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Contents

1	Introduction	3
2	Ultra High Performance Concrete.....	3
2.1	Constituents and mix design	4
2.2	Mixing, placing and curing	4
3	Use of UHPC in transportation infrastructure.....	4
3.1	General	4
3.2	UHPC in Sweden	6
3.3	UHPC in Europe.....	6
3.4	UHPC in USA and Canada.....	10
3.5	UHPC in Asia and Australia.....	11
4	Requirements and standards	13
4.1	General	13
4.2	Steering documents	13
4.2.1	Overall requirements.....	13
4.2.2	Construction requirements	13
4.2.3	Load calculations	14
4.2.4	Maintenance	14
4.2.5	Materials and execution	15
4.2.6	Management.....	15
4.3	Performance requirements.....	16
4.3.1	Technical requirements.....	17
4.3.2	Non-technical requirements.....	18
4.4	Standards.....	18
5	Repair techniques for concrete structures	19
5.1	General	19
5.2	Existing techniques	21
5.3	Application of UHPC for repairs - current situation	24
6	Cost / benefit analysis	25
7	Concluding remarks	26
	References.....	26
	Annex A	30

1 INTRODUCTION

The transportation infrastructure is exposed to some of the harshest exposures for concrete, including carbonation, frost and chloride attacks. In addition structures can be damaged by accidents or overloaded. The durability and high maintenance costs of concrete and steel bridges have become a major challenge in many industrialized countries (*Gjorv 2013, Tang et al. 2012, ACI 2006*).

One of the novel trends, rapidly spreading throughout the world, is the usage of Ultra High Performance Concrete (UHPC) mostly due to its high strength and extremely low permeability enabling manufacturing of lightweight and durable elements. The UHPC can be used for new structures as well as repairs and strengthening of existing, deteriorated elements and structures.

This state of the art report describes briefly the UHPC in respect to material as well as to the production technology. In the following section current applications for new structures will be described. The report also gives an overview of existing standards and recommendations which are applicable for concrete repair in general and for the case of UHPC. The last part of the report focusses on existing repair techniques and their comparison with concept of using UHPC in terms of technological, cost and other factors.

2 ULTRA HIGH PERFORMANCE CONCRETE

The UHPC could be shortly characterized as extremely well optimized normal concrete. The UHPC is based on Portland cement but has a very low water to binder ratio (w/b), large additions of silica fume (SF) and well packed particles. The 28-day compressive strength can reach up to 250 MPa and the flexural strength up to 35 MPa (*Russel and Graybeal 2013, Graybeal 2011 and Cwirzen et al. 2008*). Enhanced mechanical properties enable to decrease the size of the produced elements but at the same time also to sustain the same load bearing capacity, Figure 1. The microstructure of UHPC concrete is extremely dense which hinders penetration of any aggressive media and thus stop/prevents most of the deterioration processes.



Figure 1 Comparison between elements having approximately the same load bearing capacity: (left) steel, UHPC and OPC and (right) OPC and UHPC.

2.1 Constituents and mix design

The basic ingredients for UHPC concrete are very similar to OPC and especially to HPC concrete and include Portland cement, fine sand, silica fume, superplasticizers, water and normally various types of fibres. The water to binder ratio often goes below 0.2 to as low values as 0.12 (*Graybeal 2006*).

Table 1 Example of UHPC mix composition developed by Lafarge and marketed under the name of Ductal.

Material	lb/yd ³	kg/m ³	Percentage by Weight
Portland Cement	1,200	712	28.5
Fine Sand	1,720	1,020	40.8
Silica Fume	390	231	9.3
Ground Quartz	355	211	8.4
HRWR	51.8	30.7	1.2
Accelerator	50.5	30.0	1.2
Steel Fibers	263	156	6.2
Water	184	109	4.4

2.2 Mixing, placing and curing

UHPC concrete can be mixed using conventional pan or drum mixers (*Graybeal 2011*). One of the biggest problems related to mixing of UHPC concrete is its large fine content and lack of coarse aggregates which in connection with extremely low water content and required large dosage of superplasticizer lowers the efficiency of mixing. As a result the mixing time is elongated from 1-2 minutes to 10-18 minutes (*Mazanec et al. 2010*). That tends to rise the concrete mix temperature which can be reduced by using cold ingredients or ice. The mixing time can be also reduced by a better mix design, optimized particle packing, and choice of right chemical admixture or by adjusting the mixing sequence (*Mazanec et al. 2010*).

Placing of UHPC concrete especially when large amounts of fibres are used must be done in a proper way to ensure correct orientation of the fibres.

3 USE OF UHPC IN TRANSPORTATION INFRASTRUCTURE

3.1 General

Bridges and other transportation infrastructures including for example, roads, railways are mostly built using normal and to a limited extent also high strength concrete (28-day compressive strength at >60 MPa). Precast concrete has been used for bridge construction for many decades. One of the drawbacks of a normal concrete is its relatively high weight to load bearing capacity ratio, which makes road transportation of long span heavy elements often impossible. Consequently, precast concrete bridges are made from several small size concrete elements with cast on site part of the structure e.g. top deck (Figure 2).

In the case of very short span bridges (Figure 2) it is technologically possible to produce precast elements which are sufficiently light to be transported on the road. Precast technology is also used in the so called accelerated bridge construction (ABC) which is gaining a momentum throughout the world. For example in the USA the Federal Highway Administration (FHWA) started an initiative called “Every Day Counts EDC” (Roddenberry and Servos 2012). The most common reason to use the ABC method is to limit the impact of bridge construction on traveling public. Application of UHPC in precast concrete technology seems to be a perfect match with ABC technology concept. An example of a precast concrete bridge realized in ABC technology is shown in Figure 3.



Figure 2 (left) Long span concrete bridge using precast concrete beams and cast in-situ concrete deck bridge developed by A-Betong (right) Short span precast concrete bridge developed by A-Betong. (<http://www.abetong.se>).



Figure 3 Bridge made in ABC technology on the State Highway 86 over Mitchell Gulch in Colorado in 2002 (<http://utcdb.fiu.edu/bridgeitem?id=185#>).

The UHPC concrete has been extensively used in a number of countries around the world. The first full size UHPC Bridge was built in Canada in 1997. The following subsections will provide an overview of structures build in Europe, USA and Asia proceeded by the state of the art in Sweden.

3.2 UHPC in Sweden

The present project is a follow-up of earlier common study finalized in 2011 under the umbrella of Sveriges Bygguniversitet by LTH, CTH and LTU on “Robustare brobetonplatta: State-of-the-art och förslag till FUD program”. The report indicated that Ultra High Performance Fibre Reinforced Concrete has potential applications for repairs, strengthening, bridge edge beams as well as for **production of prefabricated concrete bridge elements** (Sundquist 2011). Extremely low permeability, ductile failure and high strength were emphasized. Application of UHPC could exclude for example problems with delamination of bitumen overlays (Figure 4). The high cost of UHPC was indicated as one of the main drawbacks. At the moment (6 years later) development of materials and design has progressed significantly and made UHPC bridges very competitive and more sustainable compared to traditional technologies, see section 3.5.



Figure 4 Typical delamination of damage of asphalt layer placed on the concrete bridge plate (Westergren 1999).

3.3 UHPC in Europe

A significant number of applications were realized in France where Lafarge has successfully commercialized its Ductal concrete (Graybeal 2011). The most important examples from France include the U-shaped footbridge in Sermaises, the Bourg-Les-Valence overpass bridges (Pi-shaped double tee beams), the PS 34 overpass on the A51 Campenon Bernard (post-tensioned segmental single cell box girder), the Sainte Pierre La Cour bridge in Mayenne (prestressed I-beams and deck panels), the Pinel bridge in Rouen (prestressed beams), the Passarelle des Anges (footbridge made of prestressed beams and deck to form a U-shape), TGV East High Speed Line aqueduct (post-tensioned U-shape) and the Passerelle des Anges in Herault (221-ft span and 5.9 ft-deep section).

The Bourg-Les-Valence bridges (Figure 5) in France are the first UHPC road bridges in which each bridge has two spans. Each span is made of pre-stressed beams in a double-tee shape with addition of bottom flanges similar to a Pi-shaped section and with a length of 20.5 m and 22.5 m. The UHPC was also used to create longitudinal joints. In 2013, after ca. 10 years in service and without significant maintenance, Toutlemonde et al. studied the material performance of this bridge in comparison with the design characteristics. The tests revealed the high durability and further maturity of the material with free chloride contents below 0.02% and compressive strengths close to 20% higher than the average 28-days strength.



Figure 5 Bourg-Les-Valence bridge (Toutlemonde et al. 2013).

Another example is the St. Pierre La Cour bridge (Figure 6) which consists of 10 UHPC precast, pre-stressed concrete girders. With a span of 19 m and a width of 12.6 m, it supports a continuous 7.6 m reinforced concrete road, pavement and a cycle lane. The Saint-Pierre La Cour project required just one day for casting and one day to bond the concrete slab in place (<http://www.ductal.com>).



Figure 6 St. Pierre La Cour bridge (<http://www.ductal.com>).

The overpasses on the A51 motorway in were made as precast, post-tensioned, single-cell box girder with a length of 47.4 m, a cross-section depth of 1.60 m, a top slab thickness of 140 mm. The web and bottom slab thickness were equal to 120 mm.

The Passarelle des Anges in Aniene (Figure 7) is a single-span bridge having almost 70 meters span and a height of 1.80 meters. It consists of precast segments from a single mould, assembled together by pre-stressing tendons to form two parallel beams acting as barriers. The UHPC has a compressive strength of 180 MPa.



Figure 7 Passarelle des Anges (*Mazzacane et al. 2009*).

A typical highway bridge made by Lafarge is shown in Figure 8. The bridge is built from Pi-shaped beams, pre-tensioned by wires. Decks are over 20 meters long. The UHPFRC (UHPC reinforced with fibres) in this precast structure (complete with deck) was manufactured without passive reinforcement or transverse pre-stressing. In all cases the UHPC enabled to produce lightweight long span elements which were transported on the road.



Figure 8 Example of UHPC TT-beam and highway bridge built in France (Lafarge).

The UHPC was also used in Germany to build the Gaertnerplatz bridge a pedestrian/bicycle bridge across the Fulda River in Kassel (*Fehling et al. 2008*). The structure is made as variable-depth (80-100 mm) space truss consisting of two top UHPC chords and a single bottom tubular steel cord (Figure 9). The total span is 133.2 meters.

Another example is the bridges built in Niestetal having span lengths of 7, 9, and 12 m and built as pretensioned Pi-shaped sections. Two other bridges using the Pi-shaped cross-section were built near Friedberg and Weinheim with span lengths of 12 and 18 m, respectively.

The UHPC usage in the Switzerland consisted mostly in rehabilitation and strengthening works. The most important examples include (*Brühwiler and Denarié 2008*) flooring of the Luaterbrunnen footbridge, rehabilitation and widening of the single span road bridge deck, repair of the protective layer of a crash barrier, repair of bridge pier using precast concrete panels made of UHPC.



Figure 9 The Gaertnerplatz bridge, Kassel, Germany.

The Wild bridge (Figure 10) in Völkermarkt, Austria, is an excellent example of 70 meter span arch bridge made of hollow UHPC precast concrete elements which were jointed and post tensioned at the building site.



Figure 10 The Wild bridge, Völkermarkt, Austria (<https://www.dywidag-systems.com>).

Another example of a foot bridge constructed in the Czech Republic (Tej et al. 2017) is shown in Figure 11. The bridge, a joint venture of HeidelbergCement and Metrostav, was designed as a cable-stayed structure with pre-stressed bridge deck. The bridge deck was made of prefabricated UHPC panels and reversed "V" shaped steel pylon with height of approximately 40 meters. 24 steel hangers were used to anchor the deck. The main span was 99.18 meters and the secondary span 31.9 m. The Deck was 4.5 meters wide. The capacity of the bridges enables passage of vehicles weighting up to 3.5 tons.



Figure 11 The Elbe pedestrian bridge, Celakovice, Czech Republic (<http://www.heidelbergcement.com>)

3.4 UHPC in USA and Canada

The UHPC was used in bridge construction for the first time in Canada already in 1997 (*Russel and Graybeal 2013*). The most famous project is the Sheerbrooke bridge in Quebec. Since that time more than 35 bridges were built in Canada alone. Examples are shown in Figure 12. The applications include longitudinal and transverse joints between precast components, shear connectors between beams and slabs, and a precast post-tensioned tee section for a pedestrian bridge.



Figure 12 Examples of UHPC application in bridges in Canada (*Russel and Graybeal 2013*).

More than 15 structures were also built in the USA between 2006 and 2012. Examples of lightweight UHPC bridges are shown in Figure 13. Applications include bulb-tee beams and girders, Pi-shaped girders, deck panels, shear connectors and transverse joints, longitudinal and transverse joints between beams and joints between full-depth deck panels.



Figure 13 Examples of UHPC application in bridges in USA (*Russel and Graybeal 2013*).

3.5 UHPC in Asia and Australia

In Asia, UHPC bridges were mostly built in Japan, South Korea and Malaysia. In Malaysia alone over 90 bridges were built between 2010 and 2017 (Figure 14).

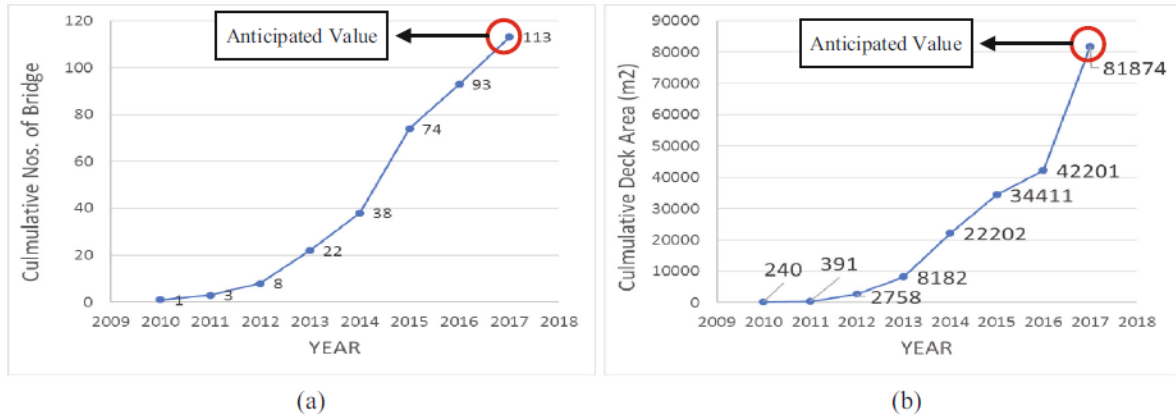


Figure 14 UHPC bridges built in Malaysia from 2010 to 2016; a) number of bridges, b) deck area.

A system developed in Malaysia called “Dura” is used to produce a wide spectrum of structures using UHPC, including concrete bridges. Examples of typical designs are shown in Figure 15.

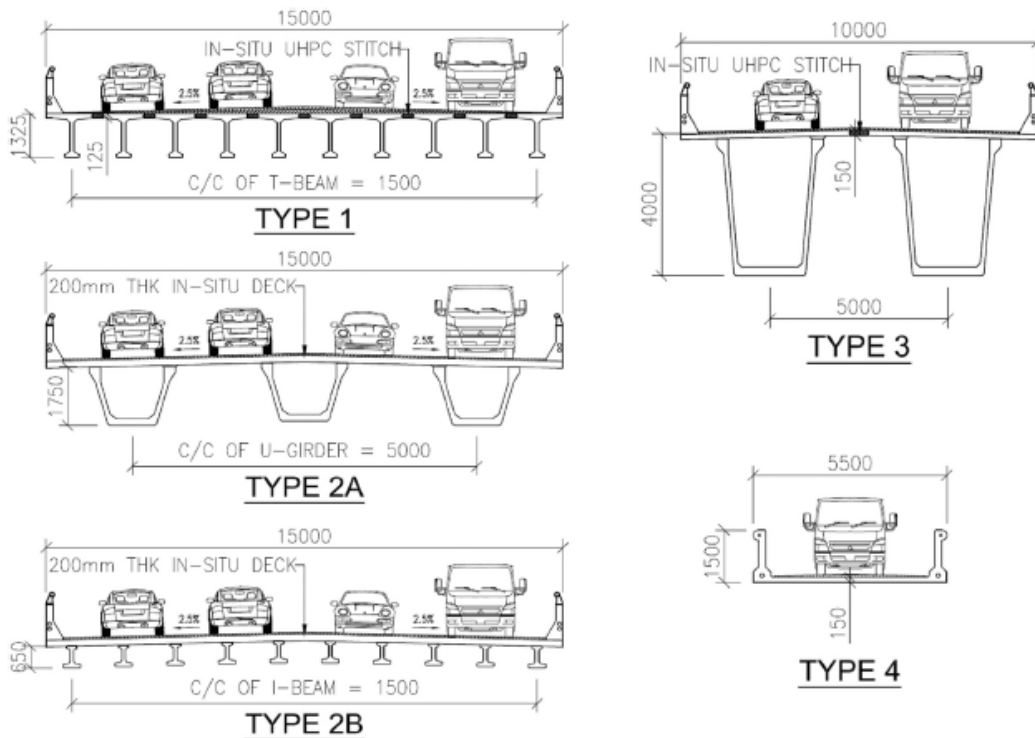


Figure 15 Different types of UHPC bridges produced in UHPC in Malaysia.

The first footbridge using UHPC concrete made in Japan was the Sakata-Mirai bridge (Figure 16) built in 2002. The bridge has 49.2 meters long and consists of pre-tensioned box girder elements which were later post-tensioned together into the final bridge. Another example is the Horikoshi Highway C-Ram bridge composed of four pre-tensioned UHPC I-shaped girders. That bridge has a deck made of a conventional concrete. The overall weight of that particular bridge was reduced by 30% in comparison with standard technology (*Tanaka et al. 2009*). Another example is one of the runways made at Tokyo Haneda International Airport. The thickness of the slab was 75 mm but consisted additional stiffening ribs which gave the total slab thickness of 250 mm. The weight of the elements was reduced by 56% when compared with standardized solution. Interestingly in total 6900 panels were produced. In total there were over 20 various types of structures made with UHPC concrete.



Figure 16 Different types of UHPC bridges produced in UHPC in Japan.

Up to date at least two structures using UHPC were made in South Korea. The most known is certainly the Seonyudo footbridge having span of 120 meters (Figure 17). It consists of post-tensioned Pi-shaped elements. The web of these elements is only 160 mm. Also in Australia and New Zealand precast pre-tensioned I-beams and precast post-tensioned Pi-girders in UHPC have been used in bridges.



Figure 17 Different types of UHPC bridges produced in UHPC in Japan.

4 REQUIREMENTS AND STANDARDS

4.1 General

In Sweden, there are approximately 30 000 bridges with a span length exceeding 2 m, including culverts (*Mattsson 2008*). The Swedish Transport Administration (STA) is responsible for 20 900 of these bridges, of which about 16 500 are road bridges (*STA 2017a*). In total, 50 percent of these are built between 1950 and 1980 and have, thus, reached an age at which the need of maintenance and repair usually increases (*Silfwerbrand and Sundquist 1998*). A large percentage (86%) of these bridges is concrete bridges.

The STA uses an integrated system and during the last decade, has transferred resources from corrective to preventive bridge maintenance (*Silfwerbrand 2011*). Presently, 10 to 15 percent of the budget is devoted to preventive maintenance whereas corrective maintenance, repair, and reconstruction comprise the remaining 85 to 90 percent. Preventive maintenance aims at measures to maintain the function of the bridge structure. A lot of the planned maintenance is bought up during a 4 or 5 year span and in the contract several of the “smaller” maintenance interventions is described whereas larger repair projects are contracted separately.

4.2 Steering documents

Since 1st of July 2013 the STA is the solely responsible for the commission of infrastructure works in Sweden. Therefore the STA uses a variety of documents pertaining to the design, construction, inspection and maintenance and rehabilitation of concrete bridges. Some of these documents are requirements or recommendations or describe different procedures. Different aspects have different requirements and usually they overlap or are dependent on each other. The requirements on bridge maintenance specified by the STA are either technical or operation procedural (*STA 2017b*). The following sub-sections give an overview of the most relevant documents as well as technical and non-technical requirements applicable to concrete bridges.

4.2.1 Overall requirements

The STA document TDOK 2015:0340 “Bro och Tunnel” (*STA 2015*) sets out the overall requirements for bridges and tunnels as well as for bridge-like structures. The purpose is to establish a common set of requirements for the STA’s infrastructure in order to fulfil both long-term traffic needs and long-term social needs. For existing bridges, for example, it is specified that maintenance measures shall be dimensioned for traffic loads equal to the current authorized traffic load whereas strengthening works shall account for increased traffic loads estimated for the next 20 years.

4.2.2 Construction requirements

The STA document TDOK 2016:0204 “Krav Brobyggande” (*STA 20016a*) lists and describes the requirements for the design and dimensioning of new bridges constructed for the STA. Municipalities may also base their requirements on this document. For repair works they may have the same demands or based on the ones in the document.

Additionally, recommendations are provided in the STA document TDOK 2016:0203 “Råd Brobyggande” (STA 2016b). For concrete bridges, some important requirements are as follows:

- The use of sliding formwork is not allowed for cast in-place concrete.
- Concrete structures shall be dimensioned for a technical service life of 40, 80 or 120 years, according to the principles described in EN 1992-1-1 (CEN 2004).
- For each concrete surface, the exposure class that provides the most stringent requirement shall apply.
- In addition to the requirements in EN 1992-1-2 (CEN 2004), for road bridges, a minimum of 65 mm cover thickness applies in the cases where reinforcement corrosion may occur.
- In roads subject to the use of de-icing salts, bridge edge beams shall be treated with hydrophobic impregnations for prevention against water and chloride ingress.
- Concrete structures exposed to de-icing salts or marine environment shall be provided with the possibility electrochemical monitoring of the reinforcement.

4.2.3 Load calculations

The STA document TDOK 2013:0267 “Bärighetsberäkning av broar” (STA 2017c) specifies the requirements that apply to load calculations of bridges located on roads, railways and pedestrian and cycling routes. It defines, among others, 1) minimum and/or characteristic values for compressive strength, tensile strength and modulus of elasticity; 2) verification procedures (e.g. location of sampling, size and number of samples); 3) models for the calculation of deformations due to shrinkage or 4) maximum crack width for the different types of bridges. Additionally, recommendations are provided in the STA document TDOK 2013:0273 “Bärighetsberäkning av broar” (STA 2017d).

4.2.4 Maintenance

The STA documents TDOK 2013:0415 “Krav Brounderhåll” (STA 2017b) specifies the requirements that apply to the design and dimensioning of maintenance (based in condition assessment) and strengthening measures of bridges and bridge-like structures. The document is divided into two parts; maintenance based in condition assessment and time programmed maintenance. The document is complemented by STA’s document TDOK 2013:0416 “Råd Brounderhåll” (STA 2017e) that gives advice for bridge maintenance. There are different types of requirements for different parts of the structure and different stages in the planning and calculations. For concrete structures some following requirements are of importance to this project:

- Casting of new concrete should have a thickness of at least 10 mm.
- Sealing of cracks should be done using cement based materials.
- The old concrete should:
 - not be damaged (have to be tested by an expert);
 - have a maximum chloride content of 0.3% at the reinforcement;
 - have enough compressive strength according to EN 13791 (CEN 2007);
 - not present microcracks after being subjected to water jetting;
 - not be carbonated at the reinforcement (SS 137242, 1988);
 - be frost resistant (SS 137244, 2005);
 - have a cover thickness at least the diameter of the reinforcement;

- Between new and old concrete:
 - the force transmission needs to be ensured (with a mechanical joint if so needed);
 - when the force transfer is only by adhesion, the casting surface must be prepared by water jetting, according to AMA Anläggning 17 (*Svenskbyggtjänst 2017*), BED.141 "Rivning av bro" and "Krav på vattenbilningsutrustning" in AMA Anläggning 17.

4.2.5 Materials and execution

AMA is a general material and work description in the construction industry. In AMA Anläggning 17 (*Svenskbyggtjänst 2017*) there are a number of repair procedures described for civil engineering structures. Chapters BED.141 and BED.14 stipulates demolitions by water jetting as required in TDOK 2013:0415 (*STA 2017b*). For each new edition of AMA the STA makes a new version of own additional requirements (e.g. *TDOK 2017:0441, STA 2017f*).

4.2.6 Management

BaTMan stands for Bridge and Tunnel Management and is the database as well as management tool for the bridges in Sweden own and managed by the STA and many municipalities. For each structure there is information about type, ownership and design, including materials. There are also a number of documents concerning maintenance and management. The STA has a lot of rules and requirements on what needs to be documented in BaTMan before the repair can be performed.

"BaTMan - Mätning och bedömning av broars tillstånd" (*STA 2008*) summarizes the information required to assess the condition of a bridge. For each type of concrete element and degradation mechanism, the document provides information on inspection procedures and choice of assessment techniques. Based on this information, a "functional class" between 0 and 3 is assigned:

- TK 3 Failure at the time of inspection
- TK 2 Failure expected within 3 years
- TK 1 Failure expected within 10 years
- TK 0 Failure expected after more than 10 years

The "functional class" of the damaged element is determined based on the functional properties of the construction element, the functional requirements set during design stage, current and previous condition assessment parameters and on the expected time to failure.

Depending on this classification an action plan is developed. For example, in TK 3 there has to be an investigation within 3 months after the inspection. For minor problems there is usually a negotiation with a contractor and some acute measurements can be done without planning or decision as long as the budget does not exceed 50 000 SEK. For larger problems and more extensive repairs a separate project is constructed. This is usually done through public procurement with contractors. The larger procedures are usually done in projects which are budgeted throughout 1 or several years.

4.3 Performance requirements

The decision related to the type and frequency of inspection, maintenance, repair and rehabilitation operations is a complicated process; it is therefore important to identify the performance requirements (Table 2) that must be considered and fulfilled to ensure a quality repair. These include both technical (service life, durability, structural stability and safety, execution of work, etc.) and non-technical aspects (legal, economic, social, and environmental, etc.).

Table 2 General performance requirements (*REHABCON 2004*).

	General performance requirements
Service life / Durability	Durability Deformation / Displacement Cracking Drainage Watertightness Slip resistance / Roughness Visibility Flexibility Inspectability Maintainability Serviceability
Structural stability / Safety	Strength Fatigue Fire and earthquake resistance
Execution	Minimisation of downtime. Rapidity Impact on environment Health and safety Disturbance Climatic conditions Need of additional equipments
Environmental factors (& Sustainability)	Service life of the repair Ecology (external environment) Indoor environment Energy consumption Health and safety
Economy	Operational costs Preparation, repair and maintenance costs Demolition and disposal costs Failure costs
Social	Aesthetics / Appearance Social perception (public confidence) Insurance and future liabilities Strength of local economy Improvement of asset values Cultural Heritage
Political	Media and press Government policies and initiatives
Legal	Legal issues

4.3.1 *Technical requirements*

4.3.1.1 SERVICE LIFE AND DURABILITY

The service life and durability of the repair is expected to be at least the same as that of the original structure. This will depend on the exposure environment, the choice of repair materials/methods and on the quality of the execution of the repair works. Of great importance are the mechanical and transport properties of the repair material, the durability of the bond between repair and old concrete (very dependent on the accurate preparation and application) and the compatibility between old and new materials (e.g. differences in shrinkage properties between the materials can lead to cracking). The selection of the repair system should be based on an evaluation of their capability to fulfil the owner's requirements for service life. Requirements associated to service life of the repair system are: carbonation and chloride diffusion rates; frost resistance; limited cracking; and bond/adhesion strength.

4.3.1.2 STRUCTURAL STABILITY AND SAFETY

By restoring the loading capacity of the structural members, after repair, the structural performance is expected to be at least the same as the new structure. When restoring the initial strength, the loss of cross-section of the member by removal of deteriorated concrete must be considered and reflected on the design of the repair and choice of repair material (e.g. use of textile reinforcements or type of concrete) in order to accommodate the redistribution of the loads. Requirements associated with structural stability are: compressive and tensile strength; bond strength between repair material and reinforcement; E-modulus; amount and depth of surface scaling; and (residual) cross-section of the reinforcement.

4.3.1.3 EXECUTION

Execution time depends on the extent of the repair and climatic conditions. It is important to minimize the execution time to reduce economical and societal impacts. Simultaneously enough time for careful application, dependent on the type of repair material/method, is required. This is of great importance in the case of temperature or moisture sensitive repair materials. Requirements related to execution have to do both with the correct execution itself but also with the adequate choice of methods. These include: methods for removing old concrete and their influence on the surface quality and bond to the repair material; methods and materials for injecting cracks and their influence on the permeability of the concrete; methods for placing the repair material and their influence on the bond to reinforcement and old concrete.

Environmental impact and health and safety aspects of the repair procedures should also be considered during its execution. Examples include energy consumption, waste management strategies, selection of materials with low environmental impact, personal protective equipment and protection of users against eventual debris.

4.3.1.4 ENVIRONMENTAL FACTORS AND SUSTAINABILITY

The environmental impact of the repair material must be considered with respect to its lifetime, in particular in terms of their effect on ecology as some repair materials can be highly toxic and their waste need special treatment.

4.3.2 Non-technical requirements

4.3.2.1 ECONOMY

Costs should be limited and reduced during the whole life cycle of the structure. Costs directly associated with maintenance and repair depends on the correct choice of repair materials and methods but also their careful execution, subsequent inspection and preventive maintenance. A cost/benefit analysis of different repair methods/materials must be performed because some materials, despite being more expensive, may require less time for application and curing and thus reducing the execution time. The use of non-renewable repair materials that cannot be recycled or reused, increases demolition and deposition costs. Unsuccessful repairs can lead to functional failure or collapse of the structure and increased failure costs. Requirements associated with economical and financial aspects have to do with procurement and type of contract, life cycle cost, and cost versus benefit to society or user costs.

4.3.2.2 SOCIAL

Aesthetics play a great role on the selection of the repair strategy and the end result depends mainly on the materials and execution. It is important that the repaired surfaces have similar look and texture as the original structure. In addition, also the durability of the aesthetics, e.g. discolouration due to leaching or UV radiation should be avoided. This will contribute a social perception of safe and to the public confidence. Requirements related to socio-cultural aspects are e.g. aesthetics, social perception/alarm, and reputation.

4.3.2.3 POLITICAL

Political priorities may define the decision on when, where and how to repair and may override technical requirements.

4.3.2.4 LEGAL

Legal implications related to the correct execution of repair works should also be considered in particular if there is a risk of partial or total collapse leading to injuries.

4.4 Standards

There are a vast number of international and European standards pertaining to repair and maintenance of concrete structures as listed in Annex A, the most relevant of which are the series ISO 16311 parts 1-4, the series EN 1504 parts 1-10, and the EN 14487 parts 1-2.

The standard ISO 16311 provides the framework for maintenance activities of existing concrete structures, specifies the requirements for assessment of structures including inspection and evaluation of the performance, identifies key stages in the planning and designing of the repair process and specifies how the application of products and systems for concrete repair shall be conducted and verified.

The European standard EN 1504 specifies the requirements for the identification, performance and safety of the various techniques, systems and products used for the repair and rehabilitation of concrete structures. More detailed information is provided in section 5 of this report where an overview of the repair principles, techniques and materials for concrete structures is described.

The European standard EN 14487 pertains to sprayed concrete, a widely used material in reparation and maintenance works. Part 1 describes the requirements for sprayed concrete, constituent materials, composition and properties (fresh and hardened) whereas Part 2 pertains to execution and quality control.

With regards to UHPC, however, until very recently there were only technical guidelines and recommendations available in e.g. France (*SETRA-AFGC 2002*), Japan (*JSCE 2006*), USA, Australia (*Gowripalan and Gilbert 2000*) and Switzerland. Legally these documents were not official standards. Recently however, official national standards were published in France covering both materials as well as design (*AFNOR 2016a-b*). A third standard covering “Execution of concrete structures – specific rules for UHPC” is expected to be published at the end of 2017 (AFNOR 2017).

5 REPAIR TECHNIQUES FOR CONCRETE STRUCTURES

5.1 General

Concrete structures are designed based on different requirements such as service life, safety, functionality, aesthetics etc. To maintain these requirements throughout the expected service life of structures a maintenance policy and inspections are needed. The following type of bridge inspections are performed in Sweden:

- *Superficial inspection* performed by the maintenance contractor at least one time per year in order to detect obvious defects at an early stage.
- *Major inspection* to identify and estimate damage that may affect the safety or function of a structure within 10 years. Should be performed minimum once every 6 years.
- *General inspection* to monitor repairs, corrections or further propagation of damage identified during the last major inspection. Also to identify and estimate any new damage that could occur. Performed within 3 years after a major inspection.
- *Special inspection* for construction parts that requires a thorough investigation and expert knowledge. Performed when needed.

If the inspection reveals that the structure does not fulfil the requirements, actions need to be taken. The EU project REHABCON (2004) distinguishes between four different types of actions, namely:

1. Do nothing at present, i.e. postpone repair for a certain time.
2. Issue restricted use.
3. Repair now.
4. Demolish and re-build.

The EN 1504-9 (*CEN 2008*) has the same overall principal but details the actions further in intermediate options. Weather to repair or replace a structure is an important issue that is addressed in an asset management system. There are several systems more or less similar. The following is a comparison between the repair and maintenance management systems described in the REHABCON project, the EN 1504-9 and the US Bureau of Reclamation (USBR).

Table 3 Phases of a typical repair project.

REHABCON	EN 1504-9	USBR
1. Assessment <i>Determine the cause, type and impact of damage</i>	1. Information about the structure <i>Condition, history and documentation</i>	1. Determine the cause(s) of damage
2. Requirements <i>Analysis of basic requirements on the structure</i>	2. Process of assessment <i>Determine cause and extend of damage</i>	2. Evaluate the extent of damage <i>Effect on the serviceability of the structure</i>
3. Technical solutions <i>Choosing type of action and technical solutions</i>	3. Management strategy <i>Options, principals and methods</i>	3. Evaluate the need to repair
4. Optimisation <i>Evaluation of repair methods and preparation for the decision process</i>	4. Design of repair works <i>Intended use of products, requirements, specifications</i>	4. Select the repair method and material
5. Final decision	5. Repair work <i>Choice and use of products and methods</i>	5. Prepare the existing concrete for repair
	6. Acceptance of repair work <i>Testing and documentation</i>	6. Apply the repair method
		7. Cure the repair properly

The repair process by REHABCON describes how a repair method is chosen while Reclamation's concrete repair and maintenance system and EN 1504-9 describe both the choice of repair method and how it is applied. Another difference is that requirements are considered in REHABCON and EN 1504-9.

5.2 Existing techniques

The EN 1504-9 establishes the main repair principles and methods in a European context. There are in total 11 principles (Table 4). Principals 1-6 are related to damaged concrete and principals 7-11 are related to reinforcement corrosion.

Table 4 Principles and methods for protection and repair of concrete structures.

1.	Protection against ingress of adverse agents (PI)
1.1	impregnation
1.2	surface coating with and without crack bridging ability
1.3	locally bandaged cracks
1.4	filling cracks
1.5	transferring cracks into joints
1.6	erecting external panels
1.7	applying membranes
2.	Moisture control (MC)
2.1	hydrophobic impregnation
2.2	surface coatings
2.3	sheltering or overcladding
2.4	electrochemical treatment
3.	Concrete restoration (CR)
3.1	applying mortar by hand
3.2	recasting with concrete
3.3	spraying concrete or mortar
3.4	replacing elements
4.	Structural strengthening (SS)
4.1	adding or replacing embedded or external reinforcing steel bars
4.2	installing bonded rebars in preformed or drilled holes in the concrete
4.3	plate bonding
4.4	adding mortar or concrete
4.5	injecting cracks, voids or interstices
4.6	filling cracks, voids or interstices
4.7	prestressing - (post tensioning)
5.	Physical resistance (PR)
5.1	overlays or coatings
5.2	impregnation
6.	Resistance to chemicals (RC)
6.1	overlays or coatings
6.2	impregnation
7.	Preserving or restoring passivity (RP)
7.1	increasing cover to reinforcement with additional cementitious mortar or concrete
7.2	replacing contaminated or carbonated concrete
7.3	electrochemical realkalisation of carbonated concrete
7.4	realkalisation of carbonated concrete by diffusion
7.5	electrochemical chloride extraction
8.	Increasing resistivity (IR)
8.1	limiting moisture content by surface treatments coatings or sheltering
9.	Cathodic control (CC)
9.1	limiting oxygen content (at the cathode) by saturation or surface coating *
10.	Cathodic protection (CP)
10.1	applying electrical potential
11.	Control of anodic areas (CA)
11.1	painting reinforcement with coatings containing active pigments
11.2	painting reinforcement with barrier coatings
11.3	applying inhibitors to the concrete

The suitable repair option depends on the cause, type and location of the damage, so for each cause and type of damage, one or several repair techniques may be applicable. According to “Reparations Handbook” (*Betongreparation.se*) and “REHABCON Manual” (*REHABCON 2004*), there is 13 main repair techniques:

1. Concrete recasting
2. Local patch repair
3. Additional cement based cover
4. Surface treatment
5. Crack injection
6. New post-tensioning reinforcement
7. Strengthening with carbon fibre
8. Strengthening with steel plates
9. Cathodic protection
10. Corrosion inhibitors
11. Chloride extraction
12. Realkalization
13. Demolishing/replacement

Each technique is then divided in several actions. According to “Reparations Handbook” (*Betongreparation.se*) the following moments are fundamental part repair techniques 1-3:

1. Removal of damaged concrete
2. Cleaning the concrete surface
3. Crack injection
4. Cleaning of reinforcement, additional reinforcement and application of inhibitors
5. Application of stirrups
6. Material selection
7. Conditioning of the concrete’s surface
8. Formwork application
9. Concrete application (casting, spraying, etc.)
10. Setting and hardening
11. Surface treatment
12. Consideration of traffic vibrations
13. Quality control

According to REHABCON Annex 4, execution of repair work is divided in a number of actions:

1. Removal of damaged concrete
2. Application of material replacing the old concrete
3. Injection
4. Replacement and additional reinforcement
5. Use of chloride extraction and re-alkalisation
6. Application of cathodic protection
7. Cleaning of concrete surface
8. Drying of concrete surface
9. Application of non-structural surface layer on the cover
10. Application of structural surface layer on the cover
11. Cleaning of reinforcement
12. Application of inhibitors

In the references “Reparations Handbook” (*Betongreparation.se*), “REHABCON Manual” (*REHABCON 2004*) and Silfwerbrand and Sundquist (1998) an extensive qualitative identification and evaluation of both repair methods and repair actions is given. In the following an example is presented.

Table 5 Qualitative identification of repair methods based on the cause and type of damage.

I: Reinforcement corrosion			
Cause of damage	Type of damage	Repair principles	Main repair method (see table 2)
I:1 Chloride induced corrosion	I:1.1 Corroded reinforcement. Spalling of cover with or without cracking.	Stop further corrosion. Recast cover. Restore load-carrying capacity and serviceability (durability).	Method 1: "Concrete recasting" Method 2: "Polymer concrete recasting" Method 3: "Local patch repair"
	I:1.2 Corroded reinforcement. No spalling. Cracking of cover.	Stop further corrosion. Restore load-carrying capacity and serviceability (durability).	Method 1: "Concrete recasting" Method 2: "Polymer concrete recasting" Method 3: "Local patch repair" Method 10: "Cathodic protection" + +Method 6: "Crack injection" Method 11: "Chloride extraction" + +Method 6: "Crack injection"
	I:1.3 Corroded reinforcement. No spalling. No cracking of cover.	Stop further corrosion. Restore load-carrying capacity and serviceability (durability).	Method 1: "Concrete recasting" Method 2: "Polymer concrete recasting" Method 10: "Cathodic protection" Method 11: "Chloride extraction" + +Method 5 "Surface treatment" (if necessary)
	I:1.4 Corrosion not yet started. Threshold concentration almost reached the bar.	Prolong time until start of corrosion.	Method 1: "Concrete recasting" Method 2: "Polymer concrete recasting" Method 4: "Additional cement based cover" Method 5: "Surface treatment" Method 10: "Cathodic protection" + +Method 5 "Surface treatment" (if necessary)
	I:1.5 Chloride induced corrosion on pre-tensioned or post-tensioned reinforcement.	Stop further corrosion. Restore load-carrying capacity and serviceability (durability).	Method 7: "New post-tensioned reinforcement" Method 13: "Demolishing/replacement"

Table 6 Qualitative evaluation of repair methods.

Main repair method		Variations/Considerations/Risks				
Method no	Short description	Service life	Structural stability	Execution	Environment and health	Economy
Method 5: Surface treatment	Classified in hydrophobic impregnations, impregnations and coatings. Application prevents deterioration and/or limits the deterioration rate. The main function is moisture control and/or protection against ingress. Satisfy principle 1, 2, 5, 6 and 8 in ENV 1504-9.	Adhesion to substrate is essential. For coatings the crack bridging capacity must be considered on cracked substrate. The product must be durable in its environment and withstand UV-radiation, moisture, alkali, ozone, etc. Temperature cycling and shrinkage can give internal stresses in coatings that might cause cracks and blisters and contribute to degradation. Experience shows that dense thin coatings can cause frost damage. Corrosion: Diffusion of carbon dioxide or chloride through the surface treatment shall be low enough (test required). Moisture control might be a possible way to reduce the corrosion rate. ASR: Moisture control might be a possible way to reduce ASR. Risk that the decrease of moisture content will be insufficient. Advisable references: <i>This Report, Annex 2</i> European standards: prEN 1504-2, ...	Can on its own only be used when residual load-carrying capacity is high enough.	Requires a clean substrate without contaminations (see further method 1 for surface cleaning). For coatings the preparation should aim at obtaining an even surface. Errors in the preparation might lead to insufficient adhesion. Penetration of a hydrophobic agent is strongly affected by the exposure time and the moisture conditions in the concrete cover. For coatings the total thickness shall meet the specified maximum and minimum thickness since many properties depend on the thickness. Application procedure shall follow the recommendations given by the supplier. Advisable references: <i>This Report, Annex 4 Manual, Annex F</i> European standards: EN 1504-10, ...	The effect on ecology, indoor environment and health and safety during the entire lifetime of the surface treatment should be considered. The effect depends on type of surface treatment used. Ecology: The effect on different ecology parameters (energy, emissions etc.) is evaluated for all life cycle phases of the repair. Health and Safety: Handling of products is regulated in the EC legislation. Relevant information is found in the Safety Data Sheet. Indoor environment: To be considered only at indoor repair activity. Parameters like self-emissions, sound etc. are evaluated. Advisable references: <i>This Report, Annex 5</i> European standards: EC Directive 91/155/EC.	See method 1. Normally the cost of surface treatments is relatively low in comparison with most other repair techniques. New costs for periodical maintenance might arise.

Table 7 Qualitative evaluation of repair actions.

Method	Working environment	Non-technical issues	Climatic conditions	Application Simplicities/difficulties	Applicability with regard to type of structure	Need of additional equipment	Speed of operation	Influence on properties of the structure
Blasting	Creates dust and noise. If the surface is contaminated additional protection is required.	Applied to infrastructure construction the method may cause disturbance of traffic and create dust and noise.	No restrictions.	Suitable for removing thin concrete layers.	Applicable to all types of structures.	Scaffolding may be needed for vertical structures. Equipment for suction of dust often needed.		Micro-crack free surface. Good bond properties. Takes away stain from reinforcement.

As summarized before, repair and strengthening methods usually involve the replacement of the deteriorated concrete by concrete with similar properties, the assessment and remediation of the reinforcement, followed by the application of a new polymer-based concrete layer and hydrophobic treatment to the final surface (*Krauss et al. 2009, Harris et al. 2015, Russel and Graybeal 2013*). Such systems are not only expensive but also environmentally aggressive, meaning that its cost effectiveness in comparison with the obtained final effect (i.e. long term durability) is not especially high.

State-of-the-art maintenance and repair solutions rely on the application of polymer-based cementitious materials, conventional reinforced concrete and hydrophobic surface treatments. These solutions bring a series of problems associated with compatibility issues between conventional concrete and polymer-based systems, poor durability associated with conventional reinforced concrete and environmental aspects related to the impregnations. The application of UHPC for repair will enable to solve some problems related to presently used repair technologies such as:

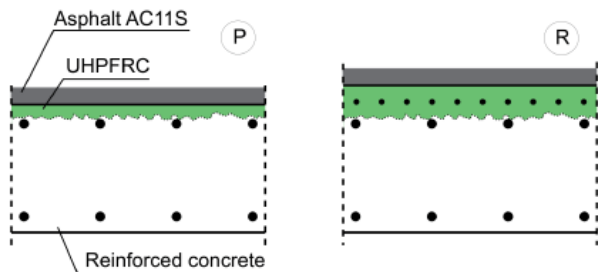
- Fibre reinforced polymers (FRP) wraps: health hazard to workers; incompatibility between concrete substrate and polymer based binders; rapid strength loss in case of temperatures exceeding 70 °C; questionable long term durability; high costs; not applicable in case of very extensive deterioration (e.g. missing large volumes of concrete due to reinforcement corrosion); esthetical issues.
- Polymer modified cement and concrete (PCC) repair materials: needs to be applied in layers (usually not casted); high material and application costs; durability cannot always be guaranteed.
- Normal strength concrete repairs: questionable long term durability; impossible to cast thin “mantels” as in the case of UHPC due to large aggregate size; very low tensile strength not exceeding 10 MPa vs 35 MPa in the case of UHPC; environmental and health issues (due to use of hydrophobic coatings).

The ideal repair solution would be to use a Portland cement based material which would ensure excellent durability in harsh environments as well as superior bond to the existing concrete surface (*Brühwiler and Denarié 2013*). The solution should be also easily produced by any concrete plant and cast as self-compacting material using conventional methods known to contractors, while not requiring any additional heat treatment. Moreover, the strength development should be rapid to enable fast repairs. A promising material which could appropriately fulfill these above requirements is ultra-high performance concrete (UHPC) is an alternative solution which is rapidly spreading around the world to repair and strengthen concrete structures (*Denarié 2009, Cwirzen et al. 2008, Žnidarič 2003*).

5.3 Application of UHPC for repairs - current situation

Recent developments showed indeed that retrofitting and strengthening of concrete bridges by casting of UHPC toppings became a viable solution. For example in Switzerland between years 2004 - 2013 more than 25 applications were successfully completed. Over 100 m³ or 3000 m² were laid. There was also one full scale application in Slovenia. This technology is rapidly spreading in Switzerland at the moment and becomes a “current practice” (*Brühwiler and Denarié 2013*).

A conceptual approach of the used solution is shown in Figure 18 and the actual repaired bridge in Figure 19. One of the main challenges especially in the case of repair or strengthening using UHPC is bond between OPC/HPC concrete and UHPC overlay (*Harris et al. 2015*). More research in this area is required.



«P»: UHPFRC 20 to 30 mm = Protection - waterproofing

«R»: UHPFRC 40 to 50 mm + fine additional rebar = Protection + Reinforcement / can double load carrying capacity !

Figure 18 Conceptual approach for UHPC toppings used in Switzerland (*Brühwiler and Denarié 2013*).



Figure 19 Rehabilitation of bridge decks using UHPC toppings (*Brühwiler and Denarié 2013*).

6 COST / BENEFIT ANALYSIS

Material related costs of the UHPC concrete exceed by 2-3 times in average the cost of conventional concretes (*Piotrowski and Schmidt 2012*). However, the simplified LCC cost analyst done by Piotrowski and Schmidt (2012), in Figure 20, shows generally higher initial costs for UHPC bridges but significantly lower maintenance costs. The authors concluded that UHPC bridges are more economical in comparison with bridges made of normal concrete. They emphasized lower maintenance costs and no need to replace the bridge within first 100 years. Others (*Graybeal 2011*) indicated that the predicted lifespan of UHPC elements could reach 500 years without the need for major repairs.

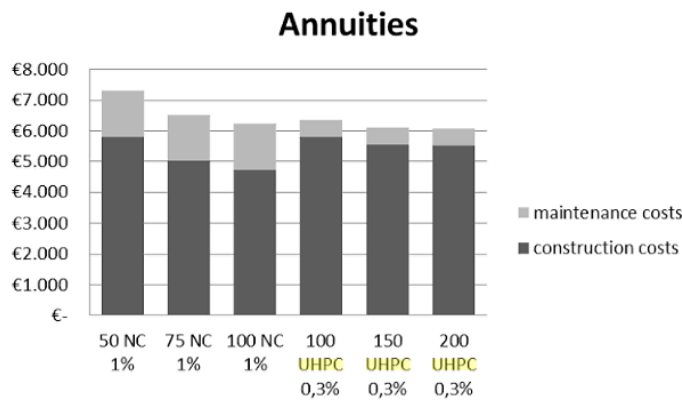


Figure 20 Estimated annuities in lifecycles for bridge made of normal concrete (NC) and ultra high performance concrete (UHPC) for 50, 75, 100, 150 and 200 years lifespan (*Piotrowski and Schmidt 2012*).

7 CONCLUDING REMARKS

The following general conclusions can be formulated:

UHPC is potentially an excellent material for applications in infrastructure (especially bridges) exposed to harsh environments.

The life cycle cost should be lower for structures made with UHPC, predicted life-span could reach far beyond 200 years, and maintenance costs should be very low or even negligible.

The application of UHPC should enable production of lightweight long span prefabricated concrete elements which will be easy to transport and quick to mount on the structure.

Existing guidelines and recently published French standards for UHPC should enable their straightforward adaptation in Sweden after experimental and theoretical research performed in this project.

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ANNEX A

Table A1 List of standards applicable in maintenance and repair of concrete structures.

Standard No.	Standard Name
ISO 16311-1	Maintenance and repair of concrete structures -- Part 1: General principles
ISO 16311-2	Maintenance and repair of concrete structures -- Part 2: Assessment of existing concrete structures
ISO 16311-3	Maintenance and repair of concrete structures -- Part 3: Design of repairs and prevention
ISO 16311-4	Maintenance and repair of concrete structures -- Part 4: Execution of repairs and prevention
EN 1504-1	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 1: Definitions
EN 1504-2	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 2: Surface protection systems for concrete
EN 1504-3	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 3: Structural and non-structural repair
EN 1504-4	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 4: Structural bonding
EN 1504-5	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 5: Concrete injection
EN 1504-6	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 6: Anchoring of reinforcing steel bar
EN 1504-7	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 7: Reinforcement corrosion protection
EN 1504-8	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and AVCP – Part 8: Quality control and Assessment and verification of the constancy of performance (AVCP)
EN 1504-9	Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 9: General principles for the use of products and systems
EN 1504-10	Products and systems for the protection and repair of concrete structures – Definitions – Requirements – Quality control and evaluation of conformity – Part 10: Site application of products and systems and quality control of the works
EN 1542	Products and systems for the protection and repair of concrete structures – Test methods – Measurement of bond strength by pull-off
EN 1543	Products and systems for the protection and repair of concrete structures – Test methods – Determination of tensile strength development for polymers
EN 1544	Products and systems for the protection and repair of concrete structures – Test methods – Determination of creep under sustained tensile load for synthetic resin products (PC) for the anchoring of reinforcing bars
EN 1766	Products and systems for the protection and repair of concrete structures – Test methods – Reference concretes for testing
EN 1767	Products and systems for the protection and repair of concrete structures – Test methods – Infrared analysis
EN 1770	Products and systems for the protection and repair of concrete structures – Test methods – Determination of the coefficient of thermal expansion
EN 1771	Products and systems for the protection and repair of concrete structures – Test methods – Determination of injectability and splitting test
EN 1799	Products and systems for the protection and repair of concrete structures – Test methods – Test to measure the suitability of structural bonding agents for application to concrete surface
EN 1877-1	Products and systems for the protection and repair of concrete structures – Test methods – Reactive functions related to epoxy resins – Part 1: Determination of epoxy equivalent
EN 1877-2	Products and systems for the protection and repair of concrete structures – Test methods – Reactive functions related to epoxy resins – Part 2: Determination of amine functions using the total basicity number
EN 1881	Products and systems for the protection and repair of concrete structures – Test methods – Testing of anchoring products by the pull-out method
EN 12188	Products and systems for the protection and repair of concrete structures – Test methods – Determination of adhesion steel-to- steel for characterization of structural bonding agents
EN 12189	Products and systems for the protection and repair of concrete structures – Test methods – Determination of open time
EN 12190	Products and systems for the protection and repair of concrete structures – Test methods – Determination of compressive strength of repair mortar
EN 12192-1	Products and systems for the protection and repair of concrete structures – Granulometry analysis – Part 1: Test method for dry components of premixed mortar
EN 12192-2	Products and systems for the protection and repair of concrete structures – Granulometry analysis – Part

	2: Test method for fillers for polymer bonding agents
EN 12614	Products and systems for the protection and repair of concrete structures – Test methods – Determination of glass transition temperatures of polymers
EN 12615	Products and systems for the protection and repair of concrete structures – Test methods – Determination of slant shear strength
EN 12617-1	Products and systems for the protection and repair of concrete structures – Test methods – Part 1: Determination of linear shrinkage for polymers and surface protection systems (SPS)
EN 12617-2	Products and systems for the protection and repair of concrete structures – Test methods – Part 2: Shrinkage of crack injection products based on polymer binder: volumetric shrinkage
EN 12617-3	Products and systems for the protection and repair of concrete structures – Test methods – Part 3: Determination of early age linear shrinkage for structural bonding agents
EN 12617-4	Products and systems for the protection and repair of concrete structures – Test methods – Part 4: Determination of shrinkage and expansion
EN 12618-1	Products and systems for the protection and repair of concrete structures – Test methods – Part 1: Adhesion and elongation capacity of injection products with limited ductility
EN 12618-2	Products and systems for the protection and repair of concrete structures – Test methods – Part 2: Determination of the adhesion of injection products, with or without thermal cycling – Adhesion by tensile bond strength
EN 12618-3	Products and systems for the protection and repair of concrete structures – Test methods – Part 3: Determination of the adhesion of injection products, with or without thermal cycling – Slant shear method
EN 12636	Products and systems for the protection and repair of concrete structures – Test methods – Determination of adhesion concrete to concrete
EN 12637-1	Products and systems for the protection and repair of concrete structures – Test methods – Compatibility of injection products – Part 1: Compatibility with concrete
EN 12637-3	Products and systems for the protection and repair of concrete structures – Test methods – Compatibility of injection products – Part 3: Effect of injection products on elastomers
EN 13057	Products and systems for the protection and repair of concrete structures – Test methods – Determination of resistance of capillary absorption
EN 13062	Products and systems for the protection and repair of concrete structure – Test methods – Determination of thixotropy of products for protection of reinforcement
EN 13295	Products and systems for the protection and repair of concrete structures – Test methods – Determination of stiffening time
EN 13295	Products and systems for the protection and repair of concrete structures – Test methods – Determination of resistance to carbonation
EN 13395-1	Products and systems for the protection and repair of concrete structures – Test methods – Determination of workability – Part 1: Test for flow of thixotropic mortars
EN 13395-2	Products and systems for the protection and repair of concrete structures – Test methods – Determination of workability – Part 2: Test for flow of grout or mortar
EN 13395-3	Products and systems for the protection and repair of concrete structures – Test methods – Determination of workability – Part 3: Test for flow of repair concrete
EN 13395-4	Products and systems for the protection and repair of concrete structures – Test methods – Determination of workability – Part 4: Application of repair mortar overhead
EN 13396	Products and systems for the protection and repair of concrete structures – Test methods – Measurement of chloride ion ingress
EN 13412	Products and systems for the protection and repair of concrete structures – Test methods – Determination of modulus of elasticity in compression
EN 13529	Products and systems for the protection and repair of concrete structures – Test methods – Resistance to severe chemical attack
EN 13578	Products and systems for the protection and repair of concrete structure – Test methods – Compatibility on wet concrete
EN 13579	Products and systems for the protection and repair of concrete structures – Test methods – Drying test for hydrophobic impregnation
EN 13580	Products and systems for the protection and repair of concrete structures – Test methods – Water absorption and resistance to alkali for hydrophobic impregnations
EN 13581	Products and systems for the protection and repair of concrete structures – Test methods – Determination of loss of mass of hydrophobic impregnated concrete after freeze-thaw salt stress
EN 13584	Products and systems for the protection and repair of concrete structures – Test methods – Determination of creep in compression for repair products
EN 13687-1	Products and systems for the protection and repair of concrete structures – Test methods – Determination of thermal compatibility – Part 1: Freeze-thaw cycling with de-icing salt immersion
EN 13687-2	Products and systems for the protection and repair of concrete structures – Test methods – Determination of thermal compatibility – Part 2: Thunder-shower cycling (thermal shock)
EN 13687-3	Products and systems for the protection and repair of concrete structures – Test methods – Determination of thermal compatibility – Part 3: Thermal cycling without de-icing salt impact
EN 13687-4	Products and systems for the protection and repair of concrete structures – Test methods – Determination of thermal compatibility – Part 4: Dry thermal cycling

EN 13687-5	Products and systems for the protection and repair of concrete structures – Test methods – Determination of thermal compatibility – Part 5: Resistance to temperature shock
EN 13733	Products and systems for the protection and repair of concrete structures – Test methods – Determination of the durability of structural bonding agents
EN 13894-1	Products and systems for the protection and repair of concrete structures – Test methods – Determination of fatigue under dynamic loading – Part 1: During cure
EN 13894-2	Products and systems for the protection and repair of concrete structures – Test methods – Determination of fatigue under dynamic loading – Part 2: After hardening
EN 14117	Products and systems for the protection and repair of concrete structures – Test methods – Determination of time of efflux of cementitious injection products
EN 14406	Products and systems for the protection and repair of concrete structures – Test methods – Determination of the expansion ratio and expansion evolution
EN 14487-1	Sprayed concrete – Part 1: Definitions, specifications and conformity
EN 14487-2	Sprayed concrete – Part 2: Execution
EN 14497	Products and systems for the protection and repair of concrete structures – Test methods – Determination of the filtration stability
EN 14498	Products and systems for the protection and repair of concrete structures – Test methods – Volume and weight changes of injection products after air drying and water storage cycles
EN 14629	Products and systems for the protection and repair of concrete structures – Test methods – Determination of chloride content in hardened concrete
EN 14630	Products and systems for the protection and repair of concrete structures – Test methods – Determination of carbonation depth in hardened concrete by the phenolphthalein method
EN 15183	Products and systems for the protection and repair of concrete structures – Test methods – Corrosion protection test
EN 15184	Products and systems for the protection and repair of concrete structures – Test methods – Shear adhesion of coated steel to concrete (pull-out test)