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Structural Rehabilitations with Ultra-High Performance Fibre Reinforced Concretes (UHPFRC)

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Abstract

The premature deterioration of reinforced concrete road structures is a heavy burden for society. In order to manage structures effectively and to reduce this burden to the minimum, the number and extent of interventions have to be kept to the lowest possible level. The extremely low permeability of Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) associated with their outstanding mechanical properties make them especially suitable to locally "harden" new or existing reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses. Composite UHPFRC-concrete structures provide a long-term durability, which helps avoid multiple interventions on structures during their service life. This paper gives an overview of the conceptual approach and first successful application of UHPFRC performed within the framework of the European project SAMARIS (Sustainable and Advanced MAterials for Road InfraStructures), for the rehabilitation of reinforced concrete structures.

Keywords: UHPFRC, rehabilitation, tensile strain hardening, restraint, composite construction

Strukturelle Instandsetzung von Betonbrücken mit Ultra-hochleistungsfähigem Faserfeinkornbeton (UHFB)

Zusammenfassung

Vorzeitige Schäden an Infrastrukturbauten aus Beton stellen aus volkswirtschaftlicher Sicht eine schwere Bürde für die Gesellschaft dar. Um Bauwerke effizient zu unterhalten und diese Bürde auf ein Minimum zu reduzieren, muss die Anzahl und das Ausmaß der Eingriffe so gering wie möglich gehalten werden. Die extrem niedrige Permeabilität von Ultrahochleistungsfähigem Faserfeinkornbetonen (UHFB) zusammen mit ihren herausragenden mechanischen Eigenschaften lassen sie für die lokale Ertüchtigung von kritischen Bereichen von bestehenden oder neuen Stahlbetonbauten, die einer aggressiven Umgebung und hohen mechanischen Einwirkungen ausgesetzt sind, besonders geeignet erscheinen. Verbundbauteile aus UHFB und Normalbeton versprechen eine lange Dauerhaftigkeit, die wiederkehrende Eingriffe an Bauwerken während der Nutzungsdauer vermeiden lässt. Der vorliegende Artikel gibt einen Überblick über den konzeptuellen Ansatz und über eine erste erfolgreiche Anwendung von UHFB, die im Rahmen des europäischen Projekts SAMARIS (Sustainable and Advanced MAterials for Road InfraStructures) für die Instandsetzung von Bauten aus Stahlbeton ausgeführt wurde.

Stichwörter: *UHFB, Instandsetzung, Verfestigung, Einspannung, Mischbauweise*

1 Introduction

Road networks are composed of a variety of structures, with a variety of sizes, geometries, local conditions, and ... common weak zones. In the very frequent case of deteriorations by chloride induced corrosion (exposure classes XD2 - direct contact, or XD3 splash zone), both the initiation time and the corrosion rate are mostly dependent on the availability of liquid water. Among all exposure cases, those where a direct contact with liquid water containing aggressive chemical substances is involved are the most severe for reinforced concrete, Fig. 1.

The premature deterioration of reinforced concrete structures is a heavy burden for our society. In order to manage structures effectively and to reduce this burden to the minimum, the number and extent of interventions have to be kept to the lowest possible level, with only preventative maintenance. However, too often, new structures have very limited durability or rehabilitations fail, and it is needed to "repair the repairs". Actually, usual reinforced concretes or mortars hardly can withstand exposure classes XD2 or XD3 for long periods of time.

Over the last 10 years, considerable efforts to improve the deformational behaviour of cementitious materials by incorporating fibres have led to the emergence of Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) characterized by a very low water/binder ratio and high fibre content. These new building materials provide the structural engineer with an unique combination of extremely low permeability, high strength and tensile strain hardening in the range of ductile metals (up to 0.2 % at localization), and excellent rheological properties in the fresh state.

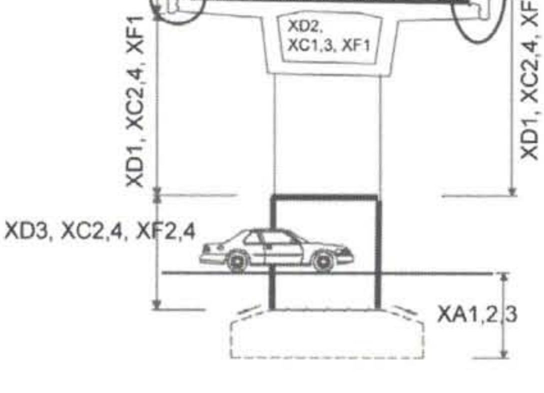

Figure 1: Exposure classes in highway structures and zones of most severe exposure (outlined).

UHPFRC are very well suited to locally "harden" reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses [1-4]. Composite UHPFRC-concrete structures promise a long-term durability, which helps avoid multiple interventions on structures during their service life. UHPFRC materials can be applied on new structures, or on existing ones for rehabilitation, as thin watertight overlays in replacement of waterproofing membranes, as reinforcement layers combined with reinforcement bars, or as prefabricated elements such as kerbs. However, the cost of these materials imposes to use them only where they are worth it and to take the maximum benefit of their outstanding mechanical properties with an optimum level of loading at service state.

The project SAMARIS (Sustainable and Advanced MAterials for Road InfraStructures) [5, 6] of the European Community dedicated a major effort to demonstrate the applicability and advantages of UHPFRC for the rehabilitation and improvement of structures. In this context an extensive research and development program was conducted to: (1) study the relevant fundamental properties of UHPFRC, (2) make a first step towards the optimization of these materials for various applications of rehabilitation, (3) provide guidelines for their use and their further optimization (conceptual design, numerical simulation tools, test methods, limit state criteria for design, compliance criteria), and (4) demonstrate their applicability on construction sites.

This paper gives an overview of the conceptual approach, and the first application of UHPFRC for the rehabilitation of reinforced concrete structures.

2 Conceptual Approach

2.1 Composite Construction

The successful rehabilitation of existing structures is a major challenge for civil engineers. When existing concrete needs to be replaced, a new composite structure formed of the new material cast on the existing substrate will result from the intervention, Fig. 2.

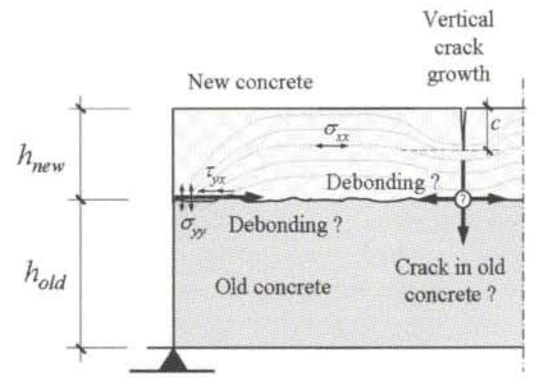

Figure 2: Composite system formed of a new concrete applied on an existing substrate, adapted after Bernard [7].

The performance of the composite system after the casting of the new layer on the existing substrate must be evaluated in terms of:

- Protective function of the new layer and its serviceability.
- Structural response (stiffness, load-carrying capacity and behaviour at ultimate limit state) of the composite member.

Fig. 3, shows the evolution of the performance of a typical composite structural member formed of a new layer cast on an existing substrate for two different materials: an advanced cementitious material (Strategy A), and a normal concrete (Strategy B). The limit states are fixed by the designer at each intervention and their severity increases with time and increasing demand. In both cases, more or less pronounced tensile eigenstresses due to restrained shrinkage deformations at early age and long term are induced in the new layer [7]. These eigenstresses constitute a net loss of the performance in terms of potential tensile capacity, shown by a faster drop of the performance on the curves in Fig. 3.

Further, under the influence of service loads and deterioration processes, the performance decreases with time.

- For strategy A; the choice of the rehabilitation technique is such that the performance decrease with time is very slow over the whole planned service life.
- For strategy B, the speed of performance drop requires several interventions during the service life of the structure.

These two strategies have very different consequences for end-users.

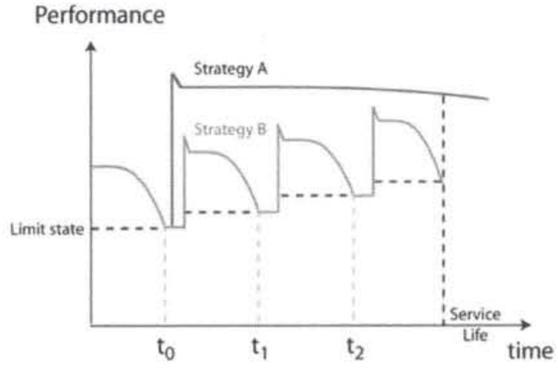

Figure 3: Evolution with time of the performance of composite structures (serviceability and load carrying capacity) and required limit states.

2.2 Strategies of Conservation

Fig. 4 presents the two different strategies of conservation from an end user's or owner's point of view. The traffic demand is continuously increasing in all cases. Strategy B usually induces during the planned service life of the structure, multiple periods of traffic disruptions, shown as shaded areas. Depending on the size of the structure and the extent of the interventions to be realised, these periods of traffic disruption can extend up to several years with dramatic consequences in terms of traffic disturbance, and end users and environmental costs. On the contrary, Strategy A aims at both: decreasing the time spent for the rehabilitation works, and increasing the durability to an extent that will make the rehabilitated structure fulfil all requirements of functionality, serviceability and resistance, for the planned service life, with only minor preventative maintenance. Strategy A is thus highly desirable.

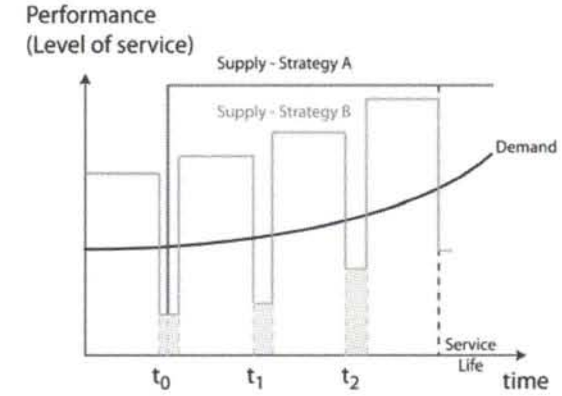

Figure 4: Evolution with time of the demand and supply for 2 conservation strategies.

3 UHPFRC Materials

3.1 Historical Perspective

Many attempts have been made to provide High Performance Cementitious Composites (HPFRCC) able to fulfil the requirements of strategy A, Fig. 3, with two different orientations:

(1) Focus on the optimization of the mechanical behaviour of the composite: decrease of the crack width by induction of finely distributed multiple cracking, to the largest extent, with no restrictions on the matrix properties, with Engineered Cementitious Composites - ECC, [8, 9] and Slurry infiltrated composites such as SIFCON, SIMCON, [10] or DUCON, [11].

Maalej and Li [12] and Li et al. [13], proposed to apply ECC to improve the durability of concrete structures, by limiting crack width. The water permeability of cracked ECC (despite cracks always smaller than 0.1 mm), is 2×10^{-10} m/s [14]. This value is low compared to cracked concretes but relatively high compared to uncracked normal concretes. According to Neville [15], the typical water permeability of a good concrete with $W/C = 0.45$ is around 10^{-12} m/s, whereas for a bad concrete ($W/C= 0.60$), it is 10^{-11} m/s. The diffusion coefficient of sound ECC is similar to concrete (with $W/C = 0.35$) for $RH < 65$ %; for $RH > 65$ %, the diffusion coefficient of ECC is higher than for concrete [16]. Attempts were made to modify the ECC composition with internal water repellent agents in order to improve durability [17].

The very high fibre content used in Slurry Infiltrated composites provides a very large deformability and significant strain hardening. However, the production process of these materials requires a very liquid matrix, which limits their density. Studies on chloride penetration into SIFCON showed that the corrosion rate is reduced compared to SFRC, but corrosion also occurs in non-damaged SIFCON elements, [18]. This can be attributed to the porosity of the SIFCON matrix and on possible shrinkage cracking at early age [19]. Slurries for SIFCON typically exhibit a water/binder ratio of 0.32 with a cement content of around 1000 kg/m^3 [19]. For such very high cement dosages, a water binder ratio of 0.36 does not imply a very low permeability.

More generally speaking, the water/binder ratio is too often taken alone as criteria for durability, which is obviously wrong. The water-binder ratio should always be considered together with the binder content to evaluate the likely durability of a cementitious material.

ECC and Slurry infiltrated materials exhibit a very high magnitude of tensile strain hardening up to several percent, and a capacity to develop finely distributed cracks of limited width under tension. These properties are very well adapted to the improvement of the mechanical performance of structures, for retrofit applications, to provide a dramatically increased energy dissipation capability. The limitation of the crack openings is also a very important factor to limit the ingress of detrimental substances through the cracks. In cracked state, ECC exhibit permeabilities significantly smaller than those of cracked concretes. However, the ECC matrix remains rather permeable compared to good concretes in uncraked state and to UHPFRC.

(2) Focus on the optimization of the matrix: decrease of the intrinsic permeability by optimization of the packing of grains and decrease of the water/binder ratio, de Larrard et al. [20] and subsequent optimization of the fibrous mix. UHPFRC are characterized by an ultra-compact matrix with an extremely low permeability [21] and by a high tensile strength (above 10 MPa) and tensile strain-hardening. They are part of the group of HPFRCC as described in Fig. 5, after Habel [22]. The very low water/binder ratio of UHPFRC (0.130 to 0.160) prevent the complete hydration of a major part of the cement and gives the material a significant hydrophilic behaviour, and a self healing capacity for microcracks [23,24]. In the fresh state, despite their very low water/binder ratio, UHPFRC can be tailored to be self-compacting and tolerate slopes up to 3 %.

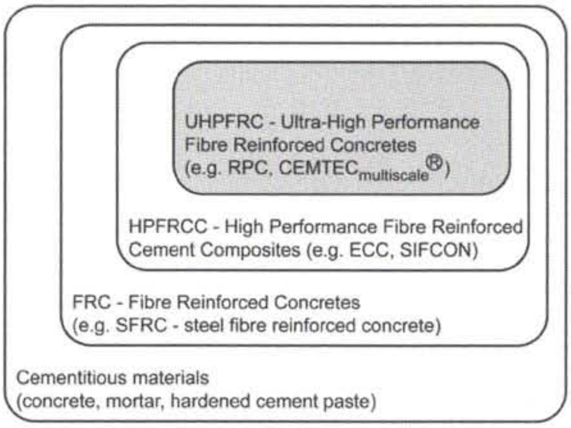

Figure 5: Classification of cementitious composites [22]

Various types of UHPFRC exist with different kinds of fibre mixes. With only one type of fibres, a compromise has to be found between the tensile behaviour pre and post peak, with limited strain hardening [25]. On the contrary, the combination of multiple types of fibres with different length, creates a multilevel reinforcement that induces significant tensile strain hardening (up to 0.2 %), and distributed cracking under tension [26-31].

In the context of the project SAMARIS, the UHPFRC of the family CEMTEC$_{\text{multiscale}}$®, developed at LCPC [26, 27] were chosen for their excellent properties at fresh state and significant tensile strain hardening, and further optimized for rehabilitation applications.

3.2 Tensile Behaviour of UHPFRC

The fibrous reinforcement necessary to obtain a strain hardening response in uniaxial tension can be compared to the necessary "minimum reinforcement" in reinforced concrete structures, to control cracking. It can be estimated by simple models such as proposed by Naaman [32].

The characterization of the tensile behaviour of cementitious materials has raised a lot of controversy regarding the most suitable testing systems: free or rigid ends, geometry of the specimens, etc.

Kanakubo [33] gives a very clear illustration of the effect of the stiffness of the supports of the testing set - up on the apparent response of different HPFRCC (ECC and UHPFRC). As expected, the free end systems tend to largely overestimate the tensile strain hardening domain of all materials (with a factor of up to 10 for the tested UHPFRC).

A tensile test is indeed already a structural test and one should be very cautious when comparing tensile test results between different authors, even for a similar material.

The aim of a tensile test is twofold: (1) characterize the tensile performance and (2) provide models for numerical simulation tools.

For the later case, the model needs to represent the mechanical response under tension without strain gradient. The closest way to reach this goal experimentally is with rigid fixed ends. Further, rigid fixed end setups tend to provide a lower bound of the possible strain hardening responses under tension.

It is the opinion of the authors that such systems are best adapted to characterize in a correct and reliable way the tensile strain hardening response of HPFRCC and UHPFRC in particular.

Finally, the tensile response of the material should be characterized on an unnotched specimen with an appropriate geometry to: (1) let strain hardening develop in a sufficiently long zone of constant cross section, (2) limit orientation effects of the fibres.

The uniaxial tensile behaviour of two different recipes of the UHPFRC CEMTEC$_{\text{multiscale}}$® type has been determined by means of a rigid fixed ends tensile test [21], on unnotched dogbone specimens (more details are given on the method in § 5.2) [34]. The average curves from five tests for each material are represented on Fig. 6, showing the range of possible strain hardening responses. Both recipes are self-compacting.

- Recipe CM0 is reinforced with a 468 kg/m^3 of a single type of 10 mm long steel fibres with an aspect ratio of 50. It has a water/binder ratio of 0.140, 1051 kg/m^3 cement, a fluid consistency (slump-flow = 700 mm) and is self-levelling.

- Recipe CM23 has more binder (1437 kg/m^3 cement) and a lower water-binder ratio (0.125). It is reinforced by a multilevel fibrous mix of macro steel fibres (10 mm long, aspect ratio 50) and microfibres (steel wool) with a total dosage of 705 kg/m^3. It can hold a slope of the substrate up to 2.5 %. The effect of the addition of microfibres is revealed on Fig. 6 by three aspects:

(1) the significant increase of the pseudo-elastic domain from 8 to above 11 MPa

(2) the increase of the strain hardening domain

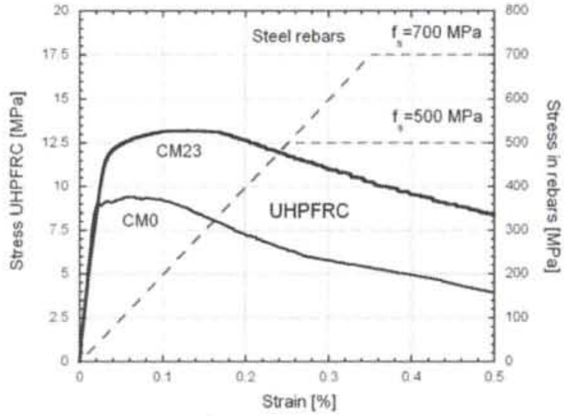

Figure 6: Tensile behaviour of two UHPFRC recipes, CEMTEC$_{\text{multiscale}}$®, unnotched tensile tests, fixed rigid boundary conditions, average curves at 28 days.

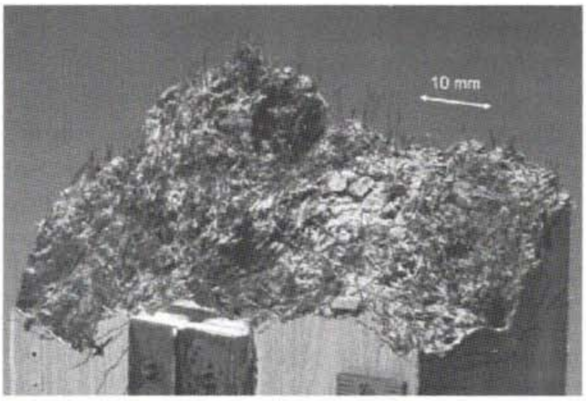

Figure 7: Fractured surface of a UHPFRC specimen, CEMTEC$_{\mathrm{multiscale}}$®, recipe CM23.

(3) the increase of the load carrying capacity in the descending branch due to the indirect action of the microfibres on the progressive pull-out of the macro fibres.

It is worth mentioning that the magnitude of strain hardening of UHPFRC such as CEMTEC$_{\mathrm{multiscale}}$® falls into the range of the yield strain of construction steel, Fig. 6. This property opens up very promising domains of combination of UHPFRC with reinforcement bars with high yield strength (700 MPa or above).

The fractured surface of a UHPFRC specimen after a tensile test shows numerous steel fibres, pulled out from the matrix, Fig. 7.

The work of pull-out of these numerous micro-reinforcements explains the extremely high specific work of fracture of UHPFRC (up to 30'000 J/m^2 compared to 200 J/m^2 for normal concrete).

A significant part of the work of fracture of UHPFRC is dissipated in the bulk of the material, during the strain hardening phase, in the form of finely distributed, multiple cracks.

A closer examination of the fractured surface of a UHPFRC specimen, Fig. 7, reveals that most of the protruding fibres exhibit a free length superior or equal to the half original fibre length. This clearly indicates that the fracture process of UHPFRC, even in the post peak domain is not similar to two separating planes but rather the progressive decomposition of a zone of finite width with intense multiple cracking at the micro and macro levels.

Finally, one should always keep in mind that the mechanical response of fibrous composites such as UHPFRC is very much application dependent. Strong anisotropy effects can be induced by the casting procedure of the materials or the width and shape of the moulds and these effects have to be considered for the analysis of test results and for design [35-36].

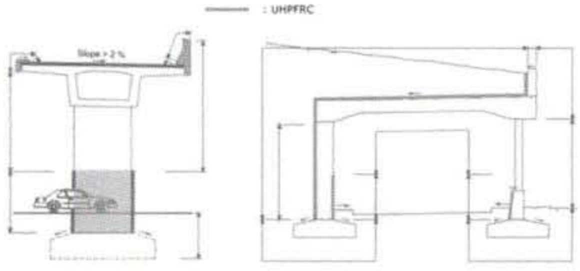

Figure 8: Concept of application of the local "hardening" of bridge superstructures with UHPFRC.

4 Concept of Application

4.1 Overview

The concept of application of UHPFRC for the rehabilitation of structural members is schematically illustrated on Fig. 8. An "everlasting winter coat" is applied on the bridge superstructure in zones of severe environmental and mechanical loads (exposure classes XD2, XD3).

Critical steps of the construction process such as application of waterproofing membranes or compaction by vibration can be prevented, and the associated sources of errors avoided. The construction process becomes then simpler, quicker, and more robust, with an optimal use of composite construction.

The waterproofing capabilities of the UHPFRC exempt from applying a waterproofing membrane. Thus, the bituminous concrete can be applied after only 8 days of moist curing of the UHPFRC.

This constitutes a very significant time saving with respect to the drying period of up to 3 weeks necessary prior to the application of a waterproofing membrane on a usual mortar or concrete.

Further, the thickness of the bituminous concrete layer can be limited to the absolute minimum necessary for the traffic loads. It is unnecessary to increase it to apply weight on the waterproofing membrane to prevent the formation of air pockets.

When it is required, the combination of the protective properties and deformation capability of UHPFRC with the mechanical performance of reinforcement bars (normal or high grade) provides a

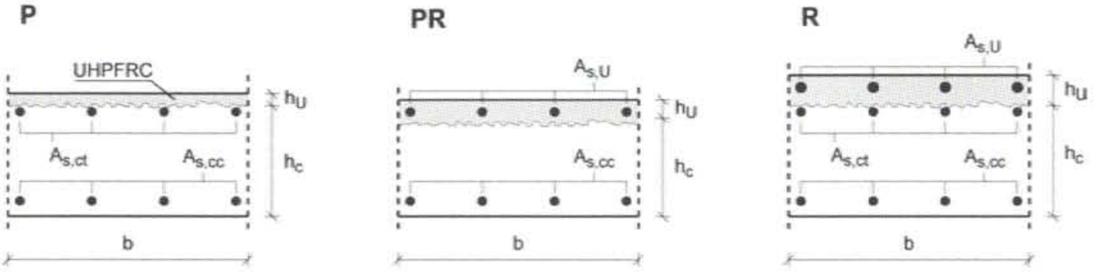

Figure 9: Geometries of "UHPFRC-concrete" elements for bridge deck slabs [22].

simple and efficient way of increasing the stiffness and load-carrying capacity with compact cross sections [22, 1-3, 37] Fig. 9.

This new construction technique is specially well-suited for bridges but can also be implemented for galleries, tunnels, retaining walls, following the same approach.

4.2 Validation

A well established principle for the application of a rehabilitation layer on an existing substrate is to try as far as possible to select a new material with mechanical properties close to those of the substrate. With this respect, UHPFRC with an elastic modulus in the range of 50000 MPa might appear to be a bad choice. This argument is however wrong for several reasons:

-First of all, in the elastic domain, the elastic modulus of UHPFRC is around 40 % larger than that of normal concretes (48'000/35'000 MPa = 1.37). This difference is however largely compensated by the improved tensile strength of the UHPFRC (10 MPa for the matrix and up to 14 MPa for the composite compared to 3 to 4 MPa for normal concretes).

-Secondly, UHPFRC exhibit a significant strain hardening, several times larger than its maximum elastic elongation, which is not the case for normal concrete.

-Thirdly, UHPFRC exhibit significant viscoelasticity at early age, comparable to high performance concretes [22]. Restrained shrinkage tests on UHPFRC specimens at an early age show that the development of stresses under incremental full restraint remain moderate (45 % of the tensile first crack strength) with respect to the uniaxial tensile characteristics of the UHPFRC tested [38-40].

- Finally, the ultimate shrinkage of UHPFRC is not higher than that of usual concretes ($\leq$ 600 µm/m = 0.6 ‰ at 6 month) and represents only around the half of the magnitude of hardening of these materials. The driving force for this shrinkage is however different. In UHPFRC, with a very low water/binder ratio, drying shrinkage is negligible after 8 days of moist curing and the main source of deformations is autogenous shrinkage [27, 38-40].

A comprehensive series of tests in the laboratory on composite UHPFRC-concrete structural members have successfully validated this concept for various geometries, and boundary conditions, at various scales from small specimens to full scale structural members, with various degrees of restraint, with or without reinforcement bars in the UHPFRC layer, [22, 41, 42]. Detailed information and examples of design of composite UHPFRC-concrete bridge deck slabs with or without reinforcement bars can be found in [22].

Comparative air and water permeability tests were performed between CEMTEC$_{\text{multiscale}}$® and concrete, on tensile specimens and on composite structural elements. The outstanding protective properties of the CEMTEC$_{\text{multiscale}}$®, without any thermal treatment, towards ingress of aggressive substances were confirmed by air permeability tests after Torrent [43-45]. Water and Glycol permeability tests [23, 24] at various levels of tensile deformation confirmed this trend and revealed the acute hydrophilic behaviour of CEMTEC$_{\text{multiscale}}$®. For an equivalent crack opening of 0.1 mm (strain of 0.1 % over 100 mm), the permeability of CEMTEC$_{\text{multiscale}}$® to glycol was 4 x 10^{-11} m/s and to water 2 x 10^{-12} m/s, compared to 2 x 10^{-10} for ECC with similar crack openings [14] and 10^{-12} m/s for a concrete with a water cement ratio of 0.45, according to Neville [15].

Strain hardening UHPFRC turn out to be an excellent compromise of density, high tensile strength, and significant deformation capability, perfectly suited for combination with normal concretes, in existing or new structures, following Strategy A, Figure 3.

5 First Application

5.1 Concept of Intervention

With the support of the Road Administration of the Swiss Canton Wallis, and under the guidance of MCS-EPFL, the bridge over the river la Morge, in Chateauneuf/Conthey (490 m above sea level), nearby Sion, Wallis, in the Swiss Alps, has been rehabilitated and widened by using Ultra High Performance Fibre Reinforced Concretes (UHPFRC) [46, 47].

It was indeed the very first time that UHPFRC of the CEMTEC$_{\text{multiscale}}$® family, originally developed at LCPC, in Paris [26, 27], and specially tailored for this application at MCS, were cast in-situ, and applied for the rehabilitation of a bridge.

The entire surface of the bridge with a span of 10 m was improved in three steps during autumn 2004, Fig. 10.

- Firstly, the downstream kerb was replaced by a new prefabricated UHPFRC kerb on a new reinforced concrete beam.
- Secondly, the chloride contaminated concrete of the upper surface of the bridge deck was replaced by 3 cm of CEMTEC$_{\text{multiscale}}$®, on October 22, 2004 for the first lane and November 5, 2004 for the second lane.
- Finally, the concrete surface of the upstream kerb was replaced with 3 cm of CEMTEC$_{\text{multiscale}}$® on November 9, 2004.

The UHPFRC was applied without reinforcement bars on the bridge deck and on the upstream kerb. Only constructive reinforcement bars were used for the prefabricated downstream kerb.

The significant traffic on the bridge required permanent circulation on one lane during construction works. As a consequence, the watertight UHPFRC overlay on the bridge deck had to be cast in two steps at 10 days interval. A longitudinal construction joint was specially designed to guarantee the transmission of tensile forces between the two layers of UHPFRC, on the two lanes, and prevent through cracking at the joint. This system was successfully applied.

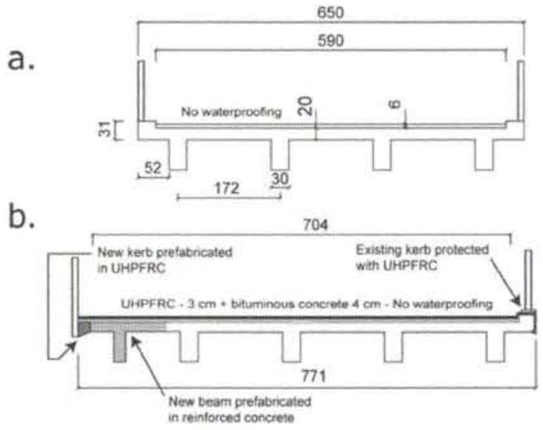

Figure 10: Cross section of the bridge, a., before, and b., after, the rehabilitation (dimensions in cm).

5.2 UHPFRC Composition

Two different recipes of the UHPFRC CEMTEC$_{\text{multiscale}}$® were used, with similar components (Cement CEM I 52.5, Microsilica, fine sand D_{max}= 0.5 mm), with a Microsilica/Cement ratio of 0.26. The reinforcement of the ultra compact matrices was provided by a mix of micro (steel wool – 1 mm length) and macrofibres (l_f=10 mm, aspect ratio: 50) with a total dosage of 706 kg/m^3 (9 % vol.).

Recipe CM22 (1410 kg/m^3 cement, Water/Binder ratio of 0.131) had been optimized in the laboratory for its tolerance to a slope of 2.5 %, and used for laboratory tests on structural members. As expected, the size effect on the volume of the batches from laboratory (40 litres) to production plant (300 litres) increased the workability for a similar composition. Thus, the recipe optimized in the lab, on small batches turned out to be too liquid for tolerating a slope but well adapted to rehabilitate the upstream kerb. A new recipe, CM23, was designed with 1434 kg/m^3 cement, and a lower Water/Binder ratio of 0.125 to guarantee a tolerance to a slope of 2.5 %. This material was used for the prefabricated downstream kerb and for the watertight overlays on the bridge deck.

Preliminary large scale tests performed at the prefabrication plant on a 3 m long and 1 m wide inclined platform with a rough substrate confirmed that mix CM23 was able to tolerate a slope of the substrate of 2.5 %. *This property was not used in the project as the existing concrete surface of the bridge deck turned out to be almost horizontal, but is essential for future applications of rehabilitation.*

5.3 Processing and Application on Site

The UHPFRC was prepared at a local concrete prefabrication plant with a standard mixer of 750 litres capacity, Fig. 11. Three batches of 300 litres each were produced consecutively, stored in a concrete truck and brought to the site. The material was then poured directly from the truck and ap-

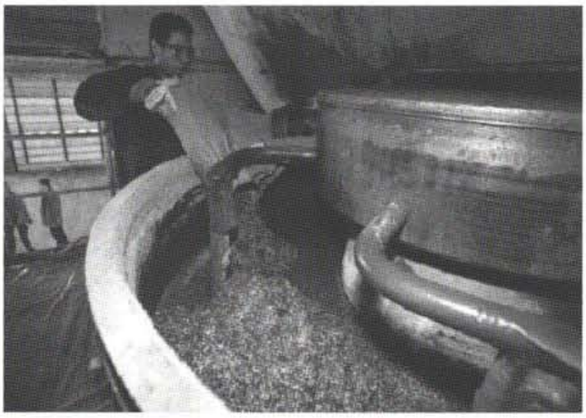

Figure 11: Fabrication of the UHPFRC (adding of the steel fibres) in a standard mixer, at the ready mix plant (Photo A. Herzog).

Figure 12: Overall view of the UHPFRC pouring on the bridge deck slab (Photo A. Herzog).

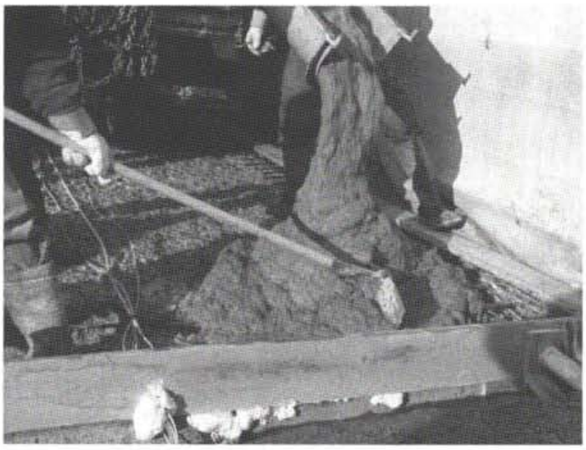

Figure 13: Pouring of the UHPFRC (Photo A. Herzog)

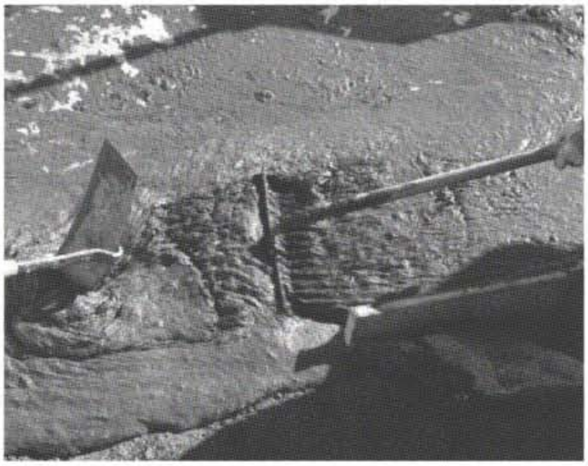

Figure 14: The thixotropic, selfcompacting UHPFRC, is handled using simple tools (Photo A. Herzog)

plied on the hydrojetted bridge deck, with no vibration. The CEMTEC$_{\text{multiscale}}$® was easy to produce and place with standard tools, Fig. 12 to 14 and very robust and tolerant to the unavoidable uncertainties of the site.

The bituminous pavement was applied on a bituminous emulsion, on the UHPFRC surfaces, after 8 days of moist curing, and the corresponding lane was reopened to traffic the next day. The bridge was fully reopened to traffic one month after the beginning of the construction work.

5.4 Properties of the UHPFRC

5.4.1 Protective function

Air permeability tests after the Torrent method [43, 44, 45] were performed on site, before the application of the bituminous pavement. These tests confirmed the extremely low permeability kT of the material cast on the bridge (kT=0.004 .10^{-16} m^2 on average, compared to 0.050 – 0.15 10^{-16} m^2 for good concretes), Fig. 15.

For each material, three sets of data are represented: individual measurements with their histogram, normalized Lognormal distribution fitted to the experimental data (all frequencies are divided by the maximum frequency), and median with lower and upper bounds of fractiles of resp. 25 and 75 %. No significant differences could be observed between the various elements (overlay on deck, prefabricated kerb and overlay on existing kerb).

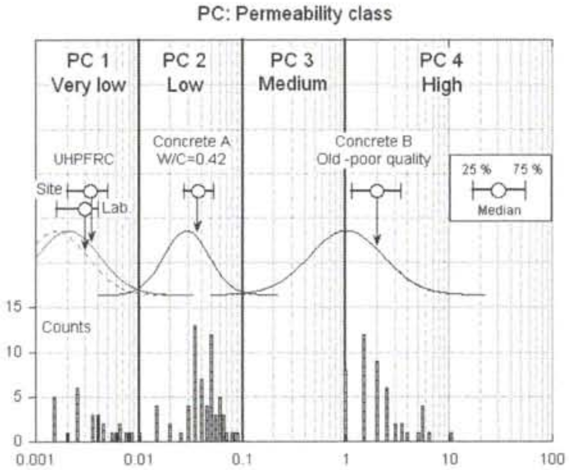

Figure 15: Air permeability tests (Torrent method). Comparative tests between concretes, and UHPFRC, cast in the laboratory and on site.

5.4.2 Mechanical Performance

The average compressive strength/modulus of elasticity of mix CM23 at 28 days were 182/46800 MPa.

Uniaxial tensile tests Fig. 16, performed at 28 days in the laboratory [34], on unnotched dogbone specimens (l = 70 cm, minimum cross section: 50 x 100 mm) cast on site with the material CM23, delivered, as expected, remarkable average properties: maximum tensile strength of 14 MPa and a maximum deformation in the strain-hardening domain of 1.5 ‰, Fig. 17, 18.

Multiple macrocracking was observed on the specimens, in the tensile hardening domain, Fig. 19, with a spacing of 5 to 7 cm.

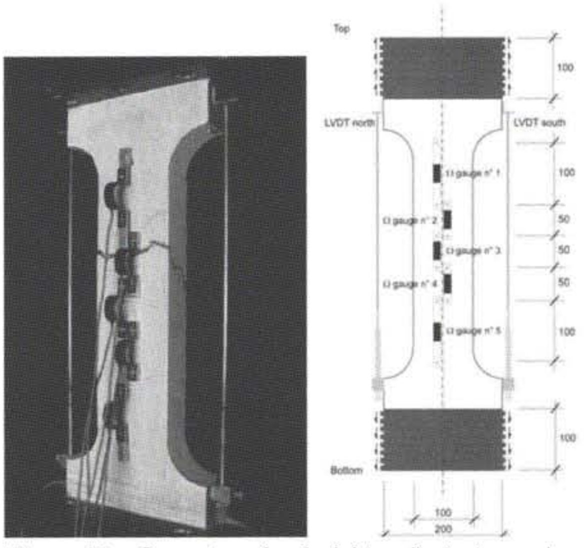

Figure 16: Geometry of uniaxial tensile tests on dogbone specimens [34].

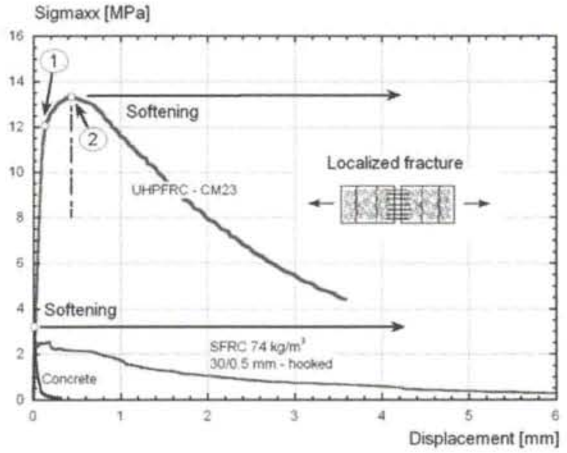

Figure 17: Uniaxial tensile tests on dogbone specimens from material CM23, cast on site, tested at 28 days. Comparison of average curve of UHPFRC with other materials.

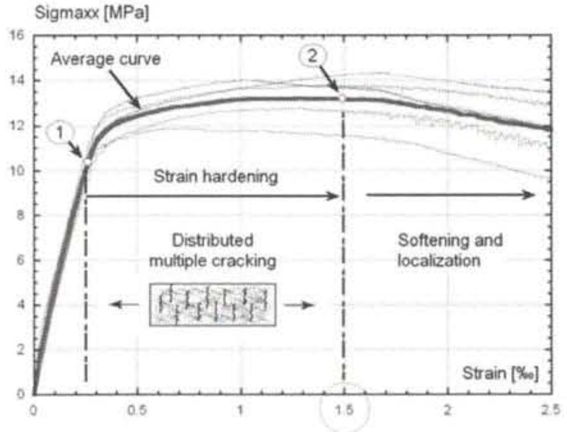

Figure 18: Uniaxial tensile tests on 5 dogbone specimens from material CM23, cast on site, test at 28 days. Average curve and scatter in hardening domain.

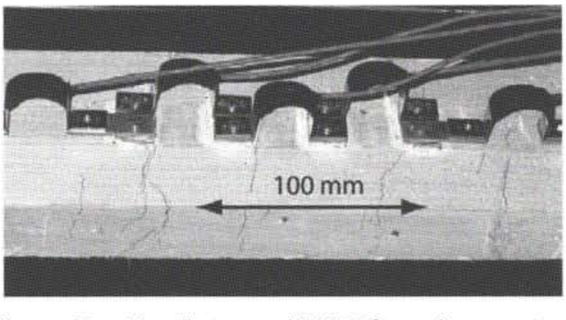

Figure 19: Tensile test on UHPFRC specimen cast on site, recipe CM23, multiple fine cracks during the strain hardening phase.

5.5 Follow-up of the Project

The analysis of the construction costs showed that the rehabilitation realised with UHPFRC was 12 % more expensive that a more traditional solution with waterproofing membrane and rehabilitation mortar (providing lower quality in terms of durability and life-cycle costs). However, in the latter case the duration of the site would have been largely increased by the drying period of the rehabilitation mortar, prior to the application of the waterproofing membrane (up to 3 weeks).

Further, assuming a price drop of 30 % for the raw components of the UHPFRC, the intervention with UHPFRC becomes only 7 % more expensive than the traditional method with mortar and waterproofing membrane. Such a price drop can be expected if the use of UHPFRC spreads.

Moreover, the small scale of the bridge used for this application and its character of prototype tend to overestimate the costs of UHPFRC.

It can thus be expected that with a wider dissemination of UHPFRC for the rehabilitation of bridges, this technique will become cheaper than traditional ones, not to mention its outstanding advantages of long term durability and reduction of traffic disruptions (and subsequent user costs) due to multiple interventions.

This full scale realization in realistic site conditions clearly demonstrates that the technology of UHPFRC is now mature for cast in-situ applications of rehabilitation, or on new structures, using standard equipment. Among the major advantages set forth by the bridge owner one can mention the ease of processing and the significant time savings on the duration of construction sites, while remaining in the same cost range.

Fig. 20 shows the bridge in November 2004, after the rehabilitation and widening.

After one winter season, an inspection of the bridge showed expected corrosion spots on the exposed surfaces of the kerbs with very significant differences depending on the type of formwork used, as shown on Fig. 21 and 22. The downstream prefabricated kerb, cast in the plant in a metal formwork, showed the most regular colour markings of corrosion. The UHPFRC overlay cast on site on the upstream kerb with a wood formwork, locally compacted by means of hammer blows applied on the formwork, showed few random surface corrosion spots. Finally, the apparent faces of the UHPFRC overlay cast on site with a wood formwork showed no significant signs of surface corrosion, Fig. 22.

Figure 20: The bridge in November 2004, after rehabilitation and widening.

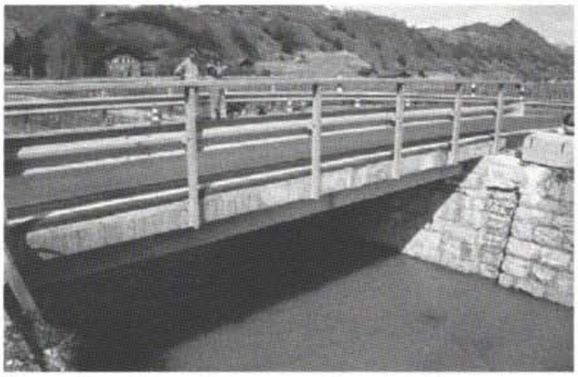

Figure 21: View of the rehabilitated bridge after one winter season.

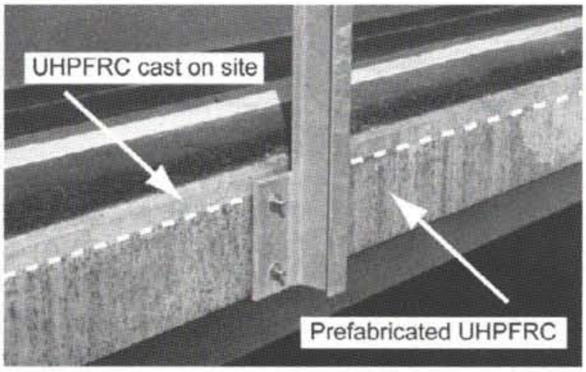

Figure 22: View of a kerb showing a slight change in colour due to corrosion of the steel fibre tips close to the surface.

Although a purely superficial and aesthetical concern, it is desirable to mitigate to the largest extent these surface markings. Further research is ongoing on this topic.

A comprehensive description of this first application of UHPFRC can be found in [47].

6 Conclusions and Outlook

- A novel concept of structural rehabilitations with Ultra High Performance Fibre Reinforced Concretes is proposed to simplify the construction process, increase the durability of structures and their mechanical performance (stiffness and resistance), and decrease the number of interventions during their service life.
- This concept has been validated technically and scientifically by numerous laboratory tests on composite structural members with configurations representing to various practical applications.
- A first on-site application of this concept has been successfully realized and validated and the required properties of the UHPFRC were achieved with a local contractor with its standard equipment.
- The construction cost of the proposed technique was not significantly higher than for traditional solutions providing lower quality, and the duration of the construction works and closing of traffic lanes could be largely reduced, to the greatest satisfaction of the bridge owner.

Further research and development efforts are in progress to optimize this new technology for wide-spread application.

Among the most relevant topics to be investigated in the near future, one can mention:

- effect of the conditions and geometry of application on the tensile response of UHPFRC in structural members,
- optimization of UHPFRC recipes to tolerate slopes up to 7 %,
- optimization of the combination of UHPFRC with high grade reinforcement bars,
- optimization of the surface preparation (roughness) of the substrate,
- development of details with UHPFRC such as severely exposed zones in dilation joints or bearings,
- design and test methods, compliance criteria,
- guidelines for the design of strain hardening UHPFRC recipes from local components.

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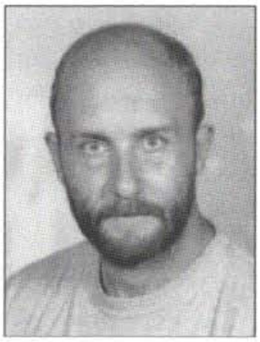

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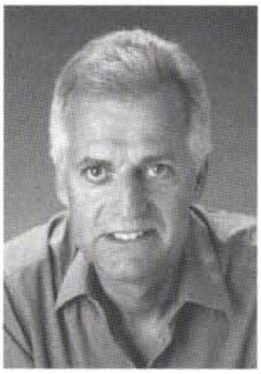

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