Using high-performance concrete for the strengthening and upgrading of structures

What do you do when the use of a building or structure changes, loads are increased, or the structure is no longer compliant to recently introduced Standards? Structural strengthening of affected members is the most common solution and the preferred option, but which one to choose? **Michael Balletta** of **Concrete Repairs Limited** and **Fahed Maida** of **Beta Design Consultants** report on a new and innovative system for strengthening concrete structures, which is now available and starting to be used with more confidence and frequency.

Repairing, restoring and upgrading concrete structures has become ever more important as the world, construction sector and concrete industry face the challenge of reducing their carbon footprints. The reuse of buildings and structures is being encouraged to reduce waste, as well as the 'embodied' carbon. However, many older buildings and structures do not comply with current Standards or require additional load capacity. To keep them in use and extend their life, some form of strengthening is usually required.

ALTERNATIVE SYSTEMS

Over the years we have used various methods and techniques to strengthen and upgrade our concrete structures. The earliest method, jacketing, was simply to dowel in extra reinforcing and encase the existing member, be it a column, beam or slab, with normal-strength concrete. This works well but the limited capacity of the existing section could lead to a large jacket with impacts on headroom and floor space – not always acceptable to clients. The design must also address the risk of slip along the interface of the concrete cast at different stages.

The next method, introduced in the late 1960s, was to install steel plates, termed epoxy-bonded reinforcing (EBR). Again, this works well, but the plates can prove extremely difficult to install. The plates required are generally heavy and getting the steel and concrete to work 'compositely' requires the use of epoxy resin as well as bolts. Bolting the plates in position can prove problematic because of the high density of reinforcing bars in the bottom of the beams.

LEFT FROM TOP:

Figure 1 – column showing prepared surface ready for formwork.

Figure 2 – steel dowels to tie the system into the structure.

Figure 3 – bespoke-designed GRP formwork.

In the 1980s, carbon-fibre-reinforced polymer (CFRP) was introduced to strengthen and upgrade structures, with the first project taking place in Germany in 1987. This process involved bonding the CFRP plates or wraps onto the concrete member using special epoxy adhesives. The CFRP plates and wraps are extremely lightweight, do not increase the cross-section and require no bolting. This proved a winner with both consultants and contractors, and the system was quickly adopted in the repair and rehabilitation sector. It is now the default technique for strengthening and upgrading concrete structures. However, CFRP feasibility studies require design checks including two main considerations:

- in the strength condition, the maximum concrete strain shall be limited to prevent delamination (main CFRP failure mode)
- in the service condition, the unstrengthened section shall resist future dead loads plus a proportion of future imposed loads to allow for potential accidental or fire damage to the CFRP.

HPC AND UHPC STRENGTHENING

High-performance concrete (HPC) is characterised by a compressive strength of 60–120MPa and 120–200MPa for ultra-high-performance concrete (UHPC). The inclusion of fibres with carefully selected fines and aggregates allows the HPC to offer superior performance properties such as durability, tensile ductility, toughness, hardness, impermeability, wear resistance, impact resistance, chemical resistance and resistance to repeated cycles of freezing and thawing.

HPC was first developed in 1978 in Denmark by Hans Henrik Bache, who was able to carefully select densified system particles containing homogeneously arranged ultrafine particles to produce HPC. It is only recently, however, that concrete professionals have started using HPC in thin layers to repair and strengthen columns, beams, slabs and bridge decks. The practical use of this strengthening technique can be seen in two recently completed projects.

COLUMN STRENGTHENING

During the redevelopment of a former store in the Birmingham city centre and while assessing the existing structure with the

ABOVE FROM TOP:
Figure 4 – pouring the HP micro-concrete into the formwork.

Figure 5 – completed column with coating applied.

Figure 6 – beam with render removed and defective concrete broken out.

Figure 7 – beam with reinforcing cage installed.

requirement for new loads from the rooftop terrace, it was identified that eight circular columns needed to be strengthened. As the columns were also located in the loading bay on the first floor, space was at a premium to ensure delivery lorries could still safely use the area.

Mapei's UK structural strengthening team worked in collaboration with the client's design team to look at the best possible strengthening options. Initially, strengthening the columns using CFRP wrapping was considered, but the required improvement in flexural and axial capacity could not be met due to the columns' high slenderness. CFRP is an effective method to increase the axial capacity of RC columns by the confining action of wraps; however, it does not induce any enhancement on the inertia of the section, so in this case it was not a viable solution.

Instead, a proposal was put forward where the columns could be jacketed with Planitop HPC, a free-flowing, high-performance and high-ductility micro-concrete with steel fibres that could be used

> "To pour $2m^3$ of concrete through slots above and keep the concrete flowing along the 10m-long beams within the enclosed formwork was a challenge, to say the least."

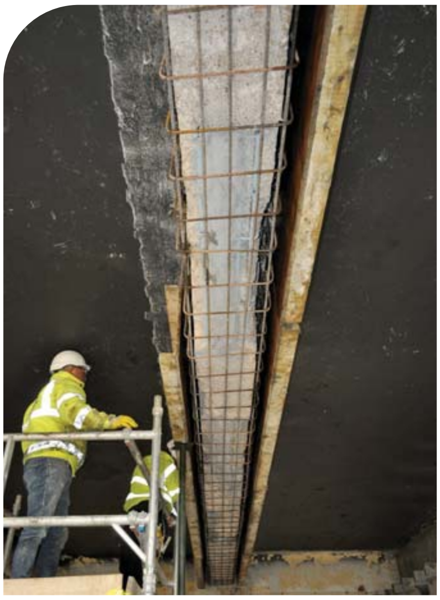
without the need for reinforcing steel, limiting the jacket thickness to 40mm. This ensured that the loss of space and the jacket's extra self-weight were minimal.

Concrete Repairs Ltd (CRL) carried out the works with the repair specification provided by Mapei UK.

Ultra-high-pressure water jetting was used to prepare the surface to the required textured finish (Figure 1) and steel dowels fixed in place with Mapefix EP 385 to tie the system into the structure (Figure 2). Bespoke-designed GRP formwork (Figure 3) were bolted together in two vertical sections and the Planitop HPC poured in (Figure 4). The columns were then protected using Mapei's Elastocolor Paint anti-carbonation coating (Figure 5).

BEAM STRENGTHENING

The works involved the strengthening of eight 10m-long beams in a previous RAF airmen's



ABOVE FROM TOP:
Figure 8 – formwork being placed around the prepared and reinforced beam.

Figure 9 – hole/slot cut through the slab to allow the HP micro-concrete to be poured into the formwork.

Figure 10 – completed beam after striking formwork.

Figure 11 – slab strengthening in hogging, showing cut-out section and new reinforcing.

> "The development of the design concept focused on enhancing the durability of the concrete V-piers that would be exposed to the harsh marine environment."

mess being redeveloped as Grade-A offices. Tests on the existing concrete showed compressive strength values below 20MPa.

An evaluation by Beta Design Consultants (BDC) quickly ruled out CFRP strengthening due to the low bond strength of the existing concrete. Traditional jacketing would have required a deep heavy section, so HPC was proposed. BDC's design was based on a 70mm three-sided HPC jacket (f_{ck}=70MPa) with additional longitudinal reinforcing bar. Typically, HPC bonds well to roughened concrete but in this case shear links were required to prevent slip along the HPC/existing concrete interface.

CRL was awarded the contract to carry out the strengthening. Recommendations for the substrate preparation, concrete repairs required, structural strengthening and protection of the beams were provided by Mapei UK.

Following the removal of render from the beams, the concrete was cleaned and prepared to the required textured finish using Mapemortar HB R3 (Figure 6). All concrete repair materials were specified according to EN 1504[1]. Reinforcement was installed to anchor the proposed 70mm three-sided HPC jacket to the existing beam and support (Figure 7). Bespoke-designed formwork was then installed around the beams using 18mm WBP ply, 100 × 50mm timber sections and supported by Titan props (Figure 8). Slots 300 × 60mm were then cut into the slab above to enable the HPC to be poured into the formwork (Figure 9).

To pour 2m^3 of concrete through slots above and keep the concrete flowing along the 10m-long beams within the enclosed formwork was a challenge, to say the least. To maintain the flowable properties of the fibre-reinforced concrete and obtain a good distribution of the fibres within the mix it was critical to keep a constant mixing time of eight minutes and have a continuous flow of concrete going into the formwork (Figure 10).

SLAB STRENGTHENING

In addition to the low-strength concrete in the beams, the existing slabs in the RAF airmen's mess did not have sufficient flexural capacity. CFRP strengthening was quickly ruled out by BDC due to the high loadings required and HPC proposed due to its superior performance in both compression and tension. Adding 20mm in the sagging areas increased the compressive areas' resistance and section lever arm to meet design requirements. Adding 30mm HPC in hogging areas with a small mesh satisfied the section demand, while small-diameter links were used to achieve a composite section (Figure 11). CRL successfully carried out the strengthening using Mapei Planitop HPC Floor.

This application has the potential for being used to repair industrial floors and bridge decks, as the finished surface could deal with stringent requirements of toughness, hardness, durability and resistance to chemicals and impact. There is currently no codified definition of UHPC. *fib Model Code 2010*[2] covers concrete up to a characteristic strength (f_{ck}) of 120MPa. ■

References:

1. BRITISH STANDARDS INSTITUTION, BS EN 1504. *Products and systems for the repair and protection of concrete structures. Definitions, requirements, quality control and evaluation of conformity. Parts 1–10*. BSI, London, various years.
2. FÉDÉRATION INTERNATIONALE DU BÉTON, *fib Model Code for Concrete Structures 2010*. *fib*, Lausanne, 2013.