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CONCRETE QUARTERLY

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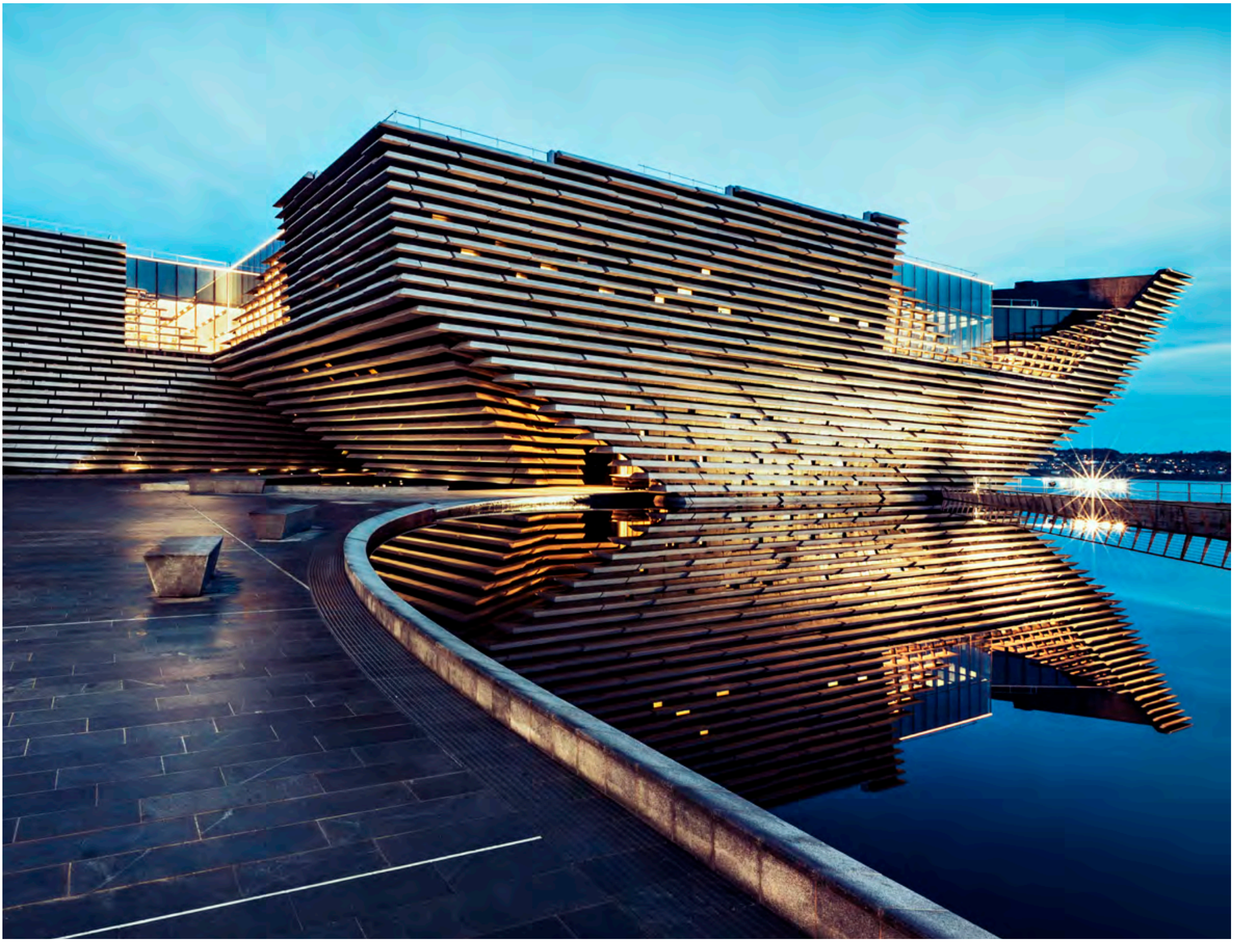

ROCK ON THE DOCK
Kengo Kuma's cliff-like V&A Dundee lands on the Tay riverfront

SLIMMING SECRETS
The technical innovations behind the resurgence of thin concrete

NO SHAKES
How Arup vanquished vibrations at University College London's neuroscience lab

CONTENTS

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AGENDA

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

The many-headed designer

A very warm welcome to readers unaccustomed to receiving Concrete Quarterly. This Autumn issue is distributed with both RIBA Journal and The Structural Engineer in addition to our regular print and online subscribers.

Our enlarged readership has caused me to reflect on the changing relationship between different members of the project team – and on the multidisciplinary working that is becoming more essential than ever. In the context of human history, the architect and engineer as discrete roles is a relatively recent innovation. Leonardo was not only an artist but an engineer, an architect and a designer; the mega-projects of the past were typically led by a master builder responsible for both design concept and structure. In the more recent history of concrete buildings, many of the 20th century's landmarks were produced by architect-engineers such as Pier Luigi Nervi and Félix Candela. In part because concrete first emerged as a structural material, engineers were the first to realise its aesthetic and sculptural possibilities.

IN THE CONTEXT OF HUMAN HISTORY, THE ARCHITECT AND ENGINEER AS DISCRETE ROLES IS A RELATIVELY RECENT INNOVATION

Of course, in an ideal world we would all understand everything – one person would have a thorough grasp of design concept, architecture and structure, not to mention building systems and specialist disciplines such as fire engineering. But many people working together is clearly likely to result in a much better end product. Even an apparently straightforward home has many more components than in the past, with the advent of modern comforts, communications and low-energy design, and on a highly technical building such as a hospital, the building services may account for more than half of the total cost. All of these things make it more complicated and therefore important that different disciplines are coordinated and working together. Sustainability is now being absorbed into everyday practice, but it is a moving target, as is designing for the future climate and anticipating and mitigating growing problems such as overheating. And for all of our technological progress, we are still wrestling with age-old problems such as keeping the rain out and preventing buildings from catching fire.

Today, the concept of a building as a solution to a client's requirements may initially be predominantly the concern of the architect – but within this are a plethora of interconnected disciplines. There are many fewer problems when the architectural concept and the structure are properly aligned, so the earlier that this collaboration happens, the better.

this is concrete

HEATED DEBATE IN THE HOUSE

The House of Commons Environmental Audit Committee claimed that modular homes are not resilient to heatwaves, sparking considerable debate during the UK's record-breaking summer, writes This is Concrete blogger Tom De Saulles. "Those ... who produce lightweight systems were not happy that the report recognises that many factory-produced homes ... lack thermal mass," he says. But the fact remains that thermal mass is an effective means of reducing overheating in conjunction with ventilation and solar shading. "If we are going to tackle the problem ... without resorting to energy-intensive air conditioning, we need to employ all the passive measures available to us."
www.thisisconcrete.co.uk

CONCRETE QUARTERLY

On the cover: V&A Dundee by Kengo Kuma. Photo: Ross Fraser McLean
Produced by: Wordmule
Designed by: Nick Watts Design

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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

Tate touted

Jamie Fobert Architects' extension to Tate St Ives in Cornwall has been shortlisted for the Stirling Prize. The dramatic subterranean gallery is spanned by 16.5m-long in-situ concrete beams, inspired by the fishing lofts used as studios by Cornish artists.

Jamie Fobert's lasting impressions P19

Pod and breakfast

Architect Innovation Imperative and engineer WSP are developing a carbon-neutral modular hotel made from diamond-shaped reinforced-concrete pods. The panels would be made from local materials and fabricated on site, allowing the concept to be realised in remote locations.

Clifton rises again

Purcell has finished the £3.1m refurbishment of Percy Thomas' brutalist masterpiece Clifton Cathedral in Bristol. The building was completed in 1974 and remains the UK's last major new church.

From the archive P19

Making light

ETH Zurich has developed a lightweight concrete ceiling built by robots with formwork 3D-printed from sand. The Smart Slab has been computationally designed to use only the minimal amount of material necessary to make it load-bearing, and is less than half the weight of usual concrete slabs.

Photos: Hufton + Crow; Innovation Imperative: Phil Boorman; Digital Building Technologies Group, ETH Zurich / Tom Mundy

Image: Hélène Binet

CAFE CONCRETE

The ever popular Cafe Concrete returns on 30 October. This pop-up event will provide inspiration and information on the design and construction of visual concrete. The venue this year is Haworth Tompkins' Coin Street Neighbourhood Centre on the Southbank in London. The event will feature:

- Presentations from designers of high-quality projects, including Feilden Fowles' Yorkshire Sculpture Park visitor centre, Stormy Castle in Gower by Chris Loyn and Co, and Villa Waalre in the Netherlands by Russell Jones (left)
- Best practice guidance on the specification of visual in-situ and precast concrete
- Seminars from technical experts and specialist product manufacturers
- Pop-up exhibits and samples of products
- A relaxing, informal environment, with a constant supply of refreshments.

Cafe Concrete is free to attend. To find out more and book tickets, go to concretecentre.com/cafeconcrete

BEHIND THE SCENES AT THE EXHIBITION

For a design museum, it is ironic that so much of the groundbreaking design of Kengo Kuma's V&A Dundee – from the formwork to the reinforcement – will never be seen. Tony Whitehead finds out what lies behind this extraordinary structure

Photos: Ross Fraser McLean

"Take two decks of cards and place them on a table a few inches apart. Then twist them so they join together." This is how one engineer describes the new V&A Museum in Dundee – surely one of the most remarkably shaped buildings to have been constructed from concrete.

None of its 21 elevations are vertical. Many of them are curved in two dimensions. Concrete walls up to 18m high incline outwards at a variety of unlikely angles and onto these are attached no fewer than 2,429 precast-concrete elements weighing up to three tonnes each.

Designed by renowned Japanese architect Kengu Kuma, this extraordinary, £80 million, 8,000m^2 building looks (from some angles) like a ship about to sail off into the Firth of Tay, on whose banks it stands. But such is the nature of the building that every perspective suggests something different: sails, a cowry shell or the stratified rock formations that were Kuma's original inspiration.

To the construction-minded visitor, however, one pressing question immediately presents itself: how does it stand up?

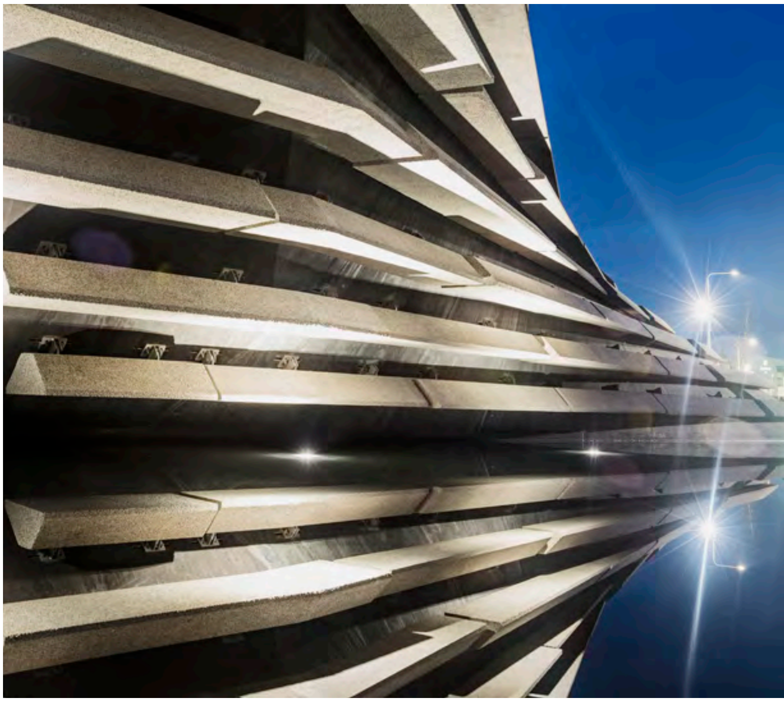
"The overall structure works as one," explains project architect Maurizio Mucciola at PiM studio. "The external walls are tied back via the slabs and the roof to the two central cores – so the building was not stable until the roof structure was complete. It meant much of the supporting exterior formwork and falsework had to stay in place for more than a year until the roof was finished."

The design presented such unique technical and construction challenges that in its early stages a variety of structural solutions, including using steel for the upper storeys, or building it entirely from precast blocks, were considered. However, says Mucciola, "In the end, in-situ concrete gave us the most flexible solution, combining technical ability with the freedom to create the shapes we wanted."

The V&A Dundee opened its doors in September. Its three floors contain a restaurant, extensive storage facilities, an auditorium, classrooms and a library as well as several galleries providing 1,650m^2 of exhibition space. It is statement architecture in every way – a new point of focus for the city and one designed to reconnect Dundee to its riverside heritage.

As such, its shape is designed to attract and fascinate, but the story of how it was created is no less intriguing. Mucciola explains that the outside of the building is formed from mainly 300mm-thick, heavily reinforced, high-strength in-situ concrete, though in some places, where the spiralling tangle of stresses was particularly high, the thickness has been increased to 400mm. "But we wanted the facade to be as thin as practically possible, not only to save weight and concrete, but also because it is punctuated with some 60 or so windows. If ▶

WE WANTED THE FACADE TO BE AS THIN AS PRACTICALLY POSSIBLE, AS IT IS PUNCTUATED WITH SOME 60 OR SO WINDOWS



WE WERE WORKING TO TOLERANCES OF ABOUT 1-2MM. AT TIMES IT WAS LIKE BUILDING A BRIDGE

the external wall was any thicker (on top of the insulation and render on the interior side of the concrete), very little light would find its way through to the gallery spaces of the interior."

Achieving the required wall thickness while accommodating the complex stresses and loadings created by the building's twisting shape was a key challenge for the principal structural engineer, Arup associate Graeme Moncur. "The early designs had 600mm-thick walls," he says, "but by extensive modelling and analysis we were able to reduce this to mostly 300mm of concrete."

This was achieved first by identifying more exactly what stresses lay where. Then, says Moncur, "We were able to reduce the wall strength needed by slightly modifying the design so that in places the height of some walls was reduced a little, or the incline made slightly less steep, all the while remaining true to the architect's original vision."

In conjunction with the concrete contractor and supplier, Arup developed a high-strength 70kN mix that included 27% fly ash. "A cement substitute was desirable because this is a high-strength mix with quite a high cement content so GGBS [ground granulated blast-furnace slag] would normally have been used, both to reduce the CO_2 footprint, and also to reduce the heat of hydration," says Moncur. "However, the facade concrete contains pigments to make it very dark – almost black – so as GGBS makes concrete paler we opted for fly ash instead."

The concrete also contained small amounts of silica fume, micro silica and limestone fines to help strengthen the mix: "The micro silica helps to infill pores and densify the concrete, which is good for durability given that the building is situated on a brackish, tidal river estuary and will have to resist salts in the air."

Finally, adds Moncur, the mix contained plasticisers to increase flowability. "This was vital because of the amount of dense reinforcement, and the many odd angles and inclines where air might become trapped."

At one point the team considered using spiral reinforcement in order to create tunnels through which vibrating pokers could be inserted, but were unable to source spirals long enough. Fortunately, this proved unnecessary: "In the end, the mix's good flowability meant we had very few problems with air."

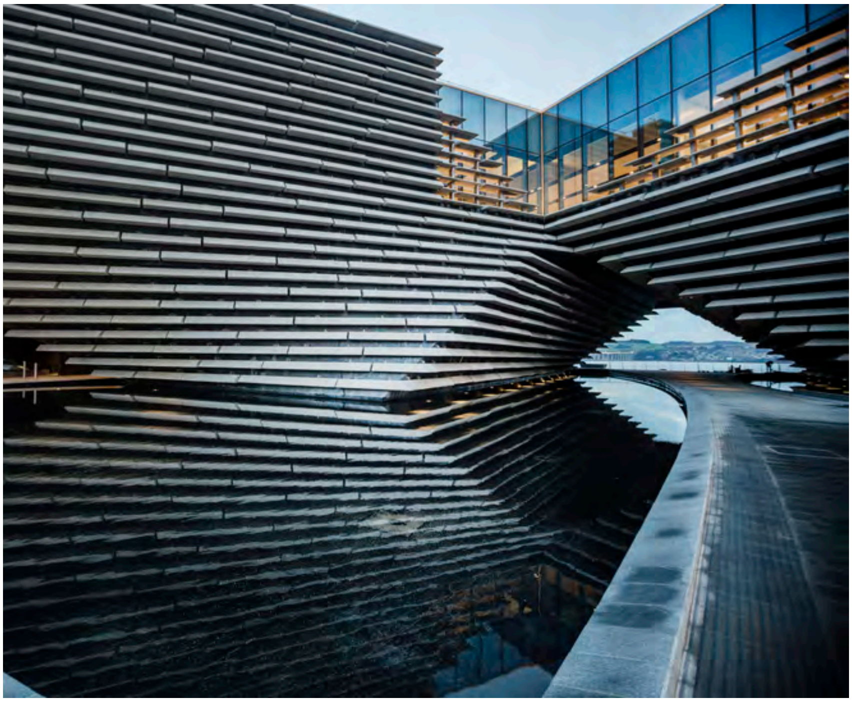
Having hit on a mix that was dark enough, strong enough, salt-resistant and flowable enough to negotiate the reinforcement, the team then had to set about creating foundations that would be able to take the unusual loads presented by the V&A's irregular shape. "It's not like a normal building," says Moncur. "You have inclined forces coming down, so you have to resolve horizontal forces through the

TOP LEFT Kengo Kuma has described the rock-like concrete exterior as "a very Scottish solution"

TOP MIDDLE The facade includes no fewer than 2,429 precast-concrete elements weighing up to three tonnes each

TOP RIGHT The two volumes of the building form a bridge over the riverside walkway

RIGHT The building will play a key role in the regeneration of Dundee's waterfront



beams and slab and into the piles."

In practice, this meant using 849m^3 of concrete to sink 198 concrete piles 11m down to bedrock. A further 2,053m^3 of concrete and 364 tonnes of reinforcement was deployed to create pile caps and a grillage of ground beams, typically 1m square, on top of which was laid the 300mm-deep ground slab.

Moncur explains that since the V&A is effectively two buildings, each tied back to its own core, each exerts its own inclined forces: "So the ground slab is in compression in some places and in tension in others, and has to act to stop the buildings pushing into each other."

These unusual forces were more active during construction, before the roofs were completed, so for additional stability a temporary concrete slab was also laid around the outside of the building to stabilise the ground and also to provide a firm basis for the huge amounts of formwork and falsework involved in creating the difficult exterior facades.

Malcolm Boyd, construction manager with BAM Construct UK, says: "Because of the nature of the walls, each piece of shuttering was unique and had to be precisely positioned in order. If the wrong shutter arrived at the wrong time, we couldn't just move on to the next one. Correct sequencing was vital." Twenty designers were working on the project for formwork supplier Peri, and such was the size of the job that it was manufactured at five locations across Europe, in Scotland, England, Ireland and Germany.

In all Peri delivered 1,200 bespoke shutters at a rate of around 1,000m^2 per month. The facility in Germany was used to provide the majority of single-use timber carcasses, which were cut with CNC machinery. These were then sent to the firm's UK depot in Rugby for the addition of plywood skins and steel formwork before delivery to site.

Construction on site required a team of 30 joiners, working in squads of four or five. "The outward-leaning shutter would go on first," explains Boyd. "To locate the shutters precisely, we used electronic distance measurers (EDMs) to scan the shutter, take readings and draw up a heatmap on screen. Positioning was vital as we were fitting unique shapes one with another. In addition, we were effectively building two buildings that had to join precisely – so we were working to tolerances of about 1-2mm. At times it was like building a bridge." ▸

9km of irregular cladding

V&A Dundee is clad with 2,429 precast "planks" up to 4.4m long and ranging in weight from 0.9 to 2.8 tonnes. Each lies horizontally against the in-situ concrete walls of the facade, but because these walls are curved and inclined, the back face of every element had to be specifically angled in order to ensure a good fit.

Over a period of 12 months, Techrete produced nearly 9km of these precast elements. To do so efficiently, it worked with a steel mould manufacturer to develop a means of producing elements with variable facets. Essentially this comprised a reusable steel mould that could be tilted. The face of the element was arranged so as to be level and horizontal, at the top of the mould, with the required angle created by tilting the mould below.

Sean Callow, Techrete's production planner, says: "We could have spent a small fortune getting a mould for every angle – so we had to find an adjustable solution. Initially we looked at maybe having a hydraulic or motor-driven mould. But this would also have been expensive. By working on the mould's centre of gravity and the point at which it rotated, we managed to get it nicely balanced – so that two men could adjust the mould and lock it into position by hand."

The length of each element could be varied by moving the moulds' adjustable stop-end panels. Some of the moulds were slightly larger to create deeper elements – again in order to accommodate the curving walls. "Altogether we had eight adjustable moulds and a couple of more standard ones," says Callow.

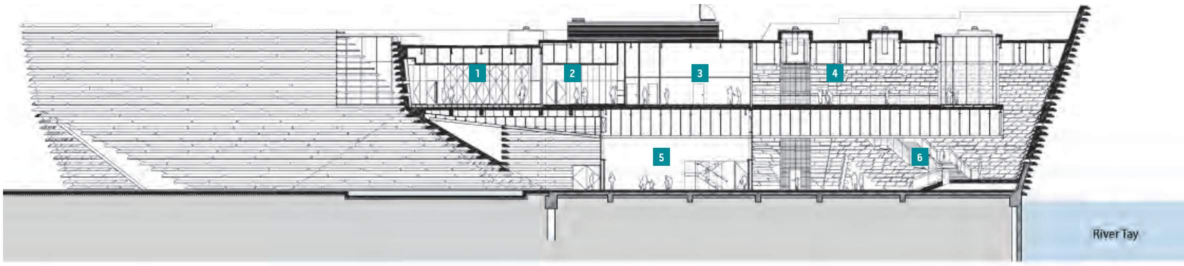
The mix, a reconstituted granite, was designed to reflect the ruggedness of the local Scottish landscape. An exposed finish was created by applying a retarder to the moulds during the production stage. This prevents the cement setting hard on the surfaces of the units, allowing a thin layer to be easily removed with a light power wash to expose the aggregates.

Each element is fixed to the building using cast-in stainless-steel hooks, which fit into brackets located in channels cast into the facade.

Techrete used building information modelling (BIM) to design all of the component parts and also developed a GPS system to place all the channels and fixings to assist site installation.

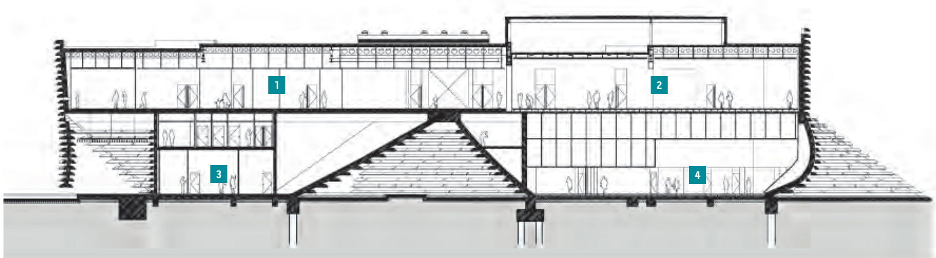
SECTION CC

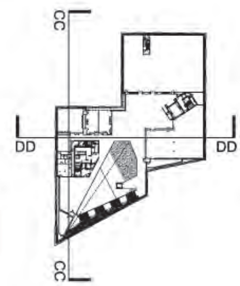
1 Auditorium
2 Design studio
3 Kitchen
4 Restaurant
5 Foyer
6 Hall



SECTION DD

1 Learning centre
2 Scottish design galleries
3 Toilets
4 Office





He adds that the formwork featured a controlled-permeability liner to reduce moisture on the surface of the concrete, a technique that results in a denser, more hard-wearing exterior finish. The shuttering also came with pre-applied forms for the cast-in channels that would be used to fix the precast cladding elements.

Positioning the reinforcement in these curved forms was something of a challenge – the starter bars for the most curved sections of walls emerged from the foundations like a twisted fan. The reinforcement was then positioned using the external shutter as a template. This also involved reverse-positioning the reinforcement with vertical reinforcement on the exterior side (to follow the line of the shutter) and horizontal bars (normally on the outside) towards the interior face.

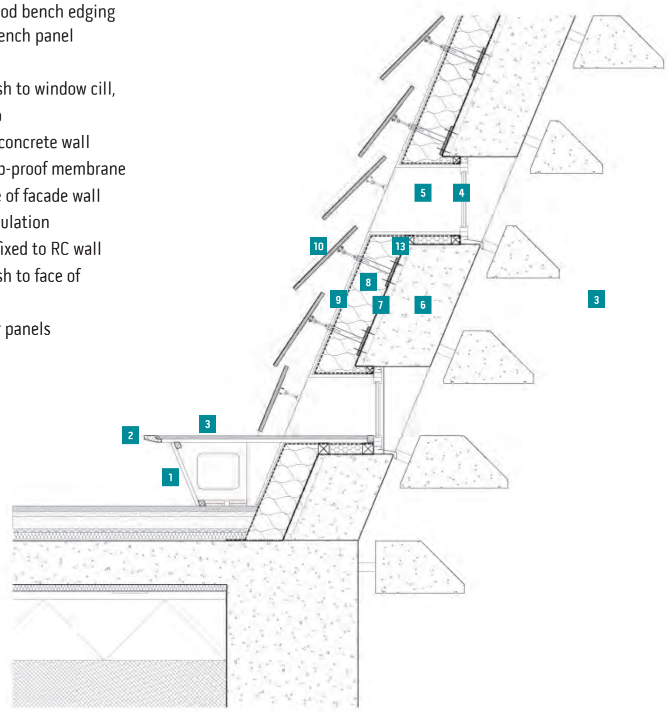
"Bar diameters ranged up to 30mm, but in sharply curved areas these would be difficult to work," says Moncur. "Some were specially shaped, but in places thicker bars were replaced by a pair of thinner ones (say, two 16mm) to enable them to be more easily bent into shape on site."

With the extraordinary formwork and reinforcement taking shape, the first pours for the facades could commence – typically in 4m x 10m sections. In all, some 2,300m^3 of concrete and 1,300 tonnes of reinforcement were used for the exterior walls alone.

As the walls rose, so the first- and second-floor metal deck and concrete composite slabs were also constructed. Along with a number of shear walls, these were vital for tying the inclined walls back to the cores. Male-female connections

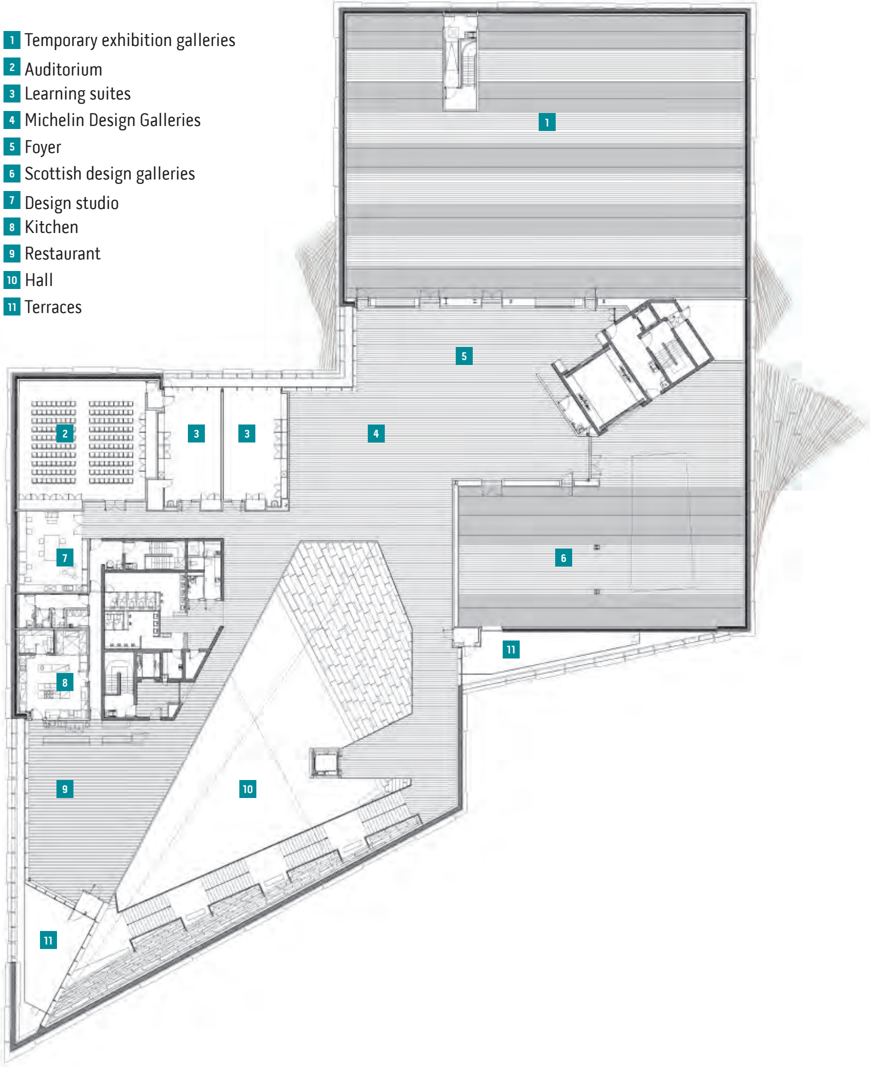
DETAIL: EXTERNAL WALL

1 Black laminated MDF
2 Oak hardwood bench edging
3 Veneered bench panel
4 Window
5 Render finish to window cill, head and jamb
6 Reinforced concrete wall
7 Liquid damp-proof membrane coating to face of facade wall
8 Thermal insulation mechanically fixed to RC wall
9 Render finish to face of insulation
10 MDF veneer panels



GALLERIES FLOOR PLAN

1 Temporary exhibition galleries
2 Auditorium
3 Learning suites
4 Michelin Design Galleries
5 Foyer
6 Scottish design galleries
7 Design studio
8 Kitchen
9 Restaurant
10 Hall
11 Terraces



had to be specially designed to cope with the forces involved and ensure the facades remained firmly connected.

"At roof level, the walls are held back to the cores via steel roof trusses, each exerting about 4,000kN in tension, the equivalent to 16 fully-loaded 6m^3 concrete trucks," says Moncur. "The cast-in steel-plate connections for these had to be very precisely positioned and weighed 1.1 tonnes each."

With roofs and structure complete, Careys could commence dismantling the external formwork which had supported the walls. "The loads spiral down," says Boyd, "so it was important to de-prop in a balanced way – simultaneously north and south, and then again east and west."

As the formwork came down, and the diaphragm ties of the building's floors and roof took the full strain of the inclined walls for the first time, Boyd admits that it was an anxious time. "We were worried about cracks," he admits, "but I'm pleased to say there weren't any."

Now it is complete, with its stunning precast cladding (see box), the construction team at times seem almost bewildered by what they have managed to create. As Moncur says: "Arup worked on the Sydney Opera House and the Taichung Opera House – so we've done some pretty unusual buildings. But nobody has ever done anything like this before."

"It certainly extended the grey matter," agrees Boyd. "The design really made you think hard every day. It might sound like a nightmare to build, but actually it was a great experience.

"I'll never get the opportunity to do anything like this again. It's been a privilege. And it looks fantastic."

PROJECT TEAM

Architect Kengo Kuma
Delivery architect PiM.studio
Main contractor BAM Construct UK
Structural engineer Arup
Concrete structure Careys
Formwork PERI UK
Precast facade supplier Techrete

Access: climbing the cliff

Rather as an overhanging rock face presents mountaineers with their most testing climbs, so constructing the outward leaning walls of V&A Dundee provided a series of unique challenges for the construction team.

"Access was always going to be tricky," says BAM construction manager, Malcolm Boyd. "We developed a number of ways to maintain access safely. For example, there was so much formwork and falsework we turned it to our advantage, building in steps and handrails as we went and strengthening the formwork tops to create platforms from which we could work on the next set of pours."

Attaching the precast elements was also much harder than if the walls had been vertical. "Obviously a crane rope hangs vertically," says Boyd, "so for the steepest inclined walls – those nearest the ground – it was impossible to use a crane as the planks would hang too far from the wall."

The solution was to use fork-lifts for the lower sections, though even this approach needed refining: "The precast planks had to be angled exactly to get the hooks to fit into the brackets," says Boyd. "To do this required fitting special tilting tables to the forklifts. Once modified we could slot them in nicely."

For the higher, less inclined levels, the cladding was attached with the help of mobile cranes and a lifting beam: "We would have the precast on one side of the beam and ballast on the other. By varying the pick up point of the beam we could tilt the plank into place on the facade."

Once in position, the element would be connected manually, using where possible the access platforms built into the supporting falsework. At the peak of construction, the team were fitting some 22 of the precast elements per day.

Photo: V&A Dundee. Drawings: KKAA

Photos: Keiko Sasaoka

RETURNED TO EARTH

David Chipperfield's red-hued cemetery near Osaka is at one with its landscape, writes Debika Ray

On a steep site in Japan's Hokusetsu Mountains, about 40km north of Osaka, David Chipperfield Architects has placed an imposing structure whose red concrete stands out amid the dense forest around it. The new chapel and visitor centre at the Inagawa cemetery is a space for gathering and reflection. "Our client asked us to create a timeless building that would be a welcoming place for everyone, irrespective of religion or cultural background," says project architect Tom Herre.

Outside the building, the grounds are laid out across terraces, bisected by a monumental flight of steps that leads up to a shrine at the highest point. The architects took these dramatic surroundings as their starting point – for example, the sloping roof of the building follows the incline of the mountain and the view line from the entrance to a shrine. The lower part of the staircase was rebuilt with a fountain at the bottom – both in red concrete – with water from the mountain running down a rill in the middle. "The connection to nature is prevalent in Japanese culture and was a consideration in shaping the project," Herre says, "with the central wildflower garden and the chapel's courtyards offering quiet places for contemplation."

Concrete was chosen partly because of the area's high seismic activity. But there is also symbolic value to the material – to imbue the building with a sense of permanence, stillness and shelter. "The solidity gives a sense of withstanding the passing of time, but it also offers a sense of temporality with its changing appearance," Herre says.

The red colour and rough texture were chosen for their earth-like quality, and were determined through a series of trials that explored the light and seasonal conditions the building would have to withstand. "The porous red concrete has an ever-changing appearance influenced by light, weather and seasons – sometimes reflecting the sunlight, at other times soaking up the rain," Herre says. The colour additives made the concrete very viscous – to make sure it was poured successfully, the contractor installed transparent perspex panels in critical areas of the formwork.

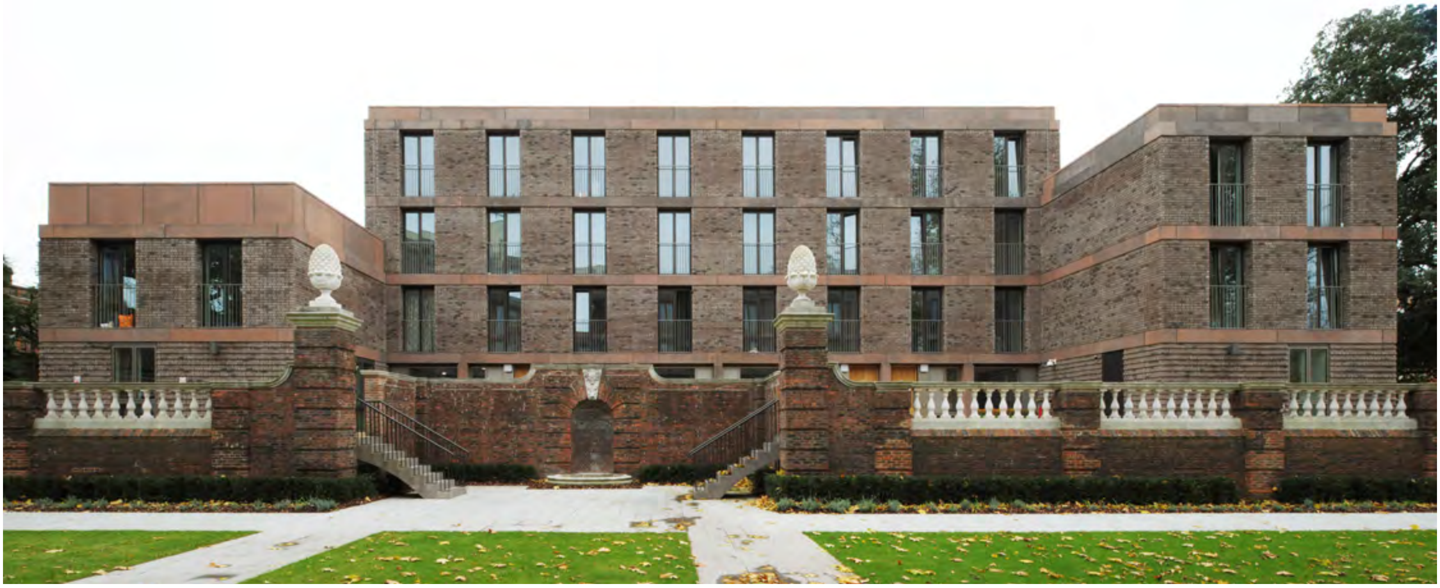
Outside, the walls, walkways and roof are ground and sandblasted, revealing the aggregate and giving the concrete a rough surface texture. This also helped to ensure there were no visible pores, which – along with the roof merging with the outer walls – gives the building its monolithic appearance. The same material is used inside the chapel, but it is honed to produce a smooth, light-reflective surface, while the internal floors are ground and honed for a terrazzo finish. This simplicity chimes with the range of specially designed furniture to create an arena of seclusion and reconnection with nature.

PROJECT TEAM

Architect David Chipperfield Architects
Landscape architect Marcia Iwatate + Kamimura
Structural consultant Jun Sato Structural Engineering
Contractor Obayashi Corporation

CLOCKWISE FROM TOP LEFT

Water from the mountain runs down a rill in the middle of the central staircase; the sloping roof follows the incline of the surrounding landscape; the red concrete changes appearance depending on light and weather



Photos: David Grandorge; Nick Kane

PURPLE POWER

The Stirling-shortlisted Chadwick Hall holds its own against its celebrated neighbours, writes Pamela Buxton

Chadwick Hall, the Stirling Prize-shortlisted student accommodation at the University of Roehampton, is quite literally a stone's throw from the celebrated grade II*-listed Alton West housing estate. Designed by Henley Halebrown, the new housing takes references from both its Corbusian neighbour and more historic properties on the university's south-west London campus. With its sense of gravitas, permanence and history, Chadwick Hall is a world away from the cheap anonymity of many student residence towers.

Henley Halebrown has been working on the site for ten years since being appointed to masterplan the campus, set in mature parkland formed from the gardens of grand historic houses. Chadwick Hall provides 210 student rooms within three new blocks around the surviving Downshire House. The North and West Courts are positioned to enclose a sunken terrace alongside the grade II*-listed Georgian property while South Court is conceived as a replacement to the house's lost south wing.

All share the same superstructure of inset in-situ concrete frame, flat slabs and columns, which was chosen as the best way to create a very adaptable building for housing. They also share a load-bearing masonry facade of dark brick and precast-concrete beams and lintels, which is tied back to the frame for stability. "It's all about the history," says Henley Halebrown principal Simon Henley. "Brick from the house and concrete from the Alton West estate develops a language that bridges the two."

The loadbearing facades relate directly to the landscape through the use of balconies that carefully mediate the threshold between private and public space. The balconies are formed as precast-concrete units, which are thermally broken from the structural frame and supported on the brick piers of the facade. These deep reveals also achieve Henley's desire to create a building that appears "visibly built". The combination of brick and precast-concrete soffits and lintels again nods to the contrasting colours on the facade of the historic house.

The precast-concrete elements measure up to 1,100mm x 3,000mm x 1,500mm, giving the desired monolithic appearance. Much thought went into their colour, which is the same for all facades, with some minor natural variation. "One of the delights is the variation in colour. It's really quite painterly," says Henley of the hue, which runs through purple-brown, red and pink and was achieved by adding pigment to the mix. All of these precast elements have a light acid-etched finish.

The overall result is a restrained, muted appearance that emphasises, he says, the enduring nature of the building and the academic institution it serves. Just as importantly, the integration of the inhabited balconies and the framing of the landscape creates a sense of community that will, more than anything, be the foundation of students' experience of university life.

CLOCKWISE FROM TOP
Each facade combines brick and precast concrete; sculptor Lynne Chadwick's The Watchers stands guard over the South Court; the precast-concrete lintels are pigmented with a light acid-etched finish

PROJECT TEAM
Architect Henley Halebrown
Structural engineers Buro Happold, Campbell Reith
Contractor Morgan Sindall

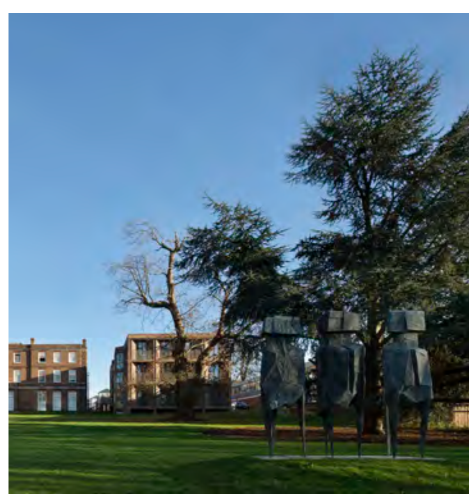


Photo: hi-con.com / Gerda van Ekris

RETURN TO SLENDER

Innovations in reinforcement are reversing the trend for thicker structures, writes Elaine Toogood

A kind of sublime structural geometry enables the thin shell structure of L'Oceanogràfic in Valencia (1994-2002), by architect Félix Candela and structural engineers Alberto Domingo and Carlos Lázaro. It is one of many dramatic long-spanning, curved structures where naturally self-supporting hyperbolic and curved forms are constructed in a concrete that seems impossibly thin. Geometry is also key to the slender profiles achieved at Acoustic Shells, Littlehampton (CQ 254), whose sprayed concrete structure is as thin as 100mm in some places.

Geometry aside, the thickness of a reinforced concrete structure is influenced by the size and location of steel reinforcement bars and by the depth of concrete cover they require. This is a response to exposure conditions, design life and fire performance. In the UK, contemporary construction standards typically lead to a greater overall thickness than was common in the 1950s and 60s for comparable structures. But this trend is now being reversed with innovation in various fields, particularly in alternative types and uses of reinforcement, providing opportunities for thinner concrete and chiming with the recent focus on resource efficiency.

The **post-tensioning** (PT) of in-situ slabs has increased dramatically in the UK over recent decades. Pre-compressing the concrete element – so that when it flexes under applied loads it still remains in compression – allows a more efficient structural design, offering a potential reduction in floor slab depth of 50-75mm. This is a major benefit for high-rise development, where an extra floor can be gained for every ten storeys. Pre-stressing, or pre-tensioning in the manufacture of precast floor slabs, is also commonplace in the UK. The "pre" in pre-stressing describes the stress applied before any normal loads. The "post" in post-tensioning refers to the tensioning of the strands

ON HIGH-RISE DEVELOPMENTS, POST-TENSIONED CONCRETE CAN GAIN AN EXTRA FLOOR FOR EVERY TEN STOREYS after the concrete has been cast and when it has gained sufficient strength to be compressed in an equal and opposite reaction to the tensioning of the strands. For more information, see The Concrete Centre guide, Post-tensioned Concrete Floors.

Progress in **fibre reinforcement** over recent years has also led to thinner forms of concrete (see House in Two Days by Cornish Concrete, below). Ultra-high performance concrete (UHPC) is a form of fibre-reinforced concrete used for factory-produced or precast products. It is poured into moulds like conventional concrete, but achieves greater bond, shear and compressive strengths of 100MPa-350MPa. The use of steel fibres also enhances the Young's modulus, tensile strength and ductility of the concrete, providing an opportunity to create thinner structures than previously possible (see Catharina Bridge, left), or types of structure that would not have been possible at all, as exemplified by the delicate laced concrete screen of Mucem, Marseille (CQ 245).

Examples in the UK have so far been seen in staircases, interiors and cladding (see Gasholders, overleaf), as well as the very specific requirements for the repair of Hammersmith flyover in west London. In Denmark, there are numerous examples of ultra-slim balconies using a version called CRC (compact reinforced composite – see overleaf), and elsewhere in Europe product development includes ultra-thin insulated sandwich panels and even precast whole-house solutions.

Glass fibre reinforcement is used in a thin cement-based composite material, glass-fibre reinforced concrete (GRC). This shares many of the aesthetic qualities of architectural precast concrete, but is used for non-load bearing applications. Its slenderness, around 15-20mm depending upon application, results from the use of strands of alkali-resistant glass-fibre

◀ Catharina Bridge, Leiden

The Catharina Bridge in Leiden is the longest bridge in high-performance concrete in the Netherlands. The pedestrian and cycle bridge, designed by Delft-based architect DP6, is 36m long and 6m across. The slender design has a slight S shape and is supported by two piers rising from the water. Ultra high-performance concrete was specified to allow for a long span between the piers and a slim deck with a shallow gradient, thereby ensuring the free flow of traffic both by road and by water. The middle of the bridge deck is 275mm deep.

▶ House in Two Days, Cornwall

Cornish Concrete Products (CCP) provided all of the structural components, except for the roof, for a two-storey private residence near Falmouth, and erected them in just two days. The four-bedroom detached property has been built with crosswall construction, using a system known as Slimcrete. The mineral fibre reinforcement used in the concrete offers greater tensile strengths than polypropylene or steel fibres, as well as being non-corroding. Because of the strength of the fibres, thinner panels are possible – an important consideration in the residential market. The house comprises a 100mm reinforced structural skin, with 150mm insulation – to achieve a 0.15W/m²K U-value – and a 50mm reinforced external skin.

Photo: Cornish Cpncrete Products

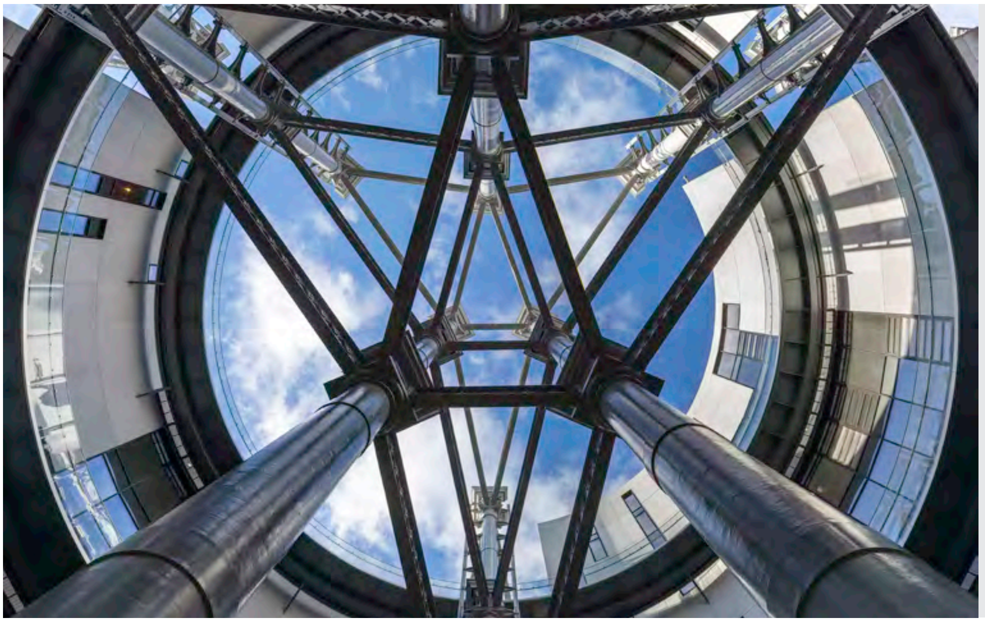


Photo: Peter Landers

◀ Gasholders King's Cross, London

Ultra high-performance concrete was used to clad the internal atrium of the Wilkinson Eyre-designed Gasholders project in King's Cross, north London. The Gasholders comprises three luxury residential towers – of eight, nine and 11 storeys respectively – constructed within the refurbished cast-iron structures of the Victorian Pancras Gasworks. In the central open atrium, formed from the space where the three cylinders meet, precast-concrete panels form a pale, controlled backdrop to the Victorian girders and columns. Thorp Precast installed 180 of the UHPC panels, which have a self-finished texture created using a Reckli rubber formliner.

reinforcement. In UK construction, it is commonly used for facade cladding panels or features such as sills, cornices and parapets where lightweight forms have a distinct construction advantage. The hollow units creating the white "veil" facade of The Broad art musuem in Los Angeles by Diller Scofidio + Renfro (CQ 254) are one such example. GRC can be either wet-cast into moulds or sprayed, offering great variation in shapes and profiles. Since they are subject to greater thermal and moisture-induced movement than standard concrete, GRC elements should be designed as an independent layer or object, with flexible support fixings. The International Glassfibre Reinforced Concrete Association (GRCA) provides guidance on codes of practice and national standards covering its manufacture and performance.

Ferrocement is another way to create super-thin, load-bearing structures – a notable recent example being the roof canopy over the Stavros Niarchos Foundation Cultural Centre in Athens (CQ 260). There it met the desire for a visually very light and fine structure which could be completely un-jointed – unlike steel cladding – combining structure, waterproofing and finish in one element. The ferrocement skins were created with layers of fine diameter stainless-steel mesh embedded in a cementitious paste. More traditional forms, such as those used for boat building, are built up in layers of ferrous steel mesh in a very cement-rich matrix.

Non-corrosive reinforcement requires less depth of cover than conventional steel reinforcement. Various alternatives are in development, such as polymer reinforcement and bars made of carbon fibre, but none are yet available as a mainstream solution.

It will be interesting to discover which other innovations might result in slimmer concrete, enabling the creation of remarkable forms that benefit from concrete's aesthetic, its low maintenance requirements and its ability to be both structure and finish.

▶ Fælledudsigten, Copenhagen

The Fælledudsigten residential project is located in Orestaden in the southern part of Copenhagen. Hi-Con supplied the project with 46 balconies in compact reinforced composite (CRC). These measure 3.55-3.85m long, 1.5-1.8m deep, 2.6m high and 70-85mm thick. The high strength of CRC and the very small cover required for the dense matrix of steel-fibre reinforcement makes it possible to produce light and slender structures while retaining the workability of concrete.

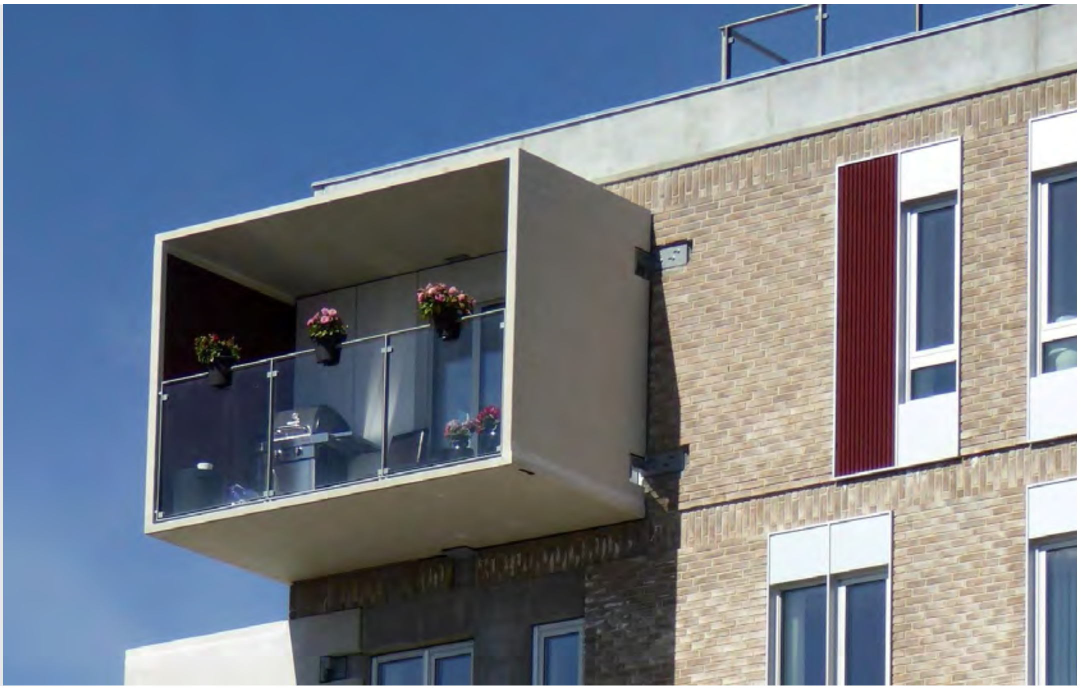


Photo: Hi-Con, hi-con.com

Photos: Russell Beard

ABOVE Graeme Massey Architects' Respite Pavilion at the Acute Mental Health and North Ayrshire Community Hospital campus – one of the case studies on The Concrete Centre's online map

SEE FOR YOURSELF

A good visual concrete specification needs to refer to both current standards and built examples, writes Elaine Toogood

Successful visual concrete is dependent on a range of contributing factors, including design and detailing, the materials used and the quality of workmanship on site. But the starting point is the specification, which should clearly state the required surface quality. This should of course be written with reference to current standards, but there are other useful sources that specifiers can consult in order to achieve the best possible result and avoid unacceptable outcomes.

The current standard for visual concrete is BS EN 13670:2009 Execution of Concrete Structures, though the previous standard, BS 8110, is still used and recognised. BS EN 13670 describes types of surface finish as Basic, Ordinary, Plain or Special. Plain is where visual appearance is of some importance, while Special requires that bespoke requirements are given.

BS 8110 classified surface finishes in two ways: by type of surface and by quality of finish. A type of surface is described as being left as-struck, either plain or profiled, or where the surface is to be removed or covered by another material. This is further divided into sub-types A, B and C giving more detail of aspects such as anticipated blemishes. The quality of finish is categorised as Class 2, 1 or Special class, where Class 1 covers most exposed concrete in buildings both inside and out and Special is reserved for the highest quality.

As BS EN 13670 only provides very brief descriptions, it also relies upon a specification of execution to define the quality and type of finish. One such specification is the National Structural Concrete Specification for Building Construction 4th Edition (NSCS), considered by many as an informal annex to the standard. The NSCS provides a detailed description of what can reasonably be expected by each type. Other standardised specifications include National Building Specification, Highways England Specification for Highway Works and Civil Engineering Specification for the Water Industry. Each has different terminology and requires different parameters.

A visual concrete specification should also make reference to built examples – relying on words alone leaves room for ambiguity, and reference to actual buildings helps to communicate aesthetic aspirations. For this purpose, test panels for reference have been produced in various locations around the country by Construct, the trade association for concrete contractors. Originally constructed to BS 8110, these panels have recently been reinterpreted to relate to the newer standard, representative of achievable quality of the Ordinary and Plain classes, using NSCS v4 with detailed descriptions provided. The Concrete Society publication Technical Report 52: Plain Formed Concrete Finishes is also a convenient reference document, containing 20 built examples created to different standards using different specification documents. It also has a useful introduction describing and comparing aspects of the most common specification standards in use in the UK.

But photographs are no substitute for the real thing. The Concrete Centre has compiled an online map of building case studies, many of which are publicly accessible (see link below). This enables design teams and clients to experience exposed concrete first-hand, and then agree on an example to include as a benchmark in the tender process – the basis upon which the Special specification is then built. This process is useful for managing and aligning expectations, recognising that concrete will always have natural variations in tone and acceptable blemishes such as small blow holes.

For a Special finish, it is recommended that a full-scale mock-up or trial panel be produced as early as possible to test the how the various aspects of one or two specification options (such as form facing material, release agent, concrete mix, workmanship) come together. It can then be agreed to represent a realistic level of quality or give an opportunity to try different parameters. For a Plain finish, NSCS v4 does not include a sample panel as standard, but a design team may still request one in order to de-risk the outcome. In this instance, the requirement for a sample panel should be made clear in the specification. It is also a good idea to specify a review process into the build, ideally after the first concrete is struck.

Whatever visual concrete finish is required, the key at this early stage in the process is for the design team to be clear on what is acceptable to the client and then to use all of the specification tools at their disposal to create the desired result.

To access The Concrete Centre's online map of case studies, go to www.concretecentre.com/casestudies

UNSHAKEABLE

James Hargreaves and Hugh Pidduck of Arup explain how the engineering team delivered low-vibration neuroscience labs for the Sainsbury Wellcome Centre in London

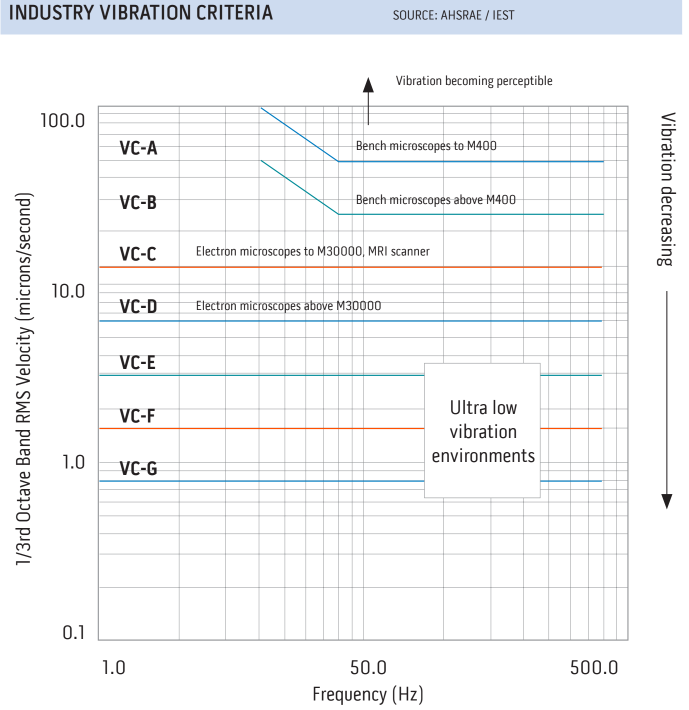
Many new laboratory buildings have been developed in recent years, dedicated to advancing subject areas such as life science, materials science, engineering and physics. This research often involves the use of scientific equipment to study very small organisms and structures in microscopic detail. This equipment is sensitive to vibration and hence this must be taken into consideration in the structural design of the building.

The Sainsbury Wellcome Centre for Neural Circuits and Behaviour at University College London, designed by Ian Ritchie Architects, became operational during 2016 and houses several laboratories. The nature of the research and the use of imaging equipment, including two-photon and electron microscopy, which is sensitive to the smallest of movements, required a low-vibration environment. A fundamental aspect of this was the selection and design of the reinforced-concrete foundation, superstructure frame and floor slabs.

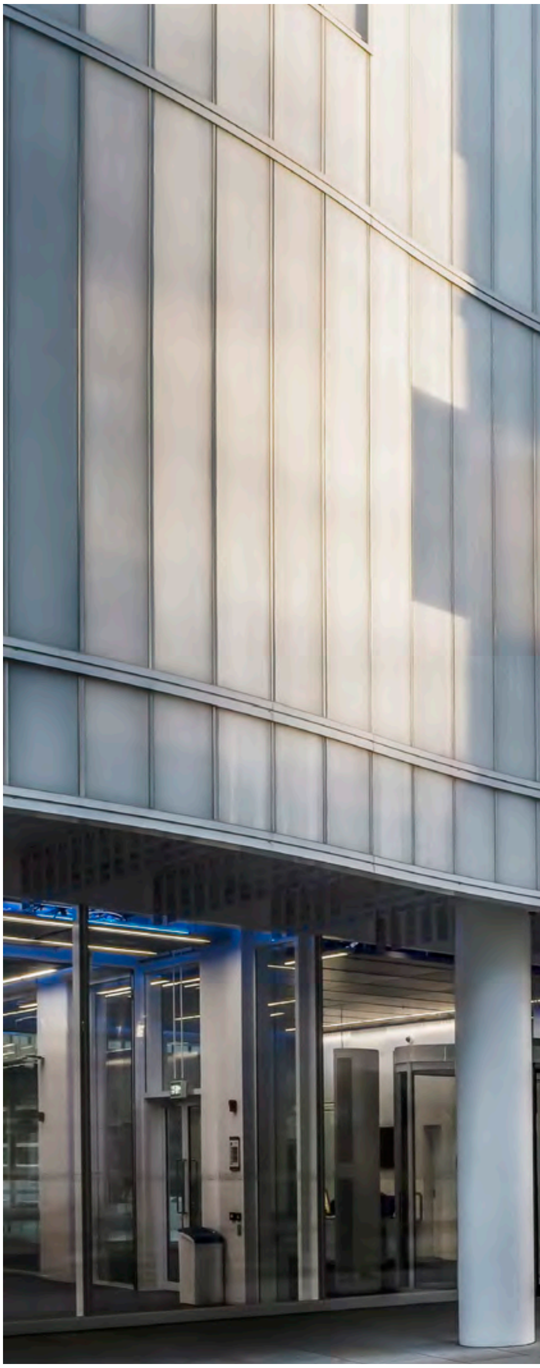
Vibration criteria

Vibration criteria must be identified early in a project because, in addition to strength, architectural, services and other considerations, they inform selection of structural forms. Industry-published or generic criteria are suitable for this purpose as they cover broad classes of equipment, and are therefore compatible with the early stages of a project when certainty about specific equipment cannot be attained. Industry vibration criteria published by ASHRAE and more recently IEST (see Further Reading overleaf) are referred to as VC criteria and their purpose is to define limits on vibration transmitted to the equipment to give acceptable functional performance (see graph, below). The VC criteria involve vibration magnitudes smaller than a human can perceive and are hence referred to as sub-perceptible. VC-A is applied to typical laboratory floors which might support many researchers and equipment often on suspended floor structures. VC-D is typically applied to specialist imaging suites, such as electron microscopy, which tend to be located on foundation slab structures.

Meeting the relevant criteria is important as it enables the building to realise its full value. Since the criteria essentially apply to the equipment, they may be attained through structural design or some combination of design and mitigation, often in the form of isolation. While vibration originates from a range of sources, the transmission of vibration is related to the structure and it is therefore necessary to evaluate it at the design



LEFT The VC criteria published by ASHRAE and IEST define limits on vibration transmitted to the equipment to give acceptable functional performance



RIGHT The Sainsbury Wellcome Centre is built on a tight inner London site bordering three busy roads. The translucent glass envelope has a high thermal performance and the light transmission levels keep lighting costs to a minimum

Photo: Grant Smith

stage. Typical external vibration sources – i.e. outside the project boundary and where vibration is transmitted through the ground to the foundation – are underground rail and highway. Typical internal vibration sources – i.e. acting directly on the structure within the building – are footfall and mechanical and electrical plant systems.

Structural design

For the Sainsbury Wellcome Centre, a vibration survey was undertaken at an early stage to evaluate the ambient site vibration from prevailing external sources. Traffic on the streets around the site boundary was the main source. While the Victoria and Northern London Underground lines un close by, they are too distant to feature prominently in the vibration at the site.

The new centre has two basement levels which include provision for an imaging suite at level –2, common support space at level –1 and four upper floor levels. Levels 1 and 3 are laboratory floors and levels 2 and 4 are designed to be adaptable so that they may become laboratory floors in future.

Many aspects of the structural design influence vibration performance. The material selected throughout was in-situ reinforced concrete (RC), including the primary structural frame and floor slabs. The selection was made primarily on the basis of cost and constructability; however, RC also has dynamic modulus, density and damping properties that are compatible with low-vibration environment structural design. Grid size was a critical parameter for the project in terms of the architecture and space utility but also for vibration. Studies at the concept design stage indicated that a grid size in the region of 6.5m would be needed to achieve acceptable laboratory floor vibration performance. A piled slab foundation form was selected to control differential settlement and to

ABOVE LEFT The painted concrete soffits are a blue of 480nm spectral wavelength, chosen for its effect on mental alertness
ABOVE RIGHT The laboratory floors have a slab thickness of 400mm to ensure stiffness and low vibration levels

enable the building gravity loads to be taken down to the Thanet Sand layer. A secant pile retaining wall structure was selected. This provides some limited "screening" for the structural piles from vibration transmitted from highways. When the vibration arrives at the piles, it is transmitted to the foundation slab by a combination of friction and direct transmission at the pile toe level and into the pile structure generally.

RC slab thickness is a key design parameter for strength and especially for vibration. Low vibration is best achieved by designing the slab to have a primary vertical mode with natural frequency above the range of the main footfall harmonics. This frequency is in the region of 10Hz. In this way resonant vibration response from footfall – i.e. where vibration builds up with each footfall – is avoided. A slab thickness of 400mm for the laboratory floors at levels 1 and 3 was found to prevent significant cracking from developing under serviceability loads. There was therefore no loss of stiffness or frequency reduction and the potential for resonant response was avoided. A thickness of 350mm for floor plates at levels 2 and 4 ensured they would have high vibration serviceability now and also strong potential for adaptability in future.

Assessing vibration

Design tools were used to help steer the structural design and to demonstrate that it would meet the criteria. For footfall in buildings, finite element (FE) methods are typically used to evaluate and assess vibration of structural designs. Arup's GSA FE code was applied to this project, it being consistent with UK concrete industry guidance and national standards concerning the effect of vibration in buildings on the occupants. These methods are adaptable to situations where the vibration output is to be considered in the context of equipment functional performance as opposed to perception. This is discussed in the CCIP-016 guidance (see Further Reading below). Walking speed is an important input in this evaluation and particularly for this design, with corridors alongside the large laboratory areas. Walking speed within laboratory environments is typically 1.8Hz and in corridors it is a maximum of 2.5Hz. The single person walking load case for corridors which run alongside laboratory spaces was evaluated as a priority, with vibration tending to increase with faster walking speeds. This computational work showed that the vibration from footfall for the proposed structural design was within the criteria for levels 1 to 4.

Vibration transmission from external sources was evaluated at the design stage using computational models in conjunction with measured data. This evaluation showed that vibration performance was within the criteria for receiver locations on the foundation and suspended slabs. Where this was not the case, mitigation was developed in the form of equipment isolation or change to the structural design.

Mechanical, electrical and public health (MEP) plant vibration is a common aspect of all building design. However, for this building, with MEP plant at the basement and roof levels, the potential for transmission of vibration through the structure to sensitive occupancies is particularly important. A vibration isolation specification was developed to define how much isolation was needed to limit MEP plant vibration transmission to slabs. Isolation vendors then proposed either a system with elastomer bearings or helical steel springs to deliver the specified isolation for the running speed range of the MEP plant. For large plant items, which produce high dynamic loads – for example, generator sets and combined heat and power units – a concrete slab supported by helical steel springs was specified. ASHRAE and CIBSE guidance on the isolation type for ranges of machine types, powers, running speeds and slab forms was used to inform the initial selection of isolation.

Laboratory and other technical buildings such as hospitals typically house vibration-sensitive equipment and occupancies. This article discusses a specific project, but many, if not all, of these aspects of vibration control would need to be assessed at the design stage for any vibration-sensitive building project. The key aspects of this process – criteria selection, identification of internal and external vibration sources, structural design to control vibration from footfall and MEP plant isolation – are typical of such a design. The concrete frame in this project was ideal to help realise a low-vibration environment because of its dynamic modulus, density and damping properties, as well as providing an efficient, economic and buildable structure.

FURTHER READING

ASHRAE HVAC Applications Handbook (2015)

IEST-RP-CC012.2: Considerations in Cleanroom Design, Institute of Environmental Sciences and Technology (2012)

A Design Guide for Footfall Induced Vibration of Structures, CCIP-016, by MR Wilford and P Young, The Concrete Centre (2007)

LASTING IMPRESSION JAMIE FOBERT

SOARING SPACES UNDER A CONCRETE SKY

A few years ago I went to Brazil and saw the most incredible set of concrete buildings within the course of a few days. Of course when you go to Brazil you expect to see Niemeyer, but it really intrigued me to see the quality of the architecture in concrete by architects that I didn't know.

The Museum of Modern Art (1) in Rio by Affonso Eduardo Reidy is a beautifully light pavilion-like building in Copacabana Park. It's from 1953 but when I saw it I thought it was from the 1970s. Soaring pilotis lift the entire building off the ground and create a subtly curved soffit and a shaded outdoor space. Above, huge curving brise-soleils of concrete create shade for the fairly simple curtain walling.

The second one was in São Paulo. We travelled out of town to go to the Faculty of Architecture and Urbanism by João Batista Vilanova Artigas and Carlos Cascaldi (2) (1961). It's a single rectilinear block of concrete hovering in the air on a series of tapered pilotis and it's open to the elements – it has no front door, so it's a totally permeable volume that you wander into. This hovering block of concrete has the most extraordinary coffered ceiling, a vast canopy which envelops the entire school. It creates a spatial continuum, so there is a sense of the school as a single community.

The final building is the Museu Brasileiro de Escultura (3), again in São Paulo, by Paulo Mendes da Rocha. It's from 1988, but you sense the continuity from the previous project. The building is deep in the suburbs, and when you arrive it feels more like a concrete landscape or park. The primary element is a single-span 200ft canopy, made from prestressed concrete beams. Below it there is a public space, with ramps leading down to the museum which is almost entirely underground – not unlike Tate St Ives.

In a country where concrete was felt to be a humble and inexpensive solution, these architects took it and over time developed a language that is very sculptural. The engineering is extraordinary and yet the pieces have an immense grace to them.

Jamie Fobert is director of Jamie Fobert Architects


1


2


3

Photos: SambaPhoto/Cassio Vasconcellos, Raul Garcez, seier+seier/CC BY. Portrait by Laura Pannack

FROM THE ARCHIVE: SPRING 1974

"ALMOST TANGIBLE SPIRITUAL REALITY"

At Clifton Cathedral, which has just been refurbished by Purcell (see page 3), CQ editor George Perkin had, if not a revelation, then at least a moment of faith restored. "At a time when I thought that I was going off boardmarked in situ concrete for ever, I am suddenly disconcerted by this fine example of a wholly in situ white concrete interior which bears the imprint of redwood boards from Russia … Never have I liked this technique so well since we visited the Paris Unesco building back in the late fifties."

The concrete was the work of John Laing Construction and structural engineer Felix Samuely, working to a design by Percy Thomas Partnership. The exposed walls were all cast in situ using detailed formwork of thin timber boards fixed onto plywood sheets. White cement gave a very light finish, which reflected the daylight drawn in through the roof's spire-like funnel. This play of light reminded Perkin of Kenzo Tange's St Mary's Cathedral in Tokyo in the way that it "inspired feelings of almost tangible spiritual reality". The skilful handling of indirect natural light, he concluded, was "surely the most effective way of invoking spiritual atmosphere".

Access the full CQ archive at www.concretecentre.com. The book, *The World Recast: 70 Buildings from 70 Years of Concrete Quarterly*, is out now, available from www.concretecentre.com/publications

FINAL FRAME: TREE-NESS HOUSE, TOKYO

Architect Akihisa Hirata has created this complex of apartments and galleries in the central Toshima district of Tokyo. Inspired by the structure of a tree, he has developed a branch-like architecture of concrete boxes, openings and voids. The boxes are arranged to create an intricate network of outdoor spaces, terraces and gardens. "I intended to create a futuristic and savage architecture," says Hirata, "that awakens human animal instincts in which the inside and outside are reversed multiple times."

Photo: Vincent Hecht