CONCRETE QUARTERLY

The Concrete Centre

APPLICATION: COLLECTED TECHNICAL ARTICLES 2020-21

CONTENTS

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CONCRETE QUARTERLY

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Town House, Kingston University (see page 8).
Photo: Ed Reeve

High tension:
An introduction to specifying post-tensioned slabs

Jenny Burridge explores the benefits and relative costs of one of the most efficient forms of construction

Post-tensioning is now widely used as an efficient way of designing floor slabs in concrete-framed buildings. It is a way of putting a pre-compression into the concrete, in this case after it has been cast. This means that when the slab is working under normal vertical loads, spanning between columns, the tension that would result in the concrete from bending forces is significantly reduced. Since the tensile strength of concrete is only about 10% of its compressive strength, this makes it work much more efficiently.

In the simplest form of post-tensioning, the concrete is prestressed by putting high-strength tendons in ducts through the slab and tensioning the tendons with a jack when the concrete has gained sufficient strength. The tendons are usually draped within the depth of the concrete, putting an additional bending moment into the span, which balances the bending moment from the vertical loads.

With the requirement for much greater material efficiency, post-tensioning is now being used much more frequently on projects. Post-tensioned (PT) slabs are one of the most efficient forms of construction, as they enable the two main construction materials to work in the most efficient way. Significant savings can be made in comparison with conventional reinforced concrete, equating to about 20% of the concrete and 50% of the steel in a flat slab.

Figures 1 and 2 provide engineers with a guide to the sizing and rates that will be required for typical flat slabs – a guide that has been agreed by specialist designers.

Benefits

Because they are more efficient, PT slabs are thinner than conventionally reinforced equivalents, and smaller floor-to-floor heights can be achieved without losing anything from floor-to-ceiling heights. This produces either lower buildings, with a consequent saving on the cladding materials, services and internal finishes, or enables a greater number of floors to be accommodated within a tall building. For example, Allford Hall Monaghan Morris' tower at 240 Blackfriars Road in London (overleaf) was able to include two additional storeys within the same building height.

The reduction in steel means that PT floors are also quicker to build than conventional in-situ reinforced concrete slabs, because the time taken to fix the reinforcement is significantly less. The fixing and stressing of the tendons are additional work items, but overall the programme is less. ▶

ABOVE RIGHT At the Newfoundland tower in Canary Wharf, London, the overall slab depth was reduced by about 17%, with a 75% saving in the amount of steel

FIGURE 1: SPAN-TO-DEPTH RATIOS AND RATES FOR POST-TENSIONED FLAT SLABS

Multiple spans (m)	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
Overall depth (mm)									
Imposed load: 2.5kN/m^2	200	200	215	240	275	310	340	390	475
IL: 5.0kN/m^2	200	210	240	270	300	325	370	400	500
IL: 7.5kN/m^2	200	235	270	300	340	375	410	500	
IL: 10.0kN/m^2	200	275	310	350	390	440	500		
Tendons (kg/m^2)									
IL: 2.5kN/m^2	3.5	3.8	4.4	5.1	5.7	6.9	7.6	9.2	10.1
IL: 5.0kN/m^2	4.0	4.6	5.3	6.3	7.1	8.4	9.3	10.8	11.2
IL: 7.5kN/m^2	4.6	5.6	6.3	7.3	8.4	9.6	10.4	11.6	
IL: 10.0kN/m^2	5.4	6.9	7.8	8.6	9.7	10.7	11.7		
Mesh and loose rebar (kg/m^2)									
IL: 2.5kN/m^2	14	14	14	15	16	19	20	24	25
IL: 5.0kN/m^2	14	14	15	16	17	19	21	25	26
IL: 7.5kN/m^2	15	15	16	17	19	23	24	27	
IL: 10.0kN/m^2	16	17	18	19	23	24	26		

Notes on table

1. These values are mid-range for the options available. It is possible to have slimmer slabs with more tendons
2. A depth limit of 200mm has been adopted as this is standard within the industry and gives a fire resistance of up to four hours
3. The mesh and loose rebar rates include an allowance for anti-burst reinforcement around the anchorages, bottom mesh, edge reinforcement, punching shear links, top mesh for slabs of >375mm for constructors to walk on, pour strips between areas of post-tensioning, construction joints, small amounts of trimming reinforcement around holes. It does not include upstands, beams, core connections or couplers
4. Exposure class XC1 assumed. This covers internal concrete, but not concrete for a car park, for example. If higher exposure classes are required then higher rates would be necessary. Eurocode 2 requires that for XD and XS exposure classes bonded tendons should lie within concrete in compression under the frequent load combination
5. Tendons are assumed to be 12.9mm or 15.7mm Superstrand (A_{ps} = 100mm^2 or 150mm^2, f_{pk} = 1,860MPa). Either can be used, but use one or the other on the same project
6. Concrete is assumed to be C32/40 with $f_{ck(t)}$ at transfer of 20.8MPa
7. A superimposed dead load of 1.5kN/m^2 is assumed with a perimeter load of 10kN/m
8. Design is in accordance with Eurocode 2 (BS EN 1992-1-1 and BS EN 1992-1-2) and Concrete Society Technical Report TR43, Post-tensioned Concrete Floors Design Handbook
9. Panels are assumed to be square with three bays in each direction.

▶ In order to take advantage of the programme savings associated with post-tensioning, the concrete has to have early strength gain so that the tendons can be stressed shortly after it has been cast. The concrete for PT slabs has therefore traditionally been specified with a high proportion of Portland cement (CEM 1). However, 50% ground-granulated blast-furnace slag (GGBS) or 40% fly ash mixes have also been successfully used to lower embodied carbon in buildings. The use of high levels of replacement cements is an issue if the concrete is cast during winter.

The increased use of PT slabs in tall buildings was demonstrated by the Post-Tensioning Association (PTA) project award for 2019. Three of the shortlisted projects were high-rise residential buildings where post-tensioning had been used to increase the number of storeys for a given building height and to speed up the construction programme. The award was won by Praeter Engineering for the Newfoundland tower at London's Canary Wharf, where the overall slab depth was reduced by about 17%, with a 75% saving in the amount of steel. The reduced size of the concrete elements led to smaller columns and a reduction in the size of the piled raft foundation.

Rates

The detailed design of post-tensioning is frequently done by specialists, but the engineer for the frame can complete a concept design to size the slab and estimate the number of tendons and amount of reinforcement using standard rates.

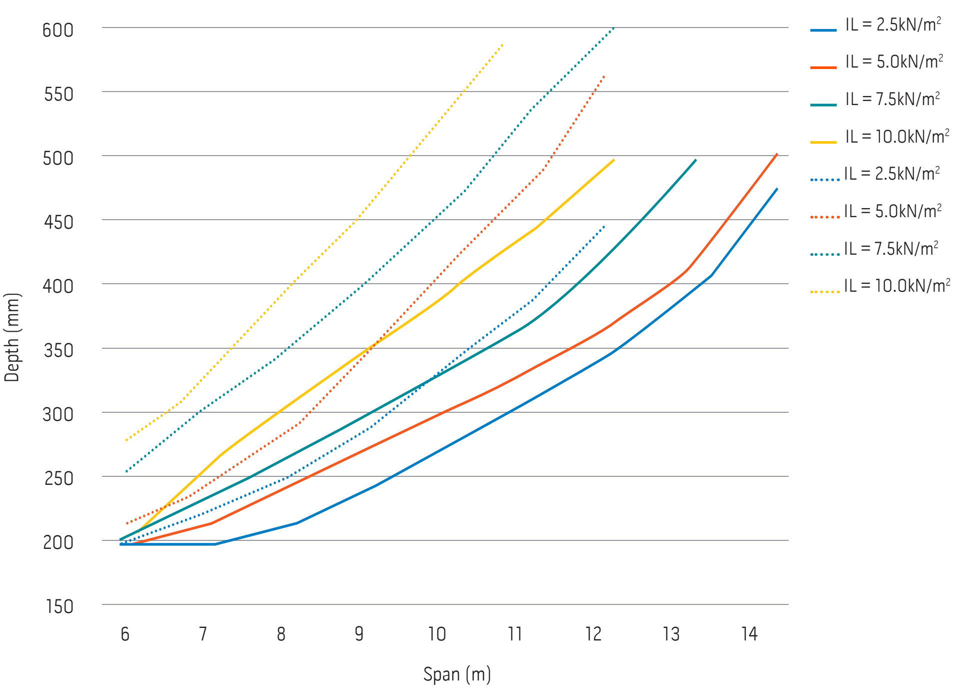
Since post-tensioning has become more mainstream, the design of PT slabs has become even more efficient. The Concrete Centre book, Economic Concrete Framed Elements, contains tables for PT slabs and beams. The specialist designers within the PTA have found that the book gives higher rates for tendons with lower rates of conventional reinforcement than would normally be the case. The numbers in the tables have therefore been revised (see figure 1, previous page), with the result that PT becomes more cost-effective. Figures 1 and 2 give a good starting point for a scheme design of a PT flat slab, the most common use of PT in the UK.

One of the benefits of post-tensioning is that it is very flexible in the design. The deflection of the slab can be counterbalanced with greater levels of pre-compression or a slightly deeper slab. The drape of the tendon can be modified to give the most economic or efficient solution. PT systems are also very efficient for long cantilevers, as the pre-tension helps to control deflecton.

The PTA has produced a model specification for the procurement of the design of PT floors from specialist designers: Model Specification for the Design and Performance of Post-tensioned Concrete Floors in Building Structures. It also provides useful guidance on the considerations for designers when designing PT slabs. A free download is available at concretecentre.com. ■

For further information, see Post-tensioned Concrete Floors, published by The Concrete Centre

FIGURE 2: SPAN-TO-DEPTH RATIOS, SHOWN AS A GRAPH



ABOVE At 240 Blackfriars Road in London, the use of PT slabs enabled the addition of two storeys without increasing the building height

Photo: Timothy Soar

Photo: Hawkins\Brown

ABOVE Hawkins\Brown's first phase of Agar Grove in Camden, London – the largest Passivhaus scheme in the UK

In search of **new lows**

Fabric first is a well-established approach for reducing energy use in buildings – but we can't stop there, writes Elaine Toogood

Reducing the energy consumption of buildings is an important part of whole-life carbon reduction, and is arguably the most impactful way for designers to improve the credentials of a new project, with savings that accumulate over the life of the building. But reducing the energy consumption of buildings has other, far-reaching potential social and economic benefits, such as tackling fuel poverty and fuel security, making it a natural priority for many clients.

Buildings account for around 40% of the UK's total energy use. The government's industrial strategy includes a mission to "at least" halve the energy use of new buildings by 2030, as part of meeting its Grand Challenge on clean growth. By the same deadline, the RIBA has set the architectural profession the more ambitious challenge of reducing operational energy demand and carbon by at least 75%, before offsetting. With the revised Part L1A of the Building Regulations for England and Wales – the Future Homes Standard – set for publication in 2020, the appropriate minimum level of energy use for new building construction and its method of measurement is the subject of heated debate.

The government's clean growth energy challenge is framed in the context of new technologies, but this is not a prerequisite for achieving better performance – the Green Construction Board's recommendations include exemplar buildings in a range of construction methods and materials, including concrete masonry. A fabric-first approach, for example, is a well-established means of ensuring long-term energy efficiency. Insulation and detailing to reduce thermal bridging and air leakage are fundamental to thermal performance – the latter becoming more significant as insulation values have improved, particularly for housing where heating makes up a significant proportion of energy use.

The concrete and masonry sector has developed a wide range of resources to assist designers in eliminating thermal bridging, including freely available high-performance details of solid and cavity blockwork wall junctions. Each detail has pre-calculated thermal bridging values for use with current and proposed amendments to Part L1A.

Airtightness

Concrete walls, floors and roofs, whether cast in situ or as precast panels, provide inherent benefits in terms of reducing air leakage, with comparatively few joints to consider and the material itself ▶

THE NEED FOR FANS AND OTHER COOLING DEVICES PUTS LOWER-INCOME HOUSEHOLDS AT RISK OF SUMMER FUEL POVERTY

Photos: James Retief, Hawkins\Brown

▶ offering durable, long-term performance. For blockwork, parging and plaster coats have been proven in research and practice to provide excellent airtightness. As high thermal performance becomes more mainstream, solutions will continue to evolve in response to the demands of larger-scale construction. Low-conductivity cavity wall ties, for example, are now commonplace.

Passive cooling

Concrete's greatest potential contribution to reducing energy use in buildings is by providing passive cooling through its high thermal mass. Exposed internal concrete surfaces, in combination with appropriate ventilation or night-time purging, is an established means of avoiding or reducing the need for air conditioning. The resulting reduction in energy use can be very significant, with associated savings in running costs. Exposed concrete soffits are useful sources of thermal mass and these can also be painted in light colours to reduce the need for lighting – and its associated energy use – without hindering cooling performance.

To date, this low-energy building strategy has been used primarily in buildings with high internal heat loads such as offices, libraries and schools. With predicted rises in temperatures, the need to provide low-energy cooling will become a higher priority for other building types, so a concrete frame is one means of future-proofing. It is now generally accepted that housing also requires some measure of passive cooling to prevent overheating, now and in a future warmer climate. The need for fans and other cooling devices puts lower-income households at risk of summer fuel poverty, an issue identified by the Zero Carbon Hub. Research published by the Department for Communities and Local Government in September 2019 found that thermal mass with night-time cooling was an effective means of passively reducing overheating risk in new housing.

Passive solar design

Beyond passive cooling, thermal mass can also help to reduce fuel consumption during the heating season through passive solar design (PSD, see page 18), whereby thermally massive internal walls and floors absorb solar energy from south-facing windows, as well as internal heat gains from activities such as cooking. The heat is then slowly released overnight as the temperature drops, helping to keep the building warm and reducing the need for supplementary heating. Simple design strategies concerning building orientation and the location and sizing of windows can provide fuel savings of up to 11% (see Thermal Mass for Housing, published by The Concrete Centre, for full reference). This increases to up to 40% where more sophisticated PSD techniques are adopted, such as sun spaces. This is not a new concept but there has been renewed interest in recent years, with rising energy prices and challenging carbon targets, as well as the shift to alternative forms of domestic heating. Buildings orientated to optimise photovoltaics can also benefit from PSD.

ABOVE The first phase of Agar Grove, a 38-unit apartment block designed by Hawkins\Brown, was completed in 2018

TOP LEFT The apartments' south-facing balconies are freestanding structures clad in glass-reinforced concrete

CENTRE LEFT The 493-home masterplan is arranged around the existing 17-storey Lulworth Tower, which will undergo a deep retrofit

BOTTOM LEFT The second phase of 57 homes designed by Mae is due to complete later this year

◀ Case study: Agar Grove, London

Agar Grove is the largest Passivhaus development in the UK to date. The first phase, a 38-unit apartment block, was completed in 2018 and is fully occupied. A subsequent phase of 57 homes has benefited from post-occupancy evaluation and feedback from "lessons learned" workshops. Both phases have an in-situ concrete frame, key to simplifying the detailing, with infill blockwork of aerated autoclaved concrete (AAC) and external facing brick facades. The project was won in competition, the 493-home masterplan created through a joint design proposal by Hawkins\Brown and Mae Architects, with Hawkins\Brown taking the design lead for phase 1A and Mae for phase 1B.

For the client, the London Borough of Camden, a major motivation for adopting Passivhaus was addressing fuel poverty among its tenants. The first building benefited from a very good form-factor ratio of 1.6 – the ratio of heat loss area to the total floor area, and a measure of efficiency. It was constructed over five to seven storeys and orientated on a north-south axis, ideal for Passivhaus principles.

Subsequent blocks have had to compensate with slightly more insulation, increasing the depth of blown mineral wool insulation in the cavity from 150mm to 200mm. Thermally broken cavity ties and structural insulated connectors help to minimise thermal bridging of the brick facade and some of its more complex details. The south-facing balconies are freestanding structures clad in glass-reinforced concrete (GRC) and restrained back to the facade using thermally broken fixings. These balconies provide shading in the summer while allowing some benefit from solar gain in the winter.

The airtightness barrier is provided by a parge coat applied to the external face of the blockwork immediately behind the insulation layer and thoroughly taped around window and concrete frame junctions. Compared to the more usual location, behind internal plasterboard linings, this innovative but robust solution offered programme benefits and reduced the risk of damage from follow-on trades – the team felt that, on balance, the advantages outweighed the potential lack of future accessibility. For the next phase of construction, they are evolving the detail to use a liquid-applied membrane with the potential to replace both the parge coat and taped junctions, which would offer yet further programme savings.

Another detail that evolved over the course of discussions was the incorporation of structural insulation breaks at the base of the lift cores and between dwarf columns in the pile caps, below the slab. This was deemed simpler than wrapping the cores and pile caps to provide a thermal break with the ground.

The second phase of construction is due to complete later this year, to be followed by further new blocks, including a deep retrofit of the concrete-framed 17-storey Lulworth Tower at the heart of the plan. This will include the extension of the perimeter to provide winter gardens, as well as the addition of two more storeys.

PROJECT TEAM

Architects Hawkins\Brown, Mae
Delivery architect (Phases 1A and 1B) Architype
Structural engineer Peter Brett Associates
Passivhaus consultant designers Max Fordham; Architype/Elemental Solutions/Enhabit
Contractor Hill Partnerships

Demand-side response

Thermal mass also supports the variable energy profile of our increasingly renewable energy supply. Demand-side response (DSR) is a more carbon-efficient way of using energy, and can assist the transition to renewable sources by spreading demand across the 24-hour cycle. This means it reduces stress on the national grid at peak times, and also that consumers can make greater use of cheaper off-peak energy tariffs, cutting fuel bills.

Combined with the electrification of heating and cooling systems and a so-called "smart grid", concrete and masonry buildings could play a significant role in demand-side flexibility due to the thermal inertia of heavyweight construction. According to renewable energy consultant 3E, buildings with high thermal mass can maximise the use of renewables and cut peak electricity demand by up to 50%.

At the Bullring shopping centre in Birmingham, which has a concrete structure, the use of DSR saved £23,000 over a six-week initial trial period for the system.

Post-occupancy evaluation

To significantly reduce the energy consumption of our buildings requires approaches on many levels, and it must become a greater focus both during design and construction and after completion. This includes use of energy performance targets, quality assurance for construction, commissioning and after-care. More accurate predictions for energy use are required, including consideration of all uses – that is, beyond those covered by regulations – and post-occupancy evaluations will have a significant role in this. As more measured data becomes available, designers will become increasingly informed and equipped to feed back successful practice into new low-energy design.

Examples of post-occupancy evaluations include Wimbish Passivhaus, a social housing development built from solid masonry walls with rendered external insulation, where 10 years of data indicate continued high performance. Publications from the Green Building Store on Denby Dale, the first cavity-wall Passivhaus in the UK, and its subsequent Golcar Passivhaus are useful resources. Similarly, Montgomery Primary School, completed in 2012 and the UK's first Passivhaus-certified school, was built using an insulated modular precast concrete system and is reported to be performing well eight years later.

The performance targets and measurement of carbon and energy related to the construction of new buildings is changing and no doubt will continue to evolve over time. It is unlikely that any single construction solution will be able to meet every performance need every time, given the variety of changing demands on the built environment. But, for the foreseeable future, energy consumption will be a key priority, and it will remain a very good place to start. ■

For more information on reducing energy use, and links to all the documents referenced in this article, go to concretecentre.com/energyefficiency

Best of both worlds? The benefits of going hybrid

Jenny Burridge explains how using precast and in-situ concrete together can often be the most buildable option

The government is currently championing the use of off-site construction as a way to improve productivity and reduce the number of hours required on site. Purely precast concrete systems are available, but there are also structural systems that use a combination of precast and in-situ concrete, with each type playing its part. This is known as hybrid concrete construction (HCC).

HCC can deliver very significant cost savings, through economic structures, increased prefabrication, faster construction and consistent performance. Although the structural frame of a building represents only 10% of the total construction cost, the choice of material has dramatic consequences for subsequent processes. Hybrid construction can reduce frame costs by using precast concrete for the repetitive elements, or to act as permanent formwork. In-situ concrete is more cost-effective for large volumes (due to reduced transport costs), for tying the frame together and for bespoke areas. Using the two together maximises cost efficiency.

The key advantage of HCC is its buildability. Because precast and in-situ concrete are used where each is most appropriate, construction becomes relatively simple and logical and important decisions are resolved at design stage.

FIGURE 1: SUITABILITY OF HYBRID OPTIONS

Hybrid option (see fig 2)	Ease of services distribution	Minimises storey height	Suitability for holes	Clear spans	Deflection control	Minimises materials	Soffit can be exposed	Maximises off-site construction	Temporary works minimsed
Type 1	✓✓	✓✓	✓✓	○	✓✓	✓✓	✓✓	✓	✓✓
Type 2	✓✓	✓✓	✓	✓✓	✓	✓	✓	✓	○
Type 3	✓	✓✓	✓	✓✓	✓✓	✓✓	○	✓✓	✓✓
Type 4	✓	✓✓	✓	✓✓	✓✓	✓✓	○	✓	✓✓
Type 5	○	○	✓	✓✓	✓✓	✓✓	○	✓✓	✓✓
Type 6	✓✓	✓	✓	✓✓	○	✓✓	✓✓	✓	✓

✓✓ Excellent ✓ Good ○ Can be used

Note on table and diagrams

The ideal combination of precast and in-situ concrete is influenced by project requirements. There is a wide range of possible options, a selection of which is presented opposite as representative of current UK practice. It is not intended to be an exhaustive list.

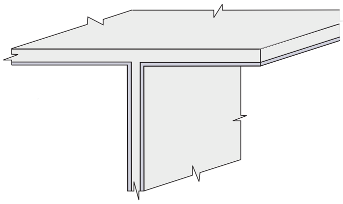
LEFT The Town House at Kingston University by Grafton Architects uses precast columns and beams with a structural in-situ screed

Photo: Ed Reeve

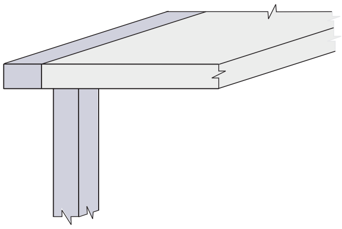
This means, for example, that precast elements can be manufactured, stored at the factory and delivered just-in-time to site. They can then be lifted from delivery truck to final position in a single crane movement, eliminating the need for site storage and reducing crane hook time. HCC also offers all of the other advantages of off-site construction, improving both speed of construction and safety. By taking a proportion of work into the factory, it reduces the duration of on-site operations critical to the programme. The precast process takes place in a controlled environment, unaffected by weather and with no need for working at height. Rigorous inspection before installation removes causes of delay on site, while better buildability helps provide safer working conditions. HCC can reduce the potential for accidents by providing successive work platforms and a tidier site. If precast spandrel beams are used, they can provide immediate edge protection.

Some HCC techniques can reduce or eliminate following trades – for example, installing ceilings and finishes. If precast concrete is used for those areas of visual concrete, the workmanship required takes place under factory conditions. This enables even faster programme times but requires greater coordination and care in detailing and protection on site. The Town House at Kingston University is an excellent example of the use of HCC to ▶

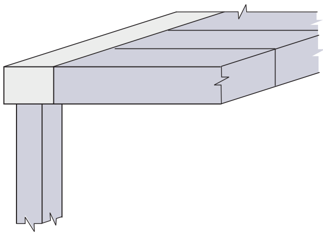
FIGURE 2: HYBRID OPTIONS EXPLAINED



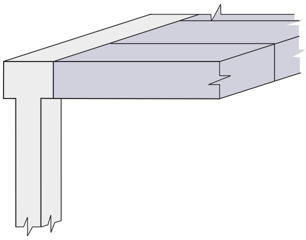
TYPE 1 Precast twinwall and lattice girder slab with in-situ concrete



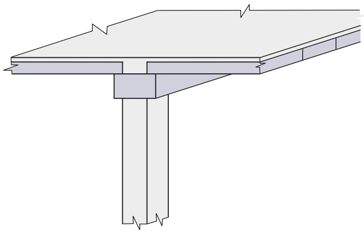
TYPE 2 Precast column and edge beam with in-situ floor slab



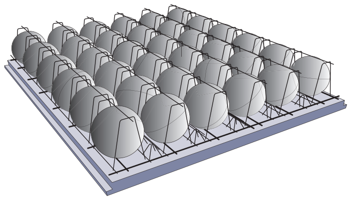
TYPE 3 Precast column and floor units with in-situ beams



TYPE 4 In-situ columns or walls and beams with precast floor units



TYPE 5 In-situ column and structural topping with precast beams and floor units



TYPE 6 In-situ columns with lattice girder slabs and optional spherical void formers

▶ provide beautiful visual concrete, while enabling many of the add-on finishes to be eliminated.

Design

As both precast concrete and HCC are very well-established forms of construction, there is plenty of guidance for the designer. Eurocode 2 covers the design of in-situ, precast and hybrid concrete construction. There are also a number of product standards for precast concrete, which also cover the precast elements of HCC, some of which are listed in figure 3 (right).

The use of precast and in-situ concrete may well lead to individual elements being designed by different companies. Therefore, it is essential that there should be a single named designer or engineer who retains overall responsibility for the stability of the structure and the compatibility of the design and details of the parts and components, even where some or all of the design, including details, of those parts and components are not carried out by the named designer. This is particularly important for hybrid structures, where there is greater scope for misunderstandings.

It is the responsibility of the named designer, before incorporating any proprietary system as part of the structure, to ensure that the assumptions made in the design and construction of the system are compatible with the whole. This should include:

- an adequate specification for that part
- ensuring that any standard product designed and detailed by the precast manufacturer is suitable for that particular structure
- reviewing the design of any such part to ensure that it satisfies the design intent and is compatible with the rest of the structure.

The design of each component should include consideration of:

- its performance in the permanent condition
- the construction method and loading
- any temporary supports required during construction.

The design should be carried out following the requirements of Eurocode 2 Part 1-1, Cl. 1.3, which assumes:

- structures are designed by appropriately qualified and experienced personnel
- adequate supervision and quality control are provided in factories, in plants and on site
- construction is carried out by personnel having the appropriate skill and experience
- the construction materials and products are

FIGURE 3: RELEVANT PRECAST CONCRETE PRODUCT STANDARDS

BS EN 1168:2005 (+A3:2011)	Hollow core slabs
BS EN 13224:2011	Ribbed floor elements
BS EN 13225:2013	Linear structural elements
BS EN 13369:2018	Common rules for precast concrete products
BS EN 13693:2004 (+A1:2009)	Special roof elements
BS EN 13747:2005 (+A2:2010)	Floor plates for floor systems
BS EN 14843:2007	Stairs
BS EN 14992:2007 (+A1:2012)	Wall elements
BS EN 15037 (parts 1-5)	Beam and block floor systems

HCC CAN REDUCE THE POTENTIAL FOR ACCIDENTS BY PROVIDING SUCCESSIVE WORK PLATFORMS AND A TIDIER SITE

Photos: Rob Parrish; Timothy Soar

Case study: The Ray, London

Hybrid concrete construction was used in the construction of The Ray, the UK home of social networking company LinkedIn. The building, by architect Allford Hall Monaghan Morris (AHMM), steps back in order to address the varying scale of the neighbouring buildings, and to create accessible terraces and allow natural daylight to flood all floorplates. Concrete was chosen as the frame material to provide thermal mass to reduce the servicing required. The structural frame is formed from post-tensioned slabs, with spans of up to 10.5m. The setbacks are achieved through either cantilevering the post-tensioned slabs or by transferring the edge columns.

The hybrid section is in the lift and stair cores, which were formed using twinwall (see figure 2, type 1, previous spread). Precast concrete sandwich panels were used for the brick facade. The concrete slab soffit is exposed throughout the building, contributing to the project's environmental strategy, while the use of ground granulated blast-furnace slag (GGBS) as cement replacement in the concrete mixes reduces the embodied carbon associated with the structural frame's construction, further enhancing the building's sustainability credentials.

used as specified in Eurocode 2 or in the relevant material or product specifications

- the structure will be adequately maintained
- the structure will be used in accordance with the design brief
- the requirements for execution and workmanship given in BS EN 13670 are complied with.

The designer should state the design assumptions, which should generally include the following construction-related information:

- sequence of construction
- exposure requirements
- pour sizes assumed (if appropriate)
- concrete strength at time of striking formwork and back-propping requirements
- breakdown of loading including allowance for construction loads
- loading history assumed. ■

For more information, see Design of Hybrid Concrete Buildings by The Concrete Centre, available at concretecentre.com/publications

OPPOSITE The Ray's in-situ concrete slab soffit is exposed throughout the building, contributing to the environmental strategy

RIGHT The building has a number of setbacks created by cantilevering the post-tensioned slabs or by transferring the edge columns

Photos: Rpb Parrish

Flood resilience **starts at home**

Anti-flood measures are an essential part of our response to climate change, not just a topic for winter or for high-risk locations, writes Elaine Toogood

Adaptation is an essential component of responding to climate change, and flood resilience is a core consideration. Around one in six UK properties are currently at risk of flooding from coastal and fluvial flood events, and this is set to double by 2050 due to changing weather patterns and increased urbanisation. Designing out avoidable repair and maintenance and extending the usable life of buildings or components will be key to achieving a net zero carbon society – repeated replacement of water-damaged fittings and fixtures has little place in a circular economy.

The threat of water damage is not limited to identified coastal or fluvial flood risk areas. Surface-water flooding, burst water mains and blocked drains affect all buildings irrespective of location. Choosing a water-resilient structure reduces not only the potential damage from external sources, but also other events such as undetected leaky pipes.

Property-level flood resilience

Property-level flood resilience (PFR) refers to physical measures or building components that reduce the risks of flooding to people and damage to buildings, and speed up recovery and reoccupation.

PFR is increasingly recognised as an important part of the strategy for dealing with flood risk. Later this year, the Environment Agency is due to publish its revised National Flood and Coastal Erosion Risk Management Strategy for England. The draft proposals indicate a shift away from potentially limitless barriers and towards an acceptance that some areas will flood, with a greater focus on flood resilience at property level.

The Social Market Foundation think tank, backed by government insurance scheme Flood Re, has proposed that flood performance certificates could, like an energy performance certificate, become an essential part of the information provided at sale or rent of a property, identifying risks and resilience measures.

As part of the Department for Environment, Food and Rural Affairs' Property Flood Resilience Action Plan, construction industry research body CIRIA has produced a code of practice for improving the flood resilience of properties, with more detailed guidance due to be published later this year. It will primarily focus on measures that can be introduced to existing buildings, either during repairs after a flood, or in anticipation of one. But as with retrofit measures for improving energy performance, it is widely recognised that improving flood resilience is much easier when considered from the outset – that is, in new buildings rather than as retrofit measures.

Strategies for property-level resilience

Establishing the type of flood event likely to affect a property is fundamental to establishing an appropriate solution. The design strategy should be based on anticipated flood depth, likely duration and source of flooding, but also take project-specific factors into account such as the cost of construction, the cost and impact of repair, and recoverability after a flood incident.

The first step is avoidance: locating the property at area of least risk and/or raising the accommodation above the predicted flood level. The second is site layout: using the landscape to reduce flood risk or delay its impact on the building, without increasing risk elsewhere, using features such as bunds, sustainable urban drainage systems and storage. Mitigation is the final step, where the layout, choice of construction materials and detailing are developed to keep the water out as far as possible (resistance measures), and minimise damage and speed up recovery when it does get in (recoverability).

REPEATED REPLACEMENT OF WATER-DAMAGED FITTINGS AND FIXTURES HAS LITTLE PLACE IN A CIRCULAR ECONOMY

The strategies for improving the flood resilience of an existing property are far more complex than for a new-build. It is rarely practical to raise floors above the predicted flood level, and opportunities for external measures to delay water ingress can also be limited. Mitigation of the building fabric, fixtures and fittings are therefore the main area of focus – but the limitations of existing layouts and sheer range of construction types mean solutions must be tailored to specific situations.

This is one of the challenges of developing appropriate guidance for retrofit. Clearly flood doors, non-return valves and other applied or integrated barriers to water ingress play an important role. More fundamental are improvements to the building enclosure and surface finishes. One method, shown to work effectively at the flood resilience demonstration house at the BRE Innovation Park in Watford, is to line the inside of the ground floor and walls with

Images: BACA Architects

◀ Case study: Shipston, West Midlands

"As a nation we end up with a cycle of flood-damage-patch-repair, and focus that dwindles away in the spring. Then comes the flood season, everyone is surprised and we are not prepared again," says Richard Coutts, director of BACA Architects. Its amphibious house, featured on Grand Designs, is often rolled out in the press as a solution for "living with water", but a development of 12 homes nearing completion just outside Stratford-Upon-Avon is far more significant as a prototype for new buildings at risk of flooding to help avoid this cycle of damage.

One could be forgiven for not noticing the flood measures carefully embedded into the development. All principle floors are raised above the Environment Agency's plus-20% climate change fluvial flood level, providing a safe haven within the properties, and there are no bed spaces on ground floors. A significant aspect of the design is the space made for flood water across the site, using a number of complementary strategies.

All the houses use cavity-wall construction, with a concrete block inner leaf. The concrete ground floors are raised on a reinforced-concrete frame, leaving an accessible void under the buildings. Internal walls forming the staircases and halls are also blockwork. "Concrete performs well in a flooded situation," says Coutts. "It is robust enough to be unaffected by being submerged and dries out at a reasonable rate."

This non-defensive flood-risk management approach is also being adopted by BACA on a 300-home development for Yorkshire Water, working with Harper Perry Architects.

a waterproofing layer and drained cavity, allowing incoming water to drain away. Such techniques, more commonly associated with basement construction, are increasingly recognised as useful.

It is possible to adopt a "sacrificial" approach, in which elements of a building and its fixtures and fittings are treated as expendable, to be ripped out and replaced after a flood event. But this must be considered very carefully to avoid unnecessary cost of replacement, quite apart from the waste created.

Flood-resilient structures

It is important that the structure is not compromised by a flood event, and crucially repeated events, as this is the most costly and disruptive part of a building to replace. A quick recovery with limited additional expenditure and resources is clearly desirable, and here concrete and masonry construction offers significant advantages. Its performance is not affected by being submerged, or from drying out. Unlike framed solutions, it can also be installed without voids and with very few joints, helping to keep water out. All the recommended and preferred wall and floor constructions in the current British standard, BS 85500:2015 Flood resistant and resilient construction, are made from concrete or masonry.

Concrete and masonry can be both structure and final finish, offering the ultimate in material efficiency both during construction and after a flood. The time taken to dry out some types of water-saturated masonry is sometimes seen as a disadvantage to speedy reoccupation, but this is not an issue with an internally lined and drained solution such as used at the BRE flood house.

Concrete itself is very slow to absorb moisture, and can even be water-resistant, as in basements and swimming pools. There are also numerous clear, surface-applied sealants that can limit moisture ingress. Those used to working in concrete understand that it can be supplied in a wide range of colours and textures, often with the appearance of stone. Where an exposed concrete surface is not desired, it also provides an excellent, stable base for other finishes, whether robust and waterproof, or sacrificial.

Concrete and masonry walls, floors and stairs, can provide resilience at the core of any building, even if all other measures are not installed from the outset. They can facilitate the application of further resilience measures in the future, as risk of flooding increases, especially if a whole building strategy has been considered from the outset. By embedding good flood-resilience thinking and materials in this quite simple way, we are better preparing our building stock for the future. "Be prepared" has become a mantra for those living with the risk of flooding, and surely all architects and developers should heed this advice. ■

Mastering mass: how schools can get the best out of exposed structures

Thermal mass could play a crucial role in combating overheating in classrooms. Nick Jones finds out how to do it right

As the planet grows hotter, keeping classroom temperatures within acceptable limits will become harder and harder. In 2017, the government imposed tougher overheating targets for school buildings, in an update to its Building Bulletin 101 guidelines on ventilation, thermal comfort and indoor air quality. The Schools Design Group at the Chartered Institute of Building Services Engineers (CIBSE) recently modelled the performance of 11 newly designed schools, both in our current climate and under future projections, using weather files to represent scenarios of 2°C and 4°C above pre-industrial levels. While all met the BB101 standard today, a number of classrooms failed under the 2°C scenario, and the majority breached the target at 4°C – a temperature rise that could occur as soon as 2065, according to the UN's Intergovernmental Panel on Climate Change. In seven of the schools, 100% of classrooms failed under the 4°C scenario.

One answer to the problem of overheating would be to install more mechanical cooling – but this is neither sustainable in terms of mitigating climate change or future-proofing schools' running costs. Instead, we need to find low-energy methods of keeping classrooms comfortable – a quest that is set to become a fundamental part of school design.

One potential strategy is to use the thermal mass of a building to even out diurnal temperature variations, by absorbing excess heat during the day. This can be very effective: CIBSE's research found that many of the best-performing schools built in recent years were thermally massive structures. But not all thermally massive schools are created equal, and some performed considerably less well, typically those without adequate ventilation. So it is vitally important that designers understand how to leverage thermal mass to its full potential – and that they pass this on to those operating the building to enable them to benefit from low-energy cooling for many years to come.

IT'S NOT ENOUGH TO DESIGN SOMETHING THAT YOU THINK SHOULD WORK, YOU HAVE TO HAVE CLIENT BUY-IN

Night purging

A low-energy cooling strategy using thermal mass has two essential components. One is a high proportion of exposed heavyweight structure, to absorb heat during the day. The other is a natural or mixed-mode ventilation system that cools the building at night, thereby "resetting" the structure so that it is ready to repeat the cycle the next day.

In order for a night-purging strategy to be successful, the building's users have to have absolute confidence in it, warns Jeremy Climas, head of education at Max Fordham, which has designed a series of high-performing naturally ventilated schools. "There are thousands of buildings where, for example, the design team allowed for natural ventilation at night but the people who operate the building don't use it like that. It's not enough to design something that you think should work, you have to have client buy-in."

Understandably, one of schools' chief concerns is security. "If night ventilation relies on opening windows then you can be pretty sure it's not going to happen," says Climas, "because nobody wants to leave windows open in an unoccupied building overnight." A safer alternative is a grilled or louvred opening, often behind a closable panel. If the school is in a noisy location, these units also need to incorporate acoustic buffers to insulate against external noise. This is particularly important in city locations and for rooms close to play areas.

In order to create a cross-draught in naturally ventilated classrooms, there needs to be both an opening through the facade and a means of exhausting air. As rooms rarely have two external facing sides, air usually has to be vented into a single-sided corridor or atrium via a fire-rated, acoustic-attenuated bulkhead against the corridor-side wall of the classroom, which allows air to escape while preventing noise from entering.

External louvres, meanwhile, should be located as close as possible to the exposed soffit, although the

ABOVE At Levitt Bernstein's recently completed building for Eltham College in south-east London, the precast-concrete structure is exposed internally to exploit the thermal mass and provide a contemporary contrast to the school's historic quad. In classrooms, acoustic baffles are hung vertically to maximise the area of soffit exposed to cross-ventilation

Photo: Ben Tynegate

layout also depends on factors such as window size and shape and the orientation of the classroom. The extra depth of side panels can be an advantage for placing acoustic buffers, says Giovanni Bonfanti, director at Walters & Cohen, which has just completed the naturally ventilated extension to St Paul's School in London (see box, overleaf). They can also provide an architectural feature – such as the vertical timber louvres on the facade of Walters & Cohen's Reigate Grammar School.

The upshot is that, for an essentially simple process, natural ventilation can feel complicated and may need a bespoke solution. "We always say to clients that a naturally ventilated building isn't necessarily a lot cheaper," says Bonfanti. "It's a simple solution, but there's a lot to build."

In the reality of today's public-sector school procurement, compromises often have to be made, particularly where layouts include double-sided corridors with no obvious means of cross-ventilation. At Penoyre & Prasad's BREEAM Excellent Bobby Moore Academy in east London, mechanical ventilation and heat recovery (MVHR) units were used, partly for acoustic reasons – the ▶

Insights: Concrete and masonry school structures

By Jenny Burridge

School buildings need to be robust, resilient and low maintenance, and concrete and masonry provide these benefits. Of particular importance is the inherent fire resistance of these materials – each year more than 2,000 schools in the UK suffer fires large enough to need action by the local fire and rescue service. Concrete and masonry not only provide fire protection for the occupants, but to the structure itself, particularly as this does not usually rely on the ongoing maintenance of additional linings to meet minimum standards. Their non-combustibility limits the extent of damage and minimises repairs and disruption, so that the school, or part of the school, can be reopened quickly.

A concrete structure can be cast in situ, precast or a hybrid of the two. The spans required in school buildings are normally around 8m x 8m, with typical room sizes ranging from 57m^2 for a junior classroom to 90m^2 for a drama studio. Concrete flat slabs, either normally reinforced or post-tensioned, are well suited to this flexible grid. They can be supported on walls or columns, depending on the requirements of the project. Using concrete or masonry walls means that the heavily trafficked corridors are enclosed in a robust material, while columns offer greater long-term flexibility. Both have been used to good effect in recently built schools. Concrete can also be left as a low-maintenance finish, a visually pleasing backdrop to school life.

ALL THE ENERGY THAT'S GENERATED FROM KIDS OBVIOUSLY NEEDS TO BE ABSORBED

Photos: Hélène Binet; Tim Crocker

TOP Louvred panels and high-level actuated windows provide cross-ventilation at Tim Ronalds Architects' science centre for Sevenoaks School

ABOVE Integrated acoustic and lighting panels at Penoyre & Prasad's Stratton Upper School, Bedfordshire leave the thermal mass above exposed

▶ building is on the flightpath to City Airport – and partly because of the energy savings that MVHR systems provide. The units, positioned at high level behind fixed louvres, incorporate an ultra-low-energy fan that can either draw air in from outside or push it out. It also enables night-time purging to take place securely without opening windows.

The BREEAM Outstanding-rated Ashmount Primary School in north London, also by Penoyre & Prasad, offers a variation on the same theme. This three-storey building uses a 'e-stack' low energy ventilation system located at the back of the classroom. In winter, the fan draws air down a chimney stack and premixes it with warm air before distributing it into the classrooms. In summer, the fan operates in the opposite direction, exhausting warm air drawn out of the classroom from windows opened in the external wall. "In terms of night purging, both systems work in a very safe way and worked well for an inner-city site," says Rafael Marks, associate partner at Penoyre & Prasad.

Automation can play a key role – at Bobby Moore Academy, the louvres are connected to a building management system (BMS), which opens them at night, as well as to air monitors, which can trigger daytime opening in response to temperature and carbon dioxide levels. Teachers do still have an element of a manual control, over an openable window at the lower level of the louvre panel.

Structure

The other key element of a successful thermal mass strategy is, of course, an exposed heavyweight structure. Concrete is ideal because its high specific heat capacity and density allow it to absorb a lot of heat, and these are combined with a moderate thermal conductivity, so absorption takes place steadily over the course of the day. From a school's point of view, concrete also offers a range of other advantages, from durability and low-maintenance to adaptability. "I would say 90% of the schools I've done have had a concrete frame," says Marks, "for thermal mass reasons but also because they give other benefits such as acoustic and fire properties. A flat slab gives you the flexibility for different services and also longer-term adaptability." In multistorey schools, where high ceilings are often unfeasible, a thermally massive soffit can be vital for moderating the classroom environment, he adds. "All the energy that's generated from kids obviously needs to be absorbed." Marks also points out that precast-concrete planks can be added to other structural systems as a means of incorporating thermal mass – such as at Penoyre & Prasad's recently completed Anna Freud Centre, a multistorey centre for children and young people's mental health, which has a hybrid structure with timber.

But exposed concrete also presents challenges, particularly since the BB93 acoustic standard for schools has become stricter on reverberation times. The government's baseline designs state that acoustic panels should cover about 40% of the classroom ceiling area, which could obstruct much of the thermal mass of a soffit. Solutions include suspending acoustic panels and incorporating them with light fittings to reduce unnecessary clutter – generally suspended systems need about 600mm clearance, so work well in room with a floor-to-ceiling height of 3.2m or more. "It's a fairly standard detail now," says Marks, "and the added benefit is that the space feels lighter and taller."

Bonfanti suggests vertical rather than horizontal baffles, which have less impact on the soffit. "In some cases they are even more effective, because both sides of the acoustic material are exposed to the sound reverberation." Carpet is an option for reducing the reverberation between soffit and floor (see St Paul's School box) – but this means forgoing the useful thermal mass of the exposed screed.

There are various techniques to make the concrete structure as materially efficient and low-carbon as possible. At Sevenoaks School Science & Technology Centre in Kent, Tim Ronalds Architects used ribbed precast-concrete soffits in some areas, to minimise the concrete used. "You don't need as much of it and it increases the surface area so the thermal mass works even better," says Climas.

Another innovative approach at Sevenoaks School was the use of groundwater-chilled pipes cast into the concrete to super-charge the slabs' cooling potential in high-occupancy, high-energy areas such as labs. Although this was a private-sector project, with a corresponding budget, Climas suggests that this solution could also be pre-installed in the state sector as a means of future-proofing new buildings. "You can cast it in now, because it's just some plastic piping – it's not a particularly expensive thing to do. The expensive bit is putting in a chiller or heat pump, but once the pipes are in, that can be installed in the future."

It is also important to remember that solutions may need to be classroom-specific – what works in a normal teaching space might not in a workshop or theatre studio. At Bobby Moore Academy, for example, larger classrooms have two MHVR panel units, and excess air can also be drawn out of the back of the classroom into the 4m-wide corridors, from where it extracts via three louvred rooflights.

Thermally massive buildings that are well-designed and well-operated are already providing relief in the more frequent heatwaves the UK is experiencing. Climas recently returned to one of his first Max Fordham projects, The City Academy in Hackney, on a scorching hot summer day. "The school had continued doing the night ventilation the way they were supposed to, and they managed to get all of the heat out of the concrete overnight. It was wonderfully cool, 6 or 7°C lower than outside." ■

▲ Case study: St Paul's School second phase, London

Walters & Cohen has just completed the second phase of its energy-efficient, concrete-framed teaching complex at St Paul's School in London. Exploiting the structure's thermal mass was one of the main drivers from early in the design process. "The MEP engineer, Max Fordham, was targeting reductions on energy use within the building, and we are always keen to embrace natural ventilation wherever possible, so a high thermal mass was a good way of bringing the two together," says Walters & Cohen associate director Tim Rowley.

All of the rooms with natural ventilation have a large, low-level manually operable panel, and a smaller, high-level automated panel. This high-level panel, linked to the BMS, opens when the room is too warm, has too much CO_2, and at night. Air is drawn across the classrooms and into the deep-plan building's circulation area, from where it is exhausted via a series of lightwells.

The acoustic strategy involved the use of fabric hanging-baffles suspended within the classrooms, augmented with some acoustic treatment on the walls. "The use of carpet was crucial as well in order to avoid sound 'bouncing' between the floor and ceiling," Rowley adds.

"We are designing state schools right now which will use exactly the same principle. We might not have the budget for the concrete to be finished quite so finely, but the greater challenge, particularly for schools in an urban context, is dealing with external factors such as noise and air pollution when trying to implement natural ventilation. Using the thermal mass for night-time cooling doesn't have this constraint so we are always keen to utilise it."

Photo: Peter Segasby

The beautiful **south**

ABOVE Gusto Homes' Woodlands Edge development near Lincoln. The majority of glazing is on the south side, maximising solar gain and minimising heat losses from north-facing elevations

The interaction of south-facing windows, shading and thermal mass can reduce a home's energy demand by up to 40%. Tom De Saulles explains how

Passive solar design (PSD) is a simple technique that helps capture the sun's energy, reducing the need for space heating from autumn to spring. It works by combining appropriate building orientation and window size with thermal mass in the building fabric, which collectively enable sunlight to be absorbed and used as a source of heat. Studies have calculated potential energy savings of around 11% in conventional masonry and concrete homes, with greater savings of around 40% (35% in Scotland) where more specific design features are applied, such as the use of sunspaces.

In spite of its recognised benefits, uptake in mainstream UK housing has been few and far between, partly due to building regulations that do little to encourage passive design, partly due to a housing industry that prioritises density and generic design over orientation and spacing, and partly due to the absence of appropriate shading on south-facing windows, which has resulted in the common misconception that a southerly aspect automatically increases overheating risk.

However, this may change over the coming years, as renewed focus is turned to passive performance. Revisions to Part L and the introduction of the Futures Homes Standard are likely to increase emphasis on dwelling orientation in response to greater uptake of photovoltaic panels, which should ideally be south-facing. Meanwhile, the need to reduce overheating risk should lead to a regulatory requirement for proper shading on south-facing windows, ideally in the form of deep roof eves, balconies and overhangs – all capable of keeping out the high summer sun without limiting solar gain during the heating season.

Design considerations

In its simplest form, PSD can be implemented by increasing the level of glazing on the south elevation so it is roughly twice that on the north elevation. North-facing windows have a net heat loss over the year, so should be sized to just provide adequate daylighting. Conversely, south-facing windows experience a net heat gain over the year, so should be sized to take advantage of this.

Designing to take advantage of PSD requires an integrated approach to find the best overall balance of glazing, orientation, and thermal mass. However, the general approach can be summarised as:

- A southerly orientation to allow passive solar gains from autumn to spring
- A sufficiently clear view of the sky from the south
- A high standard of insulation and airtightness
- A medium to high level of thermal mass
- Well-insulated double glazing that combines an inner pane designed to reduce heat loss and an outer pane of extra-clear glass to increase the amount of free heat from the sun
- Windows or an alternative means of passive ventilation that provide cooling on summer nights, while taking account of any security or noise issues
- A compact rectangular plan with the main living area on the south side of the house.

Orientation and shading

Orientation is the most critical factor in determining the amount of sun that a dwelling receives from autumn to spring. Ideally most of the window area should face within around 30° of south, with the south elevation enjoying a relatively clear view of the sky, to allow radiation from the low winter sun to pass directly inside.

In midwinter, the sun reaches a maximum altitude above the horizon of about 17° in southern England. During the height of summer it will reach about 64°, which can be particularly useful when designing a shading strategy, as a simple overhang will block the sun during the hottest part of the day. This very simple form of shading requires no user control or maintenance.

Dwelling location and spacing

The further north you are, the lower the solar gain. However, the heating season is longer, so the benefits of PSD could be more significant. A house in Scotland, in an average year, will require nearly 45% more energy to maintain a given temperature than in south-west England. Greater emphasis could be placed on winter performance in the north and more effective solar shading in the south.

To avoid overshadowing, the spacing of dwellings also varies between northern and southern Britain. Based on average house height, minimum spacing is 20m in Southampton and 25m in Leeds, increasing to 35m in Inverness. Where an obstruction is likely to reduce the amount of direct solar radiation, some heat is still obtained from diffuse and reflected radiation.

Thermal mass

A medium to high level of thermal mass is most easily and cost effectively provided by concrete and masonry floors and walls with a suitable finish that does not impede heat flow. As a rough guide, the surface area of the floor/soffits and walls providing the mass should be at least six times that of the glazing in the room, although this will to some extent be influenced by the particular thermal capacity and conductivity of the material. So, as the area of south-facing glazing increases, more thermal mass is required to maintain a stable temperature during the summer.

The position of the insulation is also very important, as the thermal mass needs to be located inside the insulated building envelope. In practical terms, a masonry cavity wall already satisfies this basic rule, as the insulation is located in the cavity, allowing the inner leaf of blockwork to be room side. For solid masonry walls, the insulation should be located behind the waterproofing layers on the outer surface of the structural wall. The insulation for solid ground floors should be located under the slab, although screed placed on top of insulation will also provide useful thermal mass.

Internal finishes

It is important that the surface of heavyweight walls and floors remain as thermally exposed as practicable. For walls, this is best achieved with a wet plaster finish, which conducts heat relatively freely, as well as providing a robust air barrier that will help minimise air leakage. Dry lining will reduce heat flow, but its impact will depend on the thermal mass potentially available in the wall. For an aircrete block inner leaf (which has relatively low thermal conductivity), plasterboard is less of a thermal bottleneck than for heavier aggregate blocks. These have higher thermal conductivity (and thermal mass), and if their full potential is to be unlocked, the choice of finish will have more impact. With some forms of concrete wall and floor construction, it is possible to achieve a high-quality, visual finish with little more than a coat of paint.

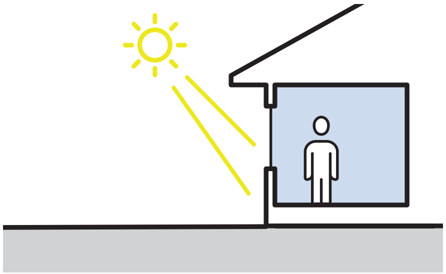
Wherever feasible, the thermal mass of the ground floor (particularly in south-facing rooms) should be optimised, with carpet avoided. Stone, ceramic or porcelain tiles are useful, as is exposed concrete. Shiny or glossy floors will absorb less heat than a dull finish; however, this must be evaluated alongside daylighting requirements and the tendency of such a surface to absorb light. These surfaces also work well with underfloor heating.

Layout

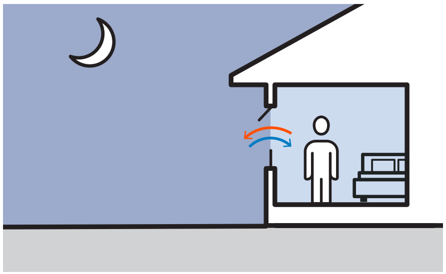
Where practicable, the most frequently used rooms should be on the south side, with bathrooms, utility rooms and halls to the north. In southern England, bedrooms are usually best located on the north side to help maintain comfortable night-time conditions during summer. Where possible, the layout of bedrooms should also enable cross-ventilation or stack ventilation, particularly effective in lowering the internal temperature during summer and removing heat from the thermal mass. ■

FIGURE 1: HOW PASSIVE SOLAR DESIGN WORKS

Thermal mass during summer

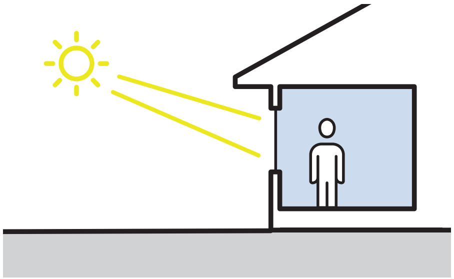


DAYTIME On hot days, windows are kept shut, and shading is adjusted as needed to minimise solar gain. Cooling is provided by the thermal mass. On cooler days, windows may be opened.

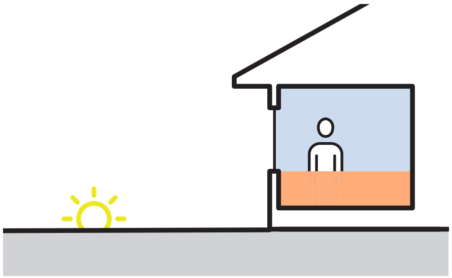


NIGHT-TIME If it has been a hot day, windows are opened to cool the thermal mass.

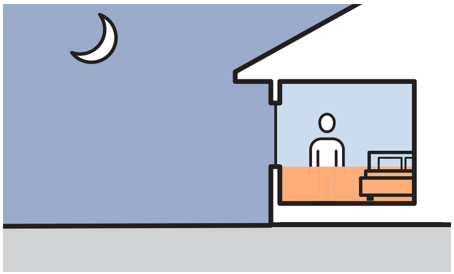
Thermal mass during the heating season



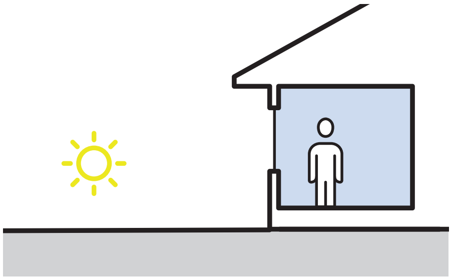
10AM – 5PM Sunlight enters south-facing windows, heating the air and the thermal mass. On most sunny days, solar heat can help maintain comfort from mid-morning to late afternoon.



5PM – 11PM By sunset, a substantial amount of heat has been stored in the thermal mass. This is then slowly released, helping to maintain comfortable conditions in the evening.



11PM – 7AM Only minimal supplementary heating is needed. Good airtightness and insulation minimise heat loss.



7AM – 10AM This is the hardest time for passive solar heating to maintain comfort, so some supplementary heating is needed.

Beyond the binder: How to specify lower carbon concrete

Understanding strength and structure is key to reducing concrete's footprint, writes Jenny Burridge

In October 2020, the UK concrete and cement industry launched its Roadmap to Beyond Net Zero. The roadmap shows how the industry can continue its decarbonisation journey, with the aim of providing net-zero concrete by 2050. The industry has already taken considerable early action, and due to investment in fuel switching, changes in product formulation and energy efficiency, its direct and indirect emissions are 53% lower than 1990. The roadmap shows that the industry could become net negative by 2050, without offsetting, removing more carbon dioxide from the atmosphere than it emits each year.

Although a net-zero concrete is not yet available, significant amounts of carbon can be saved by looking at how we specify concrete and adopting the most appropriate solution for each project. This is not simply a case of selecting the most "low-carbon" mix, but understanding the properties of cement replacements and additions, factoring in considerations such as strength gain, and using materials as efficiently as possible.

Cement replacements

If we consider the different constituents of concrete, around 85-90% of the mix is represented by aggregates and water. These have very low embodied carbon, with locally sourced primary aggregates responsible for about 4kgCO$_2$/tonne. It is the cement, forming the remaining 10-15%, that leaves the biggest footprint. A critical means of reducing concrete's embodied carbon is therefore to specify low-carbon mixes using cement replacements, or low-carbon cements.

All concretes to British Standard BS 8500 are based on Portland cement, or CEMI, but most contain secondary cementitious materials (SCMs) or additions, such as ground granulated blast-furnace slag (GGBS), fly ash, silica fume, limestone powder and pozzalana. These SCMs have a much lower embodied carbon than CEMI (see table 1).

Since the most recent version of BS 8500, ternary blends of cements have been allowed. Ternary refers to CEMI with two additions, normally limestone fines with either fly ash or GGBS. All of these cements are based on CEMI, but there are also geopolymers or alkali-activated cementitious materials (AACMs) that can be specified using PAS 8820, a publicly available specification produced by standards body BSI. These are normally based on GGBS, activated by a chemical that is added to the mix. ▶

TABLE 1: EMBODIED CO$_2$ OF UK CONCRETES*

Broad designation of cement type in concrete	Percentage of addition	Embodied CO$_2$ kgCO^2/m^3 of concrete
CEMI	0%	283
IIA	6-20%	228-277
IIB	21-35%	186-236
IIIA	36-65% GGBS	120-198
IIIB	66-80% GGBS	82-123
IVB	36-65% fly ash or pozzalana	130-188

* Based on a cement content of 320kg/m^3 of concrete

BOTH IMAGES At 12,000m^2, the Christie Proton Beam Center in Manchester is the largest treatment facility of its kind in the world. Its dense heavyweight structure, containing some 17,000m^3 of concrete, is vital for shielding staff and visitors from high levels of radiation. The mix used by contractor Interserve contained 70% GGBS cement replacement, drastically reducing the embodied carbon of the structure and also minimising heat gains and thermal cracking during curing.

Photos: Interserve


PROTON BEAM THERAPY CENTRE
THE CHRISTIE

▶ Strength gain

One of the things to note with the use of low-carbon concrete is that the higher the proportion of additions, the slower the strength gain. This might not influence the construction programme if the concrete does not need to be struck quickly or to support load shortly after being cast. For example, foundations are frequently cast against the ground and the load is applied only slowly as the project progresses. Although the standard concrete strength is specified at 28 days, a concrete made with CEMIIIB cement will still be gaining strength at that stage and may be a further 40% stronger when it has gained full strength. The designer could take advantage of this by specifying a 56-day strength.

For foundations, cement replacement of up to 80% GGBS may be possible. Elements that need to have a faster strength gain, such as suspended or post-tensioned slabs, can still use additions and do not need to be restricted to using CEMI. There have been several projects that have used CEMIIIB for a post-tensioned suspended slab, and concrete producers can add an accelerant admixture to improve the setting time.

TOP At Nicholas Hare's UCL Student Centre in London, all of the in-situ concrete and some of the precast elements use 50% GGBS cement replacement, as well as high levels of recycled aggregate

ABOVE Nithurst Farm in Kent by Adam Richards Architects also uses 50% GGBS. This both reduces the building's embodied carbon and realises the architects' desired pearl-grey finish

A CONCRETE MADE WITH CEMIIIB CEMENT MAY BECOME 40% STRONGER THAN ITS 28-DAY STRENGTH

Material efficiency

Designers should also be aware that, even where a larger proportion of cement is needed for higher-strength concrete, in some instances this can actually reduce the embodied carbon of a structure, as a smaller volume of concrete is required overall. Alternatively, as the water-cement ratio is key to the strength of concrete, use of superplasticiser admixtures reduces the cement content in the same strength concrete by reducing the water.

Structurally efficient sections such as rib or voided slabs, or post-tensioned structures also use less concrete, while foundations can be made more efficient by avoiding standardised sizes across the site.

If in doubt, the simplest way forward, at the moment, is to specify designated or designed concretes with a reduced range of cements. There is also a range of proprietary low-carbon concretes available. It is worth talking to your concrete supplier as early as possible to find out what can be achieved for the location and needs of the project.

Reducing a structure's carbon footprint takes a lot more than simply specifying a material. There is currently no single structural material that can be considered "lowest carbon" across all projects. Instead, we must look closely at its constituents and performance, and its impact on the building as a whole, and specify the most appropriate solution in conjunction with factors such as ground conditions, building height, climatic conditions, floor loading, longevity and opportunities to dematerialize generally. And once material choices have been made, we must redouble our efforts to use them as efficiently as possible. ■

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Photos: Brotherton Lock; Alan Williams Photography

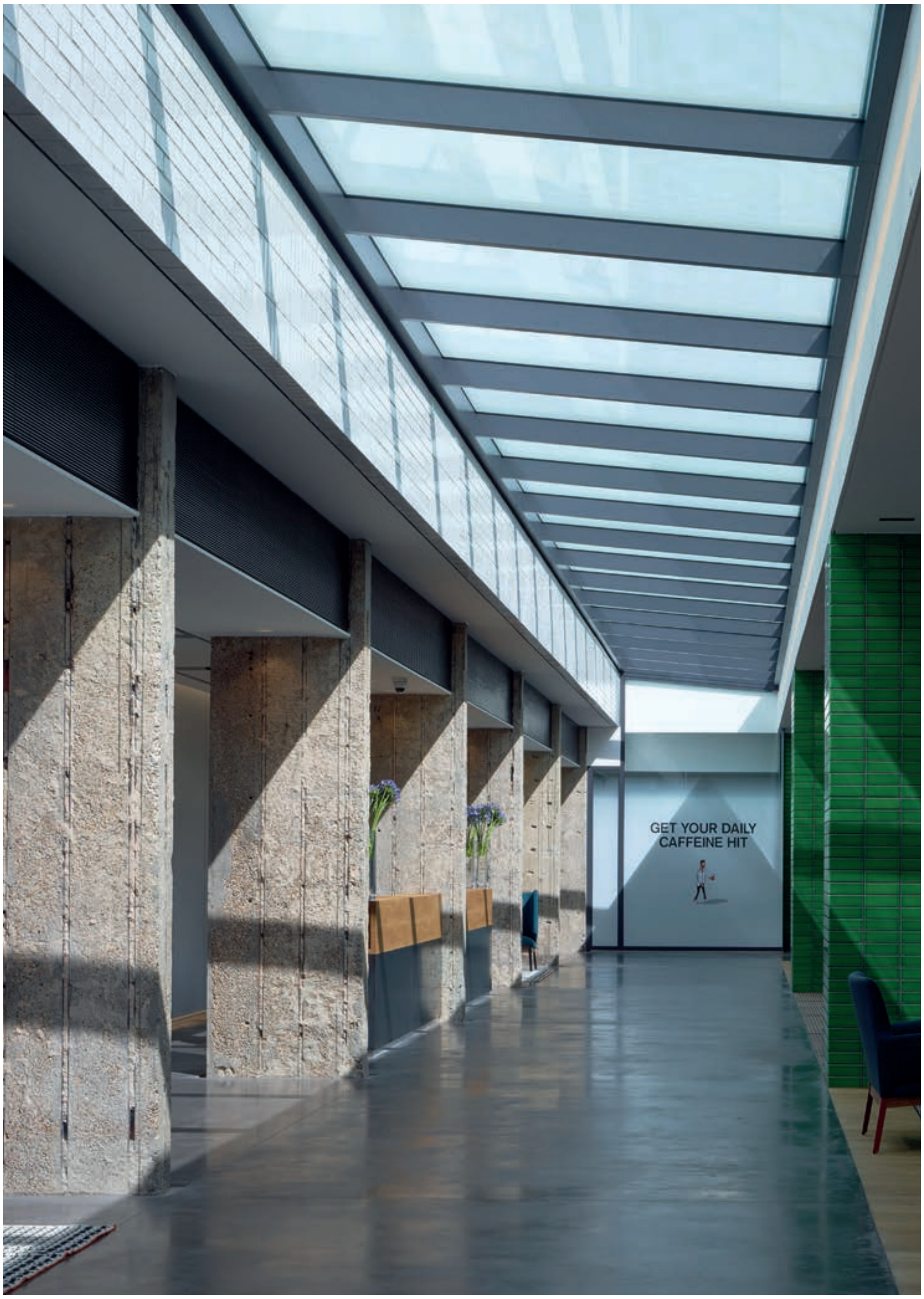
Reusing structures:
One step closer to a circular economy

An internal concrete frame can remain usable for double the original design life. Jenny Burridge offers some pointers for structural engineers

It's good to see a growing momentum in favour of reusing existing building structures and extending their lives, as the construction industry considers ways to reduce the amount of materials it consumes.

Concrete lends itself well to this approach – as can be seen by the number of buildings that have successfully been given a new lease of life. This year's Pritzker Prize was won by Lacaton & Vassal partly for the transformation of three social housing buildings at Grand Parc in Bordeaux, where the concrete frames were upgraded and generous flexible spaces added to each unit. The case study of 160 Old Street overleaf also shows how well an older concrete frame can be adapted to form the structure for a new building. In this case, 76% of the original structure was retained, reducing life-cycle emissions by 2,850 tonnes, while increasing the building's net lettable area by 70%.

This kind of project is one approach to a circular economy, where the element to be repurposed is not individual beams or columns, but the entire frame. It is possible because concrete is a very durable material – when used internally, designing for 50 ▶



RIGHT At 160 Old Street in London, the original external columns, complete with Halfen channels for the cladding, now frame the reception area (see case study overleaf)

Photos: Timothy Soar

▶ Case study: 160 Old Street, London

By 2013, 160 Old Street was looking decidedly out of place in London's high-tech quarter. Built in the 1970s as offices for the Royal Mail, it was ripe for demolition, with dated interiors, low ceilings, inflexible layouts and wheezing systems. Fast-forward eight years, however, and it has been granted an unlikely second life, swapping the humble postal service for 21st-century communications as the London base of satellite news giant CNN.

The building may look completely different, but in fact, 76% of the original concrete structure was retained. "Refurbishment is always our first port of call, because of the amount of carbon you can save," says Simon Whittaker, director at project architect Orms. "And this building had good bones to it." According to the Revit plug-in One Click LCA, this reduced life-cycle emissions by 2,850 tonnes.

The other constraints on redeveloping the site from scratch were the existing nine-storey structure's under-reamed piles, which would have been impossible to excavate, and the surrounding buildings' rights to light, which ruled out a new high-rise. Despite this, Orms and structural engineer Heyne Tillet Steel, were still able to increase the net lettable area of the building by 70%, pushing out the perimeter by 500mm, inserting strategic connections between the wings of the E-shaped plan, and adding three lightweight storeys to the top of the structure. "Part of the reason we were able to do that was that the concrete frame had such inherent capacity," says Whittaker. "We added 40% additional load to the frame without having to reinforce it."

The starting point was to understand as much as possible about the original structure. HTS managed to find about 260 of the original structural drawings, from which the team built a Revit model, using the original 1970s concrete codes. "This was one of the first projects that we as an office did in BIM," says Whittaker. "We all collaborated on the model and that gave us a really good understanding of the structure very early on." As they began to strip the building down to the frame, HTS could then confirm their assumptions by taking core samples. "That verified the strength they were anticipating, but it also verified that the concrete had gained strength since it was poured, which was very useful."

The structure may have been in good repair, but it was still designed to house a very 1970s idea of what an office should be. Floor-to-floor heights were a slightly claustrophobic 3m and the unusual E-shaped plan meant there were no fewer than five cores, two with lifts and three with stairs. The floor was a clay pot slab, which was in good condition but restricted where ceiling fixtures could go – any damaged pots had to be repaired to maintain fire integrity. All of this presented a challenge, as this was a speculative development and the client, Great Portland Estates, wanted an extremely flexible office space that could suit a variety of tenants.

Orms' guiding philosophy, however, was to work with the fabric of the building. The existing cores were kept, which resulted in the entrance moving onto the eastern elevation, away from Old Street. "Rather than making a new core with all the lifts in one place, we created this long pavilion-like reception area: you deliberately come in right in the middle of the two lift cores and are then directed to one or the other depending on what floor you're going to," says Whittaker. It's an intriguing example of form following a previous, defunct function: "Had it not been for the cores, the reception wouldn't have been quite as generous and open as it is."

Embracing the original structure went as far as leaving a wall in one of the lift lobbies, right in front of a lift entrance. "Originally we said, 'we've got to get rid of it, it's not where you'd want to have this wall', but because it was a shear wall it would have cost about £1m to remove it so we decided to expose it and make a feature of it. We grit-blasted and lit it, and it has become part of the experience of the building."

Orms continued to expose the structure wherever possible. "We were quite conscious about how honest we wanted to be with the found elements in the building, and it was just about making the most of all these different things we uncovered." The internal columns on the upper floors have been grit-blasted, while the soffits on the lower floors, once parking and storage areas, have been stripped back to celebrate their deep downstand beams. "It was a very dynamic space to turn into an office, with big structure and big spans," says Whittaker. "They were the spaces that TBS [owner of CNN] took, because of those really interesting volumes."

The columns in the reception area are just as striking. Originally external perimeter columns, these have been grit-blasted to expose the Halfen channels that once anchored the cladding, giving a steel pinstripe to the raw concrete. "We debated whether we should pull them out, but it provided a really good contrast to some of the more clinical finishes in the reception."

The exposed structure also helped to solve the problem of achieving 2.7m-high ceiling heights with so little headroom for manoeuvre. The services are channelled through a metal raft system along the middle of each wing of the building. Beneath this raft zone, the floor-to-ceiling height is 2.4m, but the rest of the soffit is clear up to the structural slab, giving the extra 30cm. "Having multiple cores came to our aid here," adds Whittaker. "We could serve the floor plates from both ends, halving the length of the ductwork, and reducing its depth."

The result – after some suitably media-friendly fitting out – is an office that comfortably holds its own against the district's best white collar factories, with flexible workspaces, new light-filled internal courtyards and external terraces on every floor. Occupants control the lighting and temperature of their desk space using a smartphone app, which is based on a digital twin that records and monitors the building's performance. In time, it will also inform any future adaptations – which should ensure that tomorrow's structural engineers don't have to root around looking for 50-year-old drawings.

ABOVE The entrance has moved to the eastern elevation, away from Old Street, creating a long pavilion-like reception area

▶ years will give at least 100 years of useable life.

Reuse is necessarily always a bespoke solution, and the decision in every case will depend on the unique circumstances of a specific building and the current requirements of the client and the market. But for structural engineers involved in potential reuse projects, there are several steps that will be key to a successful outcome.

Work out what's there

When conducting an initial investigation into the potential for reuse, a first step is to look for record drawings. This will make a huge difference to the design of the modifications – and will act as a useful reminder that the drawings and information we produce for new buildings or extensions today should be kept safe for future engineers. With a copy of the drawings, the checks required to analyse the frame for the new use and loadings becomes much easier.

If the old drawings no longer exist, it will be necessarily to conduct investigations to check what is there. In particular, the following should be analysed:

- Concrete strength, using cores taken from the concrete and analysed using BS EN 13791. Samples should be taken from around the building and include slabs, beams and columns
- Cover to the reinforcement and the distribution of the reinforcement
- Element sizes.

Concrete continues to increase in strength as it ages, so even with the drawings to hand it is worth checking the concrete strengths.

Another resource for checking existing concrete frames might be archive editions of Concrete Quarterly, which go back to 1947 and contain many detailed case studies. The full archive is available in PDF form at concretecentre.com/archive.

TABLE 1: HISTORIC DESIGN CODES FOR CONCRETE STRUCTURES

Year	Code
1915	Reinforced Concrete Regulations of the London County Council
1934	Code of Practice for the use of reinforced concrete in buildings
1948	CP114, The structural use of normal reinforced concrete in buildings
1957	CP114 revised version
1959	CP115, The structural use of prestressed concrete in buildings
1965	CP116, The structural use of precast concrete
1969	CP114, CP115 and CP116 Part 2 – metric units
1970	Addendum to CP116 to cover large-panel structures
1972	CP110 Code of practice for the structural use of concrete (first design code to include limit states)
1985	BS 8110 Structural use of concrete

Assessing capacity

The concrete frame can then be back-analysed to check its capacity and to assess whether this will be sufficient for the new use. The codes of practice that were in use when the frame was built are very helpful in this respect (see table 1, above), but it is possible to use modern methods of analysis on an old frame. Strut-and-tie modelling is particularly helpful in this regard as it can show many possible load paths within the concrete (for more information, refer to *Strut-and-tie Models*, The Concrete Centre, 2015).

Broadly speaking, design concrete strengths have increased over the years. In 1934, the ordinary grade concretes had strengths of 16–20MPa. By 1985, BS 8110 assumed minimum strengths of 20MPa for reinforced concrete, 25MPa for precast concrete and 30MPa for prestressed concrete. Concretes in the 1980s were typically a cube strength of 30MPa for normal reinforced concrete frames.

Reinforcement grades and types have also changed with time. It is advisable to test reinforcement in buildings dating from before 1960, as it tended to be quite variable. Generally, plain round mild steel bars had a yield strength of 250MPa, with high yield deformed bars 415–485MPa depending on the age and diameter. The Concrete Society's 2020 publication *TR70: Historical approaches to the design of concrete buildings and structures* is a very useful guide for the designer.

If a concrete structure does need to be strengthened, various methods can be adopted, from replacement of the over-stressed element to strengthening with additional reinforcement or carbon fibre. The 2012 Concrete Society publication TR55 Design guidance for strengthening concrete structures using fibre composite materials gives guidance on using fibre composites to strengthen both bending elements and columns. The confinement provided by wrapping the column with carbon fibre increases the capacity of the concrete significantly. ■

Circular economy: strategies for concrete buildings

Designers can help shift our throwaway culture to a circular one by extracting the maximum value from building structures, writes Elaine Toogood

There is a growing recognition among governments, businesses and the public that we urgently need to transform our take-make-dispose economy into a circular one, in which resources are kept in use for as long as possible while maximum value is extracted.

In this way, we can reduce the environmental impact of human activities and the waste that they generate, make our societies more resilient to future shocks and supply issues, and ensure that we continue to meet the needs of future generations while living in balance with the natural systems that we rely upon.

Achieving this will involve significant, sustained change in every part of society – and we need to start now. This article will consider the strategies that designers can adopt to maximise concrete structures' potential in a circular economy, and ensure that they are fit for purpose for a world in which resource use is radically lower and no material is wasted.

Reuse

Reusing a building structure is the most effective way to keep its materials in use for as long as possible and to extract the maximum value from them and the benefits of retaining and reusing concrete frames are increasingly recognised by designers, developers and planners. This may involve expanding and improving an existing building so that it can continue to perform the same function as user needs evolve, as at The Bower in London's Shoreditch where AHMM repurposed two tired 1960s office buildings (CQ 268, Summer 2019). Or it might mean using the shell of a redundant building to fulfil a completely different purpose – such as ORMS' conversion of Camden council's old offices into a home for boutique hotel chain The Standard (CQ 270, Winter 2019, and right).

This strategy reduces the demand for new materials, and the embodied carbon associated with new development. Retaining the existing concrete in buildings also provides the opportunity to tap into its thermal mass and so reduce operational energy use. For example, at Elizabeth II Court in Winchester by Bennetts Associates (CQ 255), coffered ceilings were exposed and became central to the new heating and cooling strategy.

Design for future reuse

Where a new structure or building is required, this should be designed to optimise future reuse, so embedding good circular economy practice. Here, the durability of concrete is an advantage. According to the design standards for a concrete frame located internally – in other words, in an environment classed as "low exposure" – no additional measures are required to achieve a service life of over 100 years compared to 50. (See BS 8500-1, tables A4 and A5, XC1 exposure class.)

The inherent low maintenance requirements of a concrete structure, and its resilience to fire and the impacts of weather, mean that it can remain serviceable over a long period, with the potential for multiple reuses during its lifetime. The key to optimising this therefore lies not so much in the material itself, but rather in the way that it is designed.

RIGHT Featherstone Young's Ty Pawb in Wrexham reinvents an ageing car park as an arts centre and market

Photo: James Morris

The "long life loose fit" approach to design is well established and can ensure future functionality through consideration of spans, optimum loads, regular grids and generous floor-to-ceiling heights. The many lessons being learned through current retrofit projects will also help inform the future-proofing of today's new buildings.

Design for disassembly and reuse can also maximise the lifespan of both individual components and the building structure itself. This is particularly applicable for parts of a building that are likely to be changed or replaced more frequently, such as fixtures and fittings, but is being increasingly considered for more integral elements such as cladding. Designing the less permanent layers in this way increases the reuse potential of the underlying structure by making it easier to upgrade it or to strip it back to facilitate an alternative use.

Structural elements themselves can also be designed for disassembly, especially for buildings that have relatively short lifespans. This is an approach that is already taken for precast concrete products, such as stairs and stadium seating, fencing, barriers and paving. For example, the upper tiers of London's 2012 Olympic stadium are fully demountable so that they can be reused elsewhere, though for now they continue to fulfil their original function as the home of West Ham United – a good example of the circular economy hierarchy in practice. In this way, concrete structures should be viewed as a useful resource for future development.

Recycling concrete

When concrete does eventually reach the end of its life, it can be recycled. This applies to all concrete, and the process can be repeated again and again in perpetuity to provide a low-carbon resource with a range of applications.

The majority of concrete's volume/mass is aggregates, and when recycled, it becomes aggregate again. Some of this makes its way back into new concrete, but most is used "unbound" as sub-base materials, fill and hard core. Here, one industry's waste is another's raw material. Already, over 90% of the UK's hard construction, demolition and excavation waste, of which concrete is a significant proportion, is diverted from landfill for use in construction.

The UK's geology can provide a long-term supply of low-carbon, local, responsibly sourced natural aggregates for use in concrete. As recognised in the latest version of BREEAM New Construction, this can often prove to be the most sustainable solution. Elsewhere, in countries without this security of supply, there will be a greater need to use recycled aggregates in new concrete and the ▶

CURRENT RETROFIT PROJECTS WILL ALSO HELP INFORM THE FUTURE-PROOFING OF NEW BUILDINGS

▶ technical capability to do so is developing (see case study, opposite).

Concrete's role in reusing other materials

Most concrete contains some recycled material, and each of its principle constituent parts – aggregate, water, cement and reinforcement – can include recycled content. Common secondary cementitious materials such as GGBS and fly ash are, for example, by-products of other industries and the latest data shows that most steel reinforcement made in the UK uses about 96% recycled steel.

As a structural material, quality control and performance are understandably paramount. The allowable percentage of recycled aggregate content in concrete varies according to the intended use of the concrete, its location and the durability requirements, but also the type or grade of aggregate. Recycled aggregates (RA) is aggregate resulting from the reprocessing of inorganic material previously used in construction, such as masonry rubble. Crushed concrete aggregate (CCA) is a form of RA but principally comprised of crushed concrete.

Typically, lower strength and unreinforced concrete can contain 100% CCA as coarse aggregate permitted in GEN (general concrete) designations. Many other designated concretes can contain up to 20% CCA without special declaration. Higher percentage replacements are technically possible, provided the aggregate is tested to demonstrate it meets the required quality. It is worth noting that in comparison with the typically local and low carbon natural aggregates available in the UK, recycled aggregates can sometimes raise the embodied carbon of concrete, particularly where more cement content is required to meet required strengths.

Another source of recycled content is secondary aggregates, which are by-products of other industrial processes. These materials, such as air-cooled blast-furnace slag and china clay waste, also known as stent, have similar properties to primary or natural aggregates and are commonly used as an alternative fine or coarse aggregate in concrete in some parts of the country.

Around the world, there are many research projects that seek to use local waste resources in concrete – from coffee grounds and plastics to shredded car tyres or oyster shells. The ability of concrete to "hold" other elements in its surface using aggregate transfer or seeding – well-established processes for embedding material into the surface of concrete – can also facilitate the reuse other waste materials into useful construction products, such as waste bricks in concrete cladding panels (see case study).

With the growing emphasis on circular economy principles, further innovations and examples of good practice will no doubt emerge. ■

BELOW David Chipperfield Architects' Kunsthaus Zurich was built from 98% recycled concrete. In Zurich, to qualify as recycled concrete for use on public buildings, it must contain either 50% recycled concrete aggregate or 25% mixed demolition waste aggregate

OPPOSITE At Upcycle Studios by Lendager Group, the aggregate for the concrete reuses some 904 tonnes of waste from the construction of the Copenhagen Metro

Photo: Noshe

◀ Case study: Upcycle Studios, Copenhagen

Upcycle Studios is a terrace of 22 slender townhouses in the Orestad district of Copenhagen. Everything about its appearance indicates that it has been recently completed, from the fresh finish of its staggered concrete frame and blackened timber cladding to the newly planted landscaping. And yet its main construction materials all have a bit of a history: the douglas fir cladding, wooden floor boards and interior wall surfaces are all repurposed offcuts from floor manufacturer Dinesen; the glass for the double-glazing comes from abandoned buildings in North Jutland. And the aggregate for the concrete, which is used everywhere from the foundations to the floor slabs to the roof, is 100% recycled from the surrounding area.

"We wanted to do something unique and sustainable with this project," explains Anders Lendager, founder and chief executive of architect Lendager Group. "Could we take some of the largest waste fractions in the built environment sector and convert them into new resources, within the budget of a rowhouse project?"

For this project, he was able to tap into an abundant local waste stream. The Cityring extension for the Copenhagen Metro has been described as the country's largest construction project since the 1600s, incorporating 17 new stations and 15km of new tracks. Some 904 tonnes of waste concrete – mainly demolition debris and unused precast sections from the construction of the tunnels – now resides in the walls, floors and foundations of Upcycle Studios.

When Lendager sought the advice of local concrete suppliers, he found that they were reluctant to use more than 20-40% demolition waste, especially given that they couldn't be sure of what it contained. But he had set his ambitions higher than that: he wanted to see if it was possible to use only recycled aggregates. This was partly because in Denmark, unlike in the UK, virgin aggregates are a dwindling resource, while the country produces more than 1 million tonnes of concrete waste each year. He also wondered if there was a way of using this waste close to its source, avoiding the negative impacts associated with transporting it, and retaining or even enhancing its value. "We wanted to convert this waste into a material that's purposeful and beautiful. That's very important."

So he set up his own operation for crushing and processing the concrete, buying a mobile concrete plant, and putting together his own team. The crushed concrete was graded and cleaned on site and mixed with cement and 20-30% fly ash (a standard constituent of concrete in Denmark). The results were immediately encouraging: "When we learned how to control ▶

Photo: Rasmus Hjortshøj

▶ the process, we made excellent concrete with 100% recycled aggregate – actually stronger than we would usually buy."

The concrete was certified as C25/30 strength in accordance with DS / EN 206-1: 2000, and the characteristic compressive strength after 28 days ranged from 35.7-46.9MPa, more than matching virgin concrete in the same strength class. Lendager suspects that unaccelerated cement from the recycled aggregate helped to add strength to the new mix.

In all, 837m^3 of upcycled concrete was cast in the construction of Upcycle Studios, contributing to a 32% reduction in embodied carbon, according to a lifecycle analysis carried out by developer NREP. But perhaps Upcycle Studios' true significance lies in the way that it reconstituted more than 900 tonnes of waste into an architecturally valuable asset. This in turn helps to make the recycling process more economically viable – NREP's analysis suggests that optimised production costs are slightly higher than for a benchmark standard concrete.

Lendager has subsequently used its 100% recycled aggregate on the Pelican self-storage facility, also in Copenhagen, again sourcing the raw demolition waste locally. This time, however, the source was an 80-year-old medicine factory – a much lower grade than the concrete used for the metro. They applied the same technique, crushing, mixing and casting the concrete on site to make 3,000m^3 in total. The company is now using the same approach to cast the slip-form core of an 80m-high residential tower.

It has conducted other experiments in the circular use of concrete too. At the Resource Rows housing scheme in south Orestad, the practice has come up with a novel take on brick slips, reusing old bricks by angle-grinding entire sections of existing walls and embedding them directly into 3m^2 modules of precast concrete. This solves a problem with reclaiming modern bricks: since the 1960s, the cement mortar used in Denmark is harder than the actual bricks so is extremely difficult to remove. It also lends a unique patchwork aesthetic to the new homes, as well as saving 500g of carbon per brick. "We had 1m^2 sections of brick that the precast factory put into the concrete to create different patterns," says Lendager. To get the finish mortar right on site, he set up his own bricklaying company: "To realise these ideas I have to be the circular connector between different partners, covering the holes in the supply chain."

Resource Rows also contains an ingenious example of direct reuse: a huge double T beam that Lendager lifted from a disused factory nearby and craned in to create a high-level footbridge between two blocks. "We didn't have the budget for a bridge but because we could use this one for free, we could connect the roof gardens. Now you can walk across and meet your neighbours on the other side."

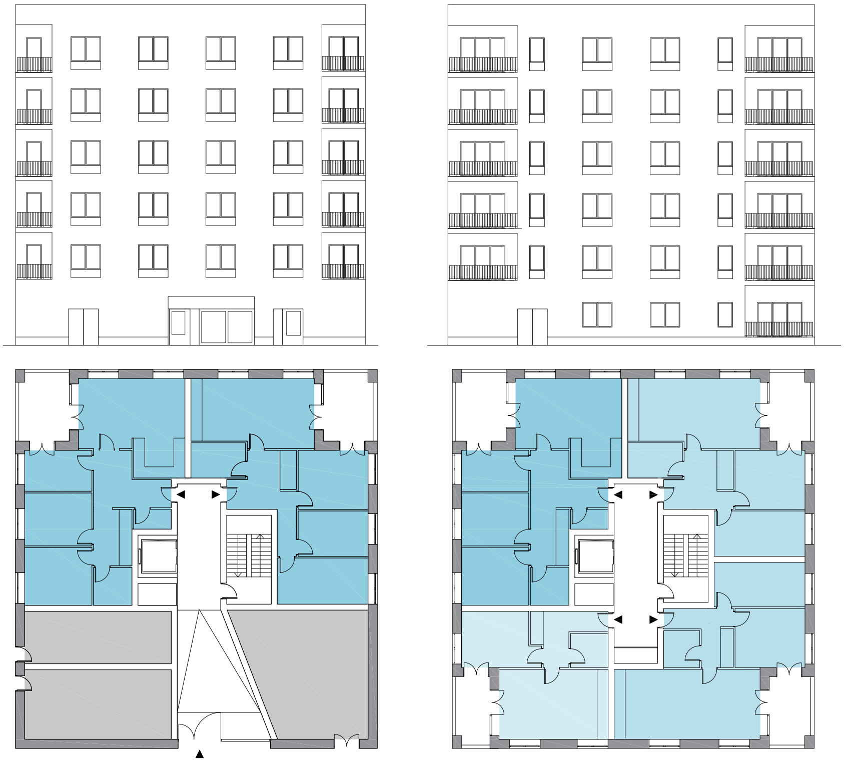
ABOVE In all, 837m^3 of upcycled concrete was cast in the construction of Upcycle Studios

RIGHT At Resources Row, Lendager reused old bricks by angle-grinding entire sections of existing walls and embedding them into precast-concrete facade panels

Photos: Rasmus Hjortshøj

Take two buildings

An independently assessed life cycle analysis compared two apartment blocks – one with a concrete structure, one made of cross-laminated timber, but otherwise virtually identical. Here are five key findings



A concrete-framed building may not be significantly more carbon-intensive than a cross-laminated timber (CLT) one, according to a life cycle analysis (LCA) conducted on two notional apartment blocks. The concrete structure could also help to make useful carbon savings in a National Grid increasingly supplied by intermittent renewable sources.

These are two of the key findings of the LCA, which was commissioned by The Concrete Centre, with the aim of gaining a better understanding of carbon emissions over the lifespan of a relatively conventional concrete-framed residential building – and by extension showing how future designs can be optimised.

The analysis focused on two study buildings, one made of concrete, the other CLT. Both were 2,500m², six-storey blocks in London, containing 22 flats. They were of the same size, shape and layout, with the same functional requirements, and the same heating, hot water and ventilation systems, all designed to meet the Future Homes Standard.

The concrete building comprised a reinforced concrete (RC) frame, with exposed 225mm-thick slabs supported on a foundation of RC ground beams, pile caps and piles. The frame was made using a C32/40 concrete with 50% GGBS. The substructure works used an FND3 and FND4 concrete with 70% GGBS. The internal walls were made with concrete blocks finished with a wet plaster to maximise their thermal mass, which was also the purpose of exposing the soffits. The CLT building comprised 160mm-thick, five-layer panels for the floors, spanning unidirectionally onto 100mm-thick, three-layer loadbearing wall panels. These were finished with mineral wool insulation and plasterboard to provide the necessary fire resistance and noise transfer performance. This building was also supported on a foundation of RC ground beams, pile caps and piles.

Analysis of the two buildings over a 60-year study period was carried out in early 2020, using IES ApacheSim for the dynamic thermal modelling and the OneClick tool for the LCA. Wherever possible, embodied carbon rates were determined using environmental product declarations (EPDs) for specific products. Where these weren't available, generic data sources were used such as the OneClick tool and the ICE database.

The results offer a practical insight into the relationship between embodied and operational carbon, and the interplay between different building materials, systems and design needs.

1

The concrete building's whole-life carbon emissions were only about 6% higher

The whole-life carbon emissions after 60 years were estimated to be around 710kgCO$_2$e/m² and 670kgCO$_2$e/m² for the concrete and CLT buildings respectively. Predicting whole-life emissions does, of course, come with a degree of uncertainty as it is looking many years into the future and depnds on LCA factors such as the future carbon intensity of grid-supplied electricity. But with this caveat, the difference between the average whole-life emissions was quite small, with the concrete building being only around 6% higher.

2

Both meet the RIBA 2025 and 2030 Climate Challenge embodied carbon targets

The results also provide some insight into the relative contributions of operational and embodied emissions. In both buildings, embodied carbon was predicted to account for about 75% of the total – made up of approximately one-third structure, one-third services and one-third architectural elements such as finishes and cladding.

When the carbon emissions from the operational energy are excluded, the embodied impact of both buildings was around 500kgCO$_2$e/m², with the concrete building marginally higher. This meets two key benchmarks: the RIBA 2025 and 2030 Climate Challenge targets. The study built on this result by developing a "low2" scenario for the concrete building. This improved the carbon performance of the base design through seven material and system enhancements that worked within the study's fixed design constraints. These included increasing the GGBS in the superstructure from 50% to 70%, switching from PIR to EPS insulation and using a heat pump refrigerant with a lower GWP. Collectively, the changes reduced the embodied carbon to around 430kgCO$_2$e/m².

3

The concrete building had significantly better passive cooling

Both buildings adopted a high standard of solar shading and ventilation to reduce the risk ▶

▶ of overheating as far as practicable, but the concrete design also made use of the structure's thermal mass.

Overheating analysis using the CIBSE TM59 methodology found that, for the period 2020-40, the concrete building could remain cool by using this thermal mass, coupled with night cooling and some very low-energy ceiling fans. The CLT building, on the other hand, needed active cooling in summer, so includes an air-source heat pump, serving chilled water fan-coil units. By 2041-80, summertime external temperatures are anticipated to rise by around 1°C, and under these conditions, the concrete building also requires a small amount of active cooling.

4

Operational energy consumption was about the same

The concrete building was predicted to use less energy for cooling than the CLT option and slightly more for heating, but overall the two balanced each other out and there was no significant difference in the total energy consumption for any of the time periods or occupancy scenarios. Overall energy consumption was close to 43kWh/m²/yr throughout the 2020-80 period. This is reduced to 34kWh/m²/y when energy produced by the roof mounted PV array is included.

It's worth noting that the study assumed a reasonable active cooling set point of 24°C for the modelling. In practice, occupants may of course opt for a lower setting closer to 20°C, resulting in more energy being used for cooling. The extent of any increase is however likely to be more modest in the concrete building, with its better passive cooling performance.

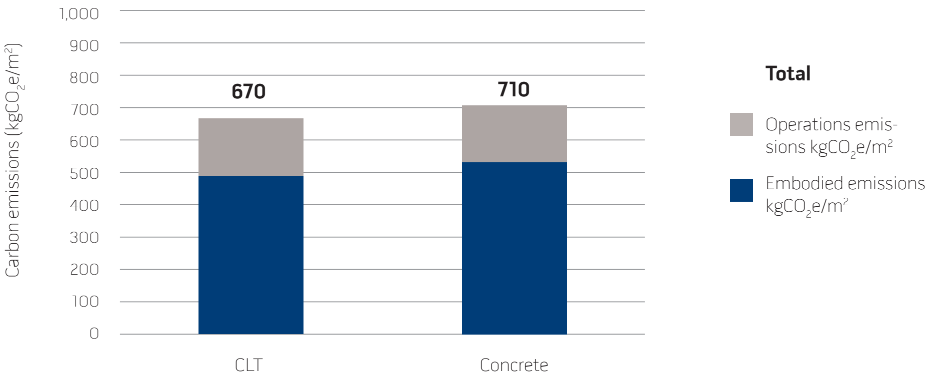
5

The concrete building's peak space heating load was on average 25% lower

For the period 2020-40, the peak electrical load for space heating was on average 25% less in the concrete building, due to its higher thermal mass. When hot water heating was included, the total peak heat electrical demand was estimated to be around 15% lower than for the CLT building.

This matters because, by reducing peak electrical demand, the National Grid is better able to balance out supply and demand. This will become an important attribute of high thermal mass buildings, as they can be actively controlled to store and release heat in response to the peaks and troughs of renewable energy supply. In this way, the building's energy demand can be shifted away from periods of high grid carbon intensity – that is, when fossil fuels are needed to meet a shortfall in renewable power. The net result is carbon savings at a national level. ■

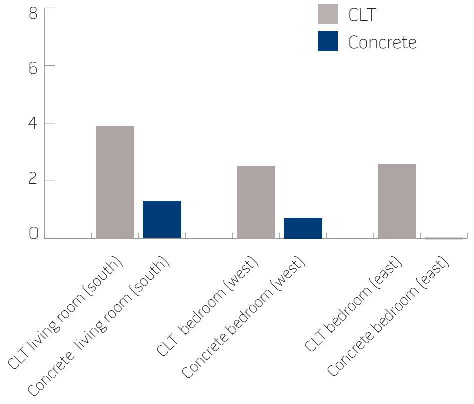
Whole-life carbon emissions



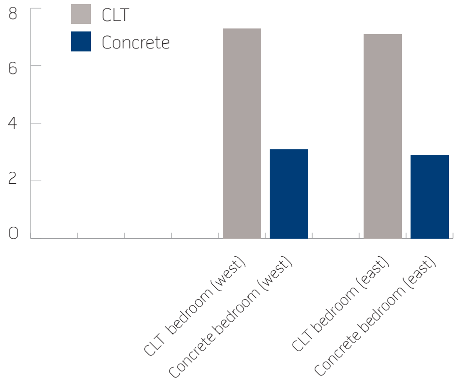
60-year lifetime, average grid intensity for operational carbon

CLT incinerated at end of life

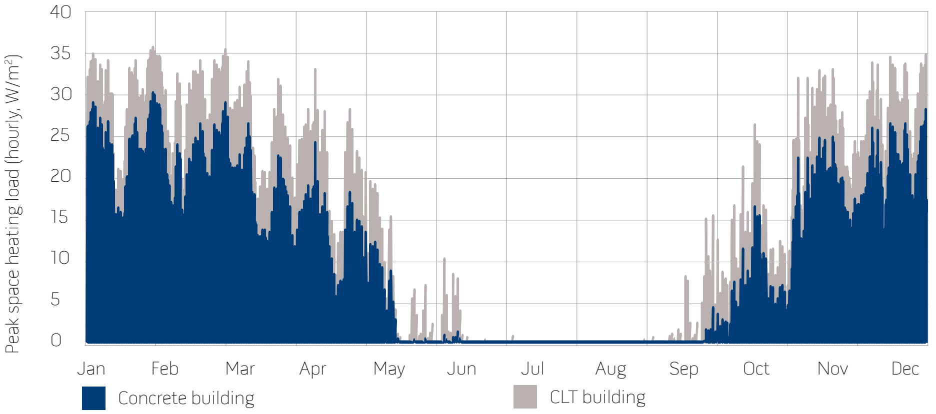
Overheating analysis results: daytime
% of occupied daytime hours > 28°C



Overheating analysis results: night-time
% of occupied sleeping hours > 26°C



Predicted peak space heating demand (2020-40 time period, intermittent occupancy)



This article, authored by The Concrete Centre, draws on technical analysis completed by Max Fordham, on behalf of The Concrete Centre. The initial designs that formed the basis of the analysis were developed by Adam Khan Architects, Price and Myers (structural engineer) and Max Fordham (environmental and services engineer). A full evaluation can be found at concretecentre.com

Photo: Blake Ezra

Fire performance: Assessing concrete structures for reuse

With increasing numbers of concrete-framed buildings being adapted for new uses, it is vital to determine the fire resistance of the structure. Tony Jones of The Concrete Centre and Octavian Lalu of BRE outline the key assessment methods

It is hardly surprising that the reuse of concrete structures is becoming more common: the reuse of a structure is almost always the lowest embodied carbon solution, and concrete buildings can often remain useful well beyond their initial 50 or 60-year design life. But if the structure is to be significantly modified, or the use of the building changed, it is often necessary to assess the structural capacity of the building, including its resistance to fire.

In some cases, it may be enough simply to establish what the fire resistance is. However, the situation can become more complicated. If the use of the building is changing, it may be necessary to increase the period of fire resistance. Updates to building codes may also mean that the information used to design the structure no longer represents best practice. Indeed, the simpler methods in newer codes often take a more cautious approach because they cover a wider range of situations, which can lead to uncertainty. ▶

▶ Information required

The ideal situation for the designers of a repurposed building is to use existing as-built drawings; however, these are often not available and may not accurately represent the current condition. To carry out an initial calculation, the minimum information required is the dimensions of the element (beam, column or slab) under consideration and the distance from the concrete surface to the middle of the main steel reinforcement, known as the axis distance. This information can normally be obtained from a geometrical survey and a cover survey, which can be confirmed by inspecting localised "breakouts".

If it is not possible to justify the element's use based on this information, a structural fire assessment will be required, and this will need an understanding of the amount of reinforcement in the element, its strength and the strength of the concrete.

Simplified methods

When the fire resistance is unknown, an initial assessment can be made with minimal structural information. This can then be refined using historical test results from standard fire resistance tests, where they exist.

The most straightforward way to determine the fire resistance is from the tables in EN 1992-1-2, the current design code for fire design of concrete structures. These tables give a required section size and axis distance for a given fire resistance period. In some cases, the tables also include a factor that represents the degree of utilisation of the section during a fire – without further information, this should be assumed to be 0.7. If no information is available on the reinforcement layout, then initially slabs and beams should be considered as simply supported.

UPDATES TO BUILDING CODES MAY MEAN THAT THE INFORMATION USED TO DESIGN THE STRUCTURE NO LONGER REPRESENTS BEST PRACTICE

If the information on concrete strength and reinforcement strength and quantity is available, it may be possible to show a lower utilisation than 0.7, leading to smaller permissible section sizes, or to demonstrate that higher temperatures are permissible in the reinforcement, leading to a lower axis distance requirement. Both refinements are relatively easy to implement using the methods in EN 1992-1-2.

Although the sections considered in EN 1992-1-2 are generic, the withdrawn British Standard BS 8110-2 contains similar information for more specific types of construction that were common in the UK – for example, hollow pot floors. Where information in the withdrawn standard is superseded by the Eurocode, the latter should take precedence, but for these specific types of flooring, the approach in BS 8110-2 may be informative.

For certain floor systems, test information has been published and summarised in BRE's Information Paper 9/12. Following a site inspection to determine the main parameters of the floor system, this test information may be used to justify the fire resistance directly. The test information includes various historic precast and prestressed floor systems, hollow pot systems and wood wool slabs. It is important to establish the relevance of the test data to the existing floor being assessed.

Photo: MICA Architects

BELOW MICA Architects' reinvention of the Centre Point tower in central London as an apartment building involved extensive analysis of the concrete structure and cladding

RIGHT The Standard hotel in central London by Orms is a radically repurposed 1970s council building

PREVIOUS PAGE At The Archives in north London, architect ROAR has converted a reinforced-concrete warehouse into a creative hub, with a cafe, climbing wall, and work and performance spaces

Similarly, test information to support some of the tables in BS 8110 is summarised in reference document BR 468. If the section being investigated was within the parameters of the testing when constructed, this may provide an alternative justification.

Advanced methods

If relevant test data is not available, advanced numerical models can be used to more accurately calculate the fire resistance of existing structures. These complex computer codes require significantly more information about the existing structural materials – for example, the thermal and mechanical properties and the correct boundary conditions.

Advanced calculation models are often used when the part of the structure under assessment has a complex geometry or the complete structure needs to be analysed. The many assumptions and approximations in advanced calculation models are usually of a higher order of refinement than in simple calculation methods. This means that a higher degree of accuracy can be expected – which in turn can provide the opportunity to develop more economical designs, while maintaining acceptable levels of life safety.

Advanced numerical analysis is usually carried out in two stages: thermal and structural analysis. The temperature rise within a member is calculated in the first stage through heat transfer analysis. This first step is important since the temperature developed within the defined section will determine the capability of the member to carry the applied load. In the second stage, the time-temperature history is used as an input to the structural model to determine the mechanical response. The heat transfer calculations require knowledge of the geometry of the element, temperature-dependent thermal properties of the materials and the boundary conditions applied in the model. For materials with low thermal conductivity, such as concrete, it is important to determine the thermal gradients developed within the concrete section since these can influence the temperature rise of the main reinforcement, moisture migration, and development of thermal stresses and creep deformations.

The computer models can be validated against test evidence to show that the boundary conditions and the material properties selected are appropriate for the end-use application.

Photo: Timothy Soar

Enhancing fire resistance

In some cases, particularly when an existing building undergoes a change of function, the fire resistance of a structural concrete member may need to be increased. This can be achieved by adding finishes to reduce the temperature of the main reinforcement bars. Where further measures are required, cementitious sprays, intumescent coatings or board types can be used. Care should be taken to ensure the protection layer retains its integrity for the duration of the design fire exposure.

Guidance on finish types (plaster or sprayed fibre) was provided in BS 8110-2. However, standard fire resistance test methods are now available to determine the contribution of applied fire protection materials to the performance of concrete structural elements in fire. The approach determines an equivalent thickness of concrete (in terms of thermal insulation) to be used in subsequent analysis. Again, further benefits may be achieved through the more advanced analysis methods. ■

A more in-depth version of this article is available at concretecentre.com

REFERENCES AND FURTHER READING

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FINAL FRAME: FARRINGDON CROSSRAIL STATION, LONDON

Some 102 precast units were used to create the Upper Apse at Farringdon Crossrail station. The design featured very few repeats, which meant that all of the timber moulds, for beams, nodes and panels, were bespoke. Each former was also lined with a fibreglass coating to prevent any imperfections transferring to the finished element, ensuring a smooth, uniform finish. The mix was a CEM III/A, containing 50% ground granulated blast furnace slag, which helped the project to achieve a BREEAM Excellent rating. For more on specifying lower carbon concretes, see page 20.

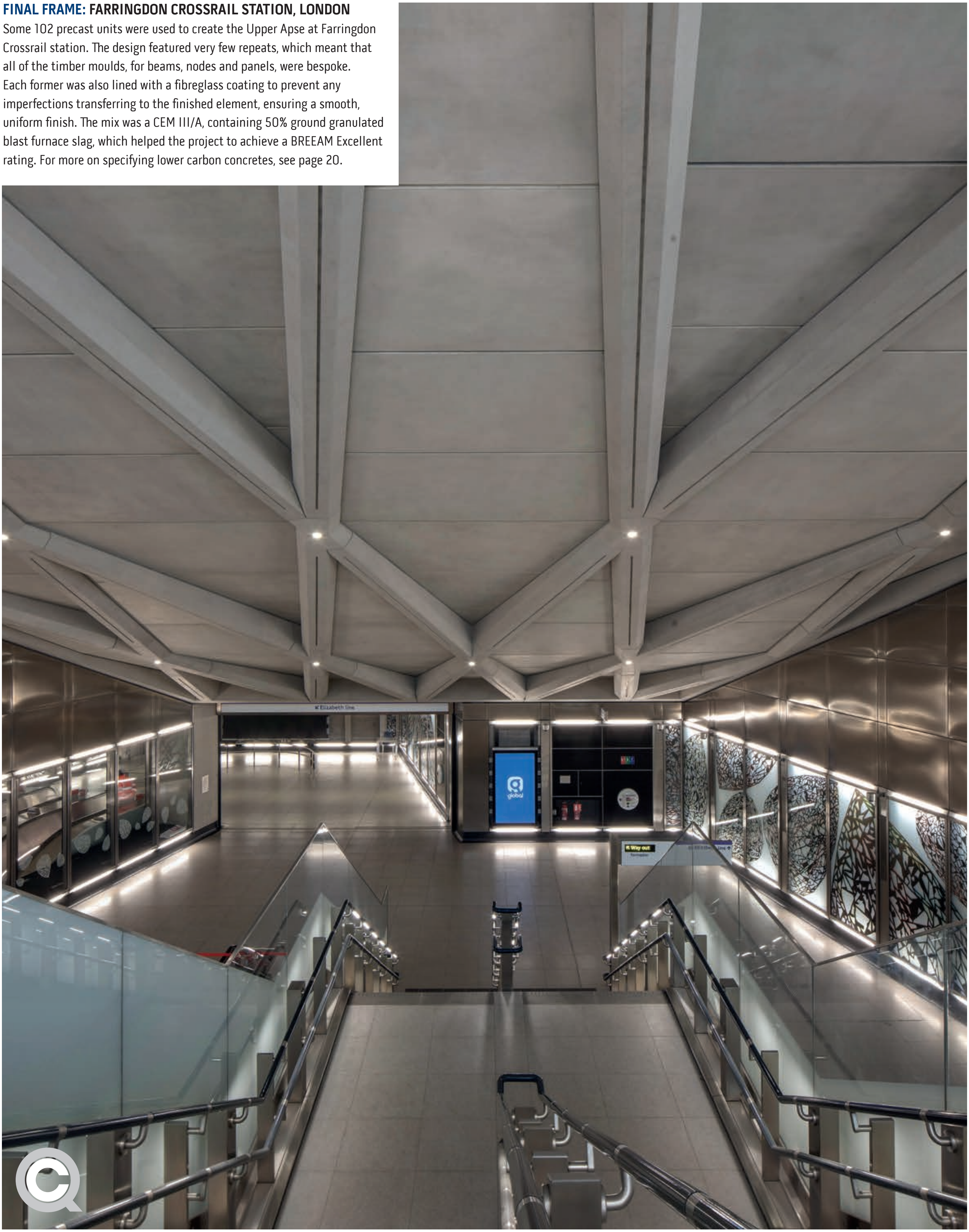

Photo: Morley von Sternberg