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Rehabilitation of concrete bridges using Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)

E. Brühwiler
Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

ABSTRACT: Rehabilitation of deteriorated concrete bridges is a heavy burden from the socio-economic viewpoint. Novel concepts for the rehabilitation of concrete structures must be developed. Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) provide the structural engineer with a unique combination of extremely low permeability and very high mechanical strength. An original lifetime oriented concept is presented for the rehabilitation of concrete bridges which consists in using UHPFRC to "harden" the zones exposed to severe environmental and high mechanical loading. This concept combines efficiently protection and resistance properties of UHPFRC and significantly improves the structural performance and life-cycle costs.

1 INTRODUCTION

Concrete bridges show excellent performance in terms of structural behaviour and durability except for the zones that are exposed to severe environmental and mechanical loading. Rehabilitation of deteriorated concrete bridges is a heavy burden from the socio-economic viewpoint since it also leads to significant user costs due to traffic disruptions.

As a consequence, novel concepts for the rehabilitation (and also the construction) of concrete structures must be developed that extend and really achieve the required durability over the planned service life. Sustainable bridges of the future will be those where the number and extent of interventions will be kept to the lowest possible minimum of only preventative maintenance without or only little traffic 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) characterized by a very low water/binder ratio and high fibre content. These novel building materials provide the structural engineer with a unique combination of (1) extremely low permeability which prevents the ingress of detrimental substances such as water and chlorides and (2) very high mechanical strength. 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.

An original lifetime oriented concept is presented for the rehabilitation of reinforced concrete bridges that often suffer from rebar corrosion damage and insufficient strength of bridge deck slabs. The main idea of the design concept is to use UHPFRC to "harden" only those zones where the bridge 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.

The concept is described and validated by several applications, i.e. rehabilitation and strengthening of bridge deck slabs as well as rehabilitation of the crash barrier walls and a one pier of two further bridges. The reasoning leading to the conceptual design of these cases of rehabilitation and the practical experiences made with UHPFRC during execution will be discussed. Life-cycle engineering is finally critically reviewed.

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 conditions (f.ex., deicing salts, marine environment) and high mechanical loading (f.ex. impact, concentrated loads, fatigue). All other parts of the structure remain in conventional structural concrete as these parts are subjected to relatively moderate exposure. This concept necessarily leads to composite structural elements combining conventional reinforced concrete and UHPFRC.

The combination of the UHPFRC 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 keeping 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.

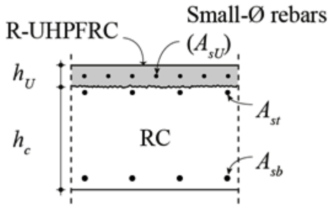

Figure 1. Basic configuration of composite structural elements combining R-UHPFRC and conventional reinforced concrete.

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

The original conceptual idea (developed in 1999) has been investigated by means of extensive researches aimed at characterizing 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 after describing UHPFRC properties.

This original concept should also be applied to new constructions such as durable new bridges (Brühwiler et al. 2007).

3 COMPOSITE R-UHPFRC – RC SECTIONS

3.1 *Mix design and fresh UHPFRC properties*

UHPFRC mixes typically contain 700 to 1'000kg/m^3 of cement as well as microsilica and fine quartz sand with a maximum grain size of 0.5mm. The water/binder ratio is 0.13 to 0.17. These components are mixed using a superplasticiser to obtain an ultra-compact matrix. More recently limestone filler was used to replace a significant amount of cement and to improve workability leading to a more economic and environmentally friendly UHPFRC (Denarié 2009). This matrix is strengthened by straight steel fibres typically of 10 to 15mm length and with an aspect ratio of 50 to 80, often with a dosage of at least 3 % in volume.

UHPFRCs have excellent rheological properties in the fresh state allowing for easy casting of the self-compacting fresh material with conventional concreting equipment on the construction site and in a prefabrication plant.

3.2 *Tensile behaviour of UHPFRC and R-UHPFRC*

3.2.1 *Plain UHPFRC*

As illustrated in Figure 2, the uniaxial tensile behaviour of UHPFRC is divided into three phases:

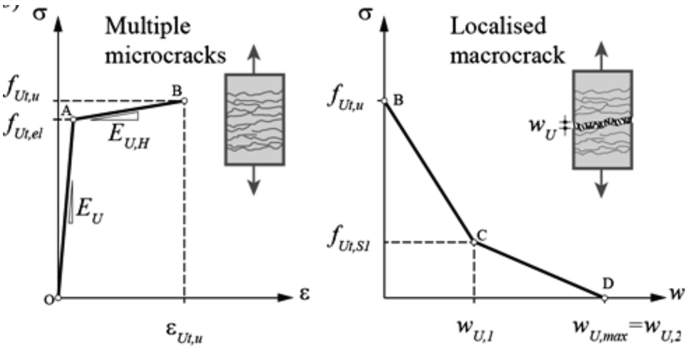

Figure 2. Tensile behaviour of UHPFRC: material laws.

First, the material is elastic up to initiation of microcracking of the matrix. Point A is denoted as elastic limit strength $f_{Ut,el}$ with typical values of 7 to 11MPa for currently used UHPFRCs.

Second, it goes into a phase of strain hardening with multiple (non-visible) microcracking of the matrix and fibre activation. The material still behaves like a continuum. Significant strain hardening behaviour is only obtained with a fibre content of at least 3% in volume. Strain hardening domain may reach to strains of $\varepsilon_{Ut,u}$ = 2 to 5‰ where the tensile strength $f_{Ut,u}$ is reached with typical values ranging from 9 to 15MPa.

Third, upon the formation of a discrete macrocrack at ultimate resistance, the phase of strain softening begins with maximum crack openings reaching about half of the fibre length, i.e., 5 to 8mm.

The tensile hardening and softening behaviour of UHPFRC depends on the random orientation and distribution of the straight steel fibres with a slenderness ratio of typically of 50 to 100 (Wuest 2007, Oesterlee 2010).

The fractured surface of a UHPFRC specimen after a tensile test shows numerous steel fibres, pulled out from the matrix. The corresponding work of pull-out explains the relatively high specific fracture energy G_F of UHPFRC (typically ranging from 20 to 30kJ/m^2). A significant part of the work of fracture of UHPFRC is dissipated in the bulk of the material, during the strain hardening phase.

The mechanical response of fibrous composites such as UHPFRC is much application dependent. Anisotropy effects can be induced by the casting procedure of the materials or the width and shape of the moulds and these effects have to be considered for the analysis of test results and for design. Adding reinforcing bars to the UHPFRC reduces these anisotropy effects.

3.2.2 *R-UHPFRC*

Scatter of the tensile behaviour of plain UHPFRC is one reason to complement UHPFRC by steel reinforcement bars. The small diameter steel reinforcing bars (arranged with small spacing) provide in-plane continuity to the UHPFRC layer and ensure its monolithic action with the RC element in flexural members (Habel 2004, Oesterlee 2010).

The rebars increase not only the resistance but also improve the deformation capacity and strain hardening behaviour of UHPFRC. The reinforcing bars enhance the apparent UHPFRC tensile behaviour.

The global tensile behaviour of R-UHPFRC can be described by the linear superposition of the steel and the UHPFRC tensile behaviour (Fig. 3).

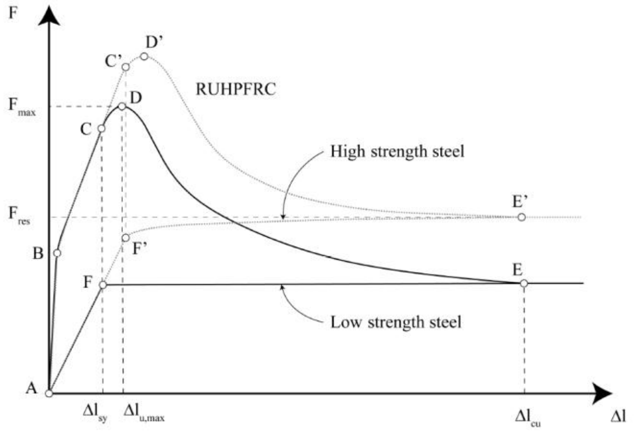

Figure 3. Characteristic tensile behaviour of R-UHPFRC.

The localization of the deformation in one macrocrack occurs at the start of yielding of the reinforcing steel. This is independent on the steel grade of the reinforcement. The magnitude of strain hardening of UHPFRC falls into the range of the yield strain of steel rebars. This property opens up the combination of UHPFRC with reinforcement bars with high yield strength (700 MPa or above).

The use of reinforcing bars with different steel grades and surface characteristics, namely ribbed and smooth bars, showed that the pre-peak behaviour is independent of the bond strength and that the crack spacing is dominated by the fibre reinforcement. Relative to ribbed reinforcing bars, smooth rebars have lower bond strength, allow for larger post-peak deformations and avoid localised stress concentration in the softening UHPFRC macrocrack.

3.3 *Structural response of R-UHPFRC – RC composite beams*

3.3.1 *Behaviour due to bending*

When in tension, the R-UHPFRC layer principally acts as an added flexural reinforcement for the RC element. Both steel rebars and UHPFRC contribute to the resistance.

The strengthening of reinforced concrete beams with an R-UHPFRC layer is characterised by a significant increase of the ultimate resistance and stiffness (depending on the type and strength of the steel reinforcement) (Habel 2004, Oesterlee 2010).

The plastic post-peak rotation capacity of strengthened RC beams is reduced by the UHPFRC layer. Through the choice of the appropriate UHPFRC reinforcement the reduction of plastic rotation capacity can be controlled. Smooth bars bring the least reduction, ribbed bars the highest. The use of smooth high yield strength reinforcing bars in the UHPFRC layer offers a high strengthening effect while the post-peak rotation capacity remains high.

The characteristic structural behaviour of composite sections subjected to bending can be described and the ultimate moment be calculated using the conventional model for RC with an extension to account for the R-UHPFRC (Fig. 4) (Habel et al. 2006, Oesterlee 2010).

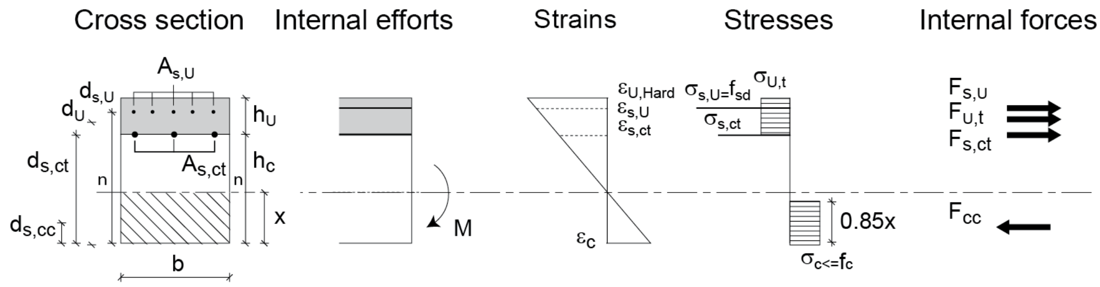

Figure 4. Determination of ultimate moment of R-UHPFRC.

When in compression, the R-UHPFRC layer acts as a compression chord but the high UHPFRC compressive strength of about 200MPa cannot be exploited in R-UHPFRC – RC members.

3.3.2 *Behaviour due to combined bending and shear*

When subjected to combined bending and shear, R-UHPFRC – RC members are susceptible to Intermediate-Crack-induced debonding (ICD) (Fig. 5) that softens the connection between the two elements (Noshiravani 2012). The relative vertical movement of the RC segments separated by inclined flexure-shear cracks in the RC generates prying stresses on the R-UHPFRC layer. These stresses are resisted by the R-UHPFRC tensile element bending in double curvature.

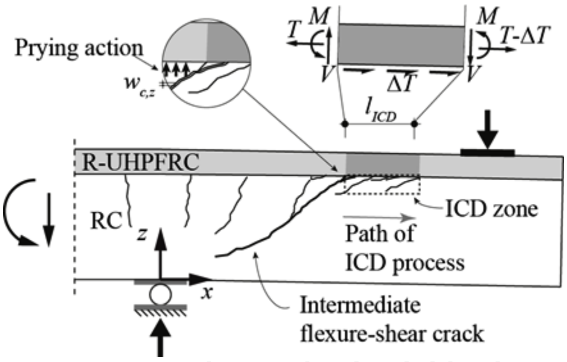

Figure 5. Intermediate-crack-induced debonding (ICD) in R-UHPFRC – RC elements subjected to combined bending and shear.

Working against the R-UHPFRC, the opening and full development of a flexural-shear crack in the RC element leads to a flexure-shear collapse mechanism of the composite member. The R-UHPFRC element contributes to the member resistance before and after formation of the flexure-shear collapse mechanism.

Models were developed to predict the ultimate resistance and the pre-peak deformation capacity of the beams (Noshiravani 2012).

3.3.3 *Fatigue behaviour*

Experimental campaign was performed on plain UHPFRC and R-UHPFRC specimens as well as R-UHPFRC – RC composite beams.

The tensile fatigue behaviour of plain UHPFRC under constant amplitude fatigue cycles up to a maximum of 10 million cycles were conducted with the objective to determine the endurance limit of UHPFRC that was supposed to exist for this material. These fatigue tests revealed that an endurance limit exists in all three domains of UHPFRC tensile behaviour (i.e., elastic, hardening and softening behaviour) at S-ratios ranging from 0.70 to 0.45 with S being the ratio of the maximum fatigue stress to the elastic limit strength of UHPFRC.

The results from bending fatigue tests on composite R-UHPFRC – RC beams (Fig. 6) revealed the existence of a fatigue limit at 10 million cycles at a solicitation level of about 50 % of the ultimate static strength of the R-UHPFRC – RC beam. At fatigue solicitation levels above this value, the fatigue life was rather short and no relevant fatigue strength seems to exist.

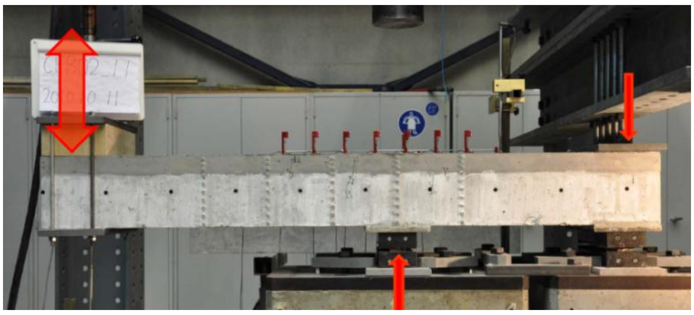

Figure 6. Bending fatigue test set-up on R-UHPFRC – RC composite beams (beam length 1900mm, depth 220mm).

Fatigue fracture process of R-UHPFRC – RC beams was determined by fatigue fracture of steel rebars in the R-UHPFRC layer. Consequently, fatigue design rules for R-UHPFRC – RC members under bending fatigue need to account for steel rebar and UHPFRC fatigue resistances.

4 APPLICATIONS

4.1 *Introduction*

Since 2004, UHPFRC is applied in Switzerland (and in one case in Slovenia following the same concept (Šajna et al. 2012)) on existing reinforced concrete bridge deck slabs as thin watertight overlays (in replacement of currently used waterproofing membranes) as well as reinforcement layer in R-UHPFRC providing both protection and load bearing functions for bridge elements and slabs in buildings without increasing the dead load of the structure (Fig. 7).

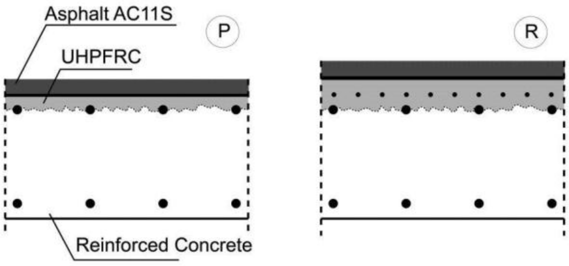

Figure 7. Applications of UHPFRC for protection (P) or as R-UHPFRC for reinforcement (R).

Specific parts of reinforced concrete structures such as crash barrier walls on highway bridges, bridge piers and retaining walls suffer from severe exposure to concrete aggressive substances such as de-icing salts and impact like action. Such elements usually show insufficient durability when built in conventional reinforced concrete. Again, UHPFRC is suitable to establish the required durability and mechanical performance of such structural elements.

4.2 *Waterproofing of bridge deck slabs*

The first field application of UHPFRC in 2004 was for the rehabilitation and widening of a short span road bridge with busy traffic (Denarié & Brühwiler 2006, SAMARIS 2005). The entire deck surface of the bridge was rehabilitated in three steps (Fig. 8).

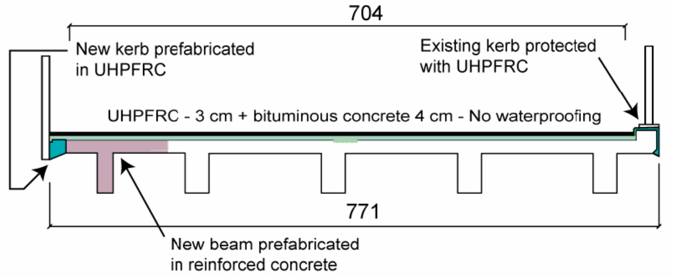

Figure 8. Bridge cross section after rehabilitation (dimensions in cm).

Firstly, the downstream curb was replaced by a new prefabricated UHPFRC curb 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 30mm of UHPFRC in two consecutive steps such that one traffic lane could be maintained open. Thirdly, the concrete surface of the upstream curb was replaced with 30mm of UHPFRC.

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 deck surface prepared by high pressure water jetting (Fig. 9). The UHPFRC was easy to produce and place with standard tools and very robust and tolerant to the unavoidable particular site conditions.

Figure 9. UHPFRC casting and handling of UHPFRC using simple tools.

The bituminous pavement was applied on a bituminous emulsion placed 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. Material tests confirmed the expected mechanical properties of UHPFRC.

Several more applications (Fig. 10) following the same principle have been conducted under various weather conditions and construction site constraints (Denarié et al. 2011). Fresh UHPFRC has also been mixed on the construction site and by optimizing additives maximum slopes of up to 10% could be cast with this self-compacting material.

Figure 10. On-site production and casting of UHPFRC.

4.3 *Protection of vertical surfaces*

A layer of UHPFRC has been applied to the concrete crash barrier walls of a highway bridge covering the areas subjected to splash exposure (Fig. 11). 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 to ingress of water and chloride ions is extremely low.

The rheological properties of UHPFRC were adapted for easy pouring into the 30mm wide formwork to fill a height of 1.20m.

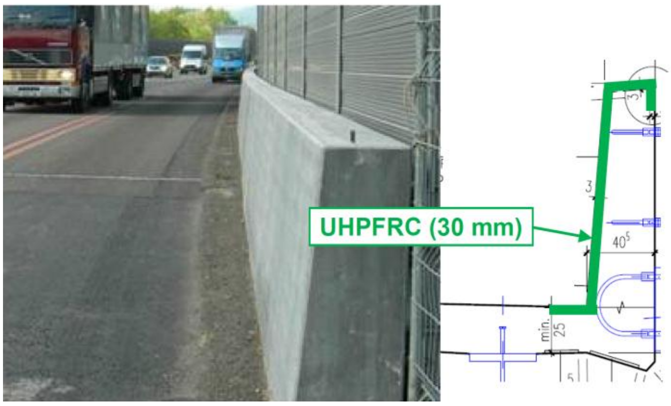

Figure 11. Typical cross section of the crash barrier wall and view after rehabilitation.

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 can cause crack formation, and the capacity of the UHPFRC to resist to these stresses were investigated by means of numerical analyses prior to the intervention (Oesterlee et al. 2007). Four months after application no crack could be found confirming the predictions made by the numerical simulations.

A next application consisted in fabricating 40mm thick UHPFRC shell elements to form an outer protection shield for an existing 40 year-old reinforced concrete bridge pier which was severely damaged by chloride induced rebar corrosion. The joints between the different UHPFRC shell elements were glued using an epoxy resin. This pier is located in the middle of a busy highway making it virtually not accessible for future maintenance interventions.

4.4 *Strengthening of bridge deck slabs*

Example 1: The deck slab of a more than 70 year old reinforced concrete bridge of high cultural value had to be rehabilitated and strengthened to accommodate for future traffic demands of a village in a mountainous area.

The intervention consisted in casting a layer of R-UHPFRC on top of the deck slab with the objective to improve the durability and to restore the structural safety (Fig. 12). Gravel was dispersed on the fresh UHPFRC such as to obtain the required roughness of the surface fit for road traffic.

Figure 12. Rehabilitation and strengthening of a bridge deck slab with reinforced UHPFRC; drivable UHPFRC surface.

Example 2: Massive RC slab bridge built in 1963 with six supporting columns was improved in autumn 2011 by applying UHPFRC and R-UHPFRC to its whole deck surface. The bridge is part of a road with heavy traffic (Fig. 13). Load bearing capacity of the bridge was found to be insufficient for todays and future vehicles. Besides, its deck slab was deteriorated due to chloride induced rebar corrosion.

UHPFRC layer of 25 mm thickness was cast for water-proofing of the deck, and the area above the columns were strengthened by a 65 mm-thick R-UHPFRC layer to increase bending and punching shear resistance (Fig. 14). The UHPFRC mix contained cement, limestone filler, silica fume, quartz sand, 4.5 % steel fibres by volume and superplasticiser. The UHPFRC material was prepared on site and about 300 litres were mixed per batch. RC top surface of 20 to 40 mm depth was first treated with high pressure water jet. UHPFRC was then cast with standard and simple tools (Fig. 16).

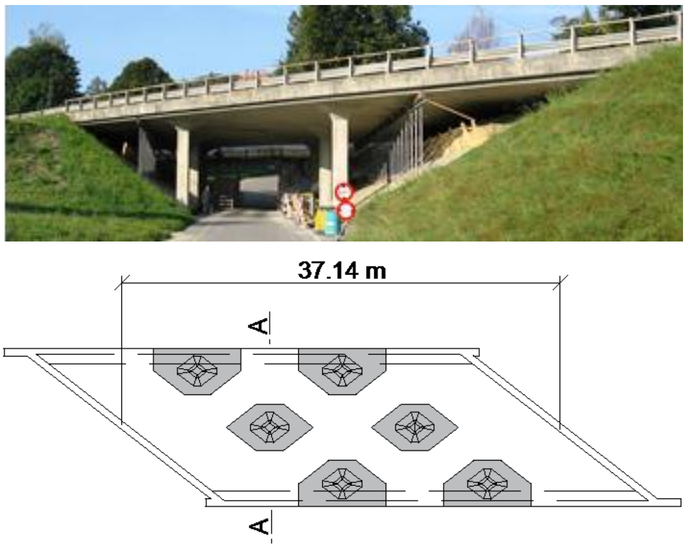

Figure 13. Massive slab bridge strengthened using R-UHPFRC over piers (dark areas).

Bituminous pavement was finally applied on a bituminous emulsion on the UHPFRC surface after more than three days of curing. Traffic in both directions was kept in service on one traffic lane during the works.

Figure 14. UHPFRC casting for R-UHPFRC strengthened zone over a pier.

5 LIFE-CYCLE CONSIDERATIONS

5.1 *Maintenance strategies*

The successful rehabilitation of existing bridges is a major challenge for structural engineers. Figure 15 presents two different strategies of bridge maintenance from an user's or owner's point of view. The traffic demand is continuously increasing in all cases.

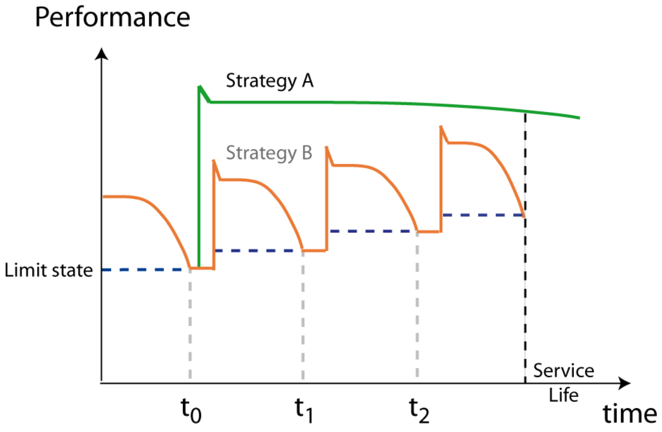

Figure 15. Evolution with time of the demand and supply for two different maintenance strategies.

During the planned service life of the structure Strategy B usually induces multiple interventions for rehabilitation with periods of traffic disruptions. 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 months each with significant consequences in terms of traffic disturbance, as well as 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.

Obviously, Strategy A is highly desirable. It ought to be the objective of any rehabilitation intervention. Strategy A may be achieved by means of novel rehabilitation technologies such as the UHPFRC rehabilitation technology presented in this paper (rather than by theoretical life-cycle considerations).

These novel rehabilitation technologies need to be economic in terms of intervention cost and environmental impact.

5.2 *Economic aspects of UHPFRC rehabilitation technology*

The significant material cost imposes to use UHPFRCs only where maximum benefit of their outstanding mechanical properties can be taken. Obviously, the more requirements (regarding durability, structural/fatigue resistance and functionality) are fulfilled with one UHPFRC layer, the more efficient and economical is the technology.

Analysis of construction costs alone showed that the rehabilitation realized with UHPFRC was in most cases not more expensive and in some cases significantly less expensive than conventional methods (which provide however lower quality in terms of durability).

In addition, the UHPFRC technology allows for significant reductions in the duration of construction sites reducing thus user costs. Also, it provides significant gains in terms of long term durability and reduction of traffic disruptions (and subsequent user costs) due to multiple interventions required in the case of conventional approaches.

These economic aspects allow for a change in paradigm in the domain of life-cycle engineering.

5.3 *Change in paradigm*

Figure 15 shows the evolution of the performance of a rehabilitated bridge over its service life, using two different rehabilitation technologies. In general, under the influence of service loads and deterioration processes, the performance of the structure decreases with time:

For strategy A, the choice of the rehabilitation technique is such that the performance decrease with time does not occur or is very slow over the whole planned service life. For concrete bridges, Strategy A may be achieved using the novel advanced UHPFRC rehabilitation technology.

For strategy B, the speed of performance drop due to deterioration processes requires several interventions during the service life of the structure. Strategy B is based on current state-of-the-art methods using ordinary concrete or mortar repair materials and technologies. Strategy B obviously has not the objective to improve structures showing deficiencies.

Strategy B is still considered by many researchers as being given or inherent to structures. These researchers don’t account for novel technologies that improve significantly existing structures after rehabilitation. Actually approaches in the domain of life-cycle management need Strategy B or similar as a basic hypothesis. Strategy A would virtually make life-cycle considerations obsolete.

Consequently, a fundamental change in paradigm, i.e., a change from Strategy B to Strategy A, is thus needed to seriously tackle the question of infrastructure management. Research efforts need to be made in the domain of material and structural engineering rather than in the domain of life-cycle costing and management.

6 CONCLUSIONS

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

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

More than 10 applications of the concept under site conditions demonstrate the potential of this novel technology.

The technology of UHPFRC is mature for cast in-situ and prefabrication using standard equipment for concrete manufacturing.

A fundamental change in paradigm, i.e., a change from the conventional strategy of multiple interventions to a strategy of a one-time intervention leading to a significant improvement of the structure after the rehabilitation intervention, is needed to seriously tackle the question of infrastructure management.

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REFERENCES

This paper summarizes research activities of MCS's UHPFRC group at EPFL, and it is referred to own articles only. References to contributions by other research groups and researchers can be found in the listed papers:

Brühwiler, E., Fehling, E., Bunje, K., Pelke, E. 2007. Design of an innovative composite road bridge combining reinforced concrete with Ultra-High Performance Fibre Reinforced Concrete. Proceedings, *IABSE Symposium "Improving Infrastructure Worldwide", Weimar,* September 2007.

Charron, J.-P., Denarié, E., Brühwiler, E. 2006. Permeability of Ultra High Performance Fiber Reinforced Concretes (UHPFRC) under high stresses, *Materials and Structures*, Vol. 40, No 3 (March), 2007, pp. 269-277.

Denarié E. & Brühwiler E. 2011. Strain Hardening of Ultra-high Performance Fibre Reinforced Concrete: Deformability versus Strength Optimization, *International Journal for Restoration of Buildings and Monuments*, Aedificatio Publishers Freiburg Germany, Vol. 12, No 6.

Denarié E., Kazemi-Kamyab H., Brühwiler E., Haddad B., Nendaz S. 2011. Béton fibré ultra performant pour la maintenance, un nouvel élan. *Tracés* No. 12: 20-23.

Denarié E. 2009. Recommendations for the tailoring of UHPFRC recipes for rehabilitation, *Deliverable ARCHES D06*, http://arches.fehrl.org.

Denarié, E., Brühwiler, E. 2006. Structural rehabilitations with Ultra High Performance Fibre Reinforced Concretes, *International Journal for Restoration of Buildings and Monuments*, Aedificatio Publishers Freiburg Germany, Vol. 12, No. 5 and 6, pp. 453-467.

Habel, K., Denarié, E., Brühwiler, E. 2006. Structural response of elements combining Ultra-High Performance Fiber Reinforced Concretes (UHPFRC) and reinforced concrete, *ASCE Structural Journal*, November (2006): 1793-1800.

Habel, K. 2004. Structural behaviour of elements combining Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) and Reinforced Concrete. *Doctoral Thesis No 3036, Ecole Polytechnique Fédérale de Lausanne (EPFL)*.

Noshiravani, T. 2012. Structural response of R-UHPFRC –RC composite members subjected to combined bending and shear, *Doctoral Thesis No 5246, Ecole Polytechnique Fédérale de Lausanne (EPFL)*.

Oesterlee, C. 2010. Structural response of reinforced UHPFRC and RC composite members, *Doctoral Thesis No 4848, Ecole Polytechnique Fédérale de Lausanne (EPFL)*.

Oesterlee, C., Sadouki, H., Brühwiler, E. 2008. Structural analysis of a composite bridge girder combining UHPFRC and reinforced concrete, Proceedings, *UHPC-2008: The Second International Symposium on Ultra High Performance Concrete*, Kassel, Germany.

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.

Šajna, A., Denarié, E., Bras, V. 2012, Assessment of a UHPFRC based bridge rehabilitation in Slovenia, two years after application, Proceedings, *HIPERMAT Conference, Kassel*.

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: HPFRCC, http://samaris.zag.si/.

Wuest J. 2007. Structural behaviour in tension of Ultra-High Performance Fibre Reinforced Concrete in composite elements. *Doctoral Thesis No. 3987. Ecole Polytechnique Fédérale de Lausanne (EPFL)*. (in French).