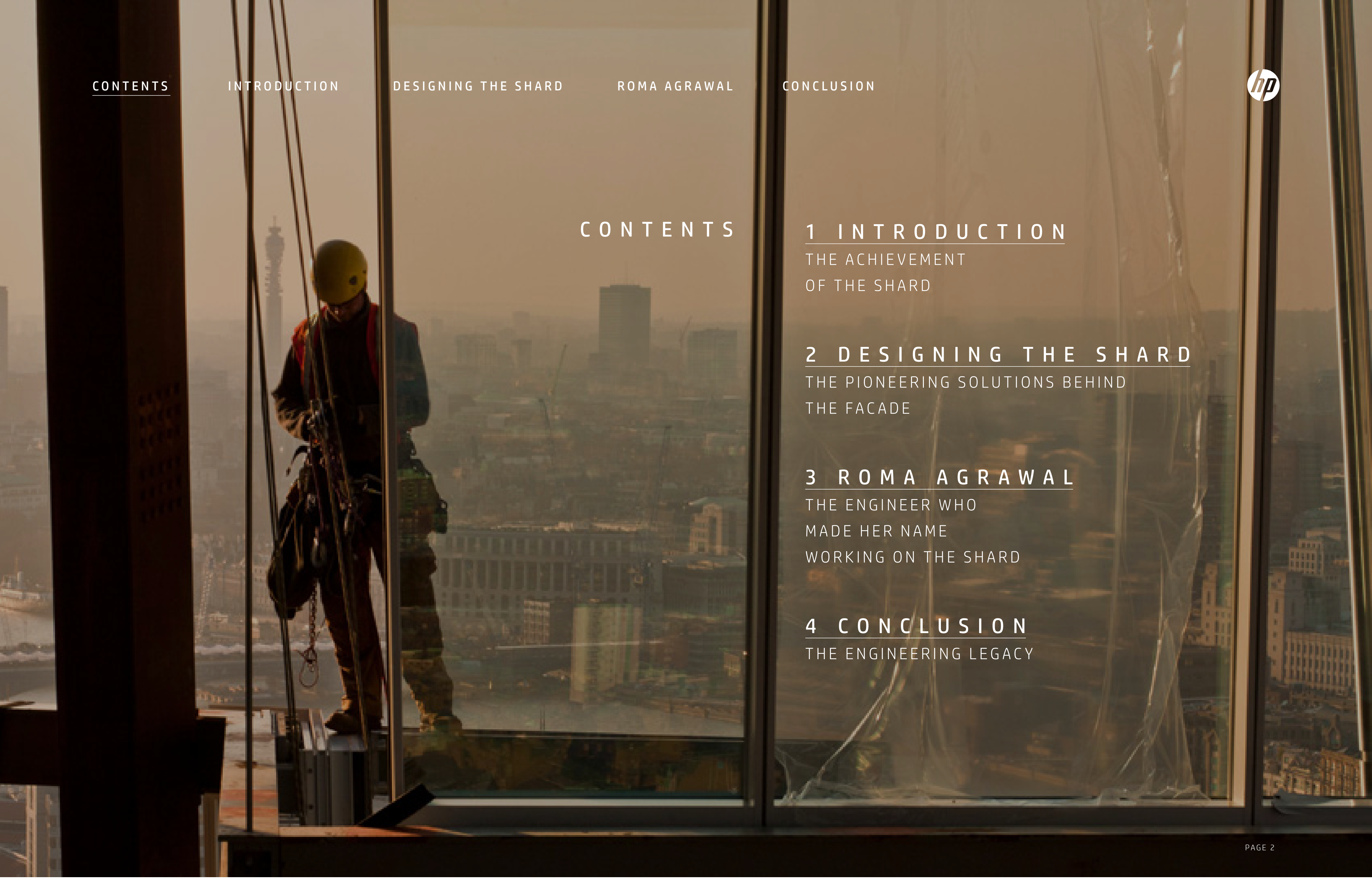
APEX OF DESIGN

With a new wave of high-rise buildings on the horizon, what can engineers learn from London's icon, **The Shard?**



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INTRODUCTION

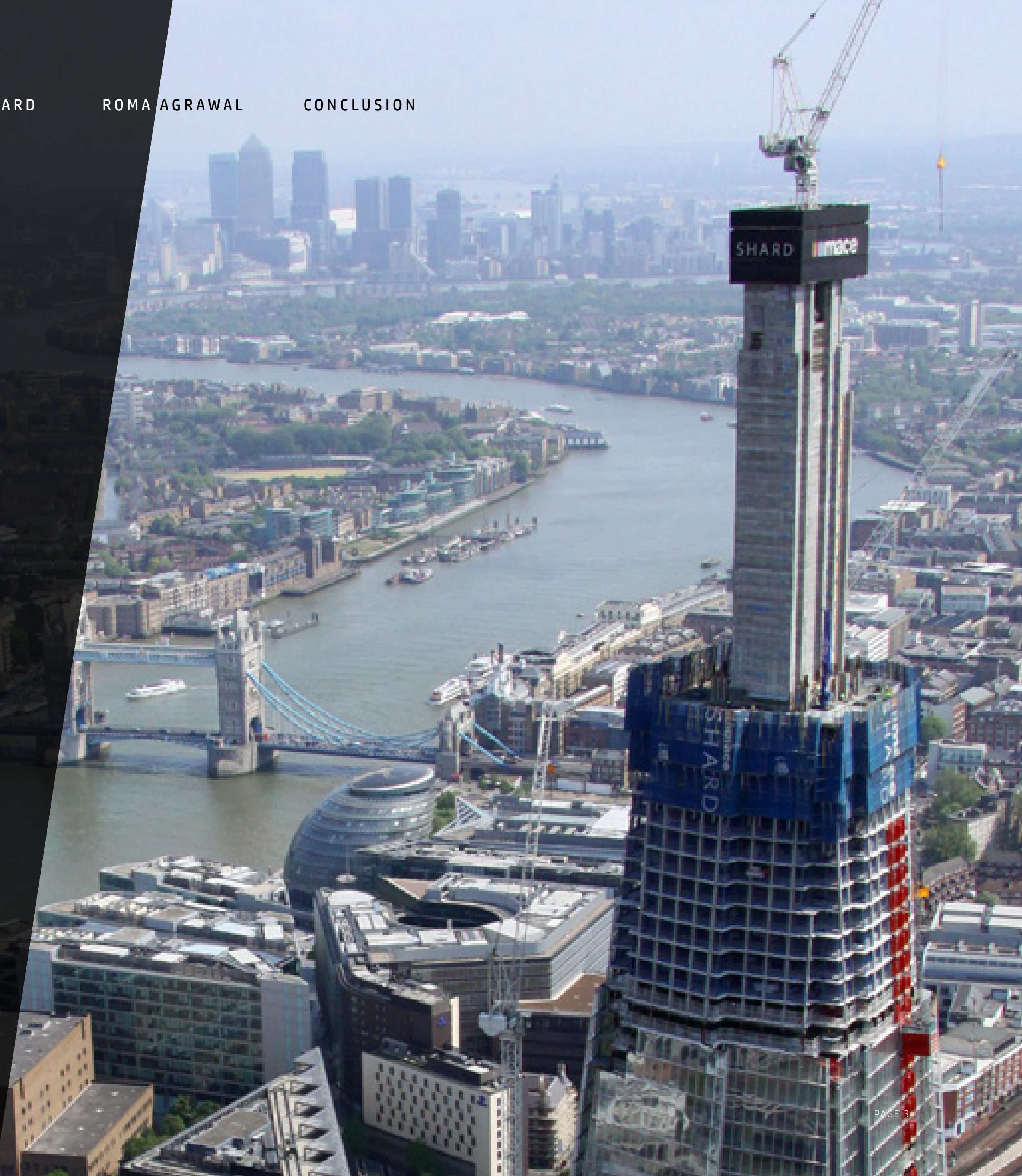
SKY'S THE LIMIT

Every major global capital boasts one stand-out high-rise icon – and in London, that building is undoubtedly The Shard.

Reaching from the banks of the Thames River to pierce the clouds 310m above, it is not just the tallest building in the city, but also the tallest in Western Europe. In the face of a catalogue of huge challenges, many said the 95-storey pyramidic tower would never be built. Yet, seven years on from its completion, The Shard continues to defy its critics, standing proudly as a globally recognised emblem for London, and a monument to what can be achieved when engineering innovation meets architectural vision.

The Shard's sleek glass façade hides a series of extraordinary engineering feats and technical design solutions that turned Renzo Piano's architectural vision into a reality.

It was designed to be a 'vertical city' – the first of a new generation of mixed use, high density super-tall tower that would have to be built on a constrained development space, without disrupting a major transport hub below. The story of how engineers from WSP pioneered solutions to overcome these hurdles is one that continues to shape the way engineers approach a new generation of high-rise design challenges around the world today.



DESIGNING THE SHARD

FUTURE ENGINEERING

Year of conception:
2000

Height:
309.6m

Year construction began:
2009

Workers during construction
1,450

Year of completion:
2012

Architect:
Renzo Piano

Total cost (approx):
£1.5bn

Structural engineer:
WSP

The logistical and technical engineering challenges posed by The Shard were both extremely complex and hugely time-consuming. It was a project of vast scale in every possible way.

Yet Renzo Piano's architectural early vision for the building's was reached remarkably quickly. It was conceived as a pen sketch on the back of a menu for Irvine Sellar, the developer and joint owner of the site, over lunch in a Berlin restaurant almost 20 years ago.

Sellar wanted to create a mixed-use development, a 'vertical city' featuring retail units, a hotel, offices and apartments – as well as restaurants and a viewing gallery for the public. To do this on such a constrained development site he would have to build tall.

While Piano was not initially keen on the prospect of designing a tower, he was attracted by the opportunity to create a 'vertical city' of mixed use in a place of vital interchange.

He drew a rough design inspired by historic London; "a giant sail emerging from the river"[1] with a steeple-like spire that tapered into the sky.

Turning that vision behind that sketch into a towering reality, would require next level innovation. More than this, it would need to solve problems in a way that considered the changing needs of a broad mix of occupiers.

"Obviously, it would need to be engineered in a way that met every possible need for the future," stated Sellar.[2] And that was no small task.

ANALYSIS AND MODELLING

BEATING THE ODDS

Perhaps the most eye-opening achievement of The Shard is that it was actually built at all. Even ignoring the context of the 2007/08 financial crisis and the planning hurdles, the odds were stacked against The Shard from the outset.

"I remember people saying to me, 'It'll never be built. No one's ever going to build it'"[3] recalls Ron Slade, design director at WSP, the firm that was selected to engineer The Shard.

The site that Sellar had acquired to build the Shard was directly above London Bridge station, one of the UK capital's busiest commuter hubs. The fact that the foundations had to contend with the force of the neighbouring River Thames and avoid interfering with underground train lines running beneath only added to engineers' headaches. Furthermore, The Shard's irregular pyramid meant complex geometry, a challenge made even more tricky due to the irregular shape of the development site. Every floor plate would be different, requiring extensive analysis and use of 3D modelling.

To put the scale of the project into context, it meant erecting a 300m+ building with a 500-tonne steel spire, more than 40 lifts and 11,000 glass panels, in a busy central London location and with a build programme of less than four years.

> *"IT'LL NEVER BE BUILT. NO ONE'S EVER GOING TO BUILD IT."*
>
> **RON SLADE**
> Design Director, WSP

TOP-DOWN CONSTRUCTION

PIONEERING DESIGN SOLUTIONS

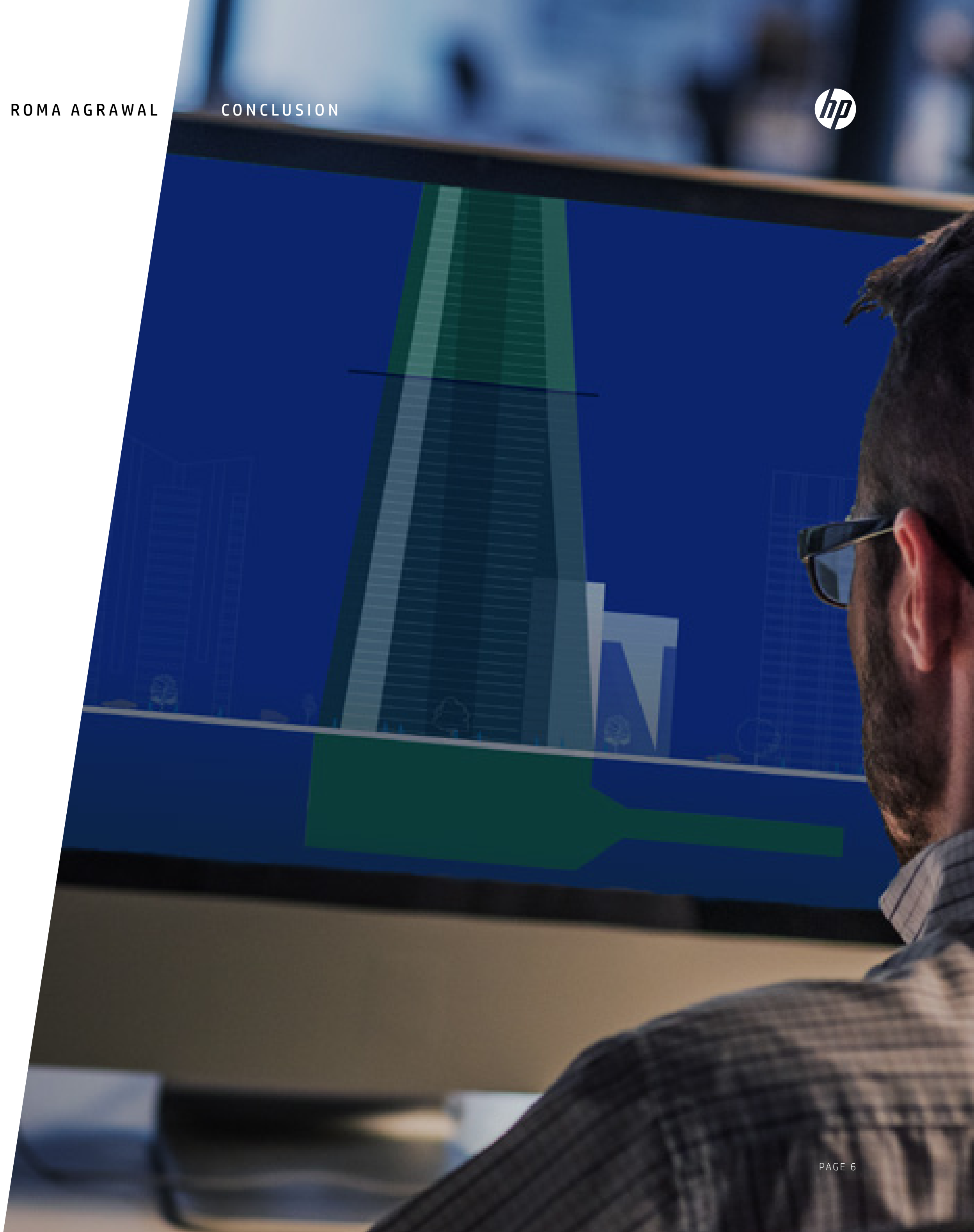
Pulling this off meant pushing new limits of design and engineering in tall buildings. The Shard's blueprint was configured to deliver Sellar's mixed-use vertical city plan, but also to improve the building dynamics and maximise the space and cost-effectiveness of construction on a constrained, complex site.

At the heart of the structural design was a massive concrete core to provide the lateral stability required to reach up into the city's sky. To accommodate this superstructure, engineers were faced with the critical challenge of approaching the substructure in a way that didn't interfere with the surrounding roads, utilities, tube lines and railway infrastructure.

But they also had to do it in a way that could fast-track an already ambitious completion date, ahead of the 2012 Olympics. The solution was to pioneer a top-down approach to constructing The Shard's huge core. This involved casting the ground floor slab and excavating the ground below at the same time as continuing work on the superstructure above.

This approach – a world first in such a tall building – saved more than three months of build time and kept the build cost below £450m.[4]

"It was a difficult thing to do, it had never been done before [with a structure as tall as the Shard]," says John Parker, Shard Technical Director at structural engineering firm WSP. "But now everybody seems to be doing it."[5]



SUSTAINABLE MATERIALS

CREATING THE SUB-STRUCTURE

A piled basement wall and other piles were installed first while steel 'plunge' columns were cast in the top 5m in strategic locations. The ground floor slab could then be cast across the piled wall and columns, leaving a gap from where excavation could proceed underneath. The plunge columns provided temporary support for the core and basement floors while underground expanses and internal structures were created.

Engineers designed the slab at basement-three level to be as thin as possible, for two key reasons. On the one hand it minimised the need for excavation, and on the other it avoided complications of having to make the secant pile walls deeper.[6]

The piled raft was 3m deep beneath the core and 1.5m deep elsewhere – a depth considered shallow for a building of The Shard's scale.

Teams were able to eliminate nearly 800 tonnes of carbon in the raft slab through use of ground granulated blast furnace slag as a substitute for 70% of the Portland cement. This reduced both absolute and differential temperatures during the curing of the concrete and minimised the risk of cracking.

By the time the substructure was complete, the superstructure had already reached 23 storeys.

SOLUTIONS BEHIND THE SHARD

REDUCING CONSTRUCTION TIME

The Shard used top-down construction – which enables building work to go down into the basement while also rising up from the ground – to shave three months of the total programme.

A TRANSPARENT, ENERGY-EFFICIENT FAÇADE

'Extra white' glass provides high levels of transparency while also reflecting sunlight and sky, giving the Shard's cladding a mirror-like quality. To limit solar gain, triple glazed units provided insulation and, combined with natural ventilation, reduced cooling energy.

SAFELY ERRECTING THE MODULAR SPIRE

The Shard's steelwork contractor trial-assembled the entire 22-storey 500-tonne steel-framed spire in two-storey prefabricated sections on an airfield in North Yorkshire first.

MANAGING THE SWAY

After dynamic analysis engineers identified alternative ways of counteracting sway by mobilising the heavy concrete floors and applying extra lateral stiffness on level 66 by using a truss to connect the central core with perimeter columns.

AVOIDING A WONKY SHARD

Structural analysis of the tower revealed how certain members needed to be offset during construction to ensure that they would be in the correct position in the finished building. Floors, for example, were built slightly off the horizontal.

WIND TUNNEL TESTING

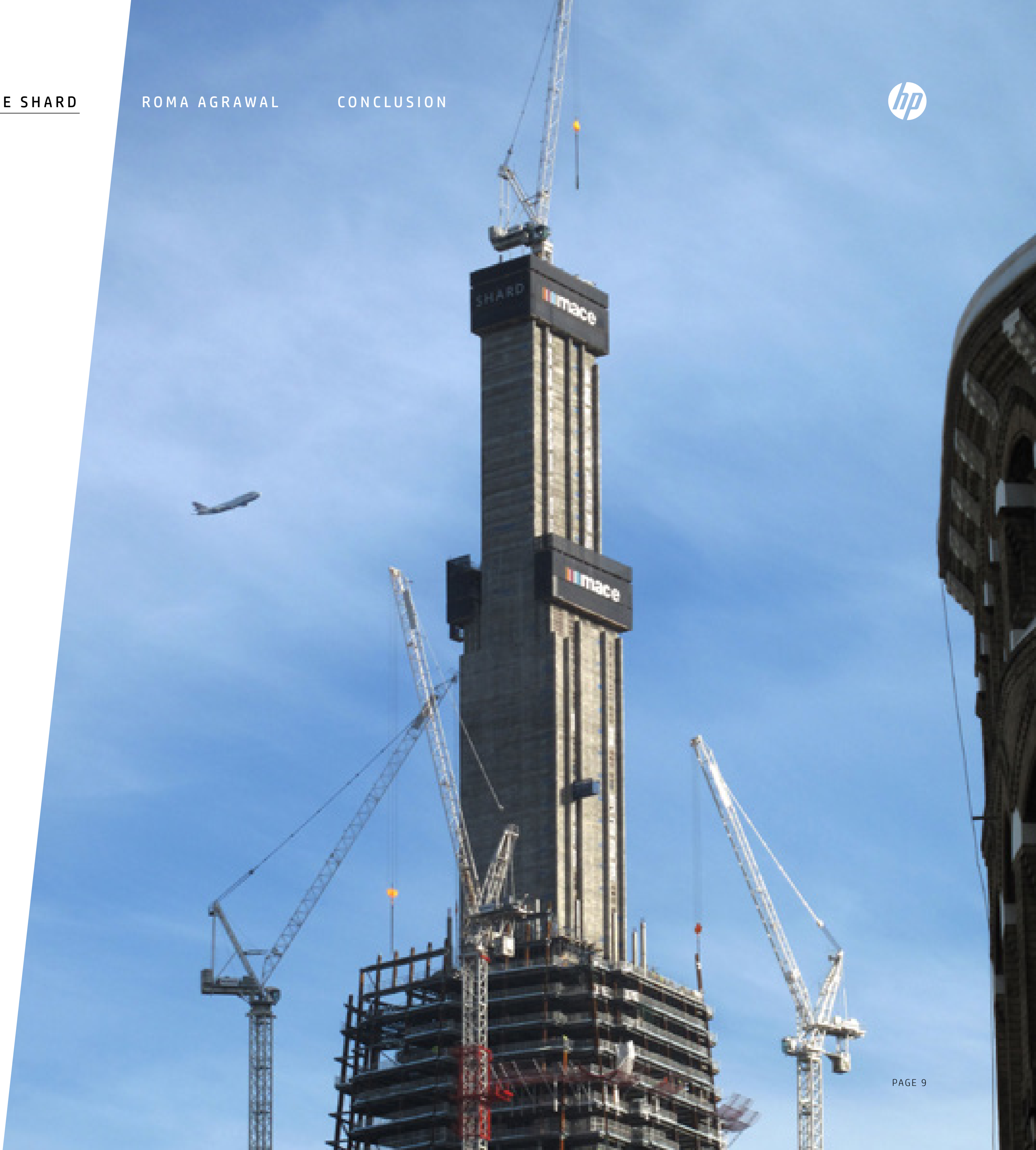
DESIGNING THE CORE

The Shard's core is its source of lateral stability for the whole structure, acting as a cantilever from level B3 to level 72.[7] Due to the height of the tower and the mixed uses specified by Sellar, WSP proposed 21 lift and stair shafts in the core at ground level.

As the height increased and the building starts to taper, the number of shafts was also reduced to maximise the amount of lettable space of the floor plates. At level 28, three levels of shaft wall were designed as a grillage to transfer stability forces while also releasing space in the core for amenities and lettable floor space.

To understand the lateral forces the core would face, wind tunnel testing was carried out. Using a rigid 1:400 scale model connected to a base by a system of springs, engineers were able to measure the forces at the base against 36 wind directions.

The core itself was built using the slipform method, whereby concrete could be poured almost continuously, while formwork slides up the building. This approach operated at a pace of 3m a day. In order to achieve accuracy of plus or minus 25mm in the position of the core, the construction contractors used GPS and laser guidance systems.[8]



A STEEL AND CONCRETE HYBRID

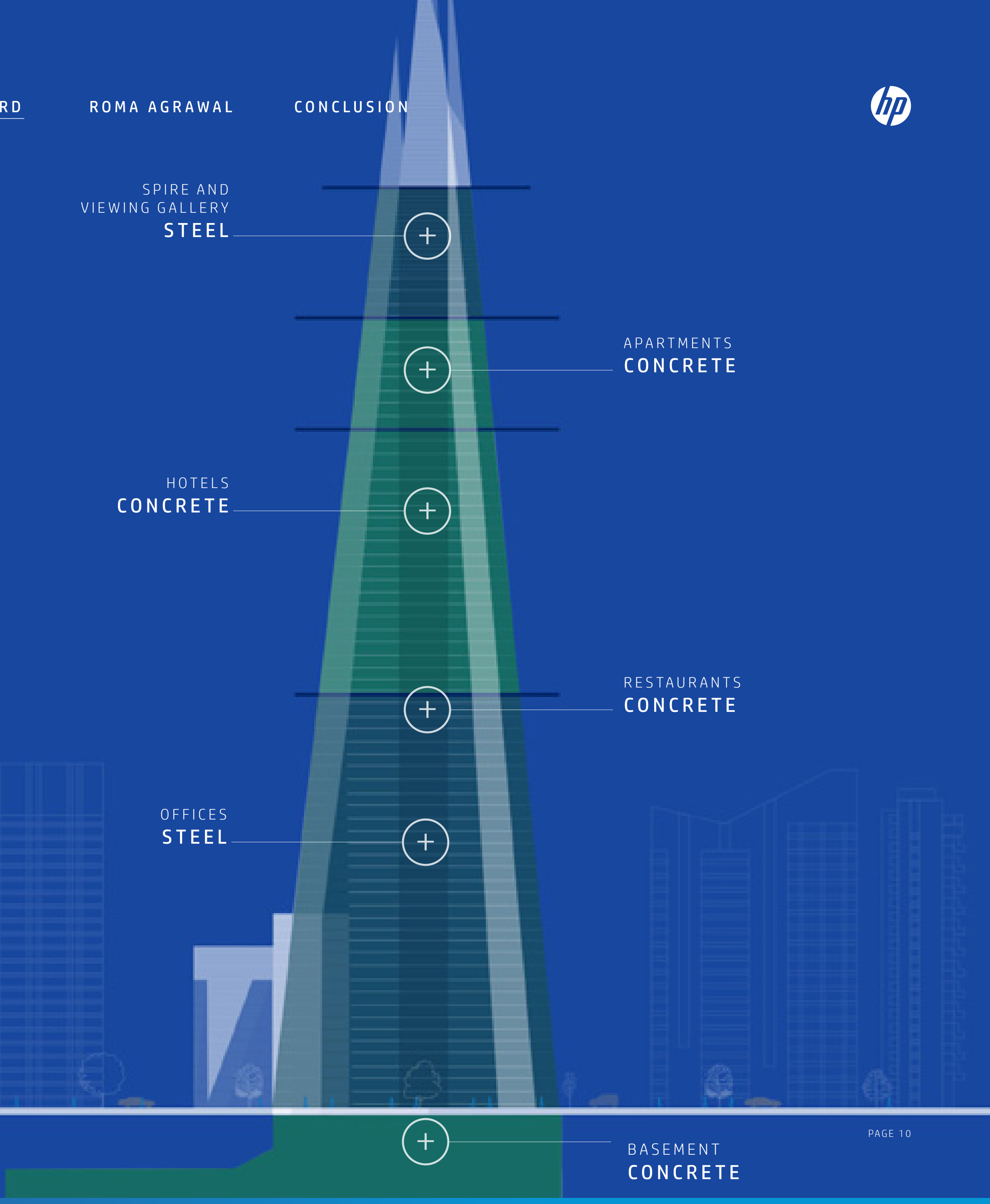
THE MATERIAL DIFFERENCE

To achieve Sellar's goal of having 900,000 square feet of lettable floor space, there was a need to consider nonconventional material choices. At the outset, Piano had intended the building to be entirely constructed using steel.

"We came along and value engineered it [The Shard design] and unusually brought in a hybrid structure," says WSP's Parker. The reason for this was that while office space required steel, hotels needed concrete. As a result, the tower alternates between steel to level 40, concrete to level 69, and is topped off by a 23-storey steel spire.

The decision to use concrete for the hotel floors and apartments meant that, by reducing the storey height from 3.75m to 3.1m, it was possible to squeeze in an extra two floors as fewer ceiling mounts were needed.[9] As well as creating valuable extra space in a part of The Shard that tapers to a maximum floor span of 9m as it gets higher, this also increased the occupation density within the confines of the height restrictions imposed on the building by the Civil Aviation Authority.[10]

The addition of concrete had additional structural benefits. "The concrete also gave us damping in the building – it absorbed energy as it moves in the wind,"[11] says Parker.



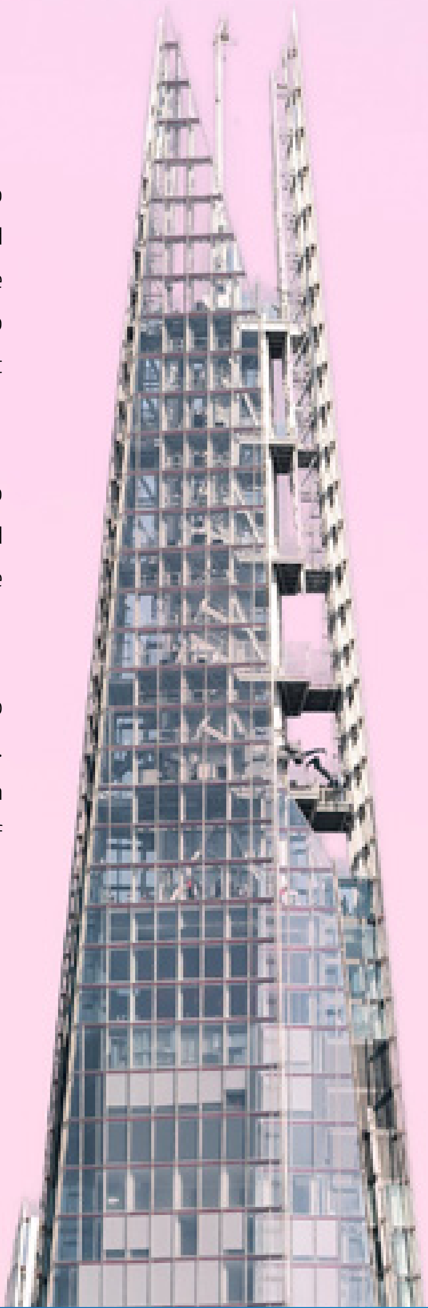
MODULAR SPIRE ASSEMBLY

PUSHING FOR THE SKY

At 310m high, The Shard would to contend with high-speed winds of up to 100mph. It therefore had to be designed to take into account sway – around 300-400mm at the top – in such a way that occupiers wouldn't notice the horizontal acceleration. While lateral movement was not a concern to WSP[12], the effects of horizontal acceleration would need to be limited to just 0.15m/s2.[13]

While the use of concrete helped counteract sway, more had to be done to increase the stiffness of the building and avoid the costly use of a tuned mass damper – an approach that would use valuable floorspace lettable space and add 600 tonnes of weight.[14]

After conducting dynamic analysis of the entire building, WSP decided to dampen the oscillations and increase stiffness with a hat truss at level 66. WSP engineers pulled this off with outrigger struts that rise diagonally from the perimeter columns to the central core, designed with the sole purpose of reducing the lateral acceleration.



The impractical logistics of the central London site posed additional challenges for erecting the spire safely.

The stakes were so high that steelwork contractor, Severfield-Reeve, did a dummy run of the operation at its Dalton Airfield site in North Yorkshire.[15] The spire had to be split into two-storey sections to make installation easier, with fewer bolted connections on site and more welding off site.[16]

Each floor was subdivided into cassettes that could be bolted together easily on-site, while individual modules included, for example, the main structure, floor, catwalk gantries and cladding rails.

"The spire just doesn't compare with anything you'd ever build anywhere – but the trial assembly resolved all the connection issues," says Doug Willis, contracts manager at Severfield-Reeve.[17]

COORDINATION ACROSS DISCIPLINES

THE COLLABORATION CHALLENGE

At the project's peak almost 1,500 cross-discipline staff were employed, ranging from structural engineers to glaziers, electricians to security staff, crane operators to lift installers. The epic collaboration was a challenge in itself.

"It's a unique example of mixed engineering," explains Claudio Boccasile of Rebus Engineering Services, which was involved in the redevelopment of London Bridge Station. "They did everything in perfect coordination. All the disciplines involved, step by step, day by day, all together."

WSP's Parker recalls that the contractor, architect and structural engineer made a point of listening to each other's concerns so as to find solutions to problems in a timely manner. This spirit of co-ordination was not confined to engineering.

"The stereotype is very much that the engineer is worried about numbers, and the architect is worried about colour, and all the builder cares about is getting it done quickly," he says.[18] "On The Shard it wasn't like that. The architect did listen to our concerns about structure, and we listened to him about his concerns about aesthetics."

"IT'S A UNIQUE EXAMPLE OF MIXED ENGINEERING"

CLAUDIO BOCCASILE

Director, Rebus Engineering Services

SUSTAINABLE EXTRA-WHITE GLASS

TRANSPARENT INNOVATION

Part of delivering on Piano's "gentle" vision for The Shard meant creating a unique glass exterior that avoided the green tint common to most high-rise buildings. The solution was to opt for a glass that would let light through the skeletal apex of the building and subtly respond to changes in the sky.

To achieve this effect, the team selected an innovative low-iron extra-white glass that maximised transparency through the panes. This required the very latest in glass technology, and the use of a double façade to install an intelligent shading system between the two 'skins' that responds to different lighting conditions.

"It's like the trunk of a tree, acting differently all the way round, depending on how much sun it gets," Piano told dezeen in a 2012 interview. "The south side will not be the same as the north."[19]

James O'Callaghan, a director at Eckersley O'Callaghan Engineers and who specialises in glass façades, explains the legacy of The Shard in this area of construction. "In many ways the simplicity of the external façade belies the complexity behind.

"That tension between energy performance and transparency has become even more of a design driver [in recent times]", he says. The Shard is "one of the first [high-rise buildings] that addresses that in an intelligent way."

O'Callaghan says the coating technology provided by Interpane used on the façade helped to "give the building its form and also a slight reflectivity."[20] It has proved so effective that it has also been used on another tall building under construction nearby, Twentytwo.

"IT'S LIKE THE TRUNK OF A TREE, ACTING DIFFERENTLY ALL THE WAY ROUND, DEPENDING ON HOW MUCH SUN IT GETS"

RENZO PIANO
Partner and Founder
Renzo Piano Building Workshop

ROMA AGRAWAL

CHARTERED STRUCTURAL ENGINEER

Roma Agrawal is considered one engineering's rising stars. She has won the Royal Academy of Engineering's prestigious Rooke Award, has been appointed a Fellow of the Institution of Civil Engineers, and is a Member of the Order of the British Empire (MBE) – not to mention the author of a critically acclaimed book, 'Built: The Hidden Stories Behind our Structures'.

When she joined WSP, the engineering firm behind The Shard, in 2005, Agrawal was still a relatively untold engineering story. She spent six years dedicated to The Shard doing some of the enabling works, designing the foundations of the building and also the iconic spire.

"A big challenge that London poses is the ground. We're in the valley of a river, which over millions of years has been depositing silt and creating clay," she says.[1] Because clay expands when wet and shrinks when dry, the engineers needed to go deep when laying the foundations.

This includes the top down construction method on the core of the building and the innovative way of constructing and erecting the spire.

"The science of building tall is evolving very rapidly," says Agrawal.[2] "We are getting more and more complicated geometry – The Shard has fairly complicated geometry, every single floor is different – and we as structural engineers are pushed to challenge the analysis we do and the construction techniques we use to build things." →

It was this challenging of convention that led the team to use a hybrid of construction materials for The Shard – beginning with a concrete foundation and then switching to steel for the office floors, concrete again for the hotel and residential floors and then back to steel for the top where the viewing gallery is.

“We thought to ourselves, why don’t we just use the right material for the right usage? Even though this sounds like a very simple concept, we only really know of one or two other buildings in the entire world that have done this.”

After completing an MSC in structural engineering at Imperial College London, she joined WSP in 2005, where her pioneering work on The Shard quickly took her career to new heights. Since then, she has worked across engineering projects ranging from footbridges and train stations to sculptures. And today, Agrawal is an associate director of buildings and places at Aecom in London, where she is focused on championing change in the profession she loves.

“People have preconceptions about what engineering is”, she says. “We as a profession need to increase awareness of the problems we solve and the contribution we make to society, from our homes to our mobile phones.”[3]

CONCLUSION

LEGACY OF INNOVATION

It's now a decade since construction work first began on The Shard, and in that time it has more than secured its place among the most recognisable structures in the world.

But its legacy speaks to much more than just recognition. Tall buildings around the globe have followed its lead in many of the elements that make it so special. Top-down construction, for which The Shard was an early pioneer, has since become widely used to speed up construction times. Australian tower Crown Sydney, due for completion in 2021, is just one of the latest examples to use it.

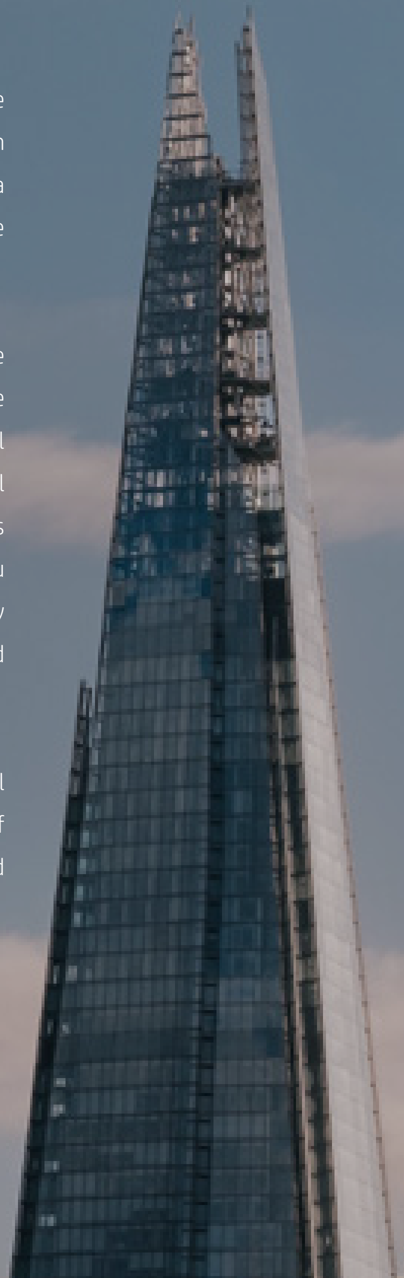
Much of The Shard's wider legacy lies in the way it has spearheaded the regeneration of an entire region of London. Its position in a previously unloved area of the city has attracted significant investment flows to the neighbourhood, and its engineers can take much of the credit.

The challenges associated with building a structure of this size – and with architectural flourishes such as its 66m, 500-tonne spire – in a constrained space were already significant. Doing it while working on top of one of the country's busiest railway stations, opposite a major hospital and with underground train lines running underneath made those challenges enormous.

But, through vast amounts of ingenuity and dedication, the engineering team found ways to collaborate and pioneer past each hurdle. In doing so, they delivered on Sellar's original vision of a 'vertical city' - a vision that is today shared by developers around the world as a solution to larger macro-global challenges.

As the restricted availability of inner-city development space combines with growing urban populations – along with the desire of many cities to make an architectural statement on the global stage – tall building projects are booming. Countless monumental constructions are currently underway across the globe, from Madrid's Caleido (181m) and Moscow's MIBC Plot 1 (405m), to China's Suzhou IFS (452m) and South Korea's Busan Lotte Town Tower (510m). Many of this new generation of scheme is set out to be a 'vertical city' – and all are facing similar challenges to those conquered by The Shard.

The Shard's true legacy, then, lies not just in the scale of the physical achievement, but in the way it has paved the way for a new wave of ambitious high-rise projects that are set to redefine the way we build cities in the future.



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