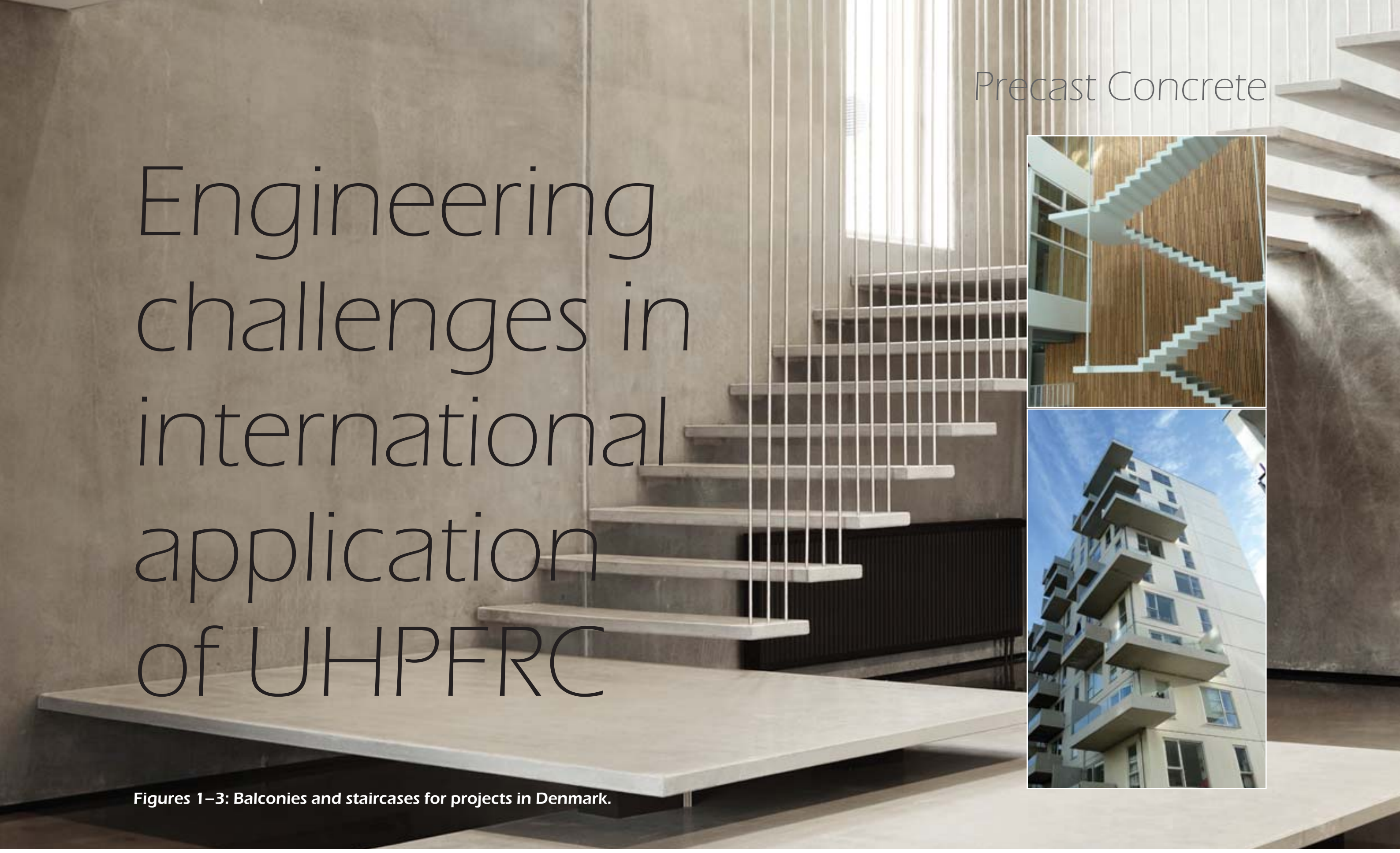
Engineering challenges in international application of UHPFRC



Figures 1–3: Balconies and staircases for projects in Denmark.

Compact reinforced composite (CRC) is the designation of a special type of ultra-high-performance fibre-reinforced concrete (UHPFRC) combining high-strength, steel-fibre reinforcement and closely spaced reinforcing bars. CRC was developed at the cement manufacturer Aalborg Portland in Denmark in 1986 and has been used in structural applications since 1995.

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UHPFRC is a concrete with a high degree of ductility combined with compressive strengths of 150MPa or higher. As well as CRC, a number of other types of UHPFRC have been developed such as Ductal (Lafarge), BCV (Vicat) and BSI/Ceracem (Eiffage and Sika) but it is only in the past ten to 15 years that interest in these materials has really intensified. Large research programmes have been initiated around the world and some of the results have been presented at a series of conferences in Kassel (2004, 2008 and 2012) and Marseille (2009 and 2013). At the same time architects and engineers have started to design projects specifically with UHPFRC in mind and the guidelines that are available for using UHPFRC are becoming more advanced(1).

CRC was originally developed with an emphasis on combining the strength and ductility of structural steel with the durability, fire resistance and formability of concrete. However, the first applications did not specifically address these properties, but instead exploited the aesthetic potentials gained from the possibility of creating slender and minimalistic concrete elements – primarily balconies and staircases.

Hi-Con, a small Danish precast producer founded in 2001, has used CRC exclusively for smaller precast structural elements such as balcony slabs, staircases, beams and columns, and mostly for the Danish market.

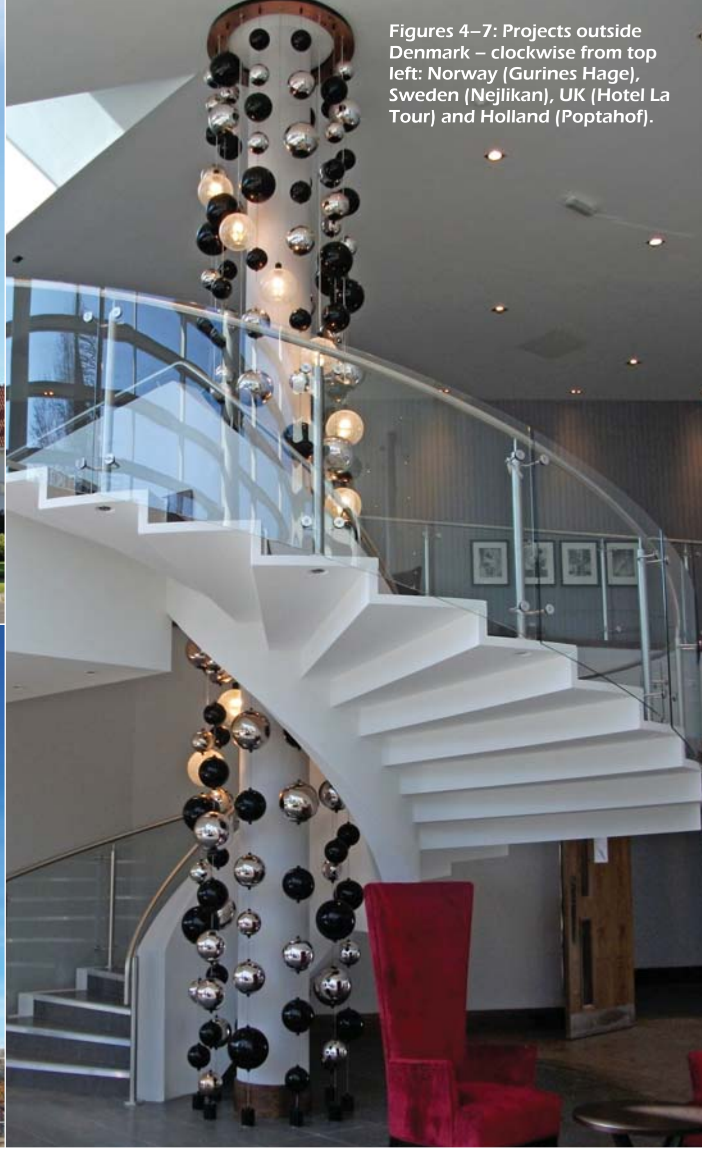
The first applications of CRC were in 1995 and production of typical applications such as balconies and staircases started in 1997 – a time when few people knew of UHPFRC, and CRC typically was compared to steel or conventional concrete. The design approach for CRC closely resembled that of the Danish Standards at the time but with some well-documented deviations. This approach has changed little from these early applications in Denmark, to the present day where CRC structural elements are in use in a number of countries.

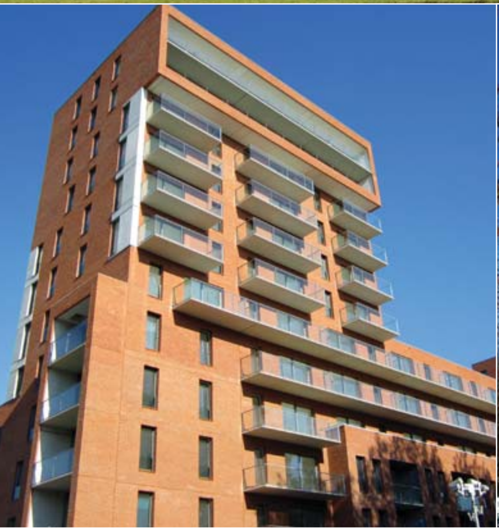
During the past five or six years, new products have been introduced and to new markets That experience has led to a better understanding of the differences in engineering practices between markets regarding the need for documentation and differences in building design. But it has also demonstrated the importance of providing the necessary testing and documentation to avoid some of the pitfalls that can present themselves when using UHPFRC.

Typical current CRC applications

Architectural balconies, staircases, beams and columns (see Figures 1–3) were the main applications on which Hi-Con was founded in 2001 and remain the main business areas for the company to the present day. Since 2001, more than 50,000 tonnes of elements have been produced and installed in Denmark alone.

While these applications were lucrative in the early part of the century, the decline of the building industry in Denmark in 2008 made it necessary to look at new products and new markets as well.



Figures 4–7: Projects outside Denmark – clockwise from top left: Norway (Gurines Hage), Sweden (Nejlikan), UK (Hotel La Tour) and Holland (Poptahof).

This has led to the use of the existing products – balconies and staircases – in a number of other countries such as Norway, Sweden, Holland, Finland and the UK (see Figures 4–7).

It has also led to the development of new products such as façade elements (Figure 8), an application where a number of architects have made designs specifically based on the properties of UHPFRC, such as for MuCem in Marseille, Stade Jean Bouin in Paris and the US Embassy in Maputo, Mozambique.

Different practices in different countries

Standards and accepted design rules for UHPFRC are not yet available, but initial steps to establish design rules have been made in Japan, Australia and within the framework of *fib*. The most elaborate guideline to date is believed to be the French AFGC (*Association Française de Génie Civil*)(1). However, this guideline, published in June 2013 in a second edition, is primarily suited for particular concrete types incorporating a combination of steel fibres and pre-tensioning. For CRC, which combines fibre reinforcement with passive reinforcing bars, the best practically applicable design tool is still – as it was for the early applications – the existing design rules for ordinary concrete, eg, the Model Code(2), ACI regulations, Eurocode 2(3) or similar.

For CRC the design basis has been the Eurocode. In specific areas (some of which will be described later) the CRC design deviates from the Standards and in those cases it is necessary to ensure that thorough and valid documentation is made available to support these changes. At the same time, it is vital to assess the loads and actions to which the structure may be subjected, as it is on the unsafe side to assume standard Code rules on some specific issues (eg, fire exposure).

As previously mentioned, the bulk of applications of CRC have been in Denmark but as design is closely related to the Eurocodes, it has also been necessary to adapt the design as CRC structures are introduced into new markets. Some of the design changes are not specific to UHPFRC but would also be necessary for conventional concrete. However, these differences can impact CRC in other ways than for conventional concrete because of the slenderness of the design, as in most European countries the NADs (national application documents) and the engineering practices to a large extent maintain their national preferences for loads, safety and calculations.

As an example, the Dutch calculation practice under the EC includes a particular short-term deflection value and a corresponding Serviceability Limit State (SLS) design limit (1/300) deviating from the normal short-term deflection value having a limit 1/250 of the system length of the harmonised Standard. As deformations typically govern the CRC design, this has significant impact and in the case of the first application in Holland, design calculations were verified through full-scale load tests.

Another example is the Finnish Code, which presently includes a double set of live-load conditions for both ULS (Ultimate Limit State) and SLS states, with one load condition being a $2kN/m^2$ live load along the circumference of balconies, in combination with an area load of $1.5kN/m^2$ and the other the 'regular' EC load of $2.5kN/m^2$.

Live loads in general also vary considerably, for example, ranging from 2.5 to $4kN/m^2$ for balconies. Finally, the ψ_x load coefficients vary greatly from country to country, as each national annex makes references to the original national Codes.

Hence, although the calculation principles between countries in theory have been harmonised, the national annexes create significant differences in design boundaries from country to country. In addition, engineering practices for structural principles and connection details to a large extent remain those nationally preferred.

All of this makes sense, since contractor practices – everyday experience accumulated over decades – are difficult to change just by introducing a common calculation tool. Building customs can also make it difficult to duplicate a system that has been successful in one country.

An example of this is the custom of building with raised floors in Denmark. Most of the floors in apartment buildings are hollowcore slabs. On top of these are placed insulation and all utilities, eg, central heating, and this is topped off with a plank floor. This means that a system of connecting cantilevered balconies (such as the ones shown in Figures 9 and 10, overleaf), where 'flaps' are bolted to the hollowcore floor, works quite well and actually thousands of balconies of this type have been installed in Denmark. In other countries, in most cases it is necessary to use a completely different installation system.

Common to the different national annexes to the EC is the absence of regulations for UHPFRC. Consequently, it is always required to present adequate documentation to obtain building permission, regardless of country. This documentation is often assessed differently from one country to the other, making it necessary to further adapt the design principles and structural solutions for each country – apart from that dictated by the difference in NADs.

In addition, it is often necessary to provide supplementary documentation with tests conducted according to local methods and conditions, and at a local test institute. Regardless of the fact that many test methods are harmonised and that comparable results may be available from other countries, building authorities often trust data only from tried and tested methods and at a trusted local test facility – even if this means duplicating existing tests from certified testing laboratories.

Consequently, it has been necessary to conduct full-scale structural and deformation tests, fire tests, pull-out tests on cast-in anchors, etc, in order to get approval for both calculation principles and structural connections and other details when starting operation in new countries.

Areas of particular design importance

UHPFRC is typically characterised by very high strength and stiffness but unless the concrete is specifically designed

Figure 8: Installation of CRC façade elements for Odense University, Denmark.

for ductility and high performance in other areas (such as durability), the finished structure may perform less than optimally. It is therefore necessary for any manufacturer to be aware of the pitfalls of UHPFRC design, production and application.

Compressive strength

Eurocode 2 covers compressive strength (based on cylinders) up to 90MPa, but includes a penalty factor to account for brittleness at higher strength. If for instance a concrete with 90MPa characteristic compressive strength is considered, the characteristic strength is reduced by 20% in the design because of this factor. Extraordinary testing and documentation demonstrating ductility also in compression is required if it is decided to deviate from this reduction factor η, described in section 3.1.7 of the Eurocode.

Durability

UHPFRC is often used in slender structural designs, where the high compressive strength is employed to reduce the cross-section dimensions. To achieve the most effective design, and hence best use of the concrete, it is often required to reduce the cover layer thickness compared to the values stated in Eurocode 2, section 4.4.1. To avoid reinforcement corrosion it is necessary to have a very dense concrete, with the associated documentation verifying that both carbonation and chloride intrusion in the loaded state are suitably slow. For slender structures with a comparatively high live load where the structure is exposed to significant bending tension, it is thus necessary to document effective crack control and to document how micro-cracks affect carbonation and chloride intrusion, something that is not typically achieved with standard testing(4).

Fire exposure

In several ways, UHPFRC may exhibit inferior performance in fire-exposed conditions compared to ordinary concrete. One of these aspects is explosive spalling, described in EN 1992-1-2(5) section 6.2 as it was observed on examples such as the Great Belt Link Tunnel in Denmark and the English–French Channel Tunnel. When these dense concrete types are heated, steam is generated that cannot easily escape and consequently very high internal pressure may build up, that can lead to explosive spalling. If the tensile strength of the material is high, the pressures that can be reached before they are released may generate relatively powerful explosions. Consequently, it is very important to have sufficient knowledge about parameters such as critical moisture content, permeability and tensile strength for a particular concrete under a particular fire exposure condition(6).

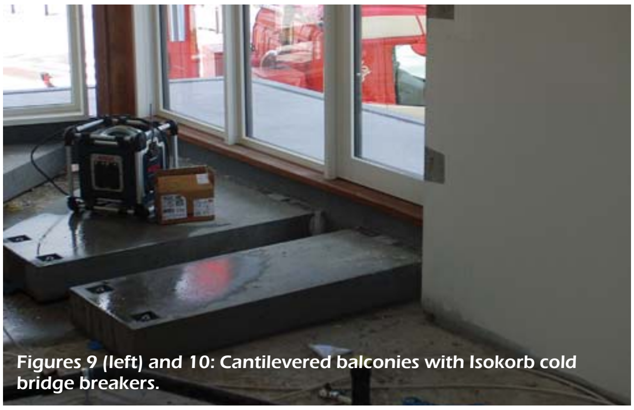
Some types of UHPFRC exhibit so low porosity, that even at very low moisture contents it is not possible to document sufficient resistance to explosive spalling. In those cases – if the structures are to be used where there is risk of fire – an option is to include polypropylene fibres or to produce a special version of UHPFRC with reduced mechanical properties.

Very dense concretes with low water:cement ratios and optionally steel fibres typically conduct heat more easily than ordinary concrete and have a lower heat capacity. On the other hand, they often exhibit better tensile and compressive strengths at elevated temperatures. But again, this underlines the necessity to properly document the material properties through fire testing before using the material in the structural fire design.

Current research and development areas

There is no doubt that UHPFRC can provide significant benefits to some applications and also in areas other than housing but as a relatively new material these areas of application are only now developing.

CRC has gained acceptance for use for specialised elements for the housing sector. Building on this experience and proven track record, Hi-Con is currently involved in a number of research projects. While other types of UHPFRC focus on applications in façade elements and bridges, CRC is being investigated for precast elements for wind turbine towers, elements for wave energy converters (and offshore applications in general) and columns and slabs designed to withstand explosive or projectile impacts. ■



Figures 9 (left) and 10: Cantilevered balconies with Isokorb cold bridge breakers.

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