

**Eugen Brühwiler**  
*Professor, Dr. Civil Engineer ETH  
Ecole Polytechnique Fédérale (EPFL)  
Lausanne, Switzerland*

**Emmanuel Denarié**  
*Senior Scientist, Dr. Civil Engineer EPFL*

## **Rehabilitation of concrete structures using Ultra-High Performance Fibre Reinforced Concrete**

### **Summary**

An original concept is presented for the rehabilitation of concrete structures. The main idea is to use Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) to “harden” those zones where the structure is exposed to severe environmental and high mechanical loading. All other parts of the structure remain in conventional structural concrete as these parts are subjected to relatively moderate exposure. This conceptual idea combines efficiently protection and resistance properties of UHPFRC and significantly improves the structural performance in terms of durability and life-cycle costs of the rehabilitated concrete structure. The concept is validated by means of four applications demonstrating that the technology of UHPFRC is mature for cast in-situ and prefabrication using standard equipment for concrete manufacturing.

*Keywords: Ultra-High Performance Fibre Reinforced Concrete; durability; composite concrete construction, rehabilitation of concrete structures.*

### **1 Introduction**

Concrete structures show excellent performance in terms of structural behaviour and durability except for those zones that are exposed to severe environmental and mechanical loading. Rehabilitation of deteriorated concrete structures is a heavy burden also from the socio-economic viewpoint since it also leads to significant user costs. As a consequence, novel concepts for the rehabilitation of concrete structures must be developed. Sustainable concrete structures of the future will be those where the interventions will be kept to the lowest possible minimum of only preventative maintenance with no or only little service disruptions.

Over the last 10 years, considerable efforts to improve the behaviour of cementitious materials by incorporating fibres have led to the emergence of Ultra-High Performance Fibre Reinforced Concretes (UHPFRC). These novel building materials provide the structural engineer with a unique combination of (1) extremely low permeability which largely prevents the ingress of detrimental substances such as water and chlorides and (2) very high strength, i.e., compressive strength higher than 150 MPa, tensile strength higher than 10 MPa and with considerable tensile strain hardening and softening behaviour. In addition, UHPFRC have excellent rheological properties in the fresh state allowing for easy casting of the self-compacting fresh material with conventional concreting equipment. Consequently, UHPFRC have clearly improved resistance

---

against severe environmental and mechanical loading and offer high potential for concrete structures with significantly improved structural resistance and durability.

This paper presents an original concept for the rehabilitation of concrete structures. The concept is described and validated by means of four applications.

**2 Conceptual idea**

The basic conceptual idea is to use UHPFRC only in those zones of the structure where the outstanding UHPFRC properties in terms of durability and strength are fully exploited; i.e. UHPFRC is used to “harden” the zones where the structure is exposed to severe environmental and high mechanical loading. All other parts of the structure remain in conventional structural concrete as these parts are subjected to relatively moderate exposure. This concept (which is also applicable to new construction) necessarily leads to composite structural elements combining conventional reinforced concrete and UHPFRC.

The combination of the protective and load carrying properties with the mechanical performance of reinforcement bars provides a simple and efficient way of increasing the stiffness and load-carrying capacity with compact cross sections (Fig. 1). Depending on the structural and material properties of the composite system, more or less pronounced built-in tensile stresses are induced in the UHPFRC due to restrained deformations at early age. This stress state needs to be analysed and evaluated [1].

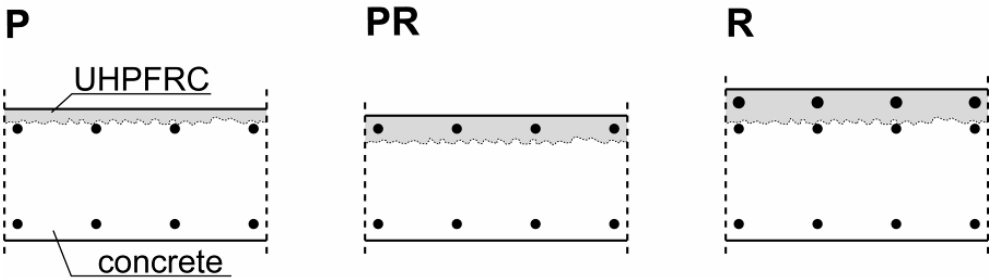


Figure 1: Basic configurations for composite structural elements combining UHPFRC and conventional structural concrete

UHPFRC is applied on existing reinforced concrete elements as thin watertight overlays (in replacement of currently used waterproofing membranes), as reinforcement layers combined with reinforcement bars, or as prefabricated elements such as kerb elements in the case of bridges. The relatively high cost of these materials imposes to use them only where they are “worth their money” and take the maximum benefit of their outstanding mechanical properties.

The original conceptual idea (developed in 1999) has been investigated by means of extensive research (see scientific papers under [2]) to characterize UHPFRC materials and the structural behaviour of composite structural members. The concept is well-suited for bridges and can also be implemented for buildings, galleries, tunnels or retaining walls. Validation by means of four applications will be described in the following.

### 3 Rehabilitation and widening of a road bridge

A short span road bridge with busy traffic has been rehabilitated and widened using UHPFRC [3,4]. The entire deck surface of the bridge with a span of 10 m was rehabilitated in three steps during autumn 2004 (Fig. 2). Firstly, the downstream kerb was replaced by a new prefabricated UHPFRC kerb on a new reinforced concrete beam which was necessary for the widening. Secondly, the chloride contaminated concrete of the upper surface of the bridge deck was replaced by 3 cm of UHPFRC in two consecutive steps such that one traffic lane could be maintained open. Thirdly, the concrete surface of the upstream kerb was replaced with 3 cm of UHPFRC.

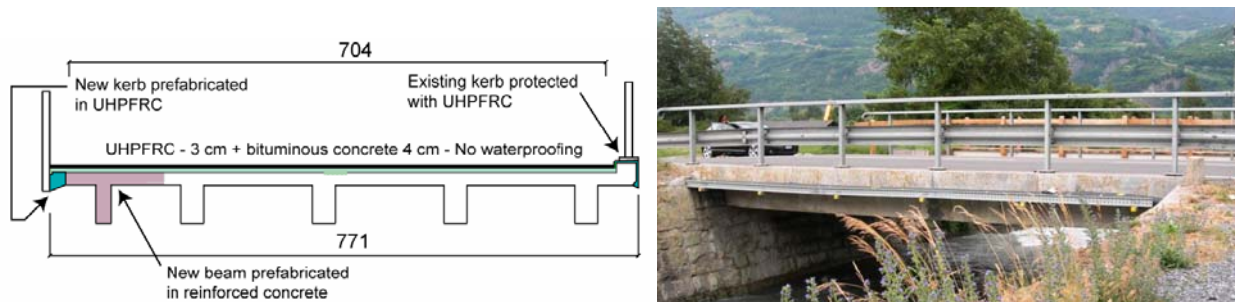


Figure 2: Bridge cross section after rehabilitation (dimensions in cm) and photo taken in 2006.

The UHPFRC mix contained  $1430 \text{ kg/m}^3$  Cement, Microsilica, fine quartz sand with a maximum grain size of 0.5 mm; the Microsilica/Cement and Water/Binder ratio were 0.26 and 0.125 respectively. The reinforcement of this ultra compact matrix was provided by a mix of microfibers (steel wool of 2 to 3 mm length) and macrofibers of 10 mm length and an aspect ratio of 50, with a total dosage of  $706 \text{ kg/m}^3$  (or 9 vol.%).



Figure 3: UHPFRC casting and handling of UHPFRC using simple tools.

The fresh self-compacting UHPFRC material was prepared at a local concrete prefabrication plant with a standard mixer, brought to the site by a truck and then poured on the hydrojetted deck surface (Fig. 3). The UHPFRC was easy to produce and place with standard tools and very robust and tolerant to the unavoidable particular site conditions. 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.

The protective function of the UHPFRC layer was verified by air permeability tests according to the Torrent method [5]. These tests confirmed the extremely low permeability  $kT$  of the UHPFRC layer; i.e. about 30 times lower than for excellent conventional concretes. The average compressive strength and modulus of elasticity at 28 days were respectively 182 MPa and 47 GPa. Uniaxial tensile tests performed at 28 days in the laboratory on unnotched dogbone specimens cast on site showed the expected remarkable average properties: tensile strength of 14 MPa and an average maximum tensile deformation in the strain-hardening domain of 1.5 ‰ (Fig. 4).

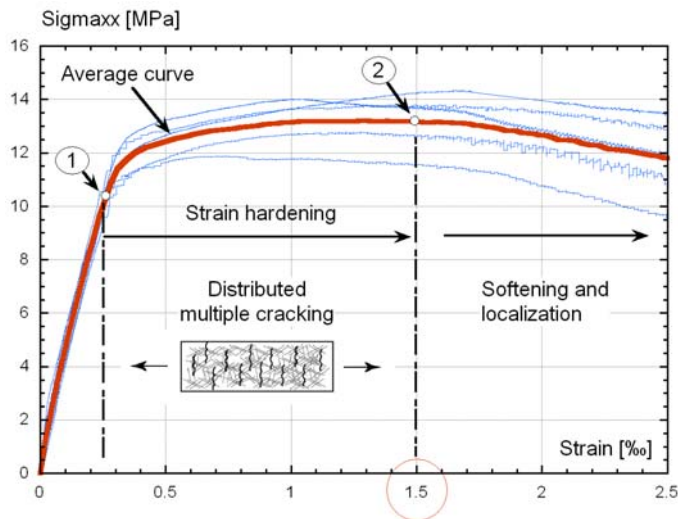


Figure 4: Uniaxial tensile test results on the UHPFRC used on site.

The analysis of the construction costs showed that the rehabilitation realised with UHPFRC was about 10% more expensive than the conventional solution (providing lower quality in terms of durability and life-cycle costs) with waterproofing membrane and repair mortar. However, in the latter case the duration of the construction site would have been largely increased by the required drying period of the mortar, prior to the application of the waterproofing membrane. It can be expected that with a wider dissemination of UHPFRC for the rehabilitation of bridges, this technique will become less costly 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.

#### 4 UHPFRC protection layer on a crash barrier wall

Specific parts of reinforced concrete structures such as crash barrier walls on highway bridges suffer from severe exposure to concrete aggressive substances such as de-icing salts and impact like action. Such elements often show insufficient durability when built using conventional reinforced concrete. Again, UHPFRC having very low permeability as well as high strength and deformability, is suitable to significantly improve the durability and mechanical performance of such structural elements.

A layer of UHPFRC has been applied in September 2006 to the concrete crash barrier walls of a highway bridge [6]. The main design requirement was to obtain long-term durable crash barrier walls since traffic interruption for future rehabilitation interventions are prohibitive due to the very high traffic volume on this highway. Long-term durability is obtained when transverse macro-cracks in the UHPFRC layer are absent and the permeability of UHPFRC layer for ingress of water and chloride ions is extremely low.

Figure 6 shows the crash barrier wall with a UHPFRC layer covering the areas subjected to splash exposure (Class XD3: reinforcement corrosion induced by chlorides). Previous research [2] indicated that a 3 cm thick UHPFRC layer would provide the required mechanical performance and extremely low permeability. The used recipe contained 1100 kg/m<sup>3</sup> cement, 26% silica fume related to the cement content, quartz-sand, 6% steel fibres by volume, superplasticiser and a w/c-ratio of 0.17. The rheological properties of UHPFRC were adapted for easy pouring into the 3 cm wide formwork to fill a height of 120 cm including a small horizontal part at the bottom of the wall that provides continuity with the conventional bridge deck with a waterproofing membrane.

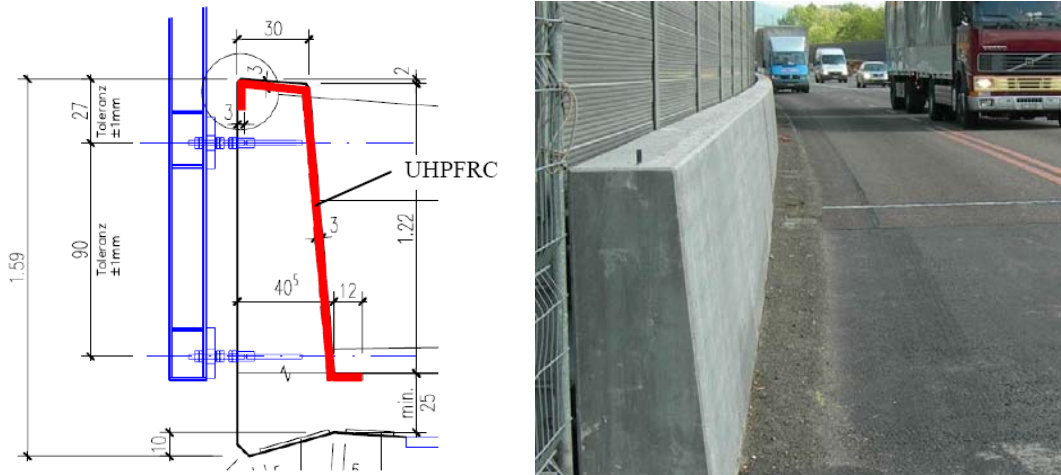


Figure 6: Typical cross section of the crash barrier wall and view after rehabilitation.

Due to restrained early age deformation of the UHPFRC (mostly due to thermal and autogenous shrinkage) bonded to the existing reinforced concrete wall, an internal stress state is built up in the composite element including, in particular, tensile stresses in the UHPFRC layer. These tensile stresses which could present a certain risk of macrocrack formation, and the capacity of the UHPFRC to resist to these stresses were investigated by means of numerical analyses prior to the intervention [6].

The fresh self-compacting UHPFRC was fabricated in a conventional ready mix concrete plant, transported to the site by a truck and successfully filled into the thin slot to realize the UHPFRC coating (Fig. 6). The required mechanical properties and the protective function of the UHPFRC layer have been confirmed by in-situ air permeability tests and laboratory tests on specimens cast on site.

The aesthetic aspect was very appealing showing a smooth surface with very few voids. Four months after application no crack could be found confirming the predictions by the numerical simulations.

### 5 Rehabilitation of a bridge pier using prefabricated UHPFRC shell elements

Bridge piers and retaining walls in the splash zone of highway traffic suffer from severe exposure to de-icing salts and impact like action. Such elements when built in conventional reinforced concrete usually show premature deterioration. In order to significantly improve durability and mechanical strength of such elements, UHPFRC is used following again the concept of locally “harden” the zones of severe exposure.

In this application, 4cm thick UHPFRC shell elements have been prefabricated to form an outer protection shield for the existing 40 year old reinforced concrete bridge pier which is located very closely to busy highway traffic which makes it virtually not accessible for future maintenance interventions (Fig. 7).

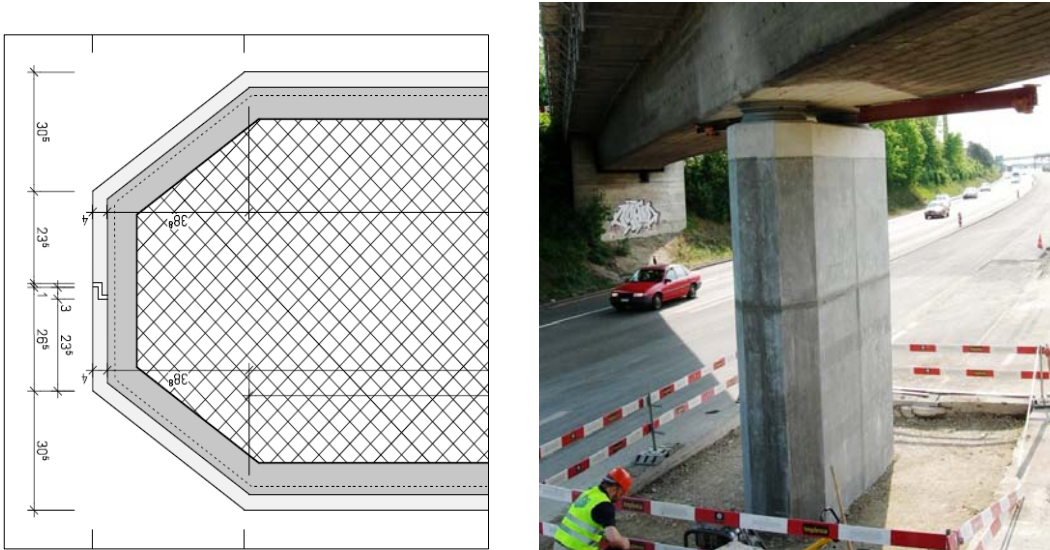


Figure 7: Cross section and general view of the rehabilitated bridge pier.

In spring 2007, the UHPFRC elements were cast (maximum element height of 4m) in a prefabrication plant, transported to the construction site and mounted, after removal by hydrojetting of up to 10cm of chloride contaminated concrete. The joints between the different UHPFRC shell elements were glued using an epoxy resin. The remaining space between the UHPFRC elements and the existing reinforced concrete was filled with self-compacting mortar.

The used UHPFRC recipe contained about 1300 kg/m<sup>3</sup> of cement, a rather small amount of silica fume related to the cement content, quartz-sand, steel fibres by volume, superplasticiser and a W/C-ratio of 0.155. Long-term durability is expected since transverse cracks in the UHPFRC protection shield are absent and the permeability of UHPFRC for ingress of water and chloride ions is extremely low as confirmed by quality control testing.

---

## 6 Strengthening of an industrial floor

The 50 year-old drivable reinforced concrete floor of a fire brigade building had insufficient load carrying capacity in view of heavier future fire engines. The concept to increase the load carrying capacity of the existing slab of 720m<sup>2</sup> area was to pour a 4cm thick UHPFRC layer on top of the existing RC slab, as a replacement of the existing cementitious non-load carrying overlay (Fig. 8). The UHPFRC layer leads to a thicker load carrying slab which provides (1) a better distribution of local wheel loads, (2) an increase in static height and (3) a high strength material to resist both compression or tension stresses.

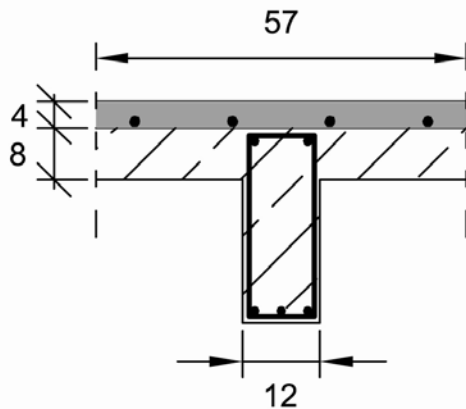


Figure 6: Cross section (dimensions in cm) with UHPFRC layer (in grey) and view of UHPFRC casting performed in autumn 2007.

The UHPFRC of a similar recipe as in Section 5 was again fabricated in a local ready mix concrete plant and transported to the site by trucks. The excellent workability of the fresh self-compacting material allowed for easy casting. The use of the UHPFRC solution turned out to be very economic (compared to the conventional solution of slab demolition and reconstruction), also because the utilization of the fire workers building was only slightly restricted during the intervention and thus user costs could be kept minimal.

## 7 Conclusions

An original concept using Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) for the rehabilitation of concrete structures has been presented and validated by means of four applications.

This conceptual idea combines efficiently protection and resistance functions of UHPFRC with conventional structural concrete. The rehabilitated structures have significantly improved structural resistance and durability.

The full scale realizations of the concept under realistic site conditions demonstrate the potential of applications and that the technology of UHPFRC is mature for cast in-situ and prefabrication using standard equipment for concrete manufacturing.

---

## Acknowledgments

The support of the Swiss National Science Fund, The Swiss Secretary of Education and Research, The Committee of Technology and Innovation, Cemsuisse, Holcim, Swiss Steel AG and the Swiss Federal Roads Office is gratefully acknowledged. The applications were possible thanks to the Road Administrations of the Swiss Cantons of Wallis and Aargau as well as the Town of Geneva.

The UHPFRC Group at MCS-EPFL consists of the following current and former members: Dr Katrin Habel, Prof. Jean-Philippe Charron, Dr Hamid Sadouki, Prof. Minoru Kunieda, Dr Aicha Kamen, Dr John Wuest, Dr Andrin Herwig, Cornelius Oesterlee, Agnieska Switek and Talayeh Noshiravani.

## 8 References

- [1] Oesterlee, C., Sadouki, H., Brühwiler, E., Structural analysis of a composite bridge girder combining UHPFRC and reinforced concrete, Proceedings, UHPC-2008: The Second International Symposium on Ultra High Performance Concrete, March 2008, Kassel, Germany.
- [2] mcs.epfl.ch 2007, <http://mcs.epfl.ch/> see under reviewed journal papers.
- [3] Denarié, E., Brühwiler, E., Structural rehabilitations with Ultra High Performance Fibre Reinforced Concretes, International Journal for Restoration of Buildings and Monuments, Aedificatio, Vol. 12, No. 5 and 6, 2006, pp. 453-467.
- [4] SAMARIS 2005, Report D22, *Full scale application of UHPFRC for the rehabilitation of bridges – from the lab to the field*, European project 5th FWP / SAMARIS – Sustainable and Advanced MAterials for Road Infrastructures – WP 14: HPRCC, <http://samaris.zag.si/>.
- [5] Torrent R., Fernandez Luco L., Non-destructive Evaluation of the Penetrability and Thickness of the Concrete Cover, State of the Art Report, RILEM TC 189-NEC, 2007.
- [6] Oesterlee, C., Denarié, E., Brühwiler, E. 2007. In-situ casting of UHPFRC protection layer on crash barrier walls. Proceedings, Advances in Construction Materials – Symposium in honour of Hans W. Reinhardt, July 2007, University of Stuttgart, Germany.