# CONCRETE QUARTERLY

mpa The Concrete Centre

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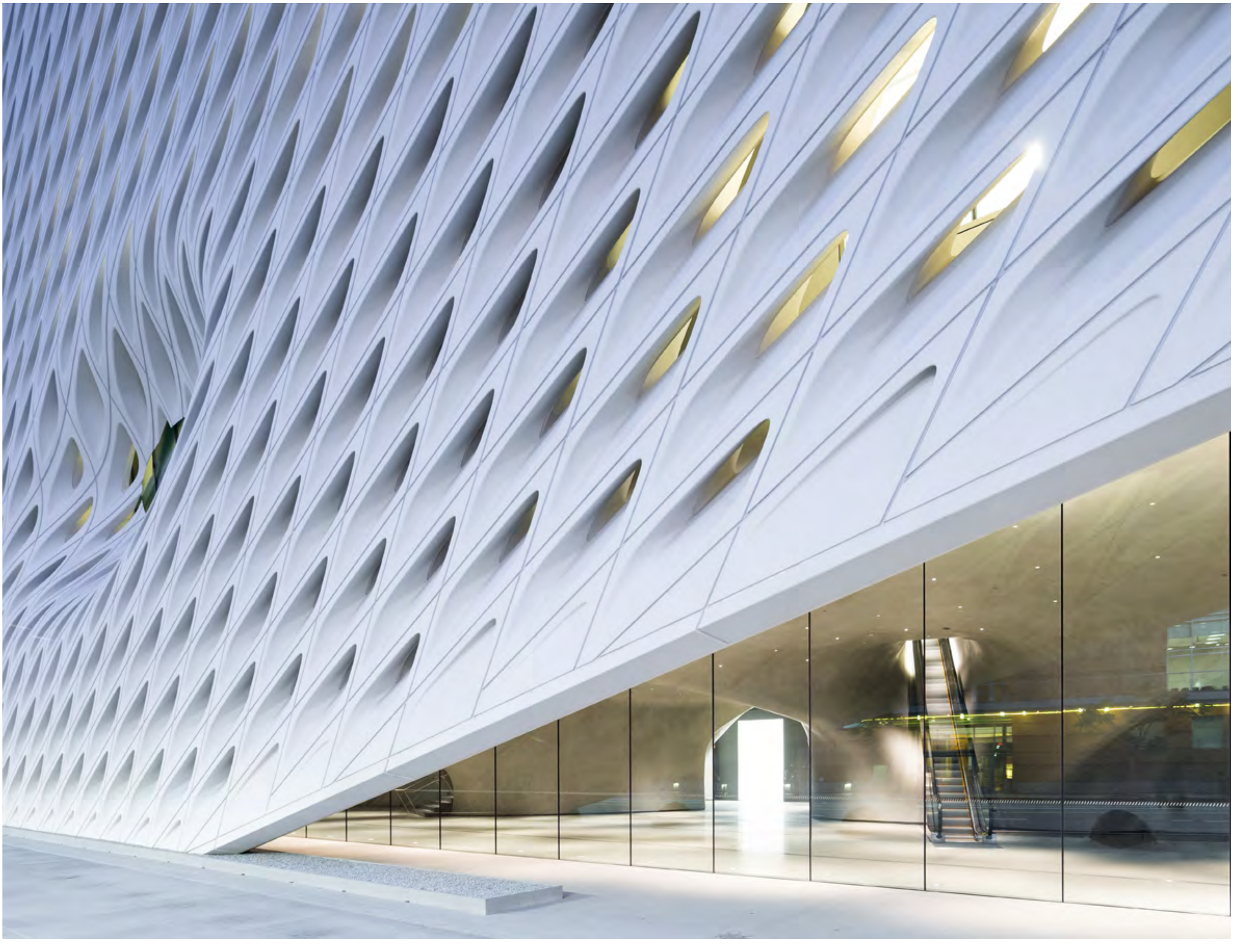

**BENEATH THE VEIL**
Uncovering the structural secrets of The Broad, Los Angeles' spectacular new gallery

**THAT MANCHESTER SOUND**
Concrete provides the perfect acoustic and aesthetic solution for the city's new arts powerhouse

**THE LIGHT STUFF**
It was good enough for the Pantheon, so why don't we use lightweight concrete more?

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## THIS IS CONCRETE


Guy Thompson
Head of architecture, housing and sustainability, The Concrete Centre


# Any shape or form

**Concrete is often described as a sculptural material, and there's a wealth of obvious and not-so-obvious examples in this issue of CQ.** The Broad museum in Los Angeles is an unashamedly bold response to the Frank Gehry concert hall next door, with a highly sculpted "veil" draped over an extraordinary "vault", where the lobby ceiling appears to float thanks to an 18m cantilever. On a very different scale, there's the London family home on page 11 where an entire extension seems to have been hewn from in-situ concrete, including the furniture.

While our Focus section explores the range of techniques for achieving stunning curves and free-form shapes, our Lasting Impression guest, artist William Mitchell, suggests that it's possible to find beauty anywhere if you know how to look. He sees great sculptural potential in the UK's concrete motorway network – works of art, according to Mitchell, rather than mere infrastructure.

MITCHELL SEES GREAT SCULPTURAL POTENTIAL IN THE UK'S MOTORWAY NETWORK

These forms span the many types of concrete, from the heaviest civils to the lightweight GFRC veil of The Broad. But few designers are fully aware of the opportunities that exist to create lighter structures by varying the type of aggregate. Our Structures section seeks to redress the balance, with another sculptural form to inspire today's designers: the Pantheon. So there you have it – from Ancient Rome to Spaghetti Junction in one seamless manoeuvre ...

this is concrete

### FOOD FOR THOUGHT

**Comparing environmental product declarations (EPDs) to food labelling is a brilliant analogy, writes This is Concrete blogger Elaine Toogood – if only establishing environmental impact was as simple and irrefutable as analysing salt or calorie content.** "It involves a complex web of data collection, at every stage of a product's manufacture and for all constituent parts, right through to end of life." And even though there is a European standard to aid consistency, experts must still make assumptions on input data. The concrete industry has begun producing usable, comparable information, but Toogood suspects BIM operators will face a steep learning curve as more EPD data becomes available.
**Join the debate at www.thisisconcrete.co.uk**

CONCRETE QUARTERLY


On the cover:
The Broad museum in Los Angeles by Diller Scofidio + Renfro. Photo by Iwan Baan


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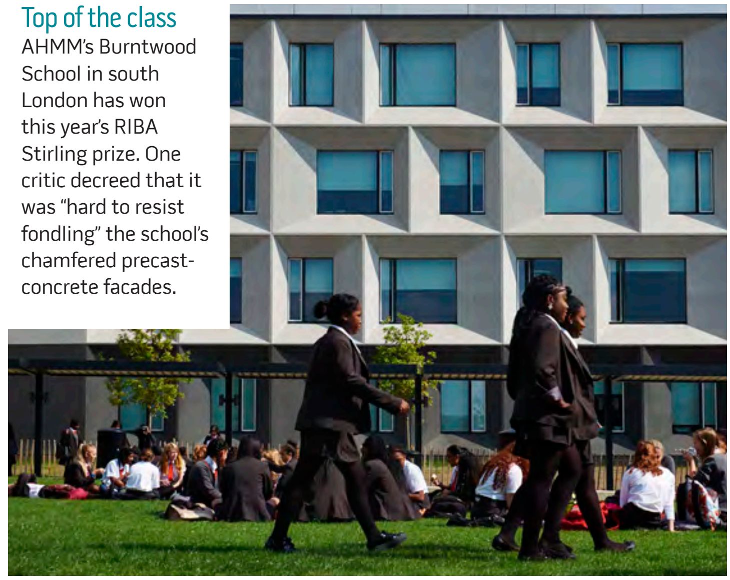
The Concrete Centre is part of the Mineral Products Association, the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries. www.mineralproducts.org

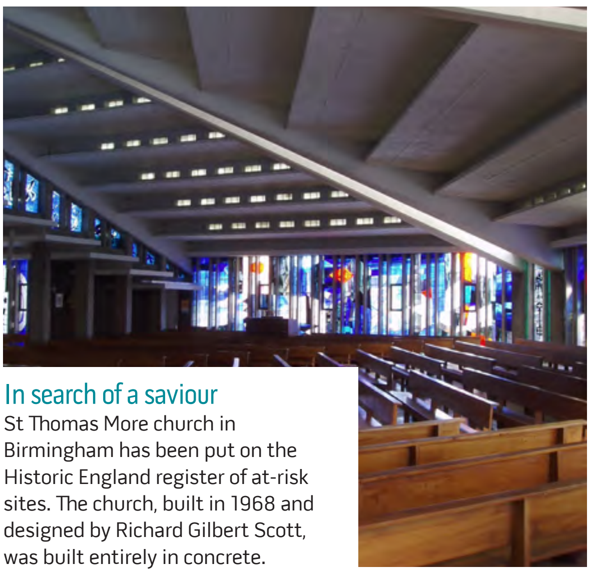
## Full steam ahead

The concrete pour on the south-west chimney at Battersea Power Station has reached 35m. All four chimneys are being rebuilt to the original fluted design, using some 2,400 tonnes of in-situ concrete.

## Top of the class

AHMM's Burntwood School in south London has won this year's RIBA Stirling prize. One critic decreed that it was "hard to resist fondling" the school's chamfered precast-concrete facades.





## In search of a saviour

St Thomas More church in Birmingham has been put on the Historic England register of at-risk sites. The church, built in 1968 and designed by Richard Gilbert Scott, was built entirely in concrete.

## Hadid strikes gold

Another CQ, another stunning Zaha Hadid building – this time, the recently completed Messner Mountain Museum in Italy. In September, Hadid's contribution to architecture was recognised with the RIBA Gold Medal.

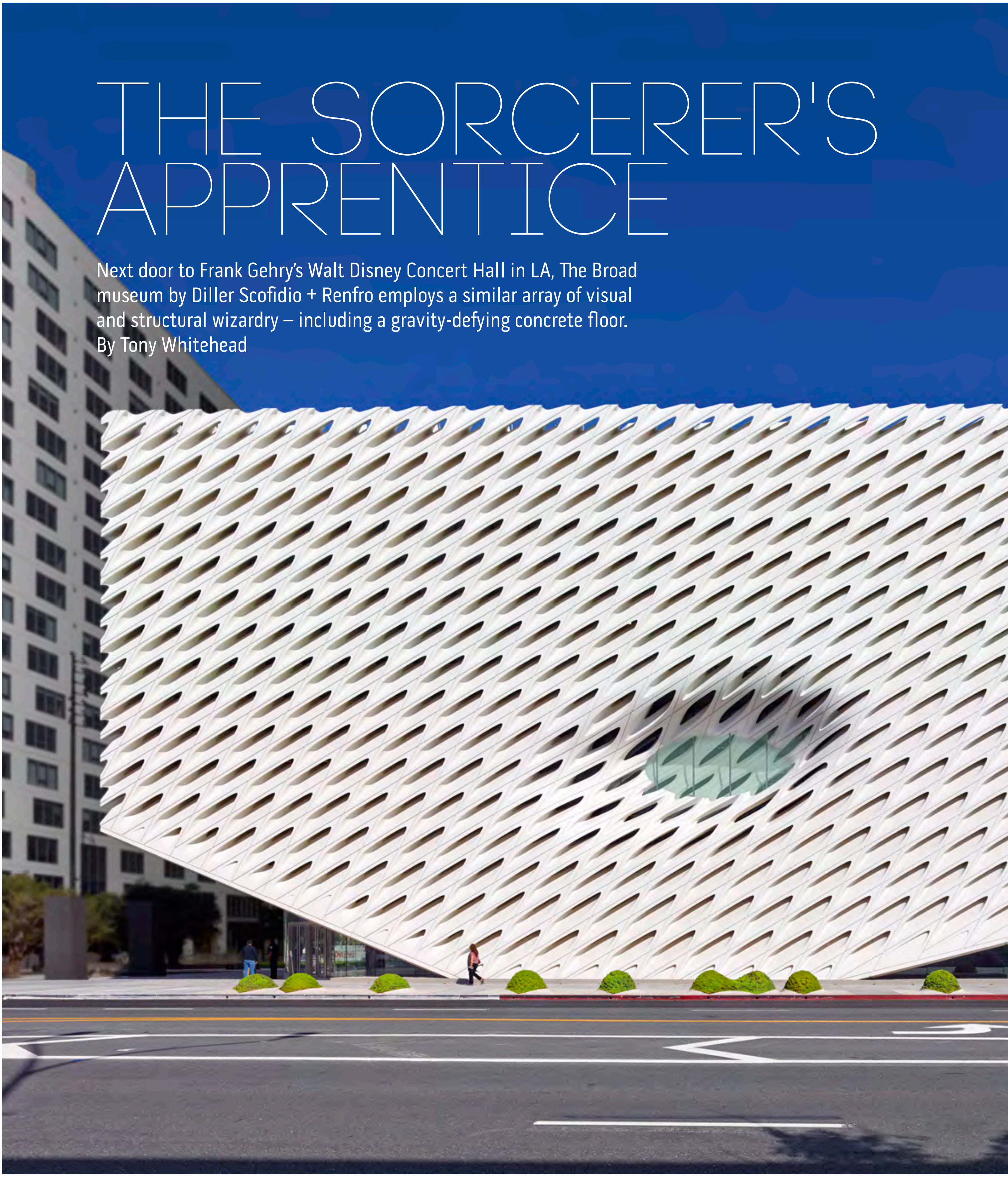
## CONCRETE ELEGANCE

The next Concrete Elegance event takes place on 1 December and focuses on "Curves and Creativity". Featured projects include the Bomnong L'or School in Cambodia (left), which makes ingenious use of fabric formwork, and Thomas Heatherwick's Nanyang Learning Hub in Singapore (right). UK projects are represented by Flanagan Lawrence's beautiful outdoor stage, Acoustic Shells in Littlehampton, West Sussex. **For more details, go to www.concretecentre.com/events**

Photos: Battersea Power Station; Timothy Soar; Aidan McRae Thomson; Werner Huthmacher; Lindsay Perth; Hufton + Crow

# THE SORCERER'S APPRENTICE

Next door to Frank Gehry's Walt Disney Concert Hall in LA, The Broad museum by Diller Scofidio + Renfro employs a similar array of visual and structural wizardry – including a gravity-defying concrete floor.
By Tony Whitehead



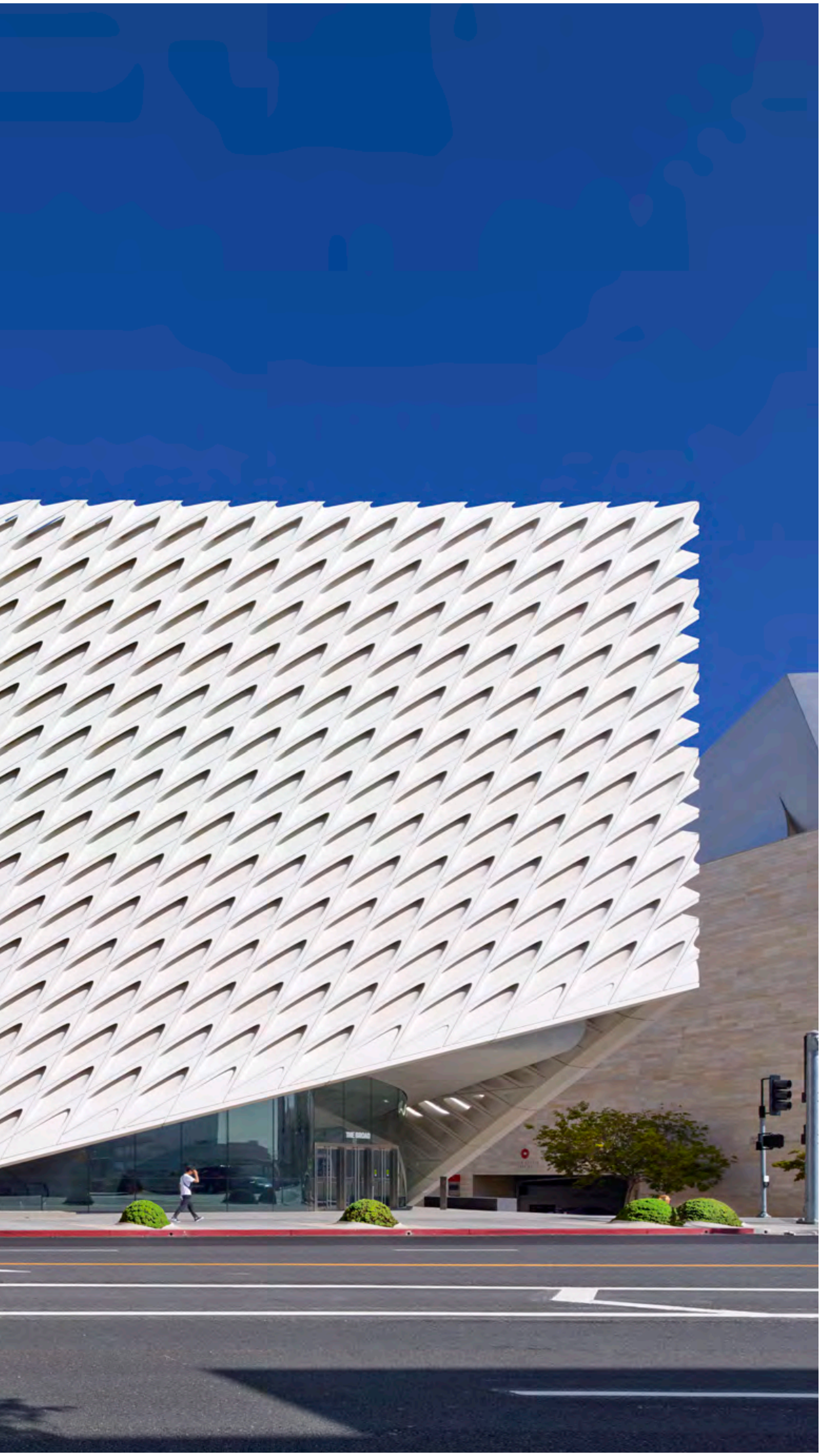



Photo: Benny Chan

**Perhaps more than any other type of building, major art galleries need to make a statement: think of the Pompidou, the Guggenheim or the Met. Now add to that list The Broad, a £70m new museum of contemporary art gifted to the city of Los Angeles by billionaire philanthropists Eli and Edythe Broad. It is a stunning three-storey building clad in a glittering white veil of glass fibre reinforced concrete (GFRC) panels. Within is a massive concrete structure housing 120,000ft$^2$ of galleries, archives and offices, which appears to float unaided over the spectacular entrance lobby.**

It is a supremely confident design which, given its location, is perhaps as well. Virtually next door are the shining silver curves of the Disney Concert Hall, designed by the architect of the Bilbao Guggenheim, Frank Gehry. Kevin Rice, project director with The Broad's designer, Diller Scofidio + Renfro, has described the challenge they faced as: "How to hold your own? How to have a conversation with Disney but not be secondary to it?"

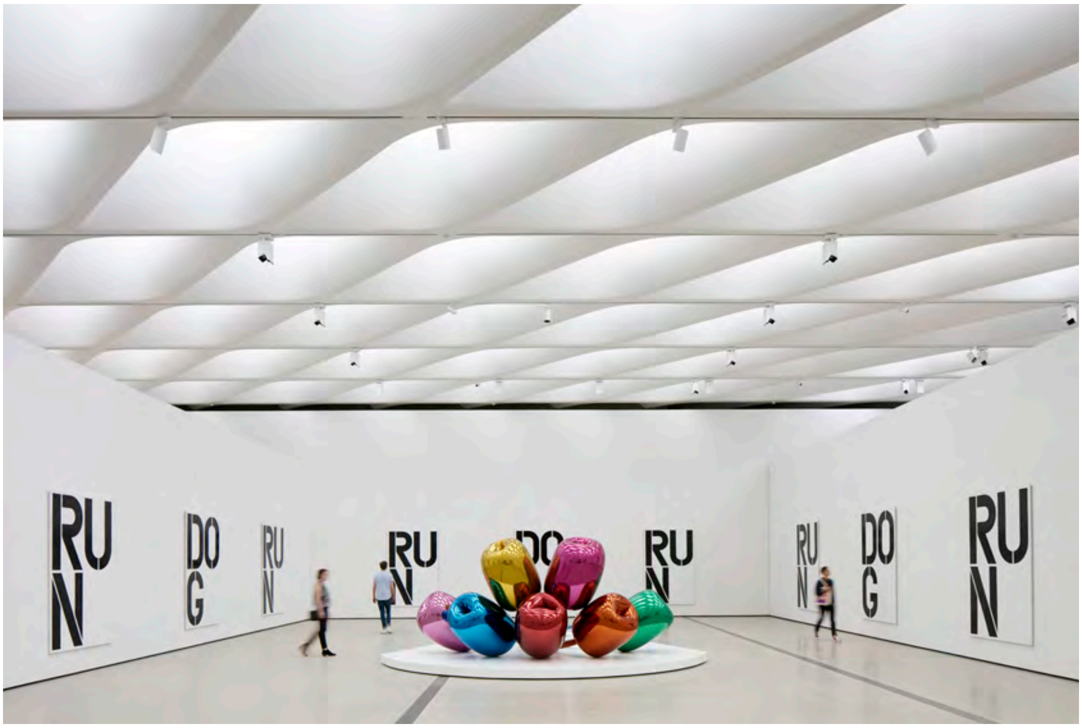
DS+R's solution has been to make The Broad, whether it is sparkling in the California sunshine or glowing from within at night, appear to contain light. It is a playful contrast to Gehry's reflective design, but DS+R's unusual aesthetic, combined with The Broad's location in an area notorious for earthquakes, presented some extraordinary engineering challenges for the construction team – many of which had to be solved more in the manner of a major civils project than a museum.

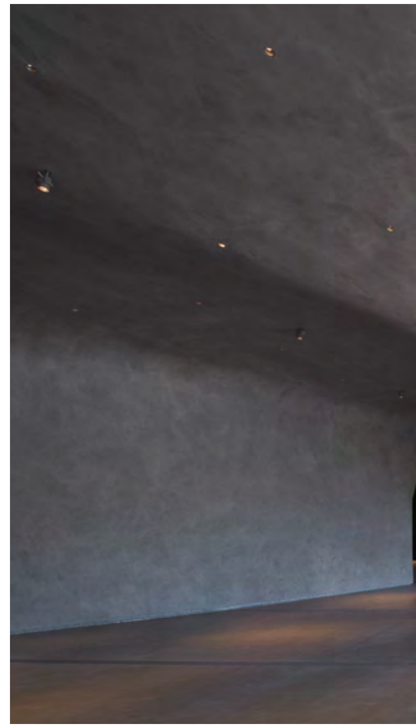
"One of our primary and overriding considerations when designing this building was the fact that it lies in a seismic zone 4," says architect David Pakshong from Gensler, which acted as executive architect on the project. Zone 4 means high risk (only zone 5 is worse) so an earthquake-resistant combination of strength and flexibility had to be built into The Broad from the beginning: the outer GFRC veil, for example is attached to the front of the building via a pivot system which can absorb seismic movement (see box, overleaf).

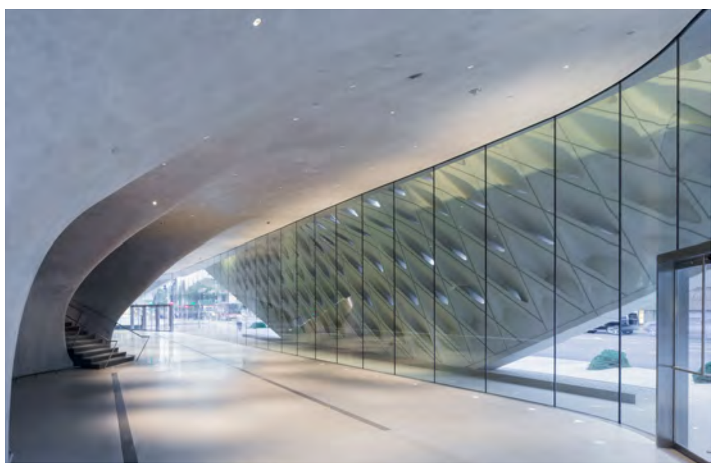
"In addition we have to consider that this is a much taller building than it appears from the front," says Pakshong. "It actually rises from a lower level service street – there are three garage levels, and then because the three gallery levels have high ceilings, the total height is equivalent to at least seven storeys."

In effect, the lower three parking levels, constructed with bell-shaped caissons and plenty of hefty reinforced in-situ concrete, have been used to form a massively strong podium on which the museum proper sits. The accommodation above is built on a 9m grid with 560mm square reinforced-concrete columns. These are typically spanned by 250mm concrete slabs with added strength provided by 900mm drop panels over the columns.

ONE OF OUR OVERRIDING CONSIDERATIONS WHEN DESIGNING THIS BUILDING WAS THE FACT THAT IT LIES IN A SEISMIC ZONE 4





**ABOVE LEFT** The galleries include "air floors" that allow the thermal mass of the structure to help cool the building

**ABOVE RIGHT** An escalator rises up from the ground floor through the cave-like vault

**LEFT** The polished concrete floors and plastered "vault" of the lobby

Visitors access the ground-floor lobby from Grand Avenue (which is actually carried on a bridge at the point it passes The Broad), and what they experience on entering is unusual to say the least. The upper galleries are reached via a 32m-long escalator that disappears through a sculpted cave-like opening in a large central structure known as the vault. A huge cantilever projects the first-floor slab of the vault for up to 18m from the central core without support over the lobby, which leads off into the ground-floor galleries. This slab also stops short of the exterior veil, thus "proving" to the observer that the outer cladding is not in any way holding up the ceiling of the lobby.

"The conceptual intent is to get the concrete mass above to look as if it is floating – that's the whole point of the cantilever," says Pakshong. "Obviously this creates a lot of moment at the spring point of the cantilever, so the first-floor slab is very thick, nearly 2m deep near the centre of the building, but tapering to just 0.3m near the front edges."

Constructing this "floating" slab required special care, as Greg Wade, senior project manager with contractor MATT Construction, explains: "The cantilevered part of the slab is post-tensioned to enable it to bear its own weight and also that of the storeys above. But this was bridge post-tensioning – a much stronger solution than the standard PT slabs we are used to working with."

Borrowing the technique from the civil engineering sector, the post-tensioning at The Broad involved pouring the slab with 150mm tubes or sleeves (as opposed to about 40mm on a more conventional building) set within the reinforcement. Bundles of steel cables some 120mm in diameter were then fed through the sleeves, anchored at the thin end of the slab facing the front elevation, and back at the 2m-thick central point of the slab at the other end. The cables were then tensioned by a hydraulic jack applying 300,000lb of force before grout was injected into the sleeves to lock the cables in place.

Wade explains that additional reinforcement was placed in the slab to provide extra strength and, whereas standard 4,000psi concrete was used elsewhere in the building, a stronger 6,000psi mix was used for the cantilevered slab. "It meant we had to coordinate very carefully where the reinforcement was going to go and where the sleeves were going to run," he says. "We also had an issue with some of the PT cables that wanted to come out in the elevator shaft in the centre of the building – so we had to rejig that, and add more reinforcement, to ensure the load was carried around the elevator."

Naturally the pour for the slab was a critical moment for the project. "We actually did it in three pours with the joints running in the same direction as the cables," says Wade. "We pumped from the service street below to avoid blocking Grand Avenue, so we needed a substantial pump, plus a back-up as we could not afford the possibility of a pump failure interrupting a pour for this critical part of the structure.

The extra cement content of the 6,000psi concrete meant that this was slightly harder to work: "We learned from doing a test pour how the exact mix would behave, and when it came to the real thing we had plenty of thermal monitors in place," says Wade. The pour was also covered in insulating blankets to prevent heat differentials that would cause the concrete to crack.

One benefit of creating the cantilever in this way, as opposed to a steel-framed solution, has been to

minimise movement at the tip of the cantilever. The live load deflection is, according to Pakshong, between just 12mm and 20mm, allowing for coordination of the lobby glass which rises between the concrete floor and ceiling to create the building's weathershield.

Given the quantity and complexity of concrete engineering involved in The Broad, it is ironic that visitors will see little of it. The cave-like walls in the lobby are formed from Parex, a cementitious plaster applied over boards attached to a lightweight steel structure, and on the upper galleries most of the concrete walls are covered in plasterboard with services generally hidden behind false ceilings.

Further subtleties are concealed beneath the floors. "Above the structural slab to the lobby and top gallery floors there is actually a steel assembly that creates an air floor to help ventilate the building," says Pakshong. "It is like an intersecting pattern of shallow barrel vaults, 300mm apart on centre and with a maximum depth of 150mm. A concrete topping slab is poured over these steel forms. This creates a system that allows air to circulate through the body of the slabs."

Pakshong adds that as well as neatly accommodating the air distribution system, the "air floors" allow the thermal mass of the floor slabs to moderate the temperature within the building: "Galleries are very expensive things to run, so anything you can do to optimise the efficiency of the mechanicals is well worth it."

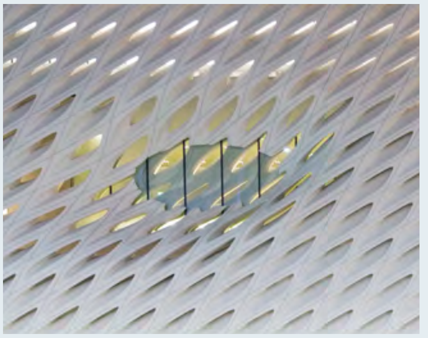
Something visitors can more readily appreciate is the highly polished concrete floor to the lobby and third-floor gallery. This polished finish involved progressively levelling and smoothing the slabs with orbital cutters until the concrete achieved the smoothness of a tile or polished granite. The finished appearance, though, depends heavily on the concrete involved: "The distribution of aggregate near the surface of the topping slab determines what the floor will look like," explains Wade. "That depends on the mix and also on how exactly level the surface of the slab is. Our client was concerned that any differences in the density of aggregate would cause too much variation in the appearance of the floor, so we used a specialist concrete contractor who took steps to ensure a surface with a consistent finish."

This involved pouring the topping slab in narrow 6m x 18m sections so they could be easily bridged by timber protectors. "The wet surface was then 'seeded' with sand and left undisturbed to cure," says Wade. "Once again we did several mock-ups to make sure we were going to achieve the required finish. The result is a very level surface which ensures that the polishers only cut into sand and not a varying density of aggregate."

In all, MATT carried out more than 100 mock-ups of the varying systems and techniques used in The Broad, though only a dozen such trials were specified in its contract. That fact alone is surely testament to just how unusual a building The Broad is, and to the extraordinary attention to detail lavished upon it by the construction team.

**PROJECT TEAM**

**Architect** Diller Scofidio + Renfro
**Executive architect** Gensler
**Contractor** MATT Construction
**Structural engineers** Nabih Youssef & Associates and Leslie E Robertson Associates
**GFRC system designer** Seele
**GFRC panel engineer and fabricator** Willis Construction



## Secrets of the veil

In early designs for The Broad, the "veil", the system of white interlocking panels which clads the building and defines its exterior aesthetic, was going to be self-supporting and constructed from precast concrete. However, seismic considerations meant that the lighter glass fibre reinforced concrete (GFRC) has been specified instead.

"Because they are GFRC, the units are hollow and much lighter than solid concrete," explains David Pakshong at executive architect Gensler. "The aggregate – in this case white with flecks of grey – is limited to the outer skin where it forms a layer less than 5mm thick. This is supported by a sprayed layer of GFRC beneath the aggregate."

In all there are 2,470 units, but only around half are a standard shape due to corners, edges, and the puckering to the front elevation, known as the oculus, which creates a distinctive window for the second-floor conference room. Fibreglass moulds were made using Styrofoam "positives", shaped by a CNC router.

On the front elevation, and a third of the way back on each side, the veil's GFRC panels are fixed to a dedicated supporting steel structure, while on the rear sections a steel tube fixing system is supported off channels cast into the concrete supporting walls.

"The entire weight of the panels on the front system is supported at only three points," explains Pakshong. "On each side the veil is connected via a pivot system to the concrete sheer walls and, at the front, the veil sits on a 20m-long steel beam just below ground that can rock in response to seismic movement."

Without the flexibility introduced by pivots and the rocker beam, says Pakshong, the supporting steel structure for the front sections of the veil would have to have been substantially larger.

This front section of the veil features units with penetrations to allow light to pass through to the separate glass weathershield fitted to the front elevations, though the design of the units means they act as a brise-soleil. The rear sections are merely indented, but the overall visual effect is consistent throughout.

Photos: Bruce Damonte; Hufton + Crow; Iwan Baan

Images: Mecanoo

# WONDERWALLS

## Concrete puts in a solid performance at Manchester's new arts centre, providing excellent acoustics and raw, honest interiors, writes Pamela Buxton

**When building a major regional arts centre requiring state-of-the-art acoustics, it's probably best not to put it next to a busy railway line. But this was the situation facing the designers of HOME, Manchester's new 7,600m² contemporary art, theatre and film centre. The answer for Dutch architect Mecanoo was to base the design around a 250mm-thick concrete frame, creating a formidable acoustic buffer against the roar of the rails.**

Commissioned by Manchester council and completed in April 2015, HOME houses the activities of the Cornerhouse arts centre and the Library theatre, which have merged. The £25m building is part of the First Street redevelopment area on the edge of the city centre, and occupies a triangular site just 7m from a railway viaduct. "The main driver was the acoustic performance," says Francesco Veenstra, associate partner at Mecanoo. "The use of concrete achieved both low vibration and low noise penetration." Added to this were the advantages of thermal mass, robustness, aesthetic qualities and long-term operational costs.

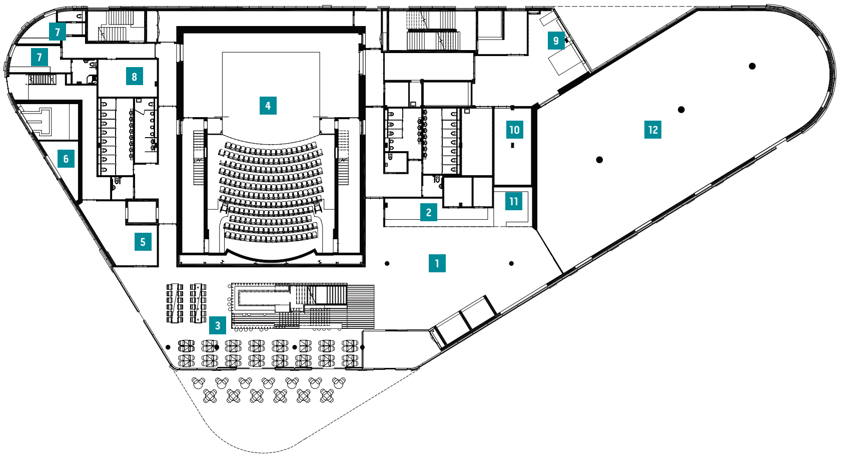
The structure was a box-in-box concept, with a 250mm-thick concrete wall behind the facade and then an additional 250mm-thick concrete box housing the main 500-seat theatre. Within this is a 300mm steel-framed inner box on resilient bearings to prevent vibration transfer from the outside and with acoustic quilts to absorb sound from within the theatre and prevent noise transfer from outside.

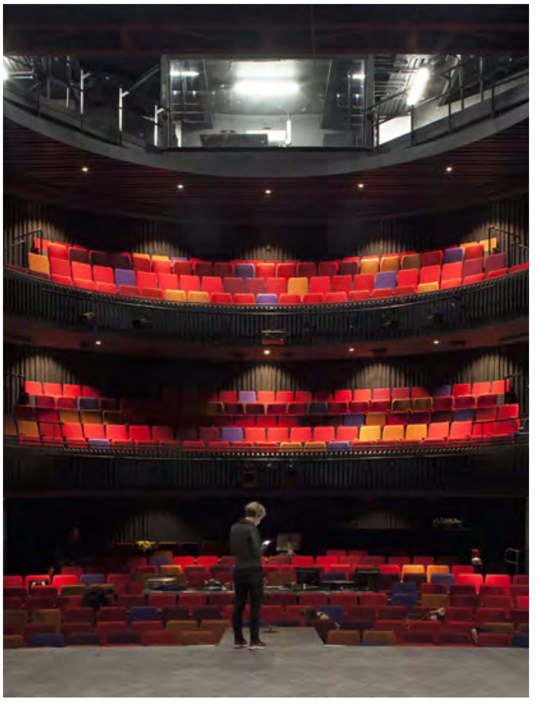
> THE MAIN DRIVER WAS THE ACOUSTIC PERFORMANCE. THE USE OF CONCRETE ACHIEVED BOTH LOW VIBRATION AND LOW NOISE PENETRATION

The main structure was cast in situ using plywood formwork to create a 4.5m floor-to-ceiling height on the ground floor and 6.5m on the first floor. It was decided to maintain consistent floor-to-ceiling heights on each level to create generous spaces not only in public zones such as the restaurant but throughout the many different areas. This allowed for repeated use of the same formwork and also gave scope for future flexibility of use – in the office accommodation, for example, a mezzanine level could be inserted if required.

As well as its performance benefits, the use of exposed concrete on floors, walls and ceilings had important aesthetic advantages that correlated with HOME's values. "The client particularly liked the use of a raw, honest material," says Veenstra.

The architects specified a non-textured, "slick" finish which was achieved using proprietary resin-coated plywood shuttering to give extra smoothness. This also gives a pleasing contrast with the prominent use of timber on the staircase

**IN PLAN (GROUND FLOOR)**

1 Foyer
2 Box office
3 Cafe/bar
4 Main auditorium
5 Bar cellar
6 Switch room
7 Dressing rooms
8 Stage manager
9 Loading bay
10 Art store
11 Retail space
12 Galleries

and bar, and with the raw steel in the restaurant. "Having a very slick concrete finish on the walls and floors gave us an opportunity to create a contrast between something that looked rough but had a silky finish," Veenstra says. "We spent a lot of time discussing how to achieve this with our subcontractor. We were able to motivate them to go for a very high-end finish and we're very happy with the result."

The overall impression of the interior is very much one of exposed concrete. The concrete finish of the walls and ceiling contrasts with that of the floor, where Mecanoo specified a polished, tinted concrete screed for public areas – with under-floor heating – above the structural concrete floor.

Concrete ceilings are exposed, although the unity is disrupted by the first-floor restaurant, which has a steel-structured overhang. "It's a really pleasant space. You're surrounded by concrete but with the contrast of the timber it gives a very strong experience to the people who visit," says Veenstra. "What we took from HOME was that if you spend more time on detailing you can do something really special with concrete."

**PROJECT TEAM**

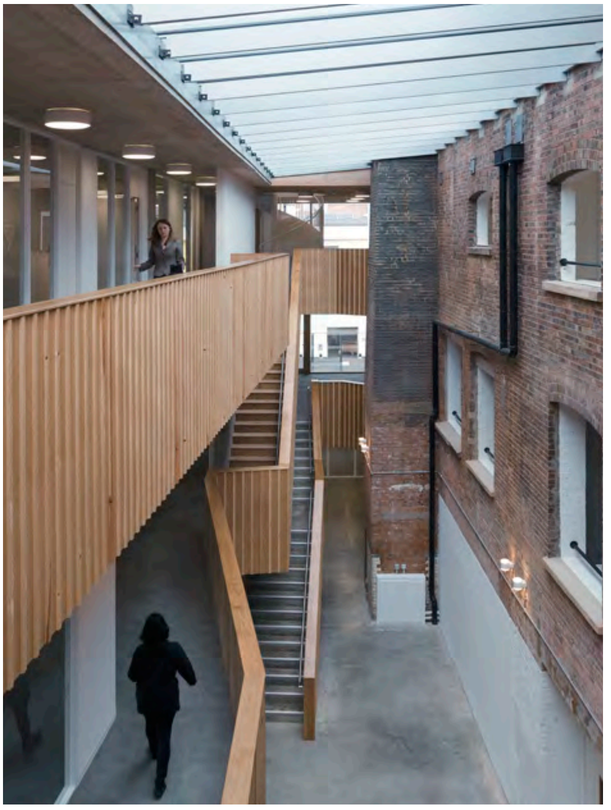
**Architect** Mecanoo Architecten
**Structural engineer** BuroHappold Engineering
**Main contractor** Wates Construction
**Concrete contractor** Adana Construction

**OPPOSITE** Resin-coated plywood shuttering gives a smooth finish to the concrete

**TOP LEFT** Timber and steel complement the bar's concrete finishes

**TOP RIGHT** The exterior is largely glazed

**ABOVE** The 500-seat theatre is housed in a 250mm-thick concrete box, which provides excellent acoustic separation



Photos: Rory Gardiner

**CLOCKWISE FROM TOP LEFT**

The floor slabs project 3m out from the facade; The atrium is meant to recall an old street between factories; GGBS lightens the concrete finishes –as well as contributing to a BREEAM Excellent rating

# SHELF RIGHTEOUS

## The Foundry social justice centre in London is an ingenious, highly adaptable space with an unlikely inspiration, writes Nick Jones

**It is perhaps rare for an award-winning piece of architecture to be as defiantly practical as The Foundry in south London. It has even been designed to look like a shelving unit, with its three concrete floor slabs projecting up to 3m out from the facade. But you don't win the RIBA London Building of the Year award merely for putting up shelves: this is also a sensitive, carefully crafted addition to a historic site and, arguably, a completely new type of office building.**

The Foundry provides offices, meeting rooms and an events space for a variety of human rights and social justice organisations. Half of these facilities are housed in a refurbished early 20th-century shoe polish factory and half in a new building alongside, its bold concrete frame complemented by a zig-zagging glass facade and a top floor that appears to comprise three zinc-clad beach huts.

Despite this playful touch, the centre has a deliberately earnest feel. This is partly because, as a social justice centre, it couldn't appear as if a lot of money had been spent on it, and partly because, with a budget of £5.2m, there wasn't a lot of money to spend. "We couldn't afford many finishes, so we deliberately made it almost a finishless building – with plasterboard partitions, exposed concrete soffits and walls and timber floors," says Lynton Pepper, co-founder of the project's architect, Architecture 00. "They are the materials that hold the building up – there's no added decoration to it."

However, this basic palette has been combined to impressive effect. The exposed concrete balances the robust, industrial brickwork of the original factory, but is softened by the 50% GGBS mix, as well as the timber and the daylight that floods the atrium, making the walls "nice to lean against and touch". This warmth was important, as the centre needed to have a social, collaborative feel, with plenty of places to pause and chat. The atrium itself, which connects the two buildings, is meant to recall an old street between factories – "it has that sense that someone might winch something down it," says Pepper. Timber-clad balconies and connecting bridges and unglazed windows on the brick facade all add to the lively, communal atmosphere.

Beyond the atrium, the overriding design principle for the offices was future flexibility. An in-situ reinforced-concrete floor slab was used as part of a moment-resisting frame to avoid the need for loadbearing internal walls. "We wanted a building that was completely adaptable, because these organisations may change in size, or there may be a high turnover of occupants. You could take all the walls out if you wanted to," says Pepper.

So important is this flexibility that it has inspired one of the building's few decorative flourishes: the projecting concrete decks. Although these appear to be part of a continuous slab, they are actually linked to the internal floors with insulated balcony connectors. "We could have kept the concrete internal and not taken it through the facade," says Pepper, "but we did that to show that these are just shelves, you can put things on them and change things throughout." As decorations go, it's a fitting one for a serious-minded building.

**PROJECT TEAM**

**Architect** Architecture 00
**Structural engineer** Momentum Engineering
**Main contractor** Bennetts Construction

# A TWIST IN THE TERRACE

McLaren Excell has tweaked the traditional London housing type with an exposed-concrete extension that's as warm as it is robust. By Nick Jones

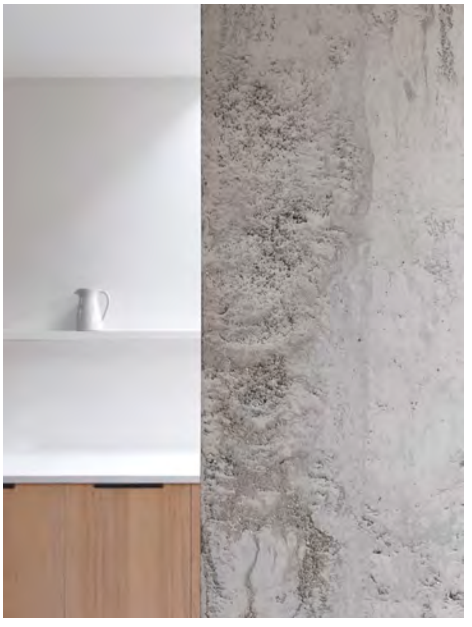
**"It started off with the floor, then progressed to the window seat and columns, and finally the dining table and kitchen island. As we approached each element of the design from a material point of view, concrete always seemed to be the winner."**

Luke McLaren is describing the extension to a terraced house in Shepherd's Bush, which his practice designed for a young family. It is a warm, inviting 3m-high space that combines a kitchen, dining area and space to relax or play. And it is made almost entirely from exposed concrete. "It all started with the client," explains McLaren. "They liked concrete from a purely aesthetic point of view, and, as they have two young children, they wanted a main living space that would be robust over the years to come."

The furniture is certainly robust – the centrepiece kitchen island is a mighty structure, packed with rebar to support the tabletop, which cantilevers off a 100mm-wide spine leg. But it is also beautiful, with the fluidity of an object created in a single pour. McLaren describes the formwork as having "the precision of joinery". The architects specified a spruce-based plywood that they knew gave a consistent, matt finish, and from this the contractor, Miles Builders, created the intricate reverse image of the island, with its many cutaways and overhangs. "The formwork had to be absolute perfect, because with furniture it's things that you sit on, touch, work on – you'll notice every mistake."

If meticulous detail was key to the project, McLaren also concedes that, with in-situ concrete, there's always an element you can't control. In this case, that element was a large concrete-clad supporting column. "The column was supporting two storeys above, so once the steelwork was in, there was no gap to pour the concrete." The solution was to make a small letterbox opening at the top of the formwork and pour it from the only side they could access. However, this resulted in a patinated finish on the reverse side: "When we struck the formwork, we all thought, oh God. But as the concrete dried and became lighter and lighter, and the project around it started to finish, it became increasingly appealing – the slightly rough appearance of this column compared to the pristine surfaces everywhere else. It actually became a real asset, and the client was really keen to keep it."

As McLaren says, this happy accident only works because of the high-quality finishes elsewhere. The concrete is given warmth through the slightly darkening effect of a 30% PFA mix, and more literally through the use of underfloor heating. The kitchen island is finished with a surface impregnator and the floor with a matt acrylic polish. The concrete surfaces are complemented by joinery in grey elm, which has a dusty quality, and the garden shrubs, which press up against the glazed back wall. It is all perfectly controlled – it just needs a couple of children to add a touch of chaos …



**CLOCKWISE FROM RIGHT**
The kitchen island was cast in a single pour; The main supporting column has a patinated finish on one side; Joinery in grey elm complements the concrete surfaces

Photos: Richard Leeney

**PROJECT TEAM**

**Architect** McLaren Excell

**Main contractor** Miles Builders

# HOW TO BEAT THE BIG HEAT

Concrete is an essential tool in designing buildings that are resilient to climate change – and not only for its thermal mass, but also because of its colour. Tom De Saulles explains

Articles on climate change invariably start with some worrying statistics, but I'm going to buck the trend. Global warming has actually slowed since 1999, despite increasing levels of $CO_2$ in the atmosphere. The last time this happened was between 1945 and 1975, which led to fears of another ice age. Fast-forward 40 years and ice is again in the news, with a report from NASA that the sea ice levels surrounding Antarctica reached a record high in 2014. Ice now covers more of the southern oceans than it has since long-term satellite mapping began in the 1970s.

Before this starts sounding like climate change denial, it should be noted that the upward trend in the Antarctic only compensates for about a third of the sea ice being rapidly lost at the opposite end of the planet in the Arctic ocean. Similarly, the current hiatus in rising global temperatures is only predicted to last for around another 10 years, and has been attributed to various theories including a naturally occurring 30-year cycle in the Atlantic ocean. The longer-term trend is still that global temperatures will rise. The latest research suggests that by 2040, summers as hot as that of 2003, when temperatures reached 38.5°C, will be very common in the UK, potentially occurring every other year. Alongside the problem of overheating buildings, the incidence of flooding has already increased – significant rainfall events that would previously have occurred only once in a century are now likely to be witnessed once every 80 years in southern England.

It is therefore unsurprising that resilience is becoming a significant design driver in construction. It now attracts credits in the BREEAM environmental assessment scheme, which includes explicit categories for durability/resilience and climate change adaptation, both areas where concrete can score well. These themes are also acknowledged in the Home Quality Mark standard currently under development, which will help to fill the void left by the outgoing Code for Sustainable Homes. Another noteworthy development is a dedicated "buildings day" at the UN Climate Summit taking place in Paris this November.

Resilience is of course a basic attribute of concrete, encompassing its mechanical and thermal properties and its durability, all of which are likely to become increasingly apposite in response to the effects of climate change. In terms of thermal comfort, concrete's inherent thermal mass is key, but concrete has another less often recognised virtue that also provides some natural resilience to overheating at both a building and a townscape level. This is the ability of exterior concrete with a light-coloured, high-albedo finish to reflect solar gains back into the sky, reducing the build-up of heat in the urban environment.

## High albedo finishes

High albedo finishes can be used to good effect on roofs, facades and paving, helping to reduce cooling loads and lower concrete's contribution to the urban heat island effect – that is, the increase in ambient temperature caused by the retention of heat in built-up areas. Reflecting solar gains also reduces the overall demand for air-conditioning, which is itself a major contributor to urban overheating, with discharge heat raising some urban temperatures by more than 1°C, according to research by Arizona State University. Any natural ability to reject heat from built-up areas will help curtail this need for mechanical cooling and prevent it from spiralling ever upwards.

Light-coloured surfaces have an albedo value of around 0.8, meaning 80% of the sun's heat is reflected, while darker surfaces with values closer to zero result in greater heat absorption. Ordinary concrete has an albedo value of around 0.2-0.4. This is higher than asphalt, for example, which has a value of 0.1-0.15, but not as high as concrete that has a high GGBS content or is made with white cement, which can lead to values of up to 0.8.

## Concrete albedo with varying GGBS content

Conventional paving materials can reach peak summertime temperatures of 48-67°C, while high albedo paving is likely to have a corresponding surface temperature around 20°C lower. Research in the US, where the use of cool pavements and roofs is more established, suggests that every 10% increase in solar reflectance could decrease surface temperatures by 4°C. It is estimated that if pavement reflectance throughout a city were increased from 10% to 35%, the air temperature could be reduced by around 0.6°C, increasing to 0.8°C if used in combination with other mitigation measures such as trees, green roofs and vegetation.

Depending on the moisture present, permeable paving is also emerging as a further means of reducing air temperature. As the surface warms, moisture within the pavement structure evaporates, thus drawing heat out and lowering the surface temperature, similar to the evaporative cooling effect from plants and trees.

Although commonly applied in warmer climates, the use of light-coloured surfaces as a means of creating natural resilience is a relatively new technique in the UK. However, it has been identified by the London Climate Change Partnership as an important adaptation measure in new and retrofit projects. Its use must of course be considered in the context of the surroundings, with consideration given to where the reflected sunlight and heat will go – that is, into the sky or towards neighbouring buildings.

It is also worth mentioning that, although the

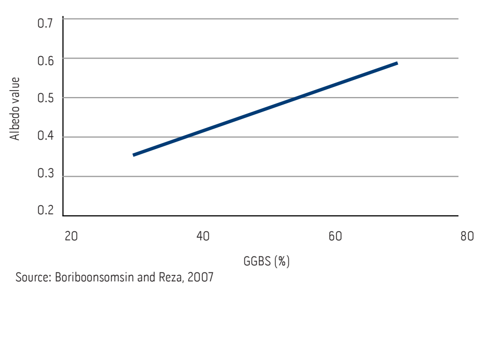
### ◀ Ash Court

**Girton College, University of Cambridge**
**Allies and Morrison, completed in 2013**

**Ash Court is a new residential wing at Girton College, Cambridge, which provides 50 en-suite student bedrooms, gym accommodation and an indoor swimming pool. The facilities also create a hub for conference guests outside of term time. The college set ambitious environmental targets, which drove the adoption of a Passivhaus approach to the design. Among the many low-energy features are exposed concrete soffits, which work in conjunction with an efficient ventilation system to help maintain a stable, comfortable environment. Resilience to climate change and changing building needs have been enhanced by installing plastic pipework in the soffits, allowing active surface cooling to be used if required in the future. This added very little to the project costs and will help ensure Ash Court's 100-year design life can be met with minimal expense and alterations should mechanical cooling be needed further down the line.**

Photo: Max Kettenacker, Allies and Morrison

FIGURE 1: CONCRETE ALBEDO WITH VARYING GGBS CONTENT




Source: Boriboonsomsin and Reza, 2007

## ◀ Abode

**Great Kneighton, Cambridgeshire**
**Proctor and Matthews, ongoing**

**This large-scale housing development so far includes 450 sustainable new homes, and could eventually provide up to 2,250. The permeable paving in light-coloured blocks has a high albedo, which will help to reflect the heat of the sun and reduce the urban heat island effect as the climate warms. As part of a sustainable drainage strategy, or SuDS, the permeable paving will also help to reduce the risk of surface-water flooding as extreme rainfall events become more common. Abode was the winner of the Housing Design Awards 2014.**

Photos: Tim Crocker

American LEED green building certification does give credit for high albedo finishes, this benefit is not yet assessed within BREEAM.

### Night cooling

Concrete's thermal mass provides another form of resilience in our warming climate. This is particularly effective when used in combination with night cooling, which allows night-time ventilation to purge the heat absorbed by the structure during the daytime. It might be thought that the combination of climate change and the urban heat island effect would render night cooling largely ineffectual in cities, and it is true that the benefit is reduced. But overall, it continues to offer a worthwhile means of purging excess heat and will continue to do so for many years to come. This is one of the findings of detailed research, led by University College London, into the relative importance of the urban heat island on comfort in London dwellings in the summer of 2050.

THE USE OF LIGHT-COLOURED SURFACES AS A MEANS OF CREATING NATURAL RESILIENCE IS A RELATIVELY NEW TECHNIQUE IN THE UK

Night-cooling should also provide a benefit for non-dwellings, although the need to control comfort more closely may limit the use of thermal mass and night cooling as the sole means of regulating temperature. However, an effective compromise can still be achieved, in which the passive benefits of night cooling in conjunction with an exposed concrete soffit, are supplemented by an active system, typically comprising chilled water pipes embedded close to the soffit to give additional cooling and better control (see CQ 252, summer 2015). In new passively cooled concrete buildings where there is no immediate need for active cooling, it can make sense to embed pipework anyway and leave it dormant until a future point in time when it may be needed (see Ash Court case study, previous page). The additional cost of doing this is quite modest, while strengthening a building's resilience to future overheating and changing occupant needs.

### Conclusion

The current slowing in global temperature rise may continue for a few years, but the longer-term trend remains unchanged. Mitigating the growing problem of overheating will require a broad range of techniques. Among these, concrete's thermal properties offer a useful degree of natural resilience to the warming climate. This largely centres on the application of thermal mass, but also includes the use of high-albedo concrete to provide cool roofs, facades and paving. The light-coloured finish provides an effective means of reflecting solar gains, helping to reduce the urban heat island effect and cut demand for air-conditioning – itself a major contributor to the heat island problem and the greenhouse gases driving climate change.

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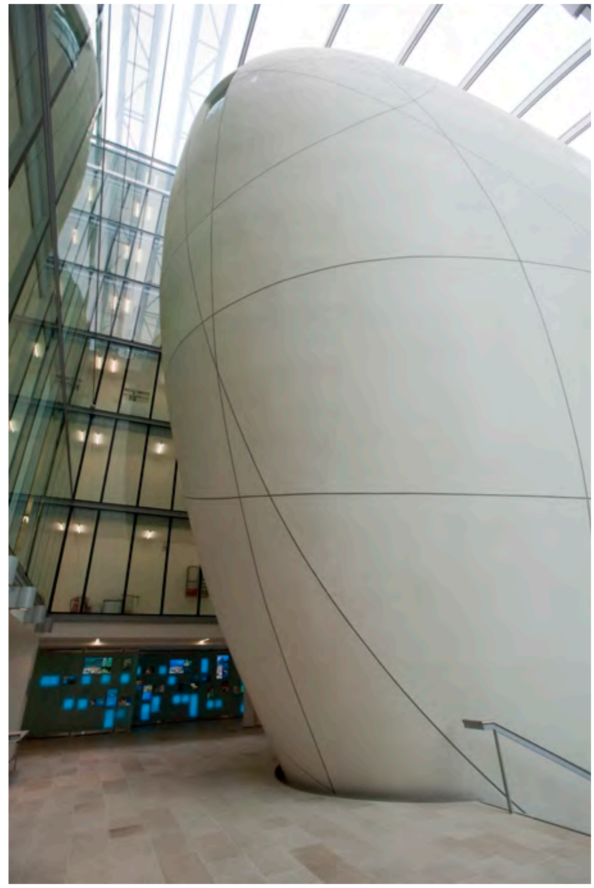


Photos: Flanagan Lawrence Architects; the Trustees of the Natural History Museum, London

# GO WITH THE FLOW

**ABOVE** Flanagan Lawrence's Acoustic Shells in Littlehampton

**RIGHT** The Darwin Centre at the Natural History Museum in London by CF Møller

## Complex curves are becoming an increasingly common feature of concrete structures. Elaine Toogood explains how it's done

One of the delights of concrete is that it can take any shape, including regular and free-form curves. Here, the challenge lies not with the concrete, but rather in making the mould, or formwork, to the desired shape, and for it to be sufficiently rigid to contain the concrete until it is strong enough to hold its own shape.

Regular two-way curves are relatively simple to form. Circular concrete columns are commonplace, and there is a range of proprietary formwork systems made from steel or cardboard-like tubes. Plywood and steel are common materials for formwork facing and can be bent, and there are proprietary systems for creating curved walls with a radius of up to 1m. Tighter curves require profiles made from metal, GRP or thinner ply, braced to provide the necessary support. For very tight curves or more complete shapes, the formwork needs to be flexible enough to be removed, or dismountable to release the concrete. Shaped polyurethane form liners offer an established technique for this, and can be made to order. Polystyrene or GRP can be used to create regular lengths of trough moulds for a curved, profiled, ribbed deck.

Three-way or free-form curved structures require different solutions. The formwork typically needs to be a material that can either be carved out or moulded itself into the desired shape. Free forms, such as the diving boards at the London Aquatics Centre by Zaha Hadid Architects, can be achieved by carving polystyrene forms with a digitally controlled five-axis router, and then using these to create more rigid GRC moulds. An alternative technique involves strengthening the polystyrene forms themselves, as used to create the 54 unique elements that make up the 20m-high Dream sculpture by Jaume Plensa outside Saint Helens, Merseyside. Each one was first strengthened using a polyurethane foam and then, after further accurate routing, sealed with epoxy resin ready for the concrete to be cast in the factory.

There are many examples of curved thin-shell structures from the last century, and the current focus on resource efficiency has led to renewed interest in these elegant forms. Felix Candela's hyperbolic paraboloid geometric shapes were created using strips of straight timber, a technique employed more recently on the Casar de Cáceres Bus Station in eastern Spain by Justo García Rubio. Flat sheets of MDF were used by Tonkin Lui to create the sinuous retaining walls of the Dover Esplanade, but here the boards were cut into curved strips and stacked on top of each other.

Sprayed concrete is an alternative solution that does not use formwork. Concrete is projected onto curved reinforcement bars or mesh, usually resulting in a slender structure. This method requires considerable skill and an appropriate mix, and is widely used in tunnel construction. The Darwin Centre at the Natural History Museum in London by CF Møller is an elegant example of the technique, an eight-storey concrete cocoon with a smooth outer coating of render. More recently, Flanagan Lawrence's beautiful Acoustic Shells on the seafront at Littlehampton, West Sussex used hand-trowelled sprayed concrete to create smooth-flowing surfaces.

Using fabric as a mould inevitably creates curved forms, with results dependant largely upon the type of fabric used and its configuration. This form of construction has not yet reached the mainstream, but a good deal of research and experimentation is underway to refine it and overcome the unusual challenges it poses. One delightful aspect is that the pattern of the fabric is left on the concrete surface. Bomnong L'or School in Cambodia (see page 3) is a rare example where fabric formwork has been used to cast a structural frame on site.

Other innovative solutions using flexible moulds include inflated pneumatic structures, wax and lattice grids. But perhaps the most revolutionary process for shaped concrete is 3D printing – the rising popularity of which suggests that the future of concrete construction may be very curvy indeed.

# SPECIFYING LIGHTWEIGHT CONCRETE

Using lighter aggregates can cut the weight of a slab by 30% without reducing strength. Jenny Burridge considers the benefits

In recent years, the use of lightweight concrete has been limited to the concrete topping in composite steel construction. However, it can also be used for regular concrete-frame construction as it can achieve the same strength as normal-weight concrete. This makes it an ideal solution where site conditions dictate that shallow or reduced foundations must be used – for example, over vulnerable sewers or rail tunnels.

Lightweight concrete has a long history – the dome of the Pantheon in Rome is constructed from it, with the lightest concrete in the top rings made from pumice stone. The main benefits come, not unsurprisingly, from the material's lower weight. For a residential building with 7m spans, the self-weight of the concrete is approximately 60% of the weight to be carried by the slab. If lightweight concrete is used, the self-weight of the slab can be reduced by around 30%, meaning that the total load carried by the slab is reduced by about 20%. This 20% reduction in loading has a knock-on effect on the size of the columns and the foundations.

As the self-weight of the slab is reduced, it can also be reduced in thickness, but only slightly. Lightweight concrete can also be post-tensioned, providing even greater savings in the self-weight of the slabs. This has the same benefits as post-tensioning of normal-weight concrete: savings in reinforcement, concrete depth and programme.

Lightweight concrete also tends to have better insulative properties than the equivalent thickness of normal-weight concrete. This is not sufficient to take away the requirement for insulation but it can be taken into account in the calculations of the U-value. It also performs well on fire resistance. The minimum dimensions for beams and slabs made from normal-weight concretes, given in Eurocode 2 Part 1-2 on structural fire design, can be reduced by 10% if using a lightweight mix.

The thermal mass of lightweight concrete is not as good as that of normal-weight concrete but is still worth taking into account. The k-value used in Part L of the Building Regulations is reduced from about 230kJ/m$^2$/K for normal-weight concrete to about 160kJ/m$^2$/K for a concrete with a density of 1,600kg/m$^3$, which is a 30% reduction.

TABLE 1: DENSITY OF LIGHTWEIGHT AGGREGATES

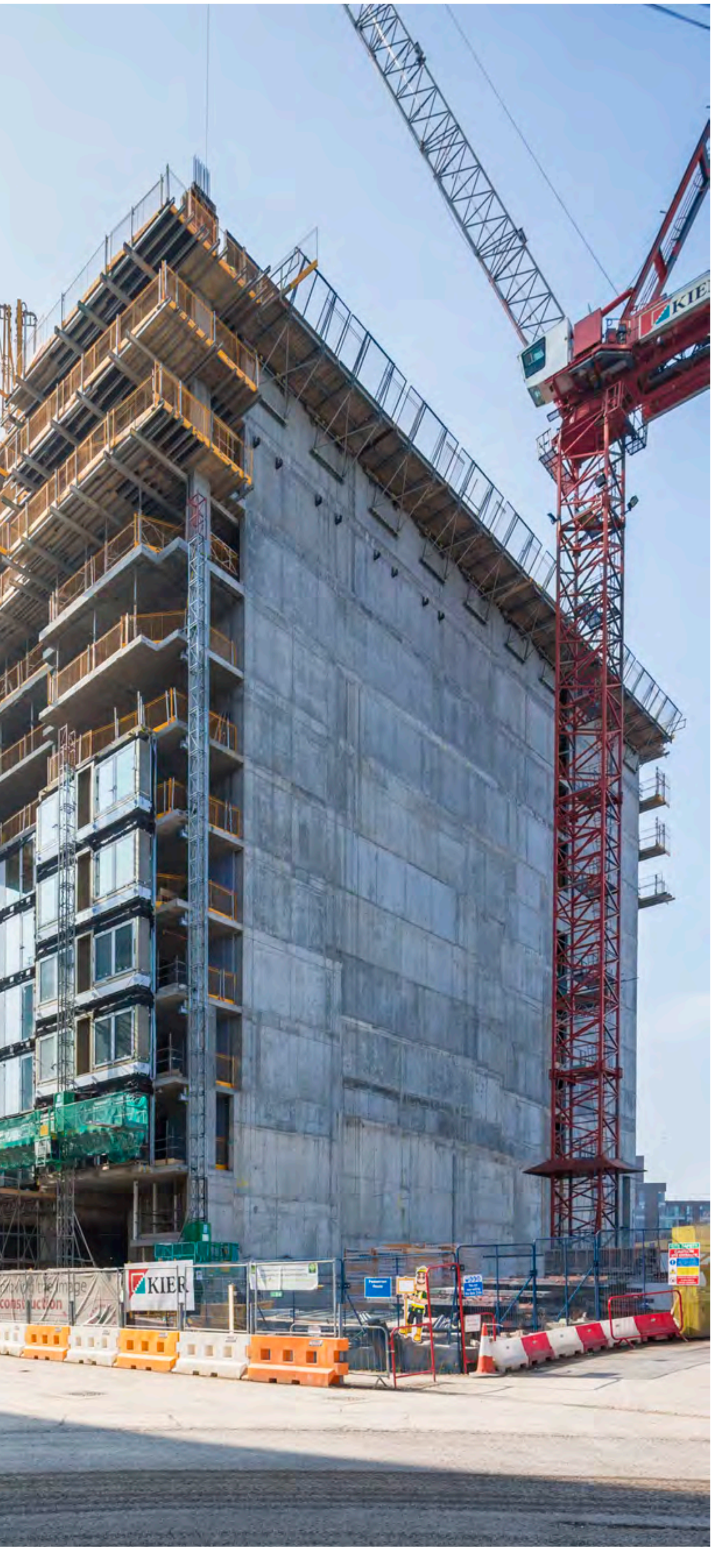
| Aggregate type | Proprietary product | Dry density (kg/m$^3$) |
|---|---|---|
| Furnace clinker | | 720-1,040 |
| Pelletised expanded slag | Pellite | 800-1,000 |
| Sintered fly ash | Lytag | 770-960 |
| Expanded clay, shale and slate | Aglite, Leca, Solite | 320-960 |
| Foamed blast-furnace slag | | 670-920 |
| Pumice | | 480-880 |
| Wood or plastic particles | | 320-480 |
| Expanded vermiculite | | 60-160 |

Source: The Concrete Society, www.concrete.org.uk

## Aggregates

Lightweight concrete is made by either using a lighter aggregate or by entraining air into the concrete. Lightweight concrete made by air-entrainment tends not to be very strong and should not be used for concrete-frame construction, but concrete made with lightweight aggregate can be as strong as normal-weight concrete. Lightweight aggregates can be used for either the coarse aggregate portion of the mix or for both the coarse and fine aggregates.

The most commonly used lightweight aggregate in the UK is made from sintered fly ash and is also known by the proprietary name Lytag. As fly ash is a by-product from the energy sector, Lytag can be considered as a secondary aggregate, which can achieve credits in BREEAM when used as part of the building or external landscape. Lytag is made in the UK and is a local aggregate, made from UK-produced fly ash.




**LEFT** The Tapestry building in King's Cross, London, by Niall McLaughlin Architects has a lightweight concrete frame using Lytag aggregate

**BELOW** Lightweight concrete made from pumice stone was used in the construction of the Pantheon in Rome, built between 118 and 128AD

The densities of commonly used aggregates are shown in table 1 (opposite page). Note that not all the aggregates in table 1 will give concretes that are strong enough for structural concrete.

## Design

The basic design of lightweight concrete structures is covered in Eurocode 2 Part 1-1. Section 11 contains the particular rules for lightweight-aggregate concretes. Concrete is considered to be lightweight if the density is not more than 2,200kg/m$^3$ (the density of normal-weight concrete is assumed to be between 2,300kg/m$^3$ and 2,400kg/m$^3$) and a proportion of the aggregate should have a density of less than 2,000kg/m$^3$. Lightweight concrete can be specified using the notation LC for the strength class – for example, LC30/33, which denotes a lightweight concrete with a cylinder strength of 30MPa and a cube strength of 33MPa.

The other property used in the design is the density class, as defined in Eurocode 2, which depends on the oven-dry density of the concrete

TABLE 2: DENSITY CLASSES FOR USE IN DESIGN TO EUROCODE 2

| Density class | | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
|---|---|---|---|---|---|---|---|
| ρ – maximum oven-dry density (kg/m$^3$) | | 1,000 | 1,200 | 1,400 | 1,600 | 1,800 | 2,000 |
| Oven-dry density range (kg/m$^3$) | | 801-1,000 | 1,001-1,200 | 1,201-1,400 | 1,401-1,600 | 1,601-1,800 | 1,801-2,000 |
| Density (kg/m$^3$) | Plain concrete | 1,050 | 1,250 | 1,450 | 1,650 | 1,850 | 2,050 |
| | Reinforced concrete | 1,150 | 1,350 | 1,550 | 1,750 | 1,950 | 2,150 |

Photos: John Sturrock; Art on File/Corbis

**ABOVE** The Isleworth campus of West Thames College, designed by MacKenzie Wheeler, has a concrete frame that uses Lytag lightweight aggregate. This reduced the weight of the frame by 25%, allowing pad foundations to be used and piling to be avoided

(see table 2, previous page).

The lighter the concrete, the greater the difference to be accounted for in the properties of the concrete. The tensile strength, ultimate strains and shear strengths are all lower than a normal-weight concrete with the same cylinder strength. Lightweight concretes are also less stiff than the equivalent normal strength concrete. However, this is mitigated by the reduction in self-weight to be carried, so the overall effect tends to be a slight reduction in the depth of a beam or slab.

Creep and shrinkage for lightweight concretes are higher than for the equivalent normal-weight concrete, and this should be taken into account when designing the structure.

## Construction

Batching of lightweight concretes is normally carried out by ready-mixed concrete producers – some plants will have lightweight aggregates available, others may require a short lead time to source the lightweight aggregate. At low workabilities, the concrete can easily be placed by skip or chute. Pumping lightweight concrete can be achieved, but care needs to be taken so that the concrete mix doesn't separate. For pumpable mixes it is usual to use a natural sand – that is, not to have a lightweight aggregate for the fine portion of the mix – and to have a high workability so that increased pump friction and blockage is avoided. This is achieved with the use of admixtures. Over-vibration of a lightweight concrete tends to cause segregation so a flowing concrete is best used when it is to be pumped, so that it requires only minimum vibration.

## Cost and programme

The basic cost of lightweight concrete tends to be slightly greater than normal-weight concrete. However, the saving on the building foundations has been shown to result in an overall reduction in the cost of construction when used in high-rise buildings. The size of the columns can also be reduced, providing a larger useable area at the lower storeys.

The programme for the main slabs is similar to that for normal-weight concrete, but due to the savings in the size and extent of the foundations, the programme for the structure as a whole can be reduced.

## Conclusion

Lightweight concrete can be used for typical concrete-frame construction. It can also provide an alternative to light-weight timber and steel solutions, and provides some superior performance benefits.

The inherent benefits of concrete also apply to lightweight concretes:

- Local sourcing
- Low embodied carbon
- Thermal mass (although this is slightly less for lightweight concretes than normal-weight mixes)
- High-quality finishes
- Durability
- Fire resistance (which is even better with lightweight concretes than normal-weight mixes)
- Good acoustic separation.

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# LASTING IMPRESSION WILLIAM MITCHELL

### MOTORWAYS AND OTHER OBJECTS OF BEAUTY

I believe that Spaghetti Junction 1 (1968-72)is one of the greatest things – it's a fantastic concrete structure. It should be used as a piece of artwork, like an abstract artistic interpretation on a wall or a mural. Think of the different colours you could use. Not enough is spoken about the aesthetics of motorway works. I did a lot of work in the Middle East, and I was very aware of the desert and how the wind turns it into sculptural shapes. When I came back here and was driving on the motorway, I could easily imagine the walls and roads as sections of desert rather than concrete. In the north, where towns like Sunderland and Newcastle are served by motorways, you come across these immense structures 2. On bypasses, the road is out of sight down below and there's an enormous retaining wall and on top of it are some buildings, and suddenly the whole thing becomes totally sculptural.

One of the biggest influences on my work was the 1951 Festival of Britain. It was a fantastic thing to go to. Nobody had ever seen anything like the Dome of Discovery, the Skylon and of course the Royal Festival Hall 3. They were expressions, sculptural statements. It's not so much that it influences you, it becomes part of your vision. You call on your memories without knowing it and up come all these images.

What I do feel very strongly is that architecture and construction is not taught enough in schools. It has a tremendous impact but it's something that happens "over there", like getting your car mended – it's not integrated into the civilisation. The star turns in architecture and engineering should be as well known as celebrities. Think of Crossrail 4 – there's this incredible tunnel being driven through the earth, being built under our feet. What a fantastic thing.

**William Mitchell is an artist, sculptor and designer. His book Self Portrait, The Eyes Within is out now**

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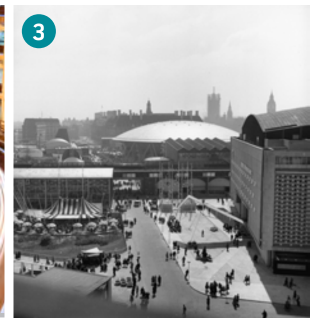

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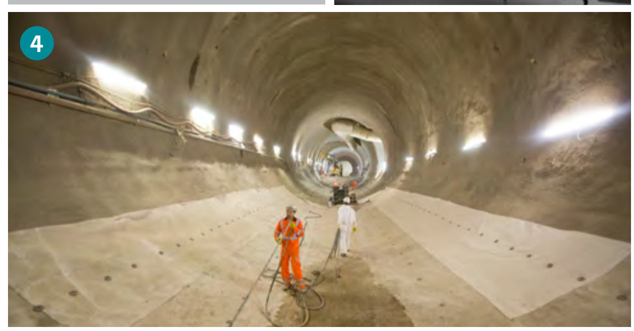

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Photos: 1. Hoberman Collection/Corbis; 2. Andrew Whitaker/Northern Horizons; 3. Colin Westwood / RIBA Collections; 4. Crossrail Ltd

# FROM THE ARCHIVE: SUMMER 1963

### SCULPT LIKE AN EGYPTIAN

Twelve years after the Festival of Britain, William Mitchell was adding his own artistic vision to London's other brutalist arts complex, the Barbican (pictured right). Mitchell's bold concrete murals prompted CQ to consider the role of the mural designer, lamenting that such reliefs are "widely regarded as an afterthought ... [and] the artist is thought of as someone called in at a late stage to rescue a building from bleakness".

Mitchell was part of a vanguard eager to show that sculpted murals and the expression of wall texture were in fact an integral part of architecture: "Take those shiny slabs over there," he told our correspondent at the Grosvenor Hotel in London. "They have no thickness – nothing; might just as well be a plastic skin ... Those Victorians knew a thing or two. Why not show the thickness of a wall?"

Mitchell's approach was to work closely with architects and contractors from the start of a project, with his knowledge of concrete construction and "continued zest for experiment" leading to some impressive results. CQ felt that his latest murals – in deeply modelled concrete, variously textured and cast against chunky sections of polyurethane – were "not unlike the sculptural ornament found in the ancient temples of Egypt".

**Access the full CQ archive at www.concretecentre.com/cq**

**FINAL FRAME: TWO MOON, SOUTH KOREA**

Architect Moon Hoon has created a pair of extraordinary reinforced-concrete mixed-use buildings in the town of Goyang, north-west of Seoul. They stand 2m apart, appearing almost as mirrors to one another thanks to the vast facing moon-shaped curves scooped out of the facades. Two pantheon-like domes above the third floor echo the moon motif. The concrete is left exposed and board-marked throughout the buildings, bringing the project back down to Earth ...

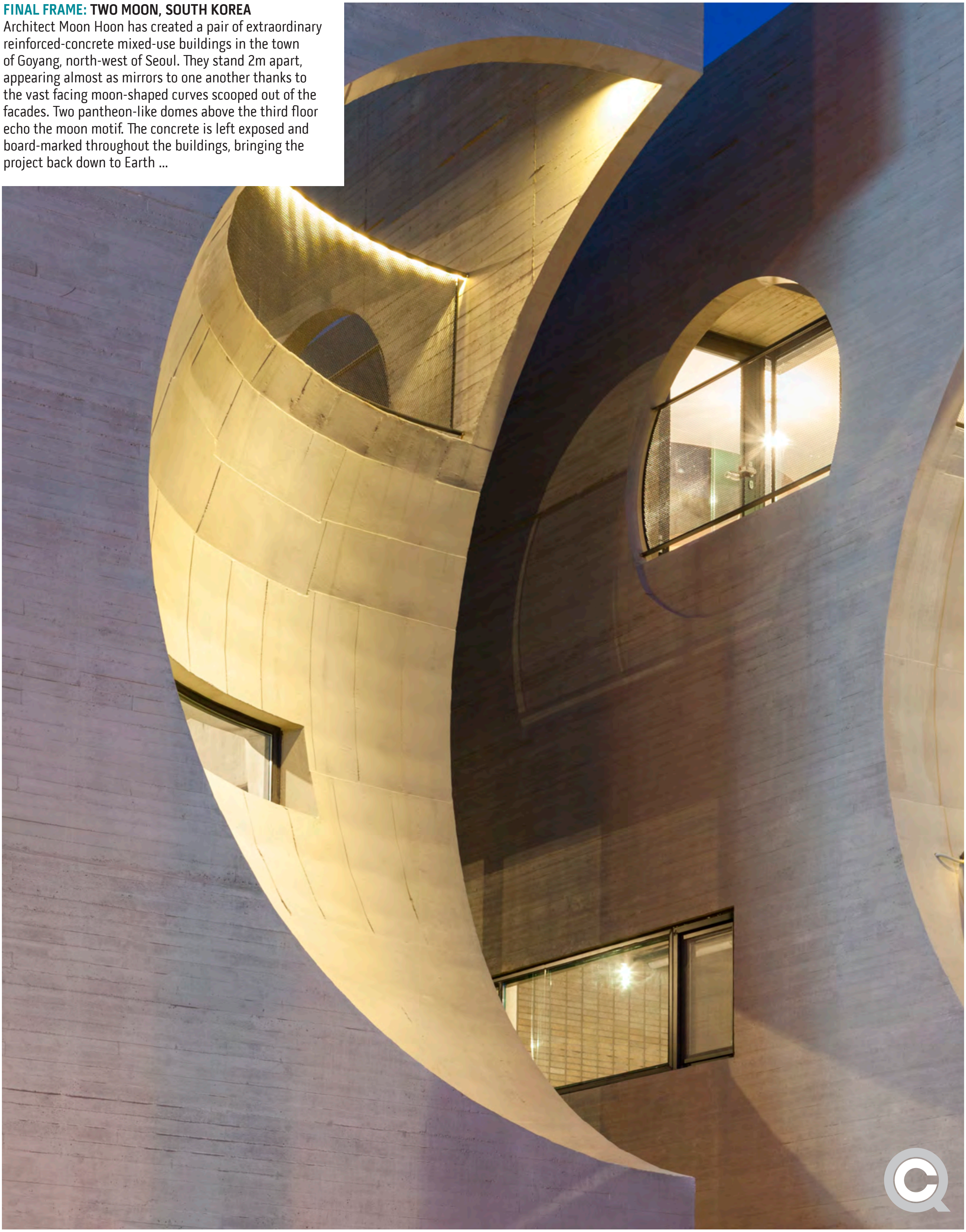

Photo: Namgoong Sun