Competitive and Sustainable Growth (GROWTH) Programme

SAMARIS

Sustainable and Advanced MAterials for Road InfraStructure

WP 14: HPFRCC (High Performance Fibre Reinforced Cementitious Composites) for rehabilitation

Deliverable D22

Full scale application of UHPFRC for the rehabilitation of bridges – *from the lab to the field*

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ABSTRACT

The premature deterioration of reinforced concrete 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" reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses. 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. This document gives an overview of the conceptual approach, and provides detailed informations on the first application performed during the European project SAMARIS (Sustainable and Advanced MAterials for Road InfraStructures), in view of the application of UHPFRC for the rehabilitation of reinforced concrete structures.

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FOREWORD AND ACKNOWLEDGEMENTS

This report is the fourth of a series covering all aspects necessary to the implementation of UHPFRC (Ultra High Performance Fibre Reinforced Concretes) for the rehabilitation of reinforced concrete structures, within the framework of work package (WP) 14 "HPFRCC for rehabilitation" of project SAMARIS. The other reports are:

- D13 - Report on preliminary studies for the use of HPFRCC for the rehabilitation of road infrastructure components
- D18a and D18b - Report on tests of UHPFRC in the laboratory, parts a. and b.
- D25b – Guidelines for the use of UHPFRC for rehabilitation of concrete highway structures
- D26 - Modelling of UHPFRC in composite structures
- D31 - Guidelines on selection of innovative techniques for the rehabilitation of concrete highway structures.

Contributors to WP 14 are: MCS-EPFL (contractor and WP leader), LCPC – Dr. P. Rossi (contractor), and TRL – Dr. R. Woodward (contractor).

The original concept of application of UHPFRC for the rehabilitation of reinforced concrete structures was proposed at MCS, by Prof. Dr. E. Brühwiler, in 1999.

The researchers and technicians who contributed to these works at MCS-EPFL under the lead of Dr. E. Denarié (WP 14 leader) and Prof. Dr. E. Brühwiler (Director of MCS-EPFL) are:

- John Wuest (civil Engineer EPFL, doctoral student at MCS-EPFL).
- Aicha Kamen (civil engineer, doctoral student at MCS-EPFL).
- Dr. Katrin Habel (former collaborator of MCS-EPFL)
- Prof. Dr. Jean-Philippe Charron (former collaborator of MCS-EPFL)
- Roland Gysler (technician)
- Sylvain Demierre (electrical engineer)

The support of the road administration of the Swiss Canton Wallis to the first application of UHPFRC is gratefully acknowledged.

Finally, Dr. Pierre Rossi of LCPC-France, inventor of CEMTEC$_{\text{multiscale}}^{®}$ and worldwide known expert of Fibre Reinforced Concretes, proposed the original UHPFRC recipes used in this study and the concepts for their tailoring to the specific applications of rehabilitation.

Lausanne, October 7, 2005 Dr. Emmanuel Denarié

EXECUTIVE SUMMARY

1. INTRODUCTION

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. 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" reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses. 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. This document gives an overview of the conceptual approach, and first application performed during the European project SAMARIS (Sustainable and Advanced MAterials for Road InfraStructures), in view of the application of UHPFRC for the rehabilitation of reinforced concrete structures.

2. CONCEPTUAL APPROACH

The successful rehabilitation of existing structures is a major challenge for civil engineers. When the 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. 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.

Figure 1 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 user 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.

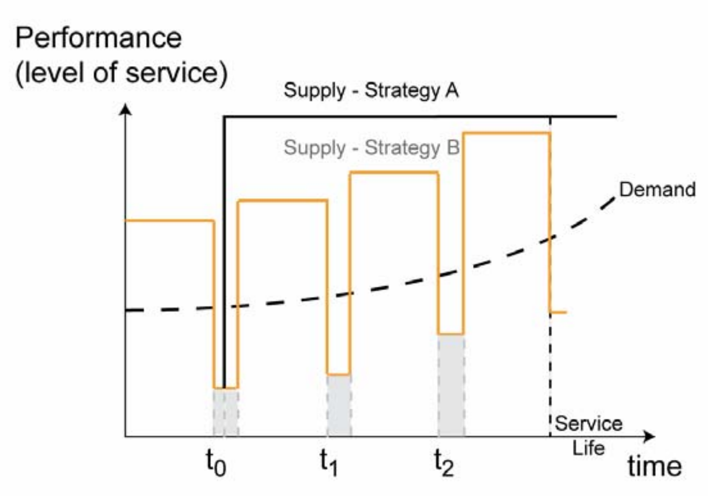

Figure 1: Evolution with time of the demand and supply for 2 conservation strategies.

3. UHPFRC MATERIALS

UHPFRC are characterised by an ultra-compact matrix with an extremely low permeability, Roux et al. (1995), and by a high tensile strength (above 10 MPa) and tensile strain-hardening, Figure 2. The very low water/binder ratio of UHPFRC (0.130 to 0.160) prevents 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, Charron et al (2005). In the fresh state, despite their very low water/binder ratio, UHPFRC can be tailored to be self-compacting. In the context of the project SAMARIS, the UHPFRC family CEMTEC$_{\text{multiscale}}$®, developed at LCPC, Rossi et al. (2002), Boulay et al. (2003) was used and optimised for rehabilitation applications.

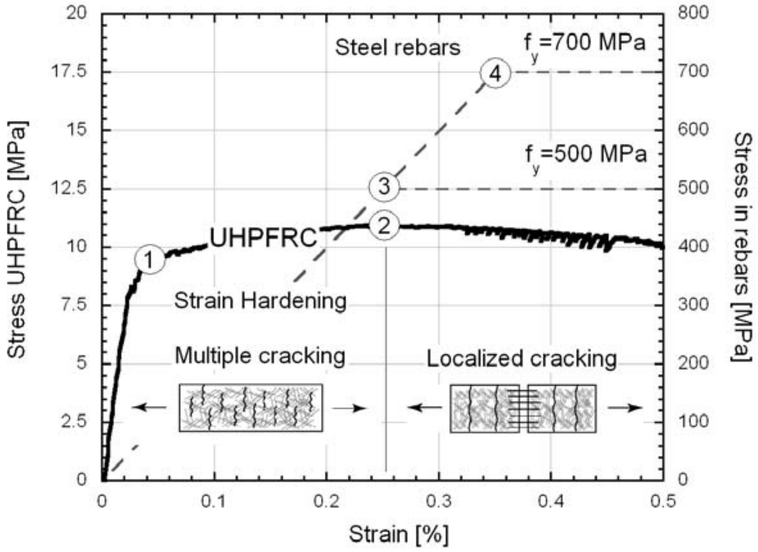

Figure 2: Tensile behaviour of UHPFRC, CEMTEC$_{\text{multiscale}}$®, adapted from Charron et al. (2004).

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 1.

4. CONCEPT OF APPLICATION

The concept of application of UHPFRC for the rehabilitation of structural members is schematically illustrated in Figure 3, Brüwhiler et al. (2004), (2005a, 2005b). An "everlasting winter coat" is applied on the bridge superstructure in zones of severe environmental and mechanical loads.

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.

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, with various degrees of restraint, with or without reinforcement bars in the UHPFRC layer, Habel (2004), SAMARIS D18a (2005), SAMARIS D18b (2005).

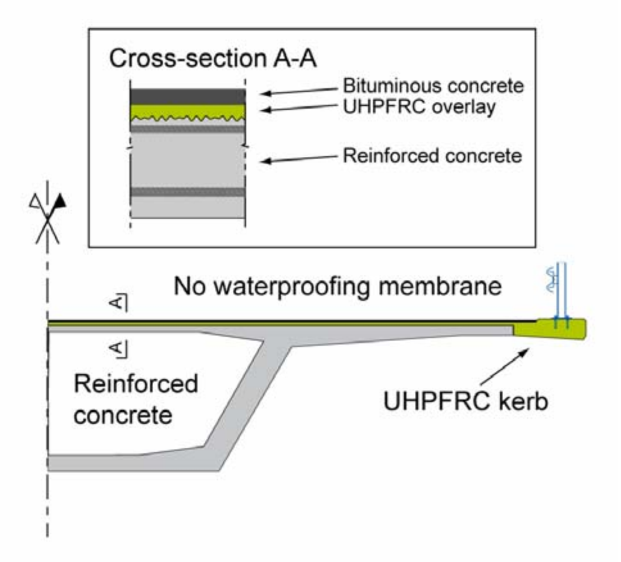

Figure 3: Concept of application of the local "hardening" of bridge superstructures with UHPFRC.

5. FIRST APPLICATION

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, nearby Sion, has been rehabilitated and widened in an unusual way by using Ultra High Performance Fibre Reinforced Concretes (UHPFRC). It was indeed the very first time that UHPFRC of the CEMTEC$_{\text{multiscale}}$$^{®}$ family, originally developed at LCPC, and specially tailored for this application at MCS, were cast in-situ, for the rehabilitation of a bridge. The entire surface of the bridge with a span of 10 m was improved in three steps during the autumn 2004, Figure 4.

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 $\mathrm{CEMTEC}_{\mathrm{multiscale}}^{®}$, on October 22 for the first lane and November 5, for the second lane. Finally, the concrete surface of the upstream kerb was replaced with 3 cm of $\mathrm{CEMTEC}_{\mathrm{multiscale}}^{®}$ on November 9. All works went perfectly well as planned. The $\mathrm{CEMTEC}_{\mathrm{multiscale}}^{®}$ was easy to produce and place, Figure 5, and very robust and tolerant to the unavoidable uncertainties of the site. Air permeability tests performed after 4 days, on site, confirmed the extremely low permeability of the material cast on the bridge. Uniaxial tensile tests performed at 28 days in the laboratory, on specimens cast with the materials used on site, exhibited remarkable average properties: maximum tensile strength of 14 MPa and a maximum deformation in the strain-hardening domain of 0.15 %.

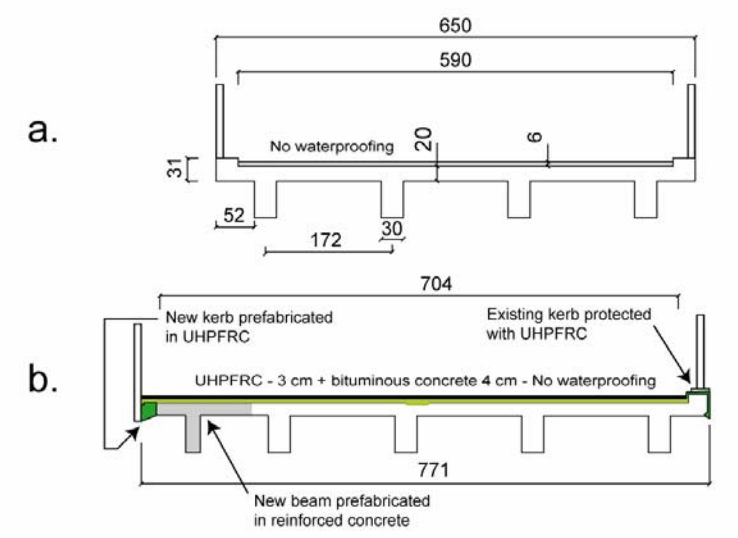

Figure 4: Cross section of the bridge, a, before, and b., after, the rehabilitation (dimensions in cm).

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 just one month after the beginning of the construction work.

Besides the intrinsic benefits associated to the outstanding properties of UHPFRC, this innovative rehabilitation technique simplifies the construction process, saving money and reducing time of intervention. Thanks to the extremely low permeability of the UHPFRC, no waterproofing membrane is needed, the fresh material is self-compacting, and the thickness of the bituminous concrete can be reduced to a minimum.

This full scale realisation in realistic site conditions clearly demonstrates that the technology of UHPFRC is now mature for cast in-situ applications of rehabilitation, using standard equipments.

a. b.

Figure 5: a. Overall view of the UHPFRC works, b. Pouring of the UHPFRC (Photos A. Herzog).

6. CONCLUSIONS AND OUTLOOK

- A new concept of structural rehabilitations with Ultra High Performance Fibre Reinforced Concretes has been 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 by numerous laboratory tests on composite structural members with configurations corresponding to various practical applications.

- A first application of this concept has been successfully realised and the required properties of the UHPFRC were achieved with standard equipments, and verified in-situ.

- The construction costs of the proposed technique were not significantly higher than more traditional solutions, 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 now needed and ongoing to optimise this new construction technique and spread it on a wider basis. 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, optimisation of UHPFRC recipes to tolerate slopes up to 7 %, optimisation of the combination of UHPFRC with high grade reinforcement bars, optimisation of the surface preparation (roughness) of the substrate, design and test methods, compliance criteria and guidelines for the design of strain hardening UHPFRC recipes from local components.

1 INTRODUCTION

Industrialised countries have invested heavily in the construction of reinforced concrete structures. In addition to the mechanical actions for which they are primarily designed, these structures are constantly subjected to physico-chemical phenomena that can result in their deterioration and subsequent reduction in their reliability to perform adequately. 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.

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) characterised 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 yield strain of steel (up to 0.2 % at localisation), and excellent rheological properties in the fresh state.

UHPFRC are very well suited to locally "harden" reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses, Brühwiler et al. (2004), (2005). 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 use 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), Denarié et al. (2004), Znidaric et al. (2004), of the European Community dedicates 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 programme is conducted to (1) study the relevant fundamental properties of UHPFRC, (2) make a first step towards the optimisation of these materials for various applications of rehabilitation, (3) provide guidelines for their use and their further optimisation (conceptual design, numerical simulation tools, test methods, limit state criteria for design, compliance criteria), and (4) demonstrate their applicability by means of application on sites.

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

2 BACKGROUND

2.1 Conceptual approach

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, Figure 1.

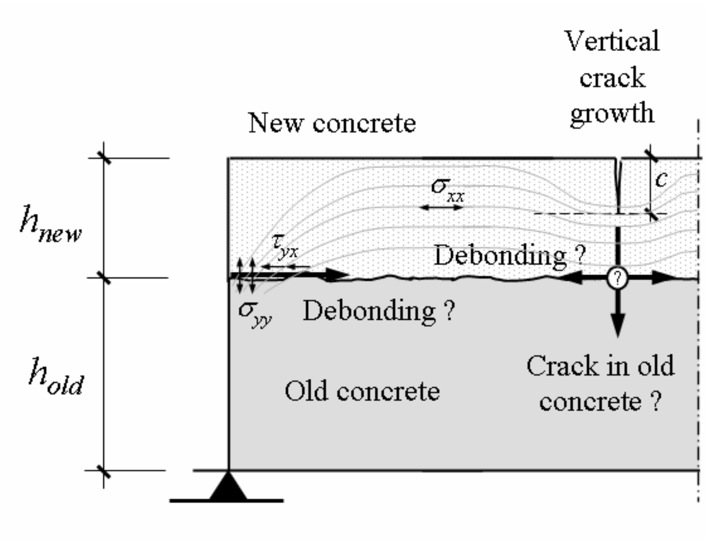

Figure 1: Composite system formed of a new concrete applied on an existing substrate, adapted from Bernard (2000).

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.

Figure 2 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, Bernard (2000). 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. Under the influence of 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.

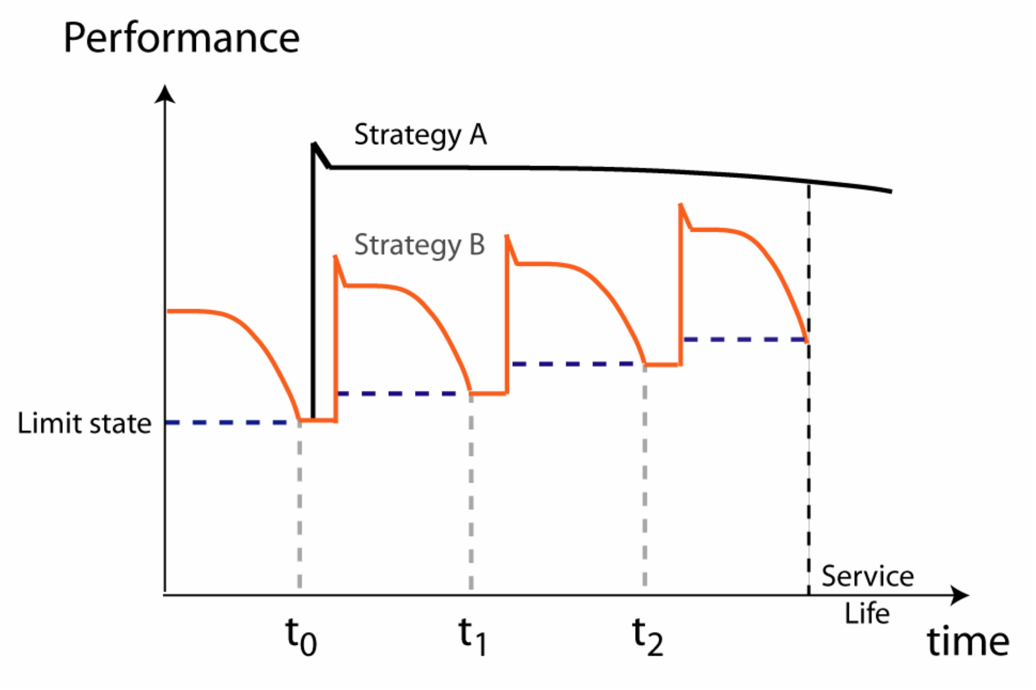

Figure 2: **Evolution with time of the performance of composite structures (serviceability and load carrying capacity) and required limit states.**

Figure 3 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.

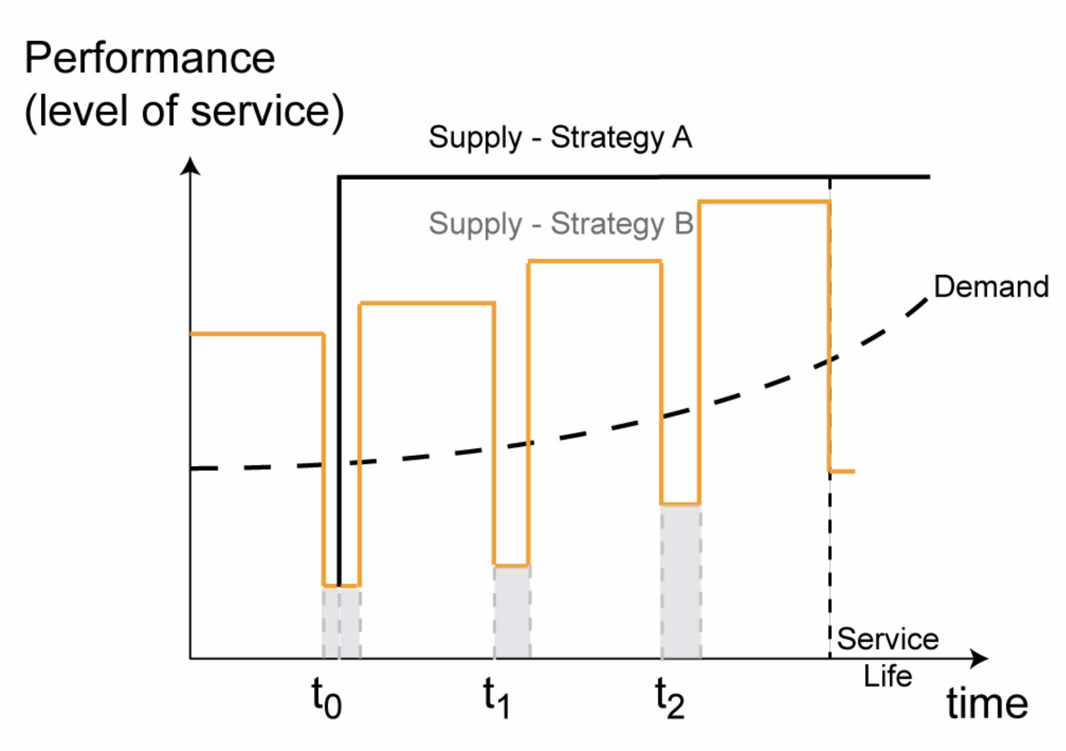

Figure 3: **Evolution with time of the demand and supply for 2 conservation strategies.**

2.2 UHPFRC materials

2.2.1 Historical development

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

(1) Focus on the optimisation 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, Li et al. (1992), Li (1993), and Slurry infiltrated composites such as SIFCON, SIMCON, Zeng et al. (2000) or DUCON, Hauser et al. (1999).

Maalej and Li (1995), 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 x 10^{-10} m/s after Lepech et al. (2005). This value is relatively high compared to normal concretes. According to Neville (1997), the typical water permeability of a good concrete with W/C = 0.40 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, Li et al. (2003). Attempts were made to modify the ECC composition with internal water repellent agents in order to guarantee durability, Martinola (2002).

The very high fibre content used in Slurry Infiltrated composites provides a very large deform-ability 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, Kosa (1991). This can be attributed to the porosity of the SIFCON matrix and on possible shrinkage cracking at early age, Lemberg (1996).

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. However, on the basis of existing research, it has not yet been demonstrated that these materials provide a protective function compliant with Strategy A of Figure 3.

(2) Focus on the protective function of the matrix with UHPFRC: decrease of the intrinsic permeability by optimisation of the packing of grains and decrease of the water/binder ratio, de Larrard et al. (1994), and subsequent optimisation of the fibrous mix. UHPFRC are characterised by an ultra-compact matrix with an extremely low permeability, Roux et al. (1995), and by a high tensile strength (above 10 MPa) and tensile strain-hardening. They are part of the group of HPFRCC as described in Figure 4, after Habel (2004). 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, Charron et al (2005). In the fresh state, despite their very low water/binder ratio, UHPFRC can be tailored to be self-compacting.

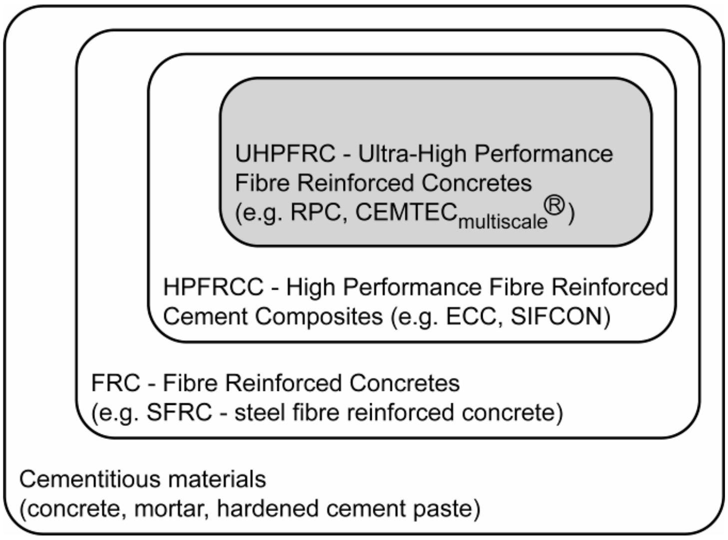

Figure 4: Classification of cementitious composites, after Habel (2004).

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, Rossi (2000). On the contrary, the combination of multiple types of fibres with different length, Rossi et al. (2002), Parant (2003), creates a multi-level reinforcement that induces significant tensile strain hardening (up to 0.2 %), and multiple crack-

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ing under tension. In the context of the project SAMARIS, the UHPFRC family CEMTEC$_{multiscale}$®, developed at LCPC, Rossi et al. (2002), Boulay et al. (2003) was used and optimised for rehabilitation applications.

It is worth mentioning that the magnitude of strain hardening of UHPFRC, such as CEMTEC$_{multiscale}$®, falls into the range of the yield strain of construction steel, Figure 5. This property opens up very promising domains of combination of UHPFRC with reinforcement bars with high yield strength (700 MPa or above).

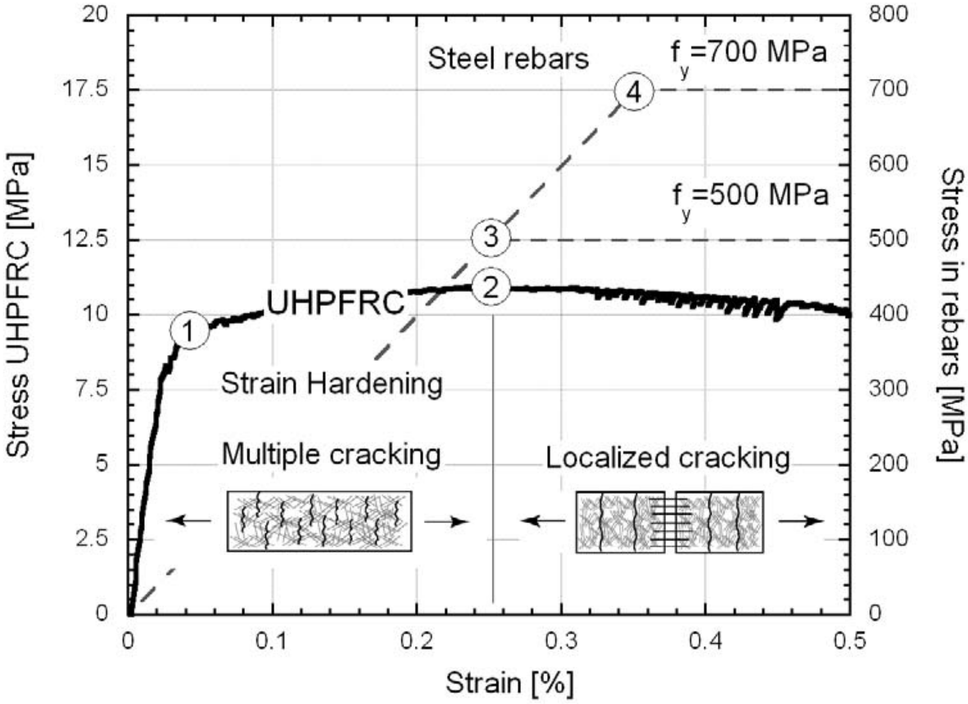

Figure 5: **Tensile behaviour of UHPFRC, CEMTEC$_{multiscale}$®, adapted from Charron et al. (2004).**

2.2.2 Protective function of UHPFRC

Comparative air and water permeability tests were performed between CEMTEC$_{multiscale}$® and concrete, on tensile specimens and on composite structural members, in laboratory and on-site. The outstanding protective properties of the CEMTEC$_{multiscale}$®, without any thermal treatment, towards ingress of aggressive substances were confirmed by air permeability tests after Torrent et al. (1992). Water and Glycol permeability tests by Charron et al. (2004), (2005) at various levels of tensile deformation confirmed this trend and revealed the acute hydrophilic behaviour of CEMTEC$_{multiscale}$®. For an equivalent crack opening of 0.1 mm (strain of 0.1 % over 100 mm), the permeability of CEMTEC$_{multiscale}$® 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, Lepech et al. (2005), and 10^{-12} m/s for a concrete with a water cement ratio of 0.45, according to Neville (1997).

2.2.3 Suitability for rehabilitation

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 a high elastic modulus up to 55000 MPa might appear to be a bad choice. *This argument is however wrong for several reasons:*

- First of all, in the elastic domain, the difference in elastic modulus of the UHPFRC with respect to normal concretes (on average 50000/35000 MPa) is largely compensated by the improved tensile strength of the UHPFRC (10 MPa for the matrix and up to 14 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.
- Finally, UHPFRC exhibit significant viscoelasticity at early age, comparable to usual concretes, Habel (2004). Restrained shrinkage tests on UHPFRC specimens at an early age show that the development of stresses under full restraint remain moderate (45 % of the tensile first crack strength) with respect to the uniaxial tensile characteristics of the UHPFRC tested, Kamen et al. (2005).

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.

2.3 Concept of application

The concept of application of UHPFRC for the rehabilitation of structural members is schematically illustrated on Figure 6, Brüwhiler et al. (2004), (2005a, 2005b). An "everlasting winter coat" is applied on the bridge superstructure in zones of severe environmental and mechanical loads.

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.

This new construction technique is specially well-suited for bridges but can also be implemented for galleries, tunnels, retaining walls, following the same philosophy. Further, 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 simple and efficient way of increasing the stiffness and load-carrying capacity with compact cross sections, Habel (2004), Brühwiler et al. (2004), Wuest et al. (2005).

A comprehensive series of laboratory tests on composite UHPFRC-concrete structural members have successfully validated this concept for various geometries and boundary conditions, with various degrees of restraint, with or without reinforcement bars in the UHPFRC layer, Habel (2004), SAMARIS D18a (2005), SAMARIS D18b (2005).

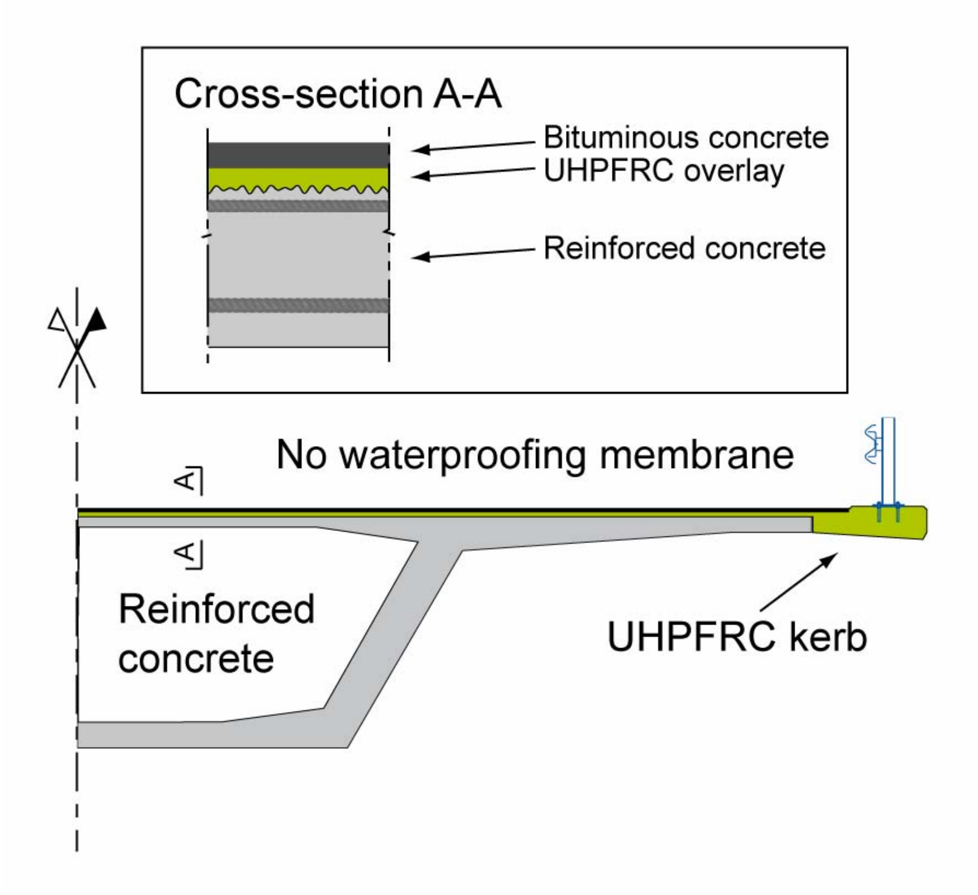

Figure 6: **Concept of application of the local "hardening" of bridge superstructures with UHPFRC.**

3 FIRST APPLICATION

3.1 Introduction

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, Figure 7, has been rehabilitated and widened by using Ultra High Performance Fibre Reinforced Concretes (UHPFRC).

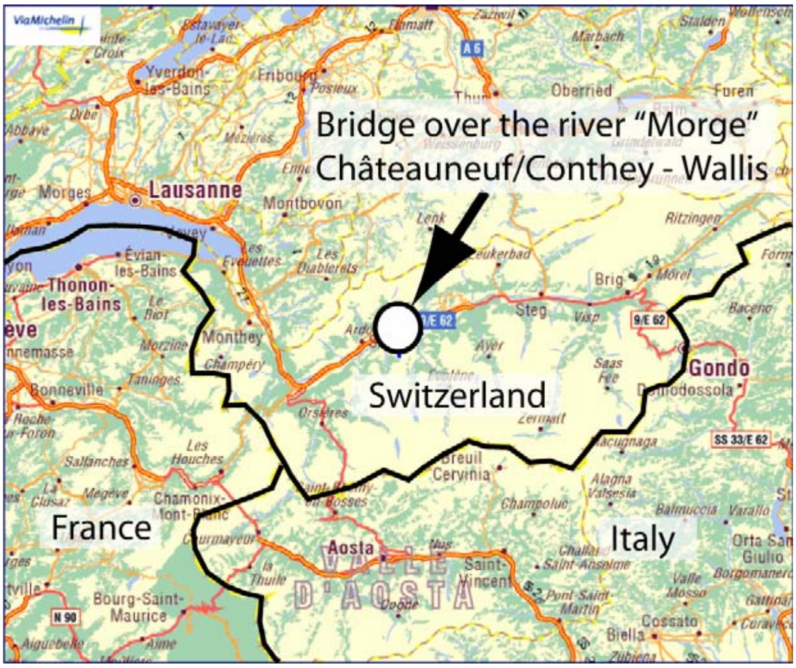

Figure 7: Geographical location of the bridge.

It was indeed the very first time that UHPFRC of the CEMTEC$_{\text{multiscale}}$® family, originally developed at LCPC in Paris, Rossi et al. (2002), and specially tailored for this application at MCS, were cast in-situ and applied for the rehabilitation of a bridge.

The date of construction of the bridge is unknown. Taking into consideration its design, geometry and condition, it is assumed to be from the period between 1940 and 1950. The bridge deck had no waterproofing membrane and the kerbs were severely damaged by chloride induced corrosion, as shown on Figure 8.

Figure 8: Bridge over river "La Morge", before the rehabilitation: a. overview, b. downstream kerb, c. upstream kerb.

3.2 Concept of the intervention

The entire surface of the bridge with a span of 10 m was improved in 3 steps during autumn 2004, using UHPFRC of the CEMTEC$_{\text{multiscale}}$® family (the two recipes used, named CM22 and CM23, are described in § 4.3).

- Firstly, the downstream kerb was replaced by a new prefabricated UHPFRC kerb on a new reinforced concrete beam, which enabled the widening of the bridge (Step A).
- 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 (Step B) and November 5, 2004, for the second lane (Step C), thus creating a continuous UHPFRC overlay on the whole surface of the bridge deck.
- Finally, the concrete surface of the upstream kerb was replaced with 3 cm of UHPFRC on November 9, 2004 (Step D).

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.

Figure 9 presents the transverse cross section of the bridge before and after the rehabilitation and widening.

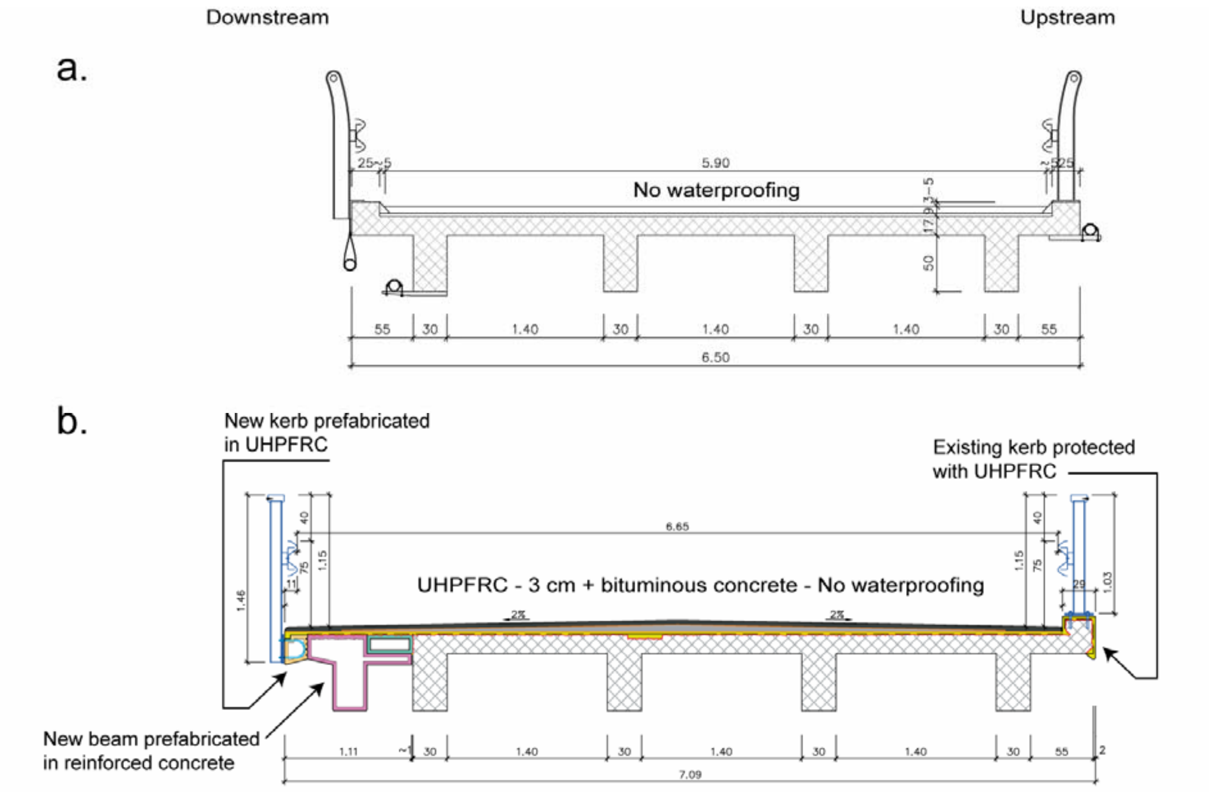

Figure 9: Cross section of the bridge, a, before, and b. after, the rehabilitation (dimensions in cm).

The sequence of operations was:

1. Casting of prefabricated UHPFRC kerb.
2. Casting of prefabricated reinforced concrete beam.
3. Closure of downstream lane.
4. Removal of existing downstream curb.
5. Installation of new prefabricated UHPFRC kerb and reinforced concrete beam.
6. Connection to existing structure with concrete cast on site.
7. Hydrojetting of bridge deck downstream.
8. Casting of UHPFRC on first lane (downstream).
9. Application of bituminous emulsion on UHPFRC and bituminous pavement on first lane.
10. Reopening to traffic of downstream lane.
11. Closure of upstream lane.
12. Hydrojetting of bridge deck and kerb upstream.
13. Casting of UHPFRC layer on second lane (upstream).
14. Rehabilitation of upstream kerb with UHPFRC.
15. Application of bituminous emulsion on UHPFRC and bituminous pavement on second lane.
16. Reopening to traffic of second lane- full reopening to traffic.

Figure 10 and Figure 11 show the principle of the intervention for both sides of the bridge. More detailed execution plans are given in Appendix 1.

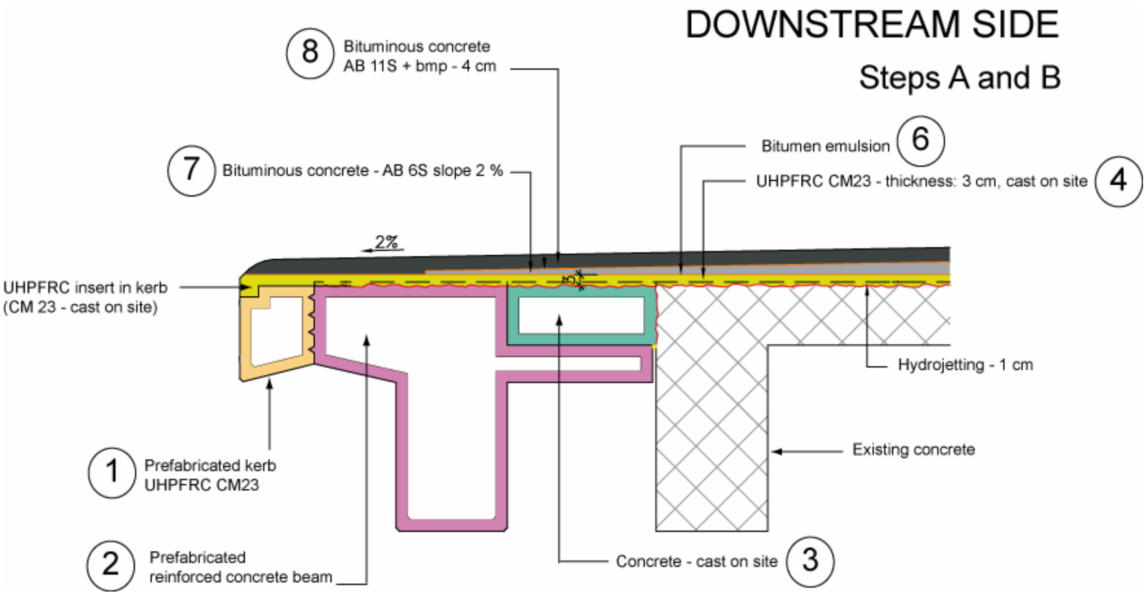

Figure 10: Principle of the intervention, downstream side.

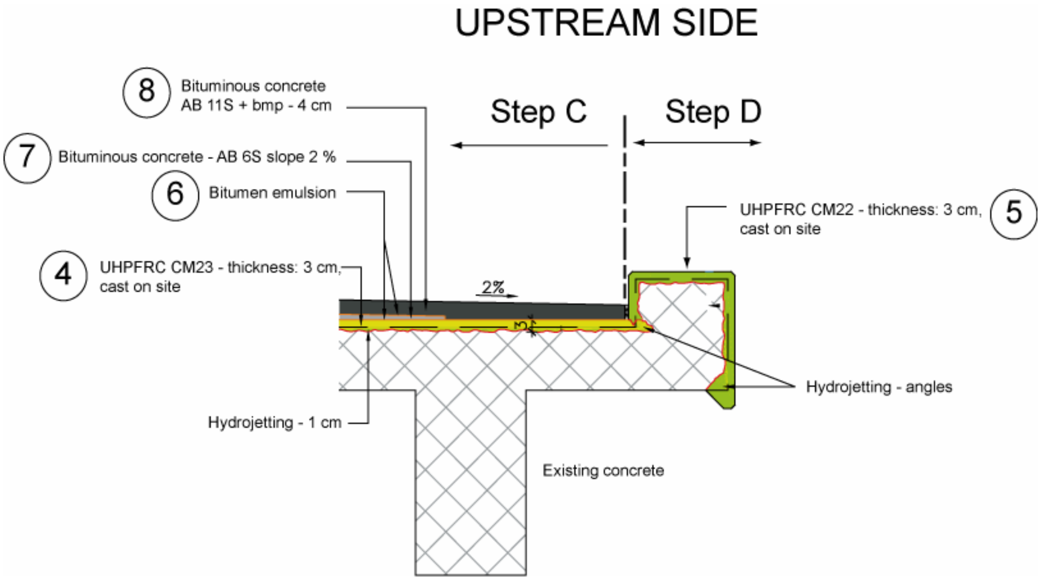

Figure 11: **Principle of the intervention, upstream side.**

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 (by means of reinforcement bars), on the two lanes, and prevent through cracking at the joint (by means of a stepwise geometry), Figure 12. This system was successfully applied.

The surface of the bridge deck, after removal of the old bituminous pavement, turned out to be almost horizontal. Two solutions were possible to provide a transversal slope to the new pavement after the rehabilitation (to evacuate rainfall water): either cast an inclined UHPFRC layer with a constant thickness of bituminous concrete, or cast a constant thickness of UHPFRC and have an inclined bituminous pavement. In the first case, the UHPFRC layer in the middle of the bridge would be 9 cm thick which is much more than necessary given the protective properties of this material. *As a consequence, the second solution was selected to respect the conceptual approach of use of the UHPFRC only were it is worth it.* According to usual practice in Switzerland, two layers of bituminous concrete were cast. The main course (with coarser aggregates) had a slope of 2 %. The wearing course had a constant thickness of 4 cm. The bonding of the bituminous concrete to the UHPFRC layer was improved by spraying a bituminous emulsion[1], prior to the application of the bituminous pavement. More details on the performances of various techniques for the connection of UHPFRC and bituminous concrete can be found in Lavoc (2004).

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[1] WEBACID ®- Spezial CR 60 P, from CTW MUTTENZ - http://www.ctwmuttenz.ch/index.cfm

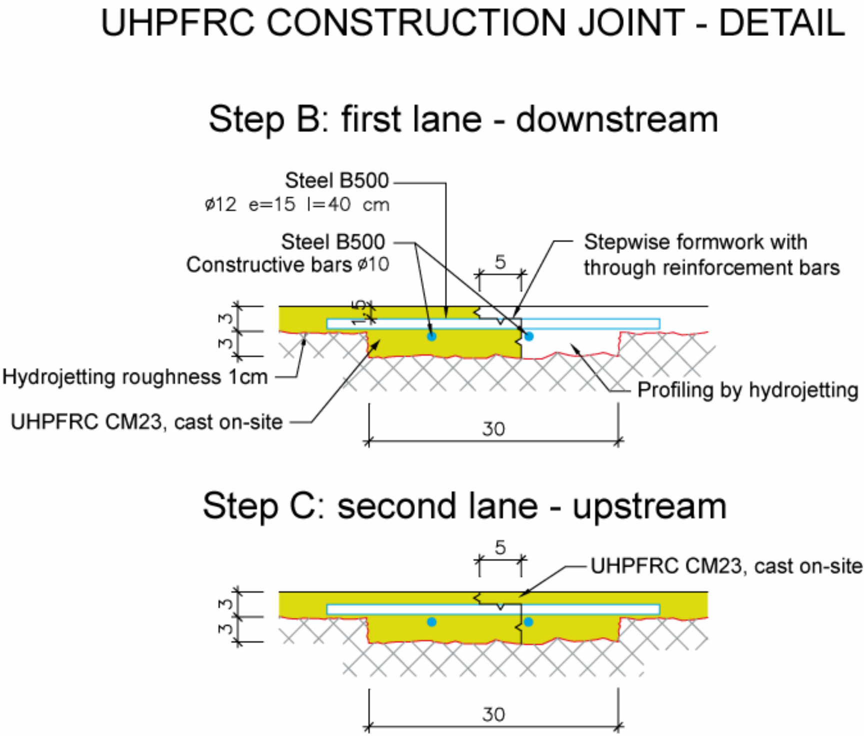

Figure 12: Construction joint for the UHPFRC of the bridge deck.

3.3 UHPFRC composition and production

Two different recipes of the UHPFRC CEMTEC$_{multiscale}$® 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 (lf=10 mm, aspect ratio: 50) with a total dosage of 706 kg/m^3 (9% vol.). The detailed recipes and origins of the components are given in Appendix 1.

Recipe CM22 (1410 kg/m^3 cement, Water/Binder ratio of 0.131) had been optimised 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 optimised 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, less fluid, CM23, was designed with a lower Water/Binder ratio of 0.125 and 1434 kg/m^3 cement, 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 (3 cm layer) was able to tolerate a slope of the substrate of 2.2 %. *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.*

The UHPFRC was prepared at a concrete prefabrication plant with a standard mixer of 750 litres capacity (technical data sheet in Appendix 4), Figure 9. The mixer turned out to be well adapted to the production of the UHPFRC. The average mixing time of all components was 8 minutes. No segregation of the matrix or fibres occurred.

Figure 13: Fabrication of the UHPFRC (adding of the steel fibres) in a common mixer of the prefabrication plant (Photo A. Herzog).

3.4 Prefabrication of UHPFRC kerb segments

The prefabricated kerb was cast in two segments with a connection joint made of producing reinforcement bars (extreme right of Figure 14, and Figure 15a). Preliminary laboratory tests on the bonding between UHPFRC and reinforcement bars had given an average necessary anchorage length of minimum *10 diameters* for B500 steel under tension[2]. The connection of the segments was realised on site during the application of the UHPFRC on the downstream part of the bridge deck, with UHPFRC CM23. Reinforcement bars were inserted on the side of the kerb to provide sufficient mechanical connection with the prefabricated reinforced concrete beam, subsequently cast in the plant. Detailed plans of execution are provided in Appendix 1, Figure 39 to Figure 44.

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[2] Following the experiences gathered on other laboratory tests since this first application, the authors of this report would recommend to use 15 diameters for the anchoring length of B500 profiled steel reinforcement bars in UHPFRC zones under tension.

Figure 14: Prefabricated UHPFRC kerb segment.

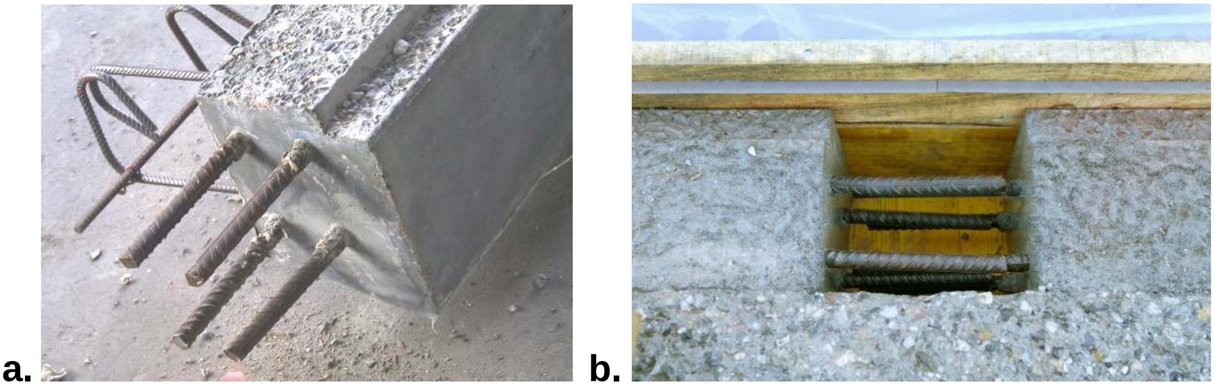

Figure 15: a. detail of connection, b. segments ready for casting of connection, on site.

The UHPFRC kerb connected to the new prefabricated reinforced concrete beam were geometrically designed to be covered by the cast on site UHPFRC to avoid any discontinuity of the protective function. In order to guarantee a good bonding of the cast-on-site UHPFRC layer on the UHPFRC kerb and new reinforced concrete beam, a rough profile had to be given to the upper surface of these two members. The reinforced concrete beam could be hydrojetted on site at the same time as the existing concrete of the bridge deck. However, due to the lack of coarse aggregates, hydrojetting of the UHPFRC would not provide a sufficiently rough surface. In order to solve this issue, the top surfaces of the kerb segments were cast against washed concrete plates, with a demoulding agent, in order to give them a rough surface (Figure 14, and Figure 15a), to guarantee a good bonding with the UHPFRC layer cast on site, on top of them. Further, in order to prevent debonding of the cast-on site UHPFRC layers in the zones of maximum shear stresses due to restrained deformations, an insert was realised on the external side of the prefabricated UHPFRC kerb segments (Figure 10, Figure 14, and Figure 15a).

No thermal treatment was applied on the kerb segments and a moist curing was applied for 7 days. The UHPFRC kerb segments were then used as formwork element for the casting of the new prefabricated reinforced concrete beam.

3.5 Optimisation of processing for on site application

The workability of mix CM23 was tested over 76 minutes with slump flow tests repeated on the same batch, at 30 minutes intervals (17 minutes after mixing, 49 minutes, and 76 minutes. The material was stored in a bucket, protected from desiccation, and stirred before the test. *The average value of the slump flow was 450 mm, with no significant loss over 75 minutes, and the material was self-compacting. One must note that compared to usual self-compacting concretes, UHPFRC with very high fibre contents, such as the ones used in this study, tend to have lower values of slump flow, despite their clear self compacting character.*

The transport of the fresh UHPFRC to the site was realised with a concrete truck. In order to have sufficient filling of the truck, it was decide to prepare consecutively 3 batches of 300 litres (maximum quantity that could be produced in the mixer), store them in the truck and leave for the site with 900 litres UHPFRC. The duration of this step was around 30 minutes. The amount of the lost UHPFRC in the truck drum was initially estimated to be around 200 litres. This quantity finally turned out to be much smaller and negligible. The drum was not pre-wetted before being filled with the UHPFRC and was not rotated during transport to prevent segregation of the fibres. Once on the site, the drum was briefly rotated to stir the UHPFRC which was then poured directly onto the bridge deck. Total duration of production of three batches of 300 litres of UHPFRC and transport to the site was 45 minutes.

3.6 Application on site

The material was poured directly from the truck and applied on the hydrojetted bridge deck, with no vibration. The bituminous pavement was applied on a bituminous emulsion, on the UHPFRC surfaces, after 8 days of moist curing[3], and the corresponding lane was reopened to traffic the next day. The CEMTEC$_{\text{multiscale}}$® was easy to produce and place with standard tools, Figure 17, 18, 19, and very robust and tolerant to the unavoidable uncertainties of the site. As an example, the last step of the works (rehabilitation of upstream kerb) was realized with low temperature conditions (around 2°C during the day), with only passive protection of the kerb (insulating mat). However, the UHPFRC did not suffer from these severe curing conditions[4], as demonstrated by various comparative measurements (compressive strength and air permeability) on site and on samples stored in the lab and on site. Of course, lower curing temperatures induce an increased setting delay, which should be taken into consideration for formwork removal time.

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[3] This moist curing is particularly important as the UHPFRC exhibits a very significant self desiccation at early age, due to its very high binder content and very low water/binder ratio. Only around 30 % of the cement grains will actually be fully hydrated at long term for such UHPFRC recipes. The unhydrated cement grains play two useful roles: (1) filler and (2) potential reactive binder for the self-healing of microcracks.

[4] The very low water/binder ratio of the UHPFRC is again here an advantage in case of casting by low temperatures, for several reasons: (1) all the water is immediately captured by cement grains in fresh state so that there is no free water prone to freezing, (2) the concentration in cement and silica fume of the liquid phase in the fresh mix is very high, which significantly decreases its freezing point.

It is worth mentioning that the quantity of UHPFRC components foreseen for the application, including preliminary tests was precisely estimated. At the end of the site, only around 100 litres of the 6.1 m^3 were left.

The bridge was fully reopened to traffic just one month after the beginning of the construction work.

Figure 16: Overall view of the UHPFRC works (Photo A. Herzog).

Figure 17: Pouring of the UHPFRC (Photo A. Herzog).

Figure 18: **The thixotropic, selfcompacting UHPFRC, is handled using simple tools (Photo A. Herzog).**

The temperature in the hardened UHPFRC layer was not monitored on site during the application of the bituminous pavement. This was however done during preliminary tests in the laboratory in a 2 cm thick UHPFRC plate with an embedded thermocouple at mid-thickness, Figure 19. The maximum temperature in the centre of the UHPFRC layer was 73 °C, for a temperature of the bituminous concrete of 155 °C. This elevation of temperature, equivalent to the one endured by normal concretes in similar conditions of application, has most probably no adverse consequences on the UHPFRC.

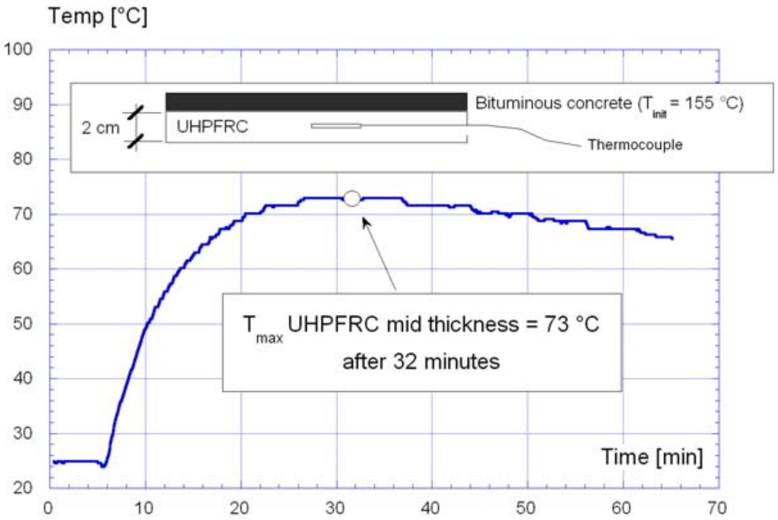

Figure 19: **Temperature in the centre of a UHPFRC layer of 2 cm, after application of a bituminous concrete with a temperature of 155 °C, laboratory tests, Lavoc (2004).**

3.7 Properties of the UHPFRC

3.7.1 Temperature evolution at early age and heat of hydration

Figure 20 presents the evolution with time of the temperatures measured in two different configurations, on UHPFRC CM22, in the laboratory: on an insulated cylinder of 16/32 cm (T – SA) and on a prism of 10 x 5 cm^2 cross section in ambient conditions at around 20 °C (T – FS). In the T – SA conditions, the temperature increase of the UHPFRC is very important (maximum value at 35 hours of 53 °C), which is two times higher than for a normal concretes in similar conditions. However, for the geometry corresponding to a layer of 5 cm thickness in ambient conditions, the temperature increase is only 4 °C. *This clearly demonstrates that for the application of UHPFRC for rehabilitation, as thin layers (3 to 10 cm), the temperature increase is negligible and cannot lead to cracking induced by thermo-mechanical effects.*

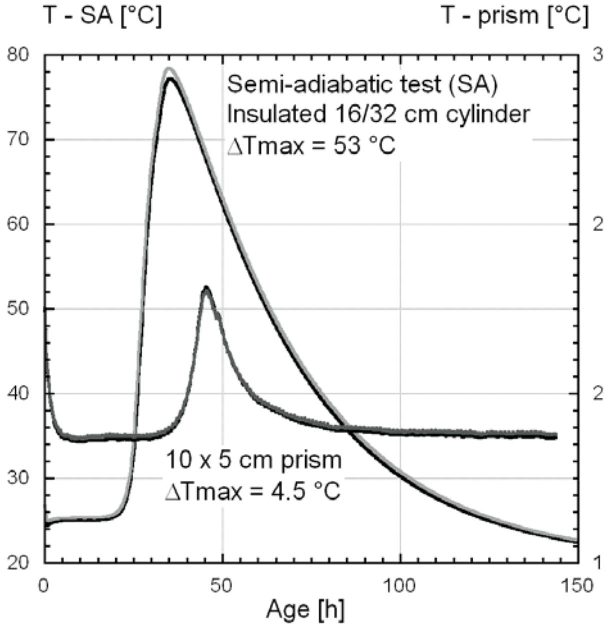

Figure 20: Temperature increase of a UHPFRC (mix CM22), at early age, for two test geometries, after Kamen et al. (2005) – laboratory tests.

The heat of hydration of the mix CM23 used for the bridge deck was characterised by means of 2 semi-adiabatic tests on insulated 16 x 31 cm cylinders. The temperature in the centre of the insulated specimen and outside was recorded as a function of time. The two specimens gave similar results. The temperature time curves were then analysed by means of the method proposed by Springenschmid et al. (1997) to determine the heat of hydration. A Danish model of Heat release was fitted to the curve, taking into consideration the maturation of the material by means of an Arrhenius function (activation energy Q/R = 4000 °K).

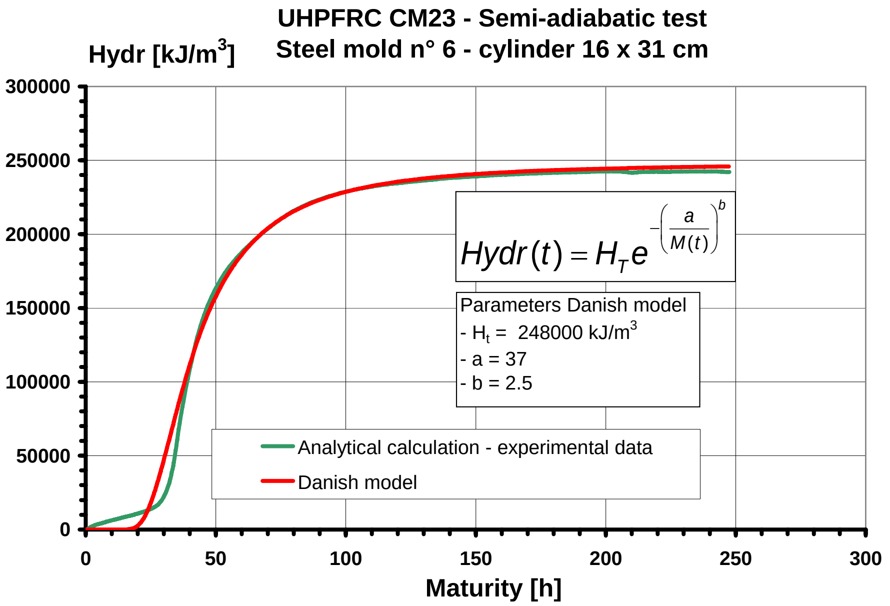

Figure 21: Heat of hydration vs. maturity for material CM23 cast on site.

The model was further refined by inverse analysis (with a finite difference model of the test) of the semi-adiabatic temperature-time curves obtained during the test, as shown on Figure 22.

The cumulative heat of hydration H_t of UHPFRC CM23 determined by this procedure was: **248'000 kJ/m³**.

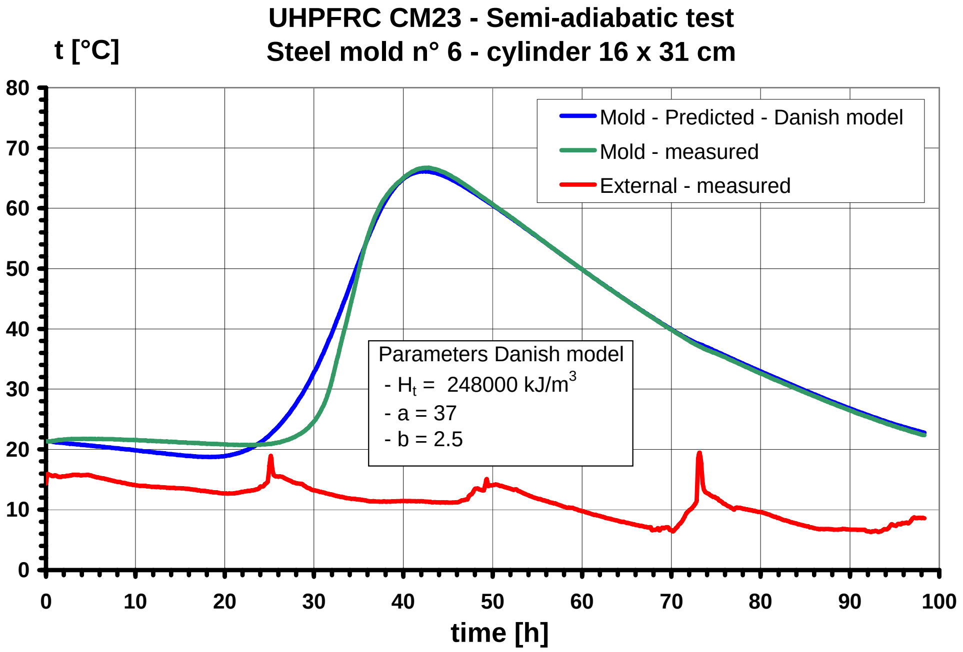

Figure 22: Semi-adiabatic calorimetry test, temperature vs. time, measured and simulated curves for material CM23, cast on site.

3.7.2 Mechanical properties

3.7.2.1 *Compression*

The average compressive strength, respectively modulus of elasticity at 28 days of mix CM23 used on site were 182, respectively 46800 MPa. Their evolution with time is shown on Figure 23, with scatter ranges of ± one standard deviation.

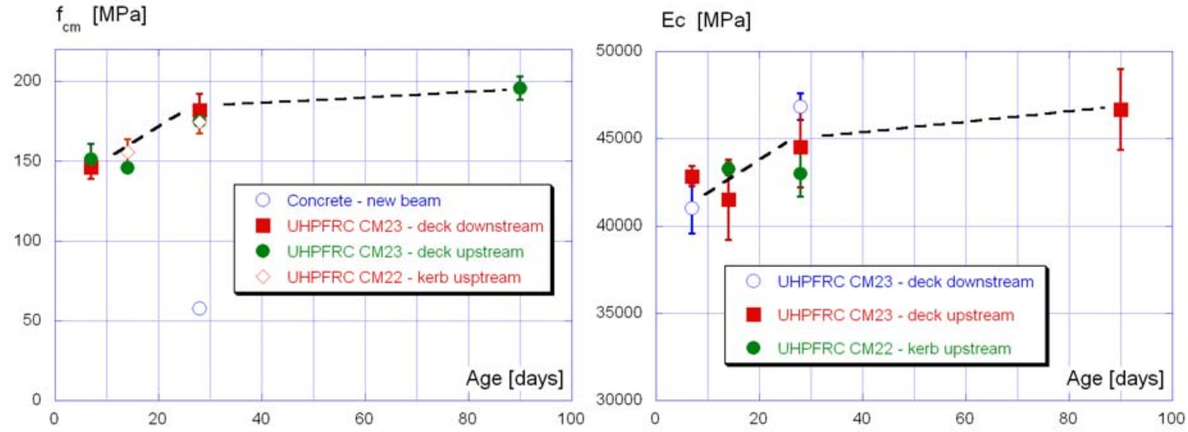

Figure 23: Compressive strength and modulus of elasticity as a function of time (cylinder 11 x 22 cm cast on site).

3.7.2.2 *Tension*

Uniaxial tensile tests performed at 28 days in the laboratory, on unnotched dog bone 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 13.7 MPa and a maximum deformation in the strain-hardening domain of 1.4 ‰ (strain over a measurement basis of 350 mm, in the centre part of the specimen), Figure 24.

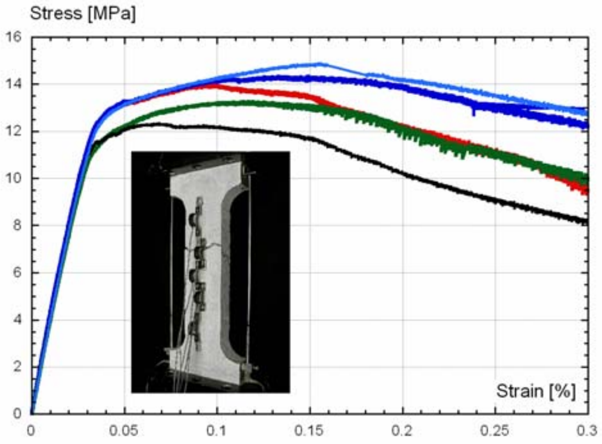

Figure 24: Uniaxial tensile tests at 28 days, material CM23, cast on site.

Multiple cracking was observed in the tensile hardening domain, on the specimens, with a spacing of 5 to 7 cm, Figure 25.

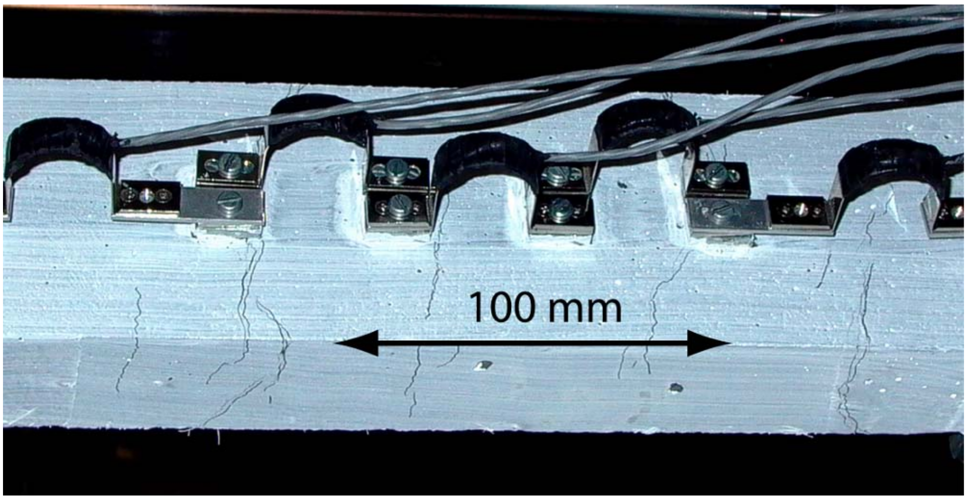

Figure 25: Tensile test on UHPFRC specimen cast during the pilot test on site, recipe CM23, multiple cracking during the strain hardening phase.

3.7.3 Protective function

Air permeability tests after Torrent (1995) performed on site at 4 to 7 days, before the application of the bituminous pavement, 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, at 28 days), as shown on Figure 26. 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).

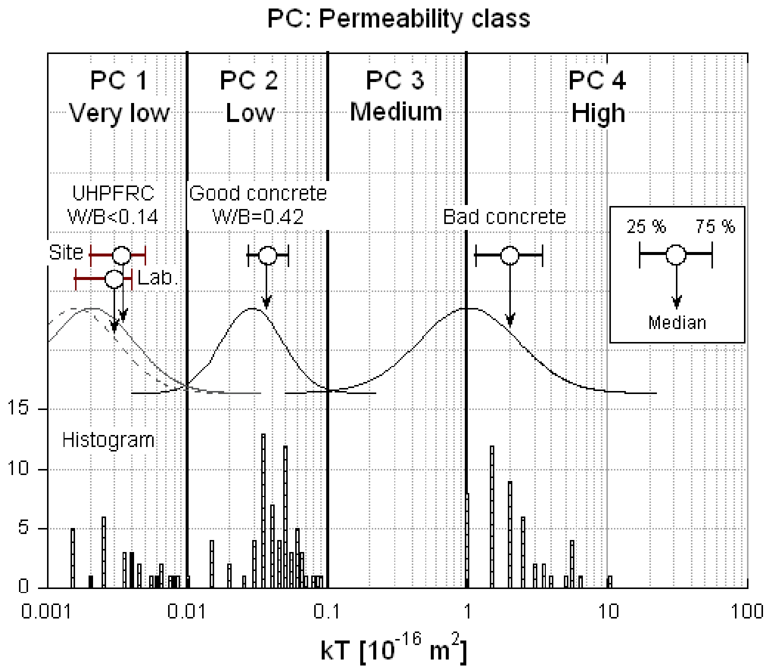

Figure 26: Air permeability tests (Torrent method). Comparative tests between concretes, and UHPFRC, cast in the laboratory and on site.

3.8 Follow-up of the project

Figure 27 shows the bridge in November 2004, after the rehabilitation and widening.

Figure 27: The Bridge in November 2004, after rehabilitation and widening.

No visible cracks could be observed:

- on the apparent surfaces of the prefabricated UHPFRC kerb after one year and
- on the surfaces of the UHPFRC overlays on the bridge deck, after application of the bituminous pavement (inspection at 4 and 5 days of age).

Two localised cracks were detected on the vertical surface of the upstream kerb, on the UHPFRC layer, at an age of 11 days. These cracks were not visible during a previous visit at 8 days of age of the UHPFRC (on the basis of image records of the visits). As a consequence, the cracks appeared between 9 and 11 days, which happens to be the period during which the pavement was applied on the upstream lane. The largest crack had maximum opening of 0.2 mm after one year and is clearly not watertight. Self-healing[5] of the UHPFRC will however most probably seal it again with time. These cracks are located in very specific places, under the anchorages of the supports of the safety barriers. These anchorages were inserted before the application of the UHPFRC, in cavities realised by hydrojetting of the existing concrete. The steep change of UHPFRC thickness (from 3 to 15 cm) might explain the localisation of cracking that does not reflect the strain hardening behaviour observed elsewhere. Numerical simulations are ongoing to try to reproduce this effect.

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. 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, Figure 29. The surface rendering of the UHPFRC was initially very agreeable and its sensitivity to the exposure to chlorides and water appears to be largely dependent on the type of formwork and the compaction technique used.

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[5] UHPFRC have a very low water content and a very high binder content. As a consequence, at long term, only around 30 % of the cement grains are fully hydrated. The remaining grains are available for reacting with water from the outside, thus giving the material a high potential for self healing of microcracks in contact with water.

Figure 28: View of the bridge in April 2005, after rehabilitation.

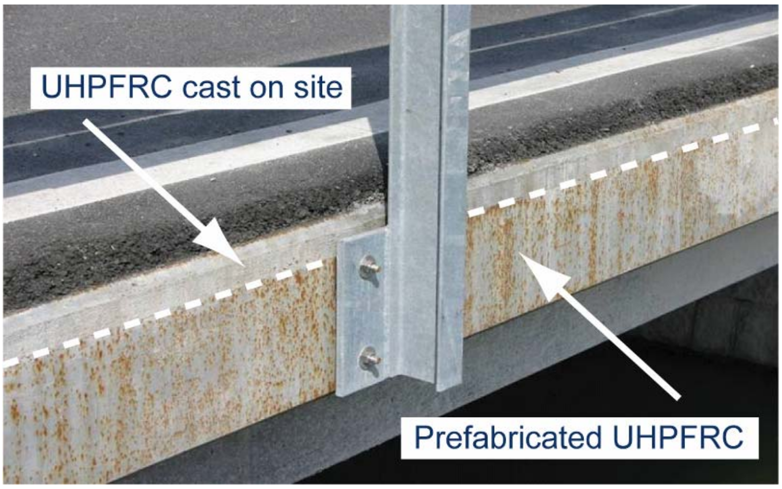

Figure 29: View of a kerb in April 2005, showing a slight change in colour due to corrosion of the steel fibre tips close to the surface.

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. One must also keep in mind that the very high density of the UHPC matrix and its associated very high tensile strength (over 10 MPa) require a significant fibrous reinforcement to provide a tensile strain hardening behaviour, with the necessary "minimum reinforcement". *In the current state of the knowledge, these properties can only be attained by the addition of short steel fibres.*

3.9 Economical analysis

Table 1 shows a comparison of the cost of three different methods of intervention:

A - The executed rehabilitation and widening with UHPFRC and no waterproofing membrane

B - Comparable works realised with usual rehabilitation mortars, with a waterproofing membrane. The rehabilitation mortar thickness is 8 cm (compared to 3 cm for the UHPFRC).

C – Comparable works with UHPFRC and no waterproofing membrane, but with a price drop of 30 % of the costs of the raw components of the UHPFRC.

	A - UHPFRC/ no WM		B - Mortar + WM		C - UHPFRC (-30 %)	
	Amount Sfr.	Amount Euros	Amount Sfr.	Amount Euros	Amount Sfr.	Amount Euros
Raw materials (UHPFRC or mortar)	30'000	19'355	12'000	7'742	21'000	13'548
Prefabrication of UHPFRC kerb	4'214	2'719	3'000	1'935	4'214	2'719
Prefabrication RC beam	11'991	7'736	11'991	7'736	11'991	7'736
Production of cast on site UHPFRC	4'827	3'114		0	4'827	3'114
Waterproofing membrane			3'000	1'935		
Casting of materials on site	10'000	6'452	10'000	6'452	10'000	6'452
Construction works on site	40'000	25'806	40'000	25'806	40'000	25'806
Bituminous pavement, markings, barriers	13'000	8'387	13'000	8'387	13'000	8'387
Scaffoldings	8'123	5'241	8'123	5'241	8'123	5'241
Hydrojetting	32'600	21'032	32'600	21'032	32'600	21'032
Engineer	25'000	16'129	25'000	16'129	25'000	16'129
Site inspection	6'000	3'871	6'000	3'871	6'000	3'871
Total including VAT of 7.6 %	**185'755**	**119'842**	**164'714**	**106'267**	**176'755**	**114'035**
Total excluding VAT	172'635	111'377	153'080	98'761	164'270	105'981

Table 1: Comparative analysis of the costs of various methods of intervention.

The analysis of the costs shows that the rehabilitation realised with UHPFRC and no waterproofing membrane (case A) is **12 % more expensive** that a more traditional solution with water-proofing membrane and rehabilitation mortar (case B). However, in the latter case, the duration of the site would be largely increased by the drying period of the rehabilitation mortar, prior to the application of the waterproofing membrane (up to 3 weeks).

Further, with a price drop of 30 % for the raw components of the UHPFRC, case C; the intervention with UHPFRC becomes only **7 % more expensive** than the traditional method with mortar and waterproofing membrane. *Such a price drop is realistic and can be expected if the use of UHPFRC spreads for such applications. Moreover, the small scale of the bridge used for this application and its character of prototype tend to overestimate the costs of application of UHPFRC. It can thus be expect that with a wider dissemination of the concept of application 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 due to multiple interventions.*

4 CONCLUSIONS AND OUTLOOK

4.1 Main conclusions

A new concept of structural rehabilitations with Ultra High Performance Fibre Reinforced Concretes has been 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 by numerous laboratory tests on composite structural members with configurations corresponding to various practical applications.

A first application of this concept has been successfully realised and the required properties of the UHPFRC were achieved with standard equipment, and verified in-situ.

The construction costs of the proposed technique were not significantly higher than more traditional solutions, and the duration of the construction works and closing of traffic lanes could be largely reduced, to the greatest satisfaction of the bridge owner.

This full scale realisation 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 of this new technique, set forth by the bridge owner, one can mention:

- the ease of processing and
- the significant time savings on the duration of construction sites.

4.2 Future research and applications

Further research and development efforts are now needed and ongoing to optimise this new construction technique and spread it on a wider basis. 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
- optimisation of UHPFRC recipes to tolerate slopes up to 7 %
- optimisation of the combination of UHPFRC with high grade reinforcement bars
- optimisation of the surface preparation (roughness) of the substrate
- design and test methods, compliance criteria and
- guidelines for the design of strain hardening UHPFRC recipes from local components.

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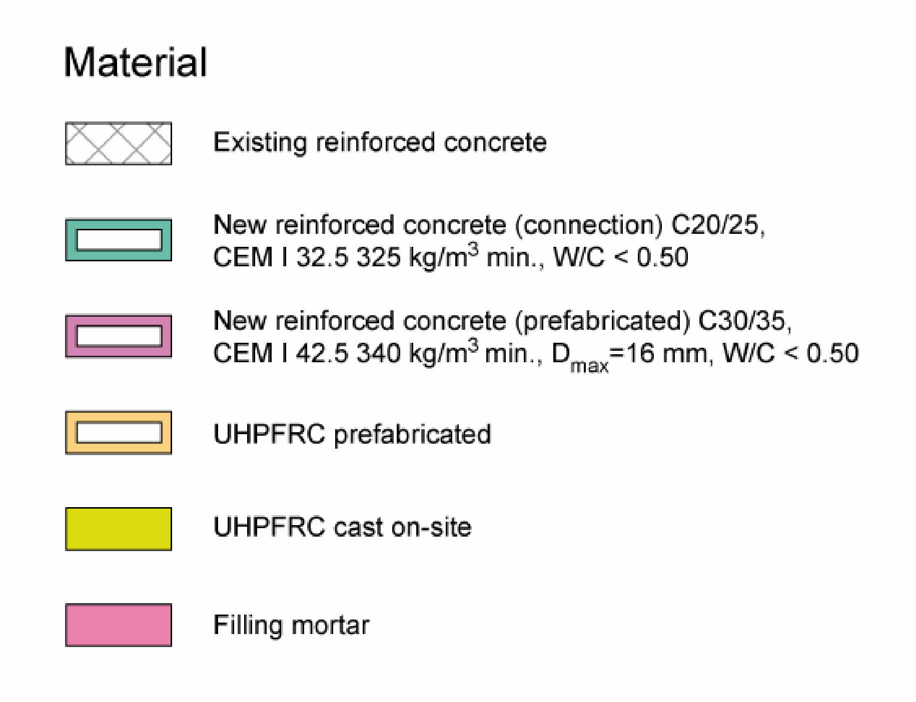
APPENDIX 1 – EXECUTION PLANS

This appendix presents executions plan originally prepared by "PRA ingénieurs conseil SA" for the realisation of the rehabilitation works, and imported from AUTOCAD to Adobe Illustrator for this report.

Legend:



Material

▨ Existing reinforced concrete

▭ New reinforced concrete (connection) C20/25, CEM I 32.5 325 kg/m^3 min., W/C < 0.50

▭ New reinforced concrete (prefabricated) C30/35, CEM I 42.5 340 kg/m^3 min., D_{max}=16 mm, W/C < 0.50

▭ UHPFRC prefabricated

■ UHPFRC cast on-site

■ Filling mortar

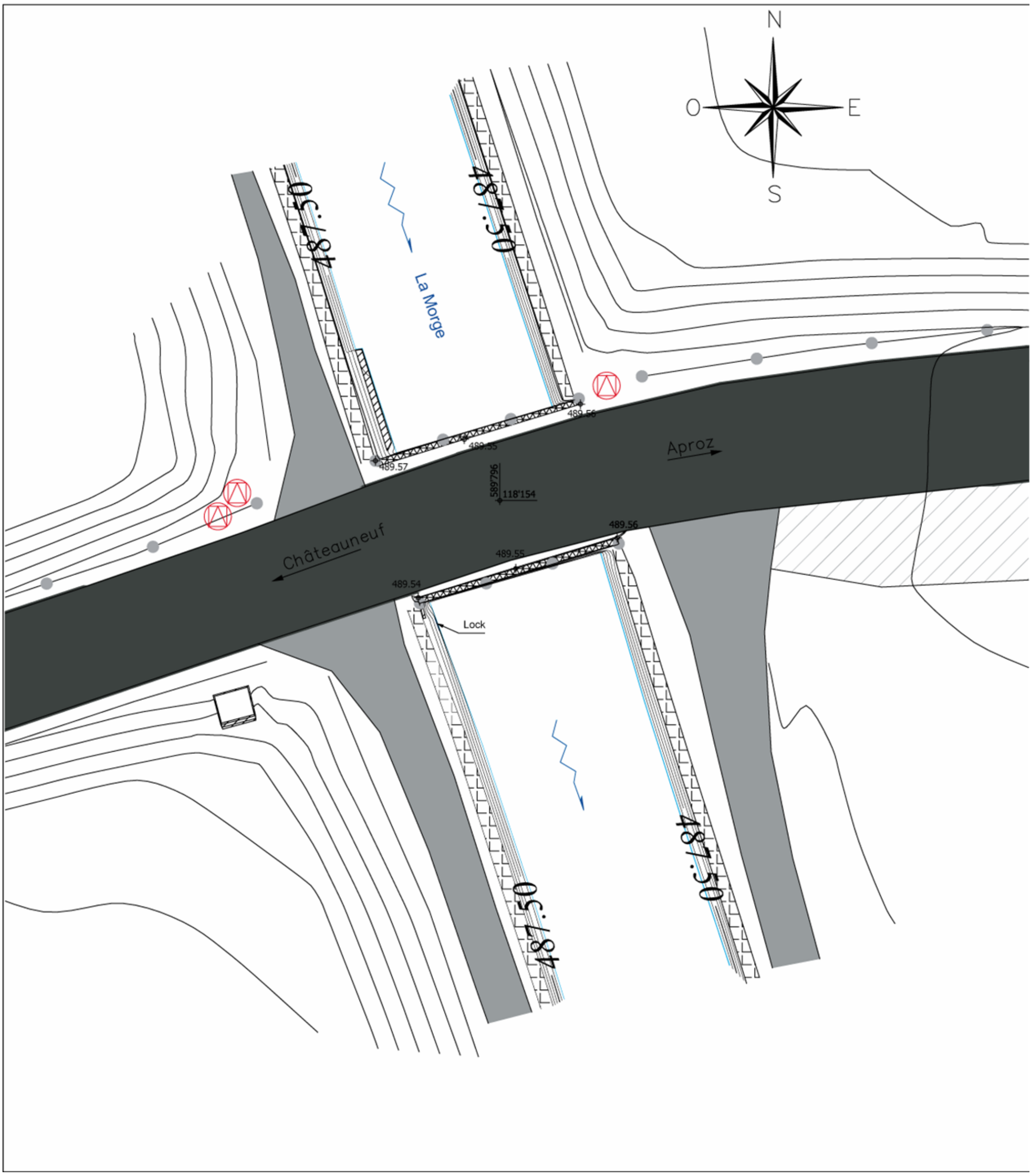


Figure 30: Situation plan, prior to rehabilitation

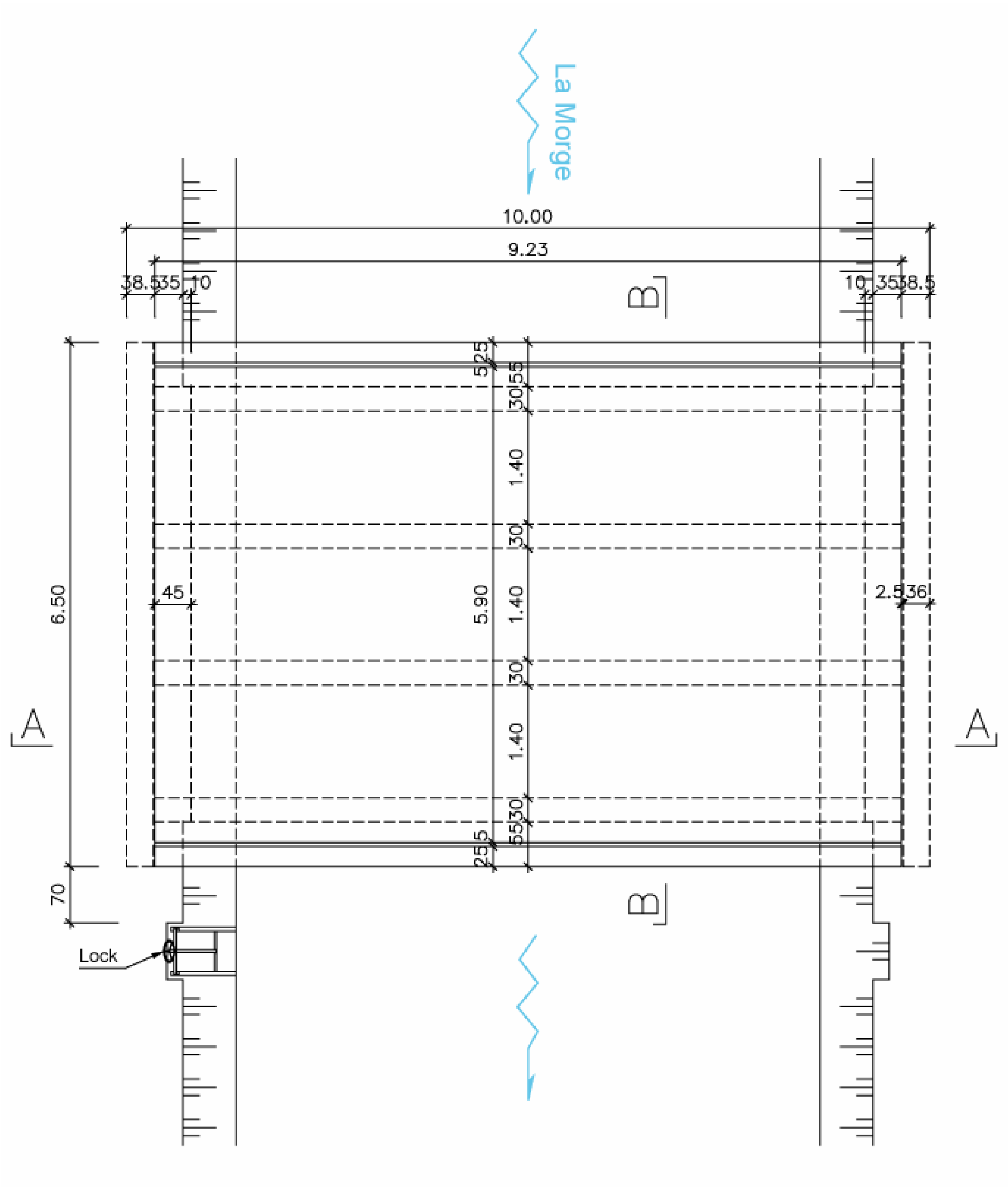


Figure 31: Plan view of the bridge, prior to rehabilitation

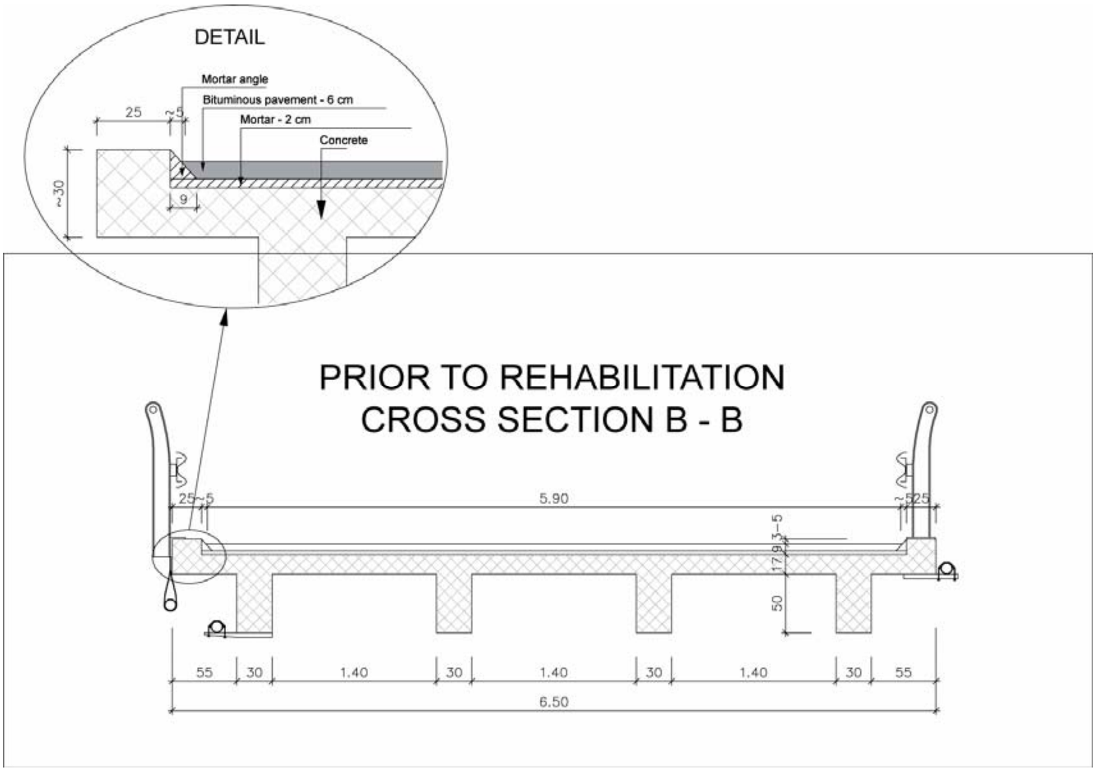


Figure 32: Transverse cross section B – B, prior to rehabilitation

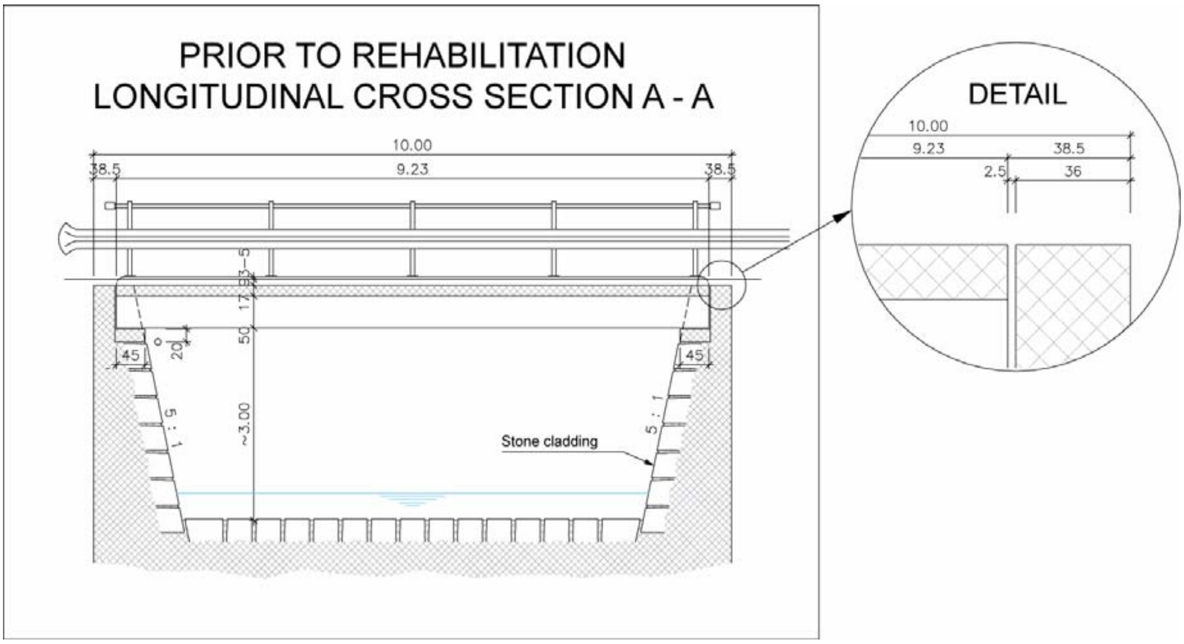


Figure 33: Longitudinal cross section A – A, prior to rehabilitation

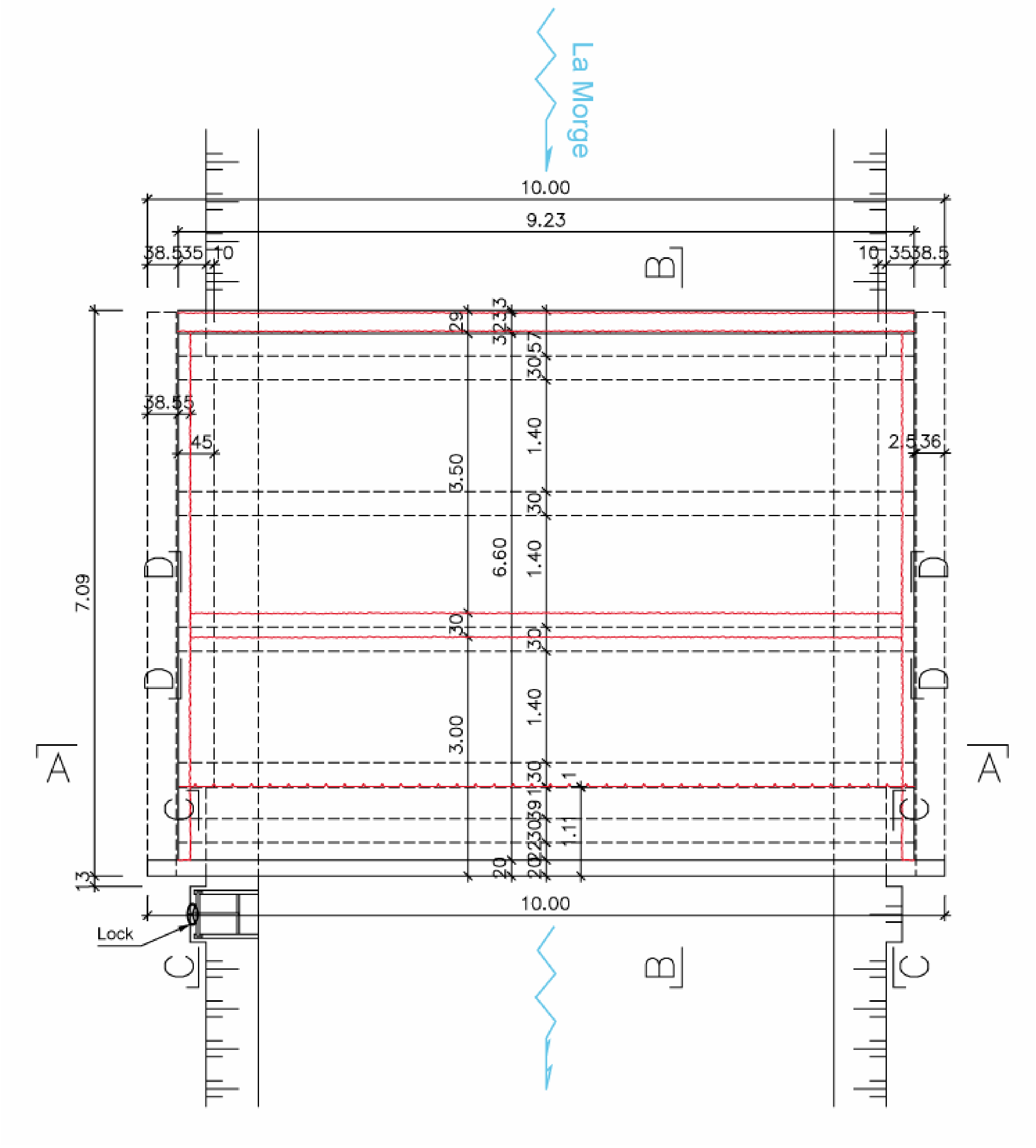


Figure 34: Plan view of the bridge, after rehabilitation

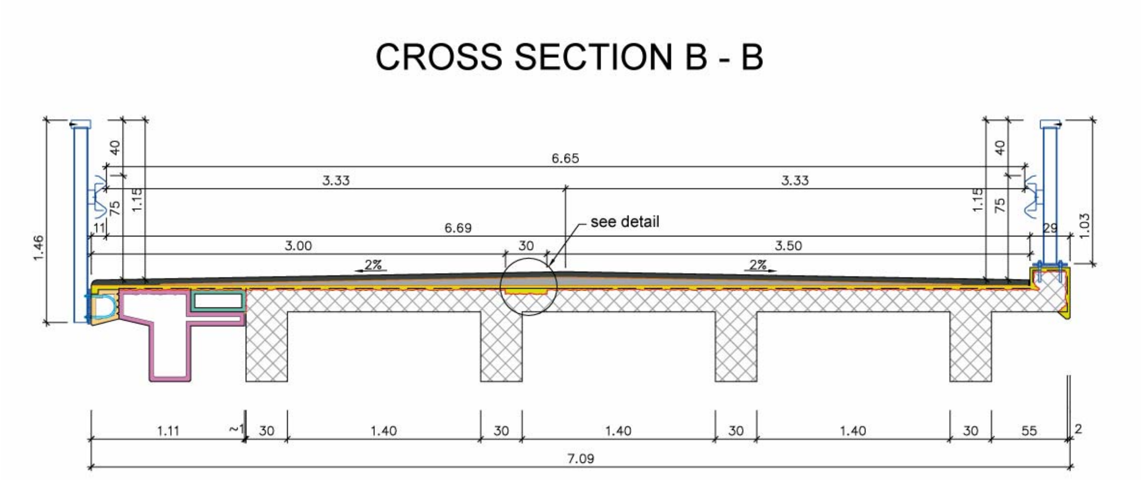


Figure 35: Cross section B – B of the bridge, after rehabilitation

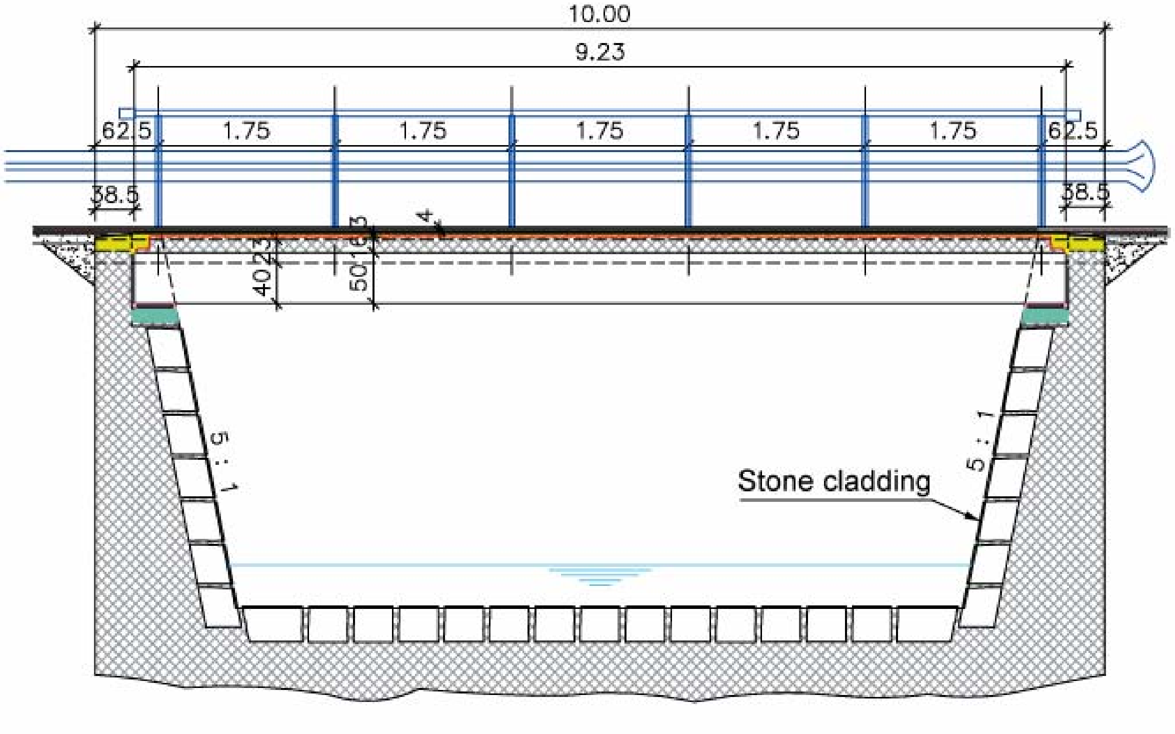


Figure 36: Longitudinal cross section A – A of the bridge, after rehabilitation

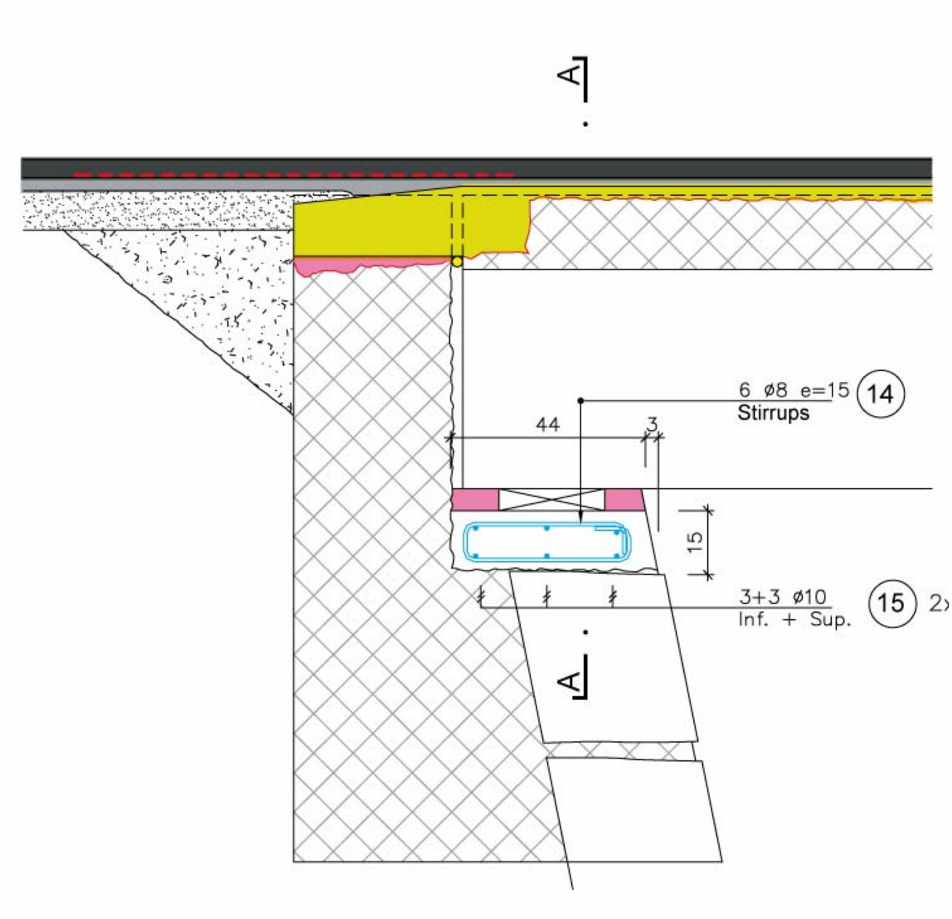


Figure 37: Transition slab, after rehabilitation

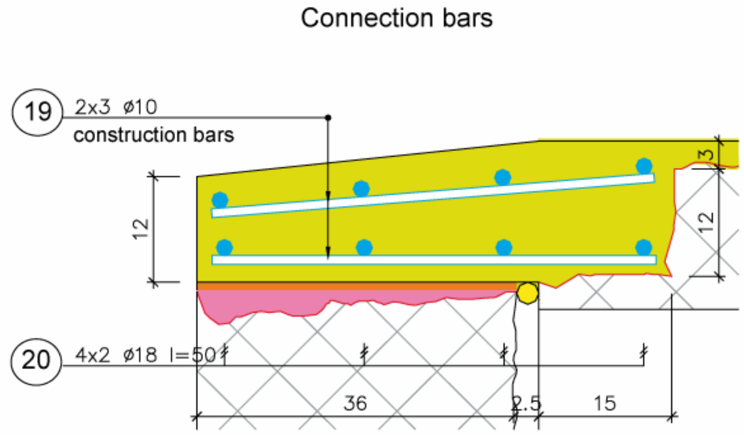


Figure 38: Detail of transition slab, after rehabilitation

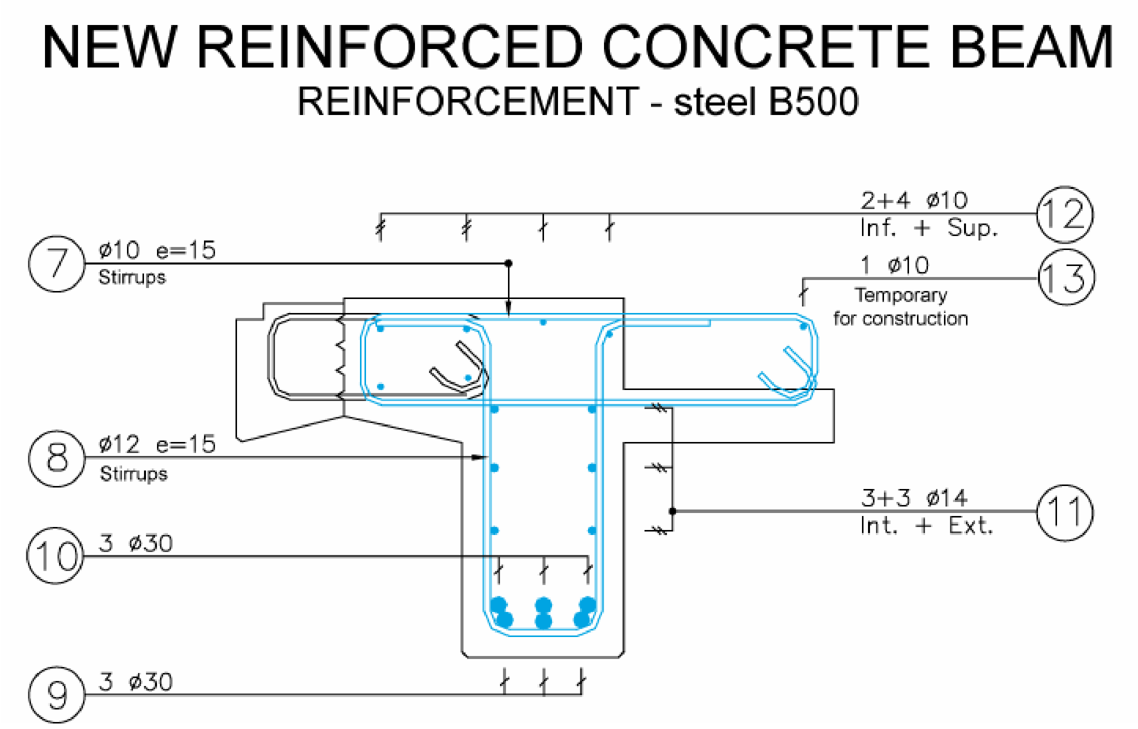


Figure 39: New reinforced concrete beam – reinforcement plan

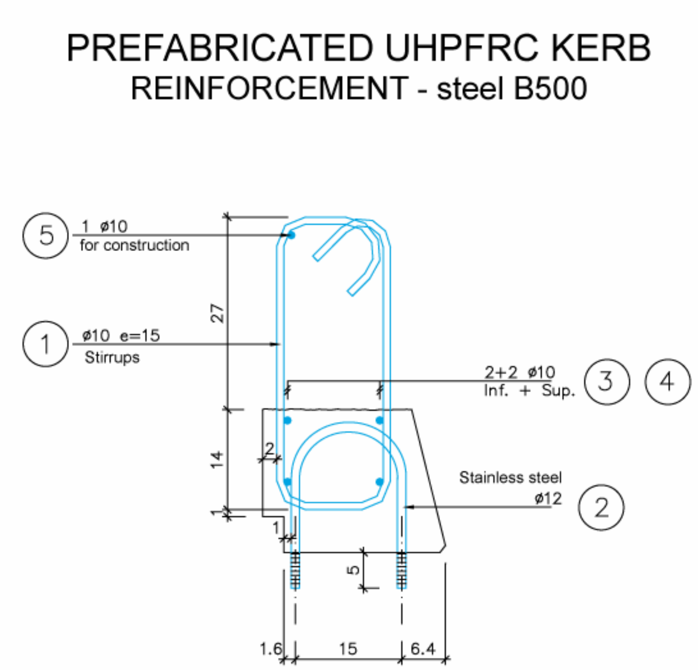


Figure 40: Prefabricated UHPFRC kerb, reinforcement plan, cross section

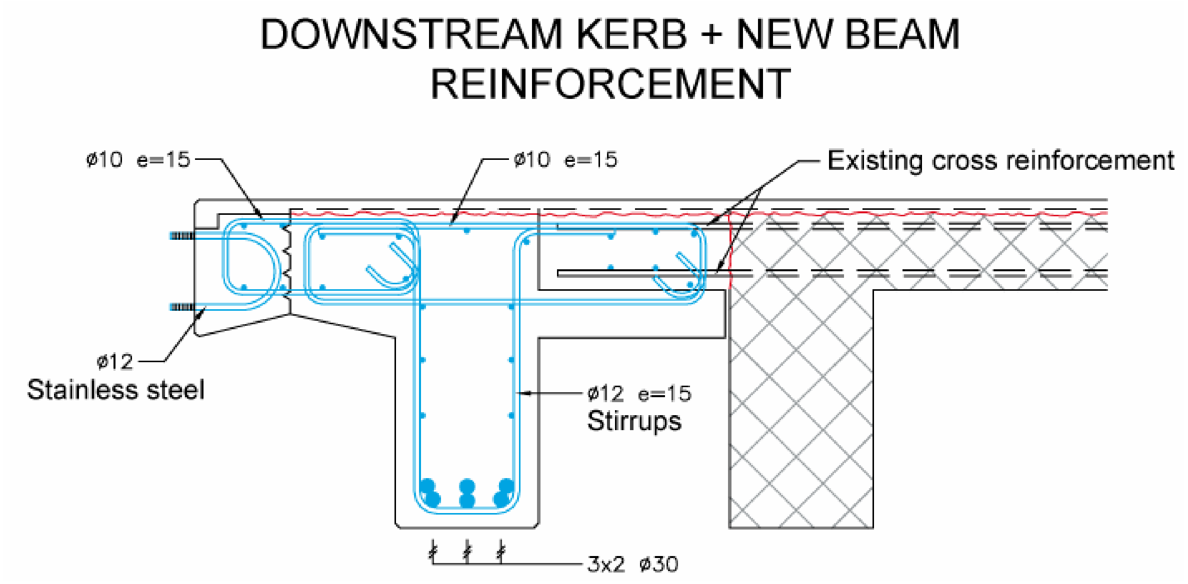


Figure 41: Widening of the bridge, reinforcement

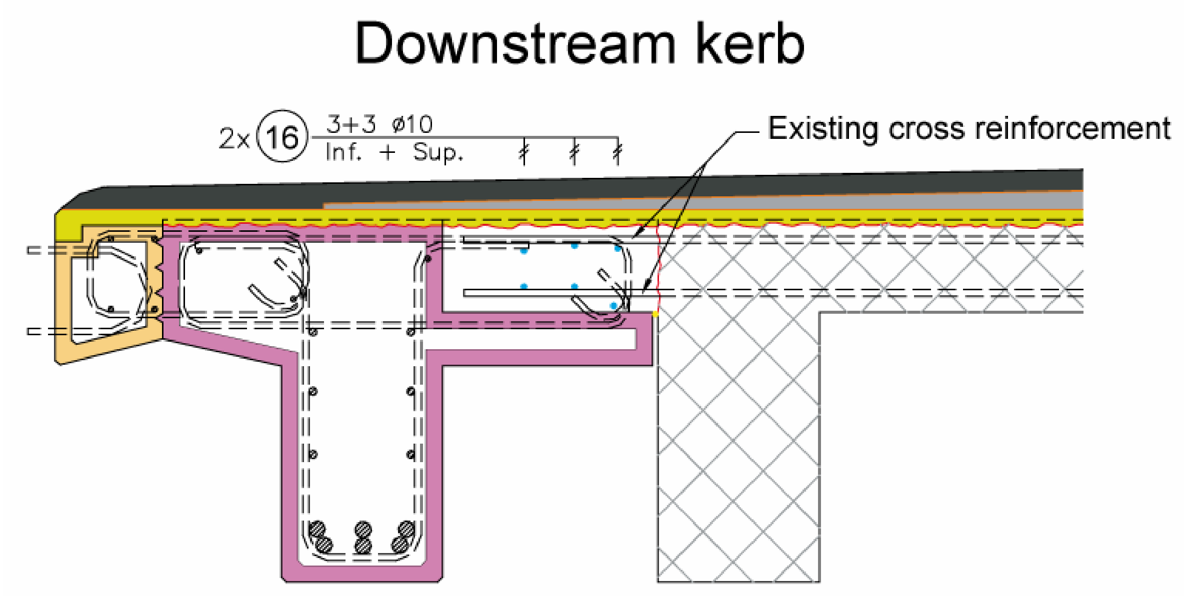


Figure 42: Widening of the bridge, principle.

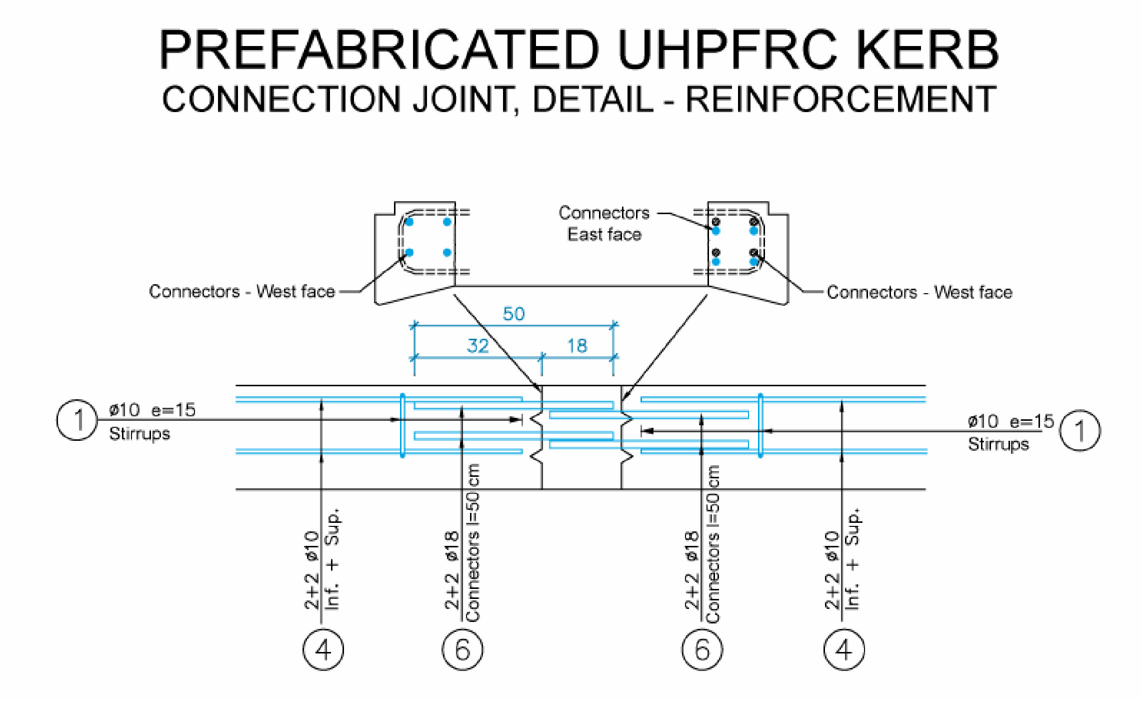


Figure 43: Connection of prefabricated UHPFRC kerb segments, reinforcement

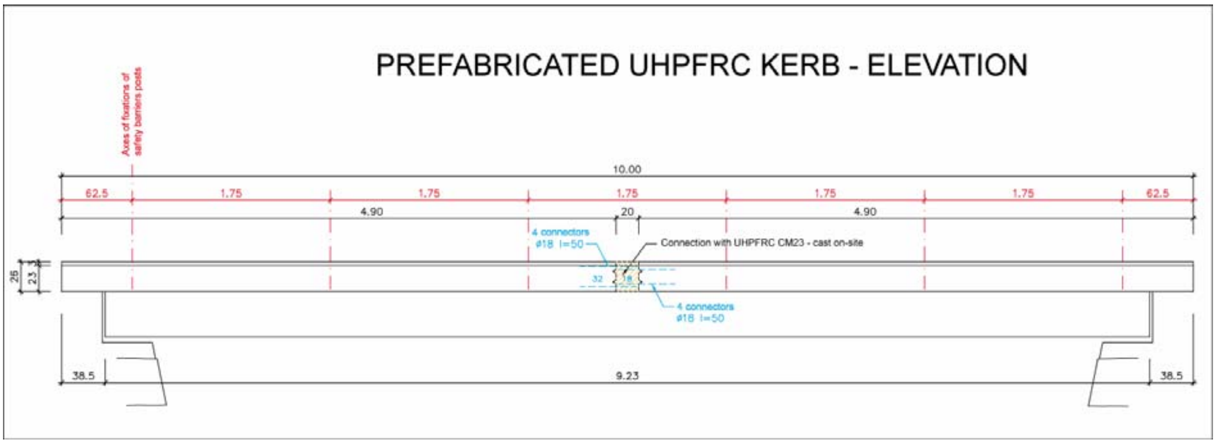


Figure 44: Connection of prefabricated UHPFRC kerb segments, elevation

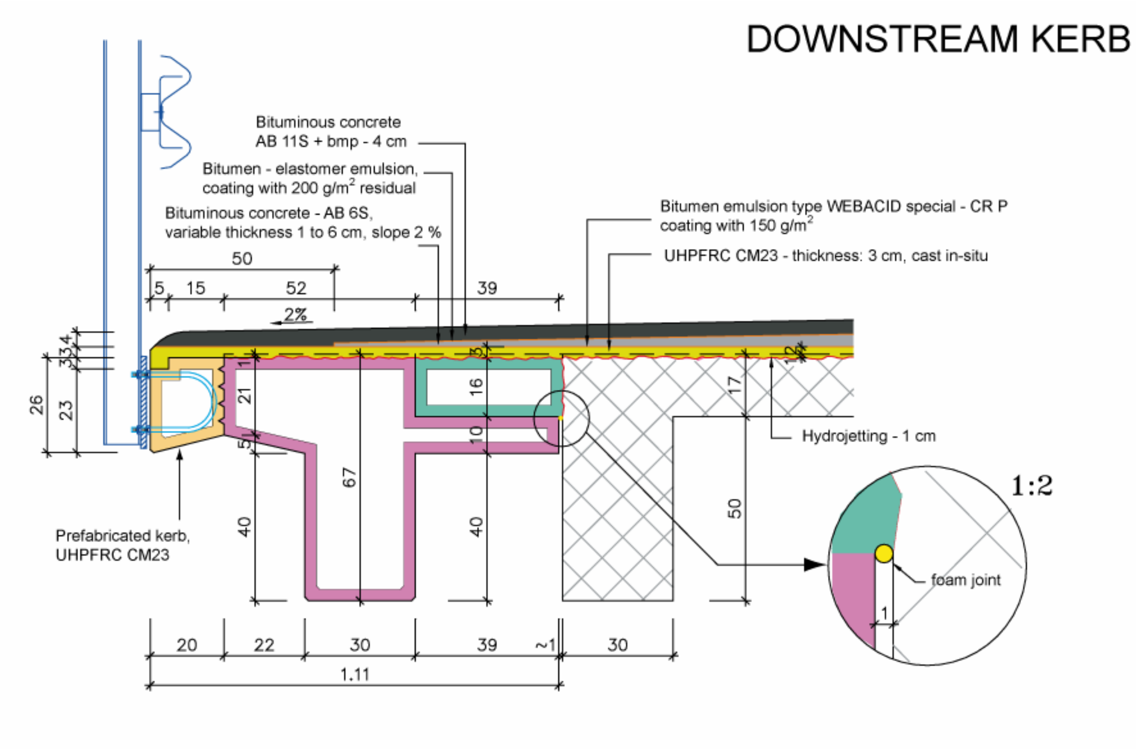


Figure 45: Principle of the intervention, downstream side

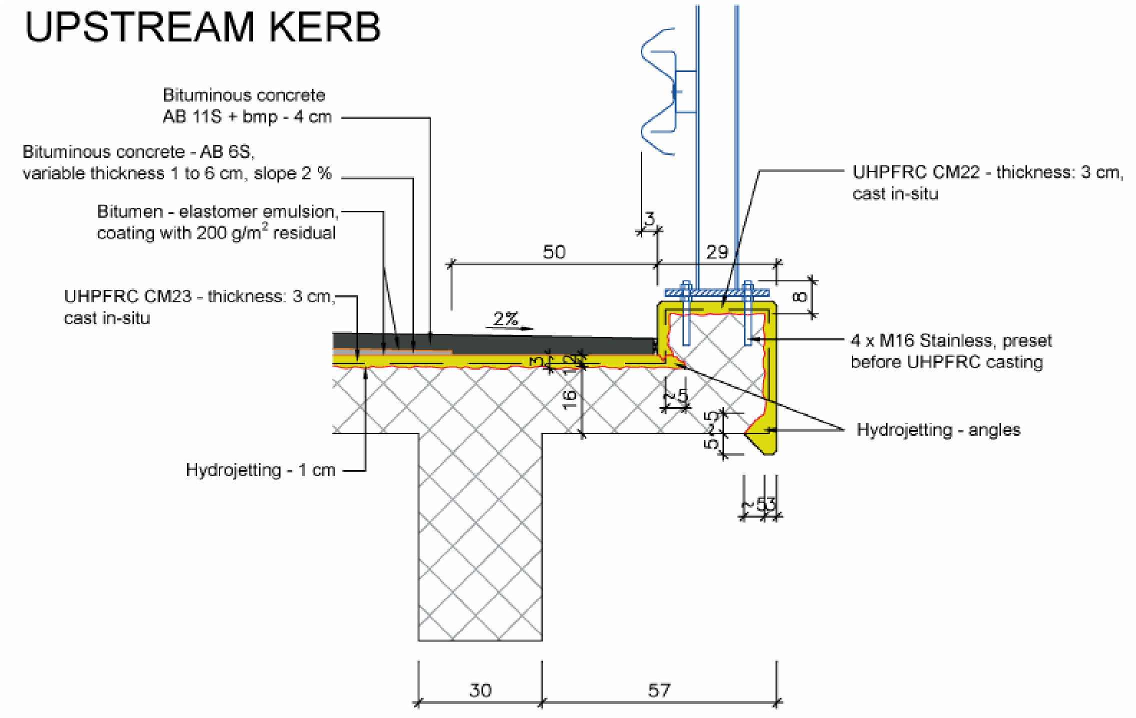


Figure 46: Principle of the intervention, upstream side

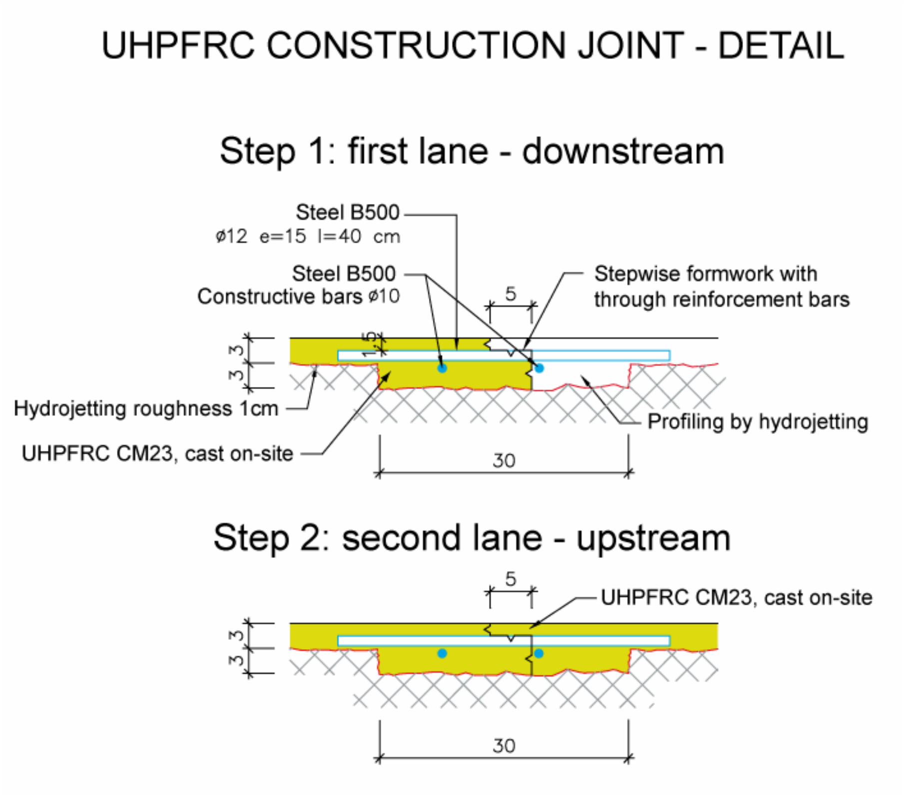


Figure 47: **Principle of the UHPFRC construction joint**

APPENDIX 2 – UHPFRC RECIPES

Component	**Fibres [%]**	**ρ [kg/m³]**	**Mass [kg/m³]**	**Volume [l/m³]**
Powders				
Cement		3.140	**1410.2**	449.1
Microsilica (SF)		2.200	**366.6**	166.7
(Fine sand + quartz)		2.680	**80.4**	30
Added water		1.000	**200.1**	200.1
Steel wool[6]		7.850	**706.5**	90
Steel fibres 10 mm		7.850		
Admixture **Superplasticiser**		1.055	**46.5**	44.1
Dry extract 30 %			14.0	
Water 70 %			32.6	32.6
Total water		1.000	232.7	232.7
Air				20.0
Total	**9**		**2810.4**	**1000.0**

Water/(Cement + SF)	**0.131**
Water/Cement	**0.165**
Admixture/Cement	**0.033**
SF/Cement	**0.260**

Table 2: Composition of material CM22

Note: The UHPFRC recipes used in this study belong to the family CEMTEC$_{\text{multiscale}}$® developed by Dr. P. Rossi – LCPC Paris, and modified at MCS-EPFL for the application to rehabilitation. CEMTEC$_{\text{multiscale}}$® *an recipes are covered by the French patent applications #FR2806403 and #FR2806404 (both published on 9th September 2001) and by the PCT patent application WO0168548 (published on 9th September 2001).*

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[6] The detailed composition of the fibrous mix is patent protected and is available upon request, with a license of exploitation.

Component	**Fibres [%]**	**ρ [kg/m³]**	**Mass [kg/m³]**	**Volume [l/m³]**
Powders				
Cement		3.140	**1433.7**	456.6
Microsilica (SF)		2.200	**372.8**	169.4
(Fine sand + quartz)		2.680	**80.4**	30
Added water		1.000	**189.1**	189.1
Steel wool[7]		7.850	**706.5**	90
Steel fibres 10 mm		7.850		
Admixture **Superplasticiser**		1.055	**47.3**	44.8
Dry extract 30 %			14.2	
Water 70 %			33.1	
Total water		1.000	222.2	222.2
Air				20.0
Total	**9**		**2829.8**	**1000.0**

Water/(Cement + SF)	**0.123**
Water/Cement	**0.155**
Admixture/Cement	**0.033**
SF/Cement	**0.260**

Table 3: Composition of material CM23

Note: The UHPFRC recipes used in this study belong to the family CEMTEC$_{\text{multiscale}}$® developed by Dr. P. Rossi – LCPC Paris, and modified at MCS-EPFL for the application to rehabilitation. CEMTEC$_{\text{multiscale}}$® *an recipes are covered by the French patent applications #FR2806403 and #FR2806404 (both published on 9th September 2001) and by the PCT patent application WO0168548 (published on 9th September 2001).*

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[7] The detailed composition of the fibrous mix is patent protected and is available upon request, with a license of exploitation.

APPENDIX 3 MATERIALS AND SUPPLIERS (UHPFRC)

Component	Type	Supplier
Cement	CEM I 52.5 N HTS CE PM-ES-CP 2, Lafarge, Le Teil	Proz Frères SA, matériaux de construction, CH-1908 Riddes, Switzerland Mr. M.A. Proz **Tel.: +41 27 305 15 15** **Fax. : +41 27 305 15 20** **marc-andre@proz.ch**
Microsilica	SEPR (mean diameter 0.5 µm) Quality 2 Specific surface 12 m^2/g, SiO2 > 93.5 %, white	SEPR, B.P. 40, F-84131 Le Pontet Cedex, France Mr Detalle **Tel.: +33 4 90 32 70 17** **Fax. : +33 4 90 32 71 47** **jean-marie.detalle@saint-gobain.com**
Fine quarz sand	Fontainebleau sand type MN30 (SiO_2>5%), D_{max} < 0.5 mm	Gilbert Gauthier SA, Case Postale 139, CH- 1225 Chêne-Bourg/Genève, Switzerland Mr. Richard **Tel.: +41 22 348 08 45** **Fax. : +41 22 348 73 25**
Steel fibres	Straight l_f=10 mm, d_f=0.2 mm	Redaelli tecna, Zona Ind. – Localita Pascarola, I-80023 Caivano (Napoli, Italy) Mr Mignosi **Tel.: +39 - 081 88 94 246** **Fax. : :+39 -081 83 49 333** **g.mignosi@redaellitecnasud.com**
Steel wool	Crushed steel wool . ref. FbGV2 Code LALACD.BR	Gervois, 1, rue Boucher de Perthes, F-80580 Pont-Remy, France, Mr. Riquiez **Tel.: +33 3 22 27 11 22** **Fax. : +33 3 22 27 14 27** **gervois01@hexanet.fr**
Superplasticiser	Chrysofluid OPTIMA 175	Difutec SA, chemin St-Hubert 37, CH-1950 Sion, Switzerland Mr. Joye **Tel.: +41 27 322 58 84** **Fax. : +41 27 322 58 86** **Cell.: +41 79 628 27 90** **difutec.sa@bluewin.ch**

APPENDIX 4 – TECHNICAL SPECIFICATIONS OF THE CONCRETE MIXER USED

Mixer type: Teka THZ 750 pan mixer (http://www.conspare.com/index.cfm?id=441)

	Teka THZ **750**	
Füllmenge Mischer	Liter	**750**
Füllmenge Zuschlagstoffe	Kg	**1200**
Festbetonausstoß pro Spiel	m³	**0,5**
Antriebsleistung Mischer	KW	**22**
Drehzahl Rotor	UpM	**29**
Leergewicht Standardmischer	Kg	**2500**
Füllung Beschickerkübel Aufzug 60º	Kg	**1100**
Antriebsleistung Beschicker		
mehrlagige Seiltrommel	KW	**5,5**
einlagige Seiltrommel	KW	**7,5**
Geschwindigkeit Beschickerkübel	m/Sek	**0,4**
Leergewicht Beschicker	Kg	**1000**

APPENDIX 5 - PRECAUTIONS FOR THE PRODUCTION AND USE OF CEMTEC$_{\text{MULTISCALE}}$®

- The concrete mixer should not be pre-wetted before the filling with the raw components of the UHPFRC.
- The barrel of the concrete truck should not be pre-wetted before the filling with the fresh UHPFRC.
- Safety precautions to be followed are identical to those prescribed for the production of normal concretes with silica fume.
- During all steps of the production and casting of the UHPFRC and after its hardening, special care has to be taken to protect the skin and eyes of the personal from injury by protruding short steel fibres (10 mm long). During the handling of 10 mm long short steel fibres, during the mixing and pouring of the UHPFRC, and during the cleaning of the batching equipments (mixer, etc.) and of the moulds and forms when the UHPFRC has hardened, it is mandatory to protect the eyes of the operators with fully covering glasses from accidental projection of fibres in the face. Further, the aspect ratio of the 10 mm long steel fibres makes them especially prone to penetrate under the skin. For this reason, the use of thick protection gloves is mandatory during all steps of the production process of UHPFRC.
- The duration of mixing of the 10 mm long steel fibres has to be, according to the performances of the mixer, sufficient to insure a uniform dispersion of the fibres in the UHPFRC, but short enough in order to avoid the formation of agglomerates of fibres.
- The presence of protruding steel fibres on the surface can constitute a danger during the handling of hardened UHPFRC specimens (for the personal and for the lifting equipments such as slings). Hardened UHPFRC specimens shall be cautiously examined before manipulation.
- Free surfaces of fresh UHPFRC shall be protected from desiccation as soon as possible. Due to its extremely low W/B ratio, and to the small thickness of the layers applied for rehabilitation applications, UHPFRC overlays are very sensitive to desiccation. A plastic foil shall be applied on the fresh UHPFRC as soon as possible after casting. A moist curing (daily spraying of water) of 8 days shall then be applied as soon as the material is hardened (around 30 hours after contact between binders and water for the UHPFRC recipes described in this report).

APPENDIX 6 - BATCHING SEQUENCE OF CEMTEC$_{\text{MULTISCALE}}$®

- Add cement, microsilica and steel wool in dry mixer.
- Mix for 2 minutes, then stop mixer.
- Add fine quartz sand.
- Mix for one minute.
- Add all water followed by all superplasticiser while mixer runs.
- Let mixer run until getting a homogeneous mix, with liquid consistency (duration around 4 minutes with mixer used for this application – see description in Appendix 4).
- Stop mixer and add half the quantity of short steel fibres (10 mm).
- Mix for 30 seconds until all fibres are properly coated and dispersed.
- Stop mixer and add second half of the fibres.
- Mix for 30 seconds until all fibres are properly coated and dispersed.

Note: the first batch, in the dry mixer, always shows a stiffer consistency than subsequent batches with the same UHPFRC.

APPENDIX 7 - LIST OF PARTNERS OF THE PROJECT

Following partners were involved in the project

Owner: Département des Travaux Publics du canton du Valais, Sion, Suisse, Service des routes et Cours d'eau, Section du Valais central/Sion, Switzerland.

Concept and supervision: Laboratory for Maintenance and Safety of Structures, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Advice for the UHPFRC recipes and processing: Dr. P. Rossi, Laboratoire Central des Ponts et Chaussées (LCPC), Paris, France.

Execution plans and local direction of works: PRA ingénieurs conseil SA, rue de la Majorie 9, CH-1950 Sion, Switzerland, tel.: +41 27 329 60 30, fax.: +41 27 322 24 70

Production of UHPFRC, realisation of prefabricated UHPFRC kerb and reinforced concrete beam: Proz Frères SA, matériaux de construction, CH-1908 Riddes, Switzerland, tel.: +41 27 305 15 15, fax.: +41 27 305 15 20.

Contractor: Evéquoz SA, entreprise de construction, rue des Peupliers 16, CH- 1964 Conthey, Switzerland, + Valjet/Etter as subcontractor for hydrojetting.