Rehabilitation and Strengthening of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete

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Abstract

An original concept is presented for the durable rehabilitation and strengthening of concrete structures. The main idea is to use ultra-high performance fibre reinforced concrete (UHPFRC) complemented with steel reinforcing bars to protect and strengthen those zones of the structure that are exposed to severe environmental influences and high mechanical loading. This concept efficiently combines the protection and resistance properties of UHPFRC and significantly improves the structural performance of the rehabilitated concrete structure in terms of durability. The concept has been validated by means of field applications, demonstrating that the technology of UHPFRC is now well developed for cast *in situ* and prefabrication using standard equipment for concrete manufacturing. This novel technology is a step forward towards more sustainable structures.

Keywords: existing concrete structures; rehabilitation; strengthening; ultra-high performance fibre reinforced concrete; composite UHPFRC–RC structures; durability; ultimate resistance.

Introduction

Reinforced concrete (RC) structures show excellent performance in terms of structural behaviour and durability except for the zones that are exposed to severe environmental influences and high mechanical loading. Rehabilitation of deteriorated concrete structures is a heavy burden from the socio-economic viewpoint since it leads to significant user costs. As a consequence, novel concepts for the rehabilitation of concrete structures must be developed. In the future, sustainable concrete structures will be those requiring just minimum intervention for preventive maintenance with no or 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 various types of ultra-high performance fibre reinforced concrete (UHPFRC). These novel building materials provide the structural engineer with a unique combination of properties: extremely low permeability that prevents the ingress of detrimental substances such as water and chlorides[1] and high strength including compressive strength higher than 150 MPa and tensile strength higher than 10 MPa. The tensile behaviour shows significant strain hardening and softening behaviour.[2]

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Consequently, UHPFRC has an increased resistance against severe environmental influences and high mechanical loading. Thus, this building material can be used to significantly improve structural resistance and durability of concrete structures.

This paper presents an original concept for the rehabilitation and strengthening of concrete structures. The concept is described and some scientific background regarding the structural behaviour of RC elements strengthened with UHPFRC is given. Finally, this novel technology is validated by means of applications. This paper summarizes more than 12 years of research and development of a new technology to improve concrete structures.

Conceptual Idea

The basic concept is to use UHPFRC only in the zones of a structure where outstanding UHPFRC properties in terms of durability and strength are fully exploited; i.e. UHPFRC is used to strengthen the structure where it is exposed to severe environmental conditions (e.g. de-icing salts, marine environment) and high mechanical loading (e.g. concentrated forces, fatigue, impact). Parts of the structure that are subjected to relatively moderate exposure remain in conventional structural concrete. This concept is applicable both to rehabilitate existing structures and to build new structures. It necessarily leads to composite structural elements combining conventional RC and UHPFRC.

The protective and mechanical properties of UHPFRC combined with steel reinforcing bars (reinforced UHPFRC or R-UHPFRC) provides a simple and efficient way of increasing the stiffness and structural resistance capacity while 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 in the range of 3 to 6 MPa (or 30 to 60% of the elastic limit strength f_{Ute}) are induced in the UHPFRC layer owing to restrained deformations at an early age. This state of stress needs to be analysed and evaluated but is usually resisted by the UHPFRC without crack formation.

The original concept (developed in 1999) has been investigated by means of extensive research activities aimed at characterizing the properties of UHPFRC and the structural behaviour of R-UHPFRC–RC composite structural members, combining material and structural engineering sciences. The concept is well suited for bridges, buildings, galleries, tunnels and retaining walls.

Composite R-UHPFRC–RC Sections

Mix Design and Fresh UHPFRC Properties

UHPFRC mixes typically contain 650 to 1400 kg/m^3 of cement as well as microsilica and fine quartz sand with

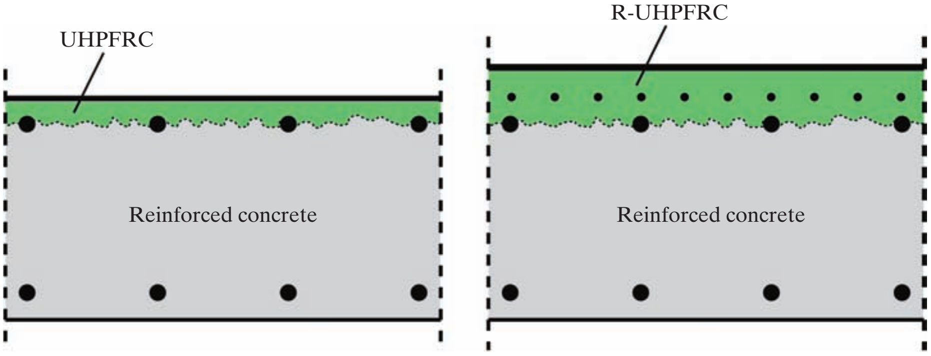

Fig. 1: Basic configuration of composite structural elements combining R-UHPFRC and conventional RC

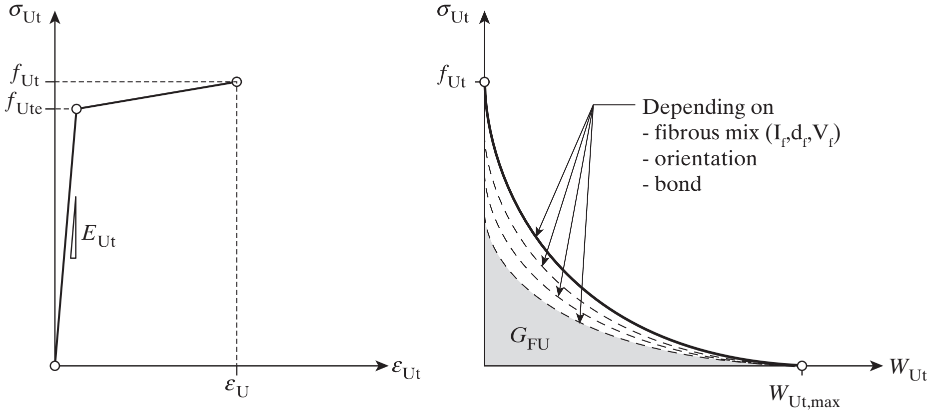

Fig. 2: Tensile behaviour of UHPFRC: material laws for elastic-strain hardening behaviour and for softening behaviour

a maximum grain size of 0,5 mm. The water/binder ratio is between 0,13 and 0,17. The components are mixed using a superplasticizer 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 more economic and environmentally friendly UHPFRC.[3] This matrix is strengthened with straight steel fibres of 10 to 15 mm length with an aspect ratio of 50 to 80, with a dosage of at least 3% in volume.

UHPFRC has excellent rheological properties in the fresh state, allowing easy casting of the self-compacting fresh material with conventional concreting equipment, on the construction site and in the prefabrication plant.

Tensile Behaviour of UHPFRC and R-UHPFRC

Plain UHPFRC

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

First, the material is elastic up to the elastic limit strength f_{Ute}, with typical values of 7 to 11 MPa for the currently used UHPFRC. Second, it goes into a strain-hardening phase characterized by fibre activation accompanied by multiple (non-visible) microcracking of the matrix. The material still behaves as a continuum. Significant strain-hardening behaviour is only obtained with a fibre content of at least 3% by volume. The strain-hardening domain may reach strains ε_U of 2 to 5‰ while the tensile strength f_{Ut} reaches values ranging from 9 to 15 MPa. The third phase starts upon the formation of a discrete macrocrack at ultimate resistance, and strain softening begins. The maximum crack opening $w_{Ut,max}$ equals about half of the fibre length, i.e. 5 to 8 mm. With these openings, no more tensile stress is transferred. For a given elastic tensile strength f_{Ute}, the tensile hardening and softening behaviours of UHPFRC depend on the bond, aspect ratio, content and random orientation of the straight steel fibres.[4,5]

The fractured surface of a UHPFRC specimen after a tensile test shows numerous steel fibres, pulled out from the matrix. The corresponding work to pull out these fibres explains the relatively high specific fracture energy G_{FU} of UHPFRC (typically ranging from 20 to 30 kJ/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 materials such as UHPFRC is application dependent. Anisotropic fibre orientation can be enforced by the casting procedure or the width and shape of the moulds. This has to be considered in the analysis of test results and in design. Adding reinforcing bars to the UHPFRC reduces this anisotropic fibre orientation.

In the present article, UHPFRC implies, in particular, materials with a pronounced strain-hardening behaviour as this is an important property for applications in composite members.

R-UHPFRC

The main reasons to complement UHPFRC by steel reinforcing bars are a significant improvement of the tensile behaviour of plain UHPFRC and a reduction of the scatter in the material properties. Small diameter steel reinforcing bars (arranged with relatively small spacing) provide in-plane continuity to the UHPFRC layer and ensure its monolithic action with the RC element in flexural members.[5,6] The rebars not only increase the resistance but also improve the deformation capacity and strain-hardening behaviour of UHPFRC. Thus, the reinforcing bars enhance the apparent tensile behaviour of UHPFRC.

The overall tensile behaviour of R-UHPFRC can be described by linear superposition of the steel and the UHPFRC tensile behaviours (*Fig. 3*). The deformation is localized to one macrocrack at the start of yielding of the reinforcing steel. This was observed to be independent of 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 makes it possible to combine UHPFRC with high yield strength reinforcing bars (700 MPa or above).

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

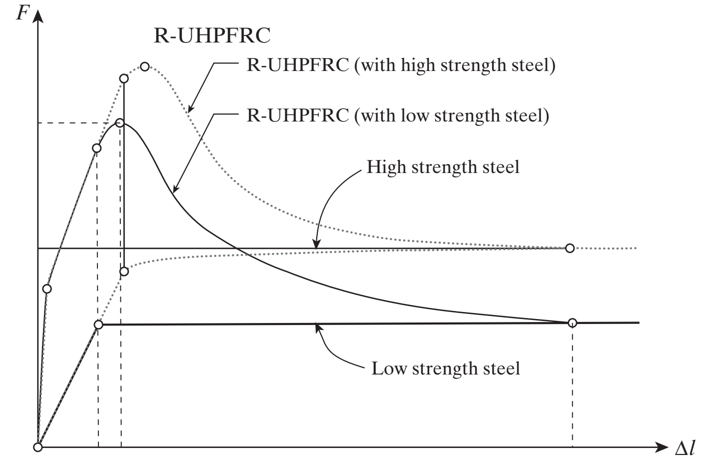

Fig. 3: Characteristic tensile behaviour of R-UHPFRC

Structural Response of R-UHPFRC–RC Composite Beams

Behaviour in Bending

When in tension, the R-UHPFRC layer principally acts as an added flexural reinforcement for the RC element. Both the steel rebars and the UHPFRC contribute to the resistance. RC beams strengthened with an R-UHPFRC layer are characterized by a significant increase in the stiffness and the ultimate resistance. This increase depends on the type and strength of the steel reinforcement.[5,6]

The bond between UHPFRC and concrete is obtained by preparing the concrete support surface with high pressure water jet or sand blasting. It is sufficient to avoid separation between UHPFRC and concrete. In fact, in all fracture tests there was no separation along the interface zone beyond the ultimate resistance and significantly into the post-peak domain. Since there is no slip between the two layers, shear connectors would not be effective.

The plastic post-peak rotation capacity of strengthened RC beams is reduced by the UHPFRC layer. With an appropriate design of the UHPFRC reinforcement, the reduction in plastic rotation capacity can be controlled. Smooth bars bring the least reduction, and ribbed bars the highest. The use of smooth high yield strength reinforcing bars in the UHPFRC layer offers a large increase in resistance while the post-peak rotation capacity remains high.

The structural behaviour of composite sections subjected to bending and the ultimate bending moment are calculated using the conventional model for RC with an extension to account for the R-UHPFRC layer (*Fig. 4*).[5,7]

When in compression, the R-UHPFRC layer acts as a compression chord but the high UHPFRC compressive strength of about 200 MPa cannot be fully exploited in R-UHPFRC–RC members. This is why compressive behaviour of UHPFRC requires less attention in the case of R-UHPFRC–RC members.

Behaviour Due to Combined Bending and Shear

When subjected to combined bending and shear, R-UHPFRC–RC members develop close to the ultimate resistance

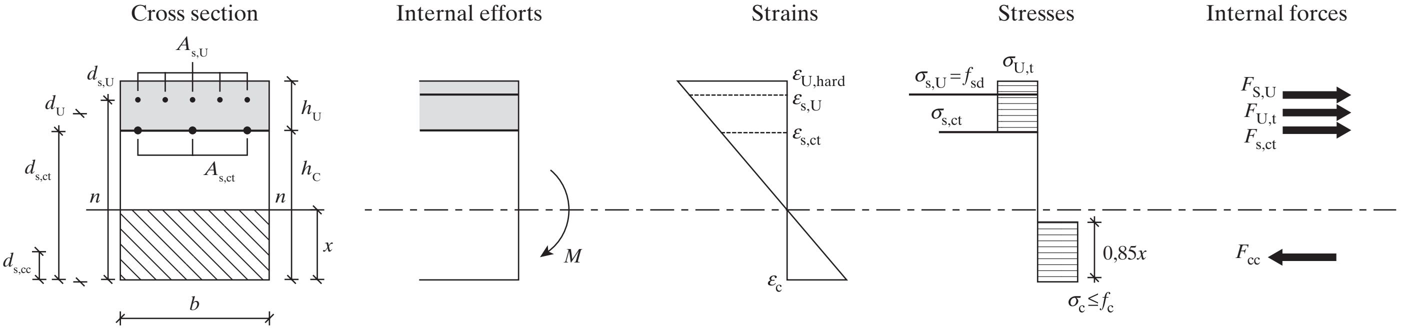

Fig. 4: Determination of ultimate moment of R-UHPFRC–RC members

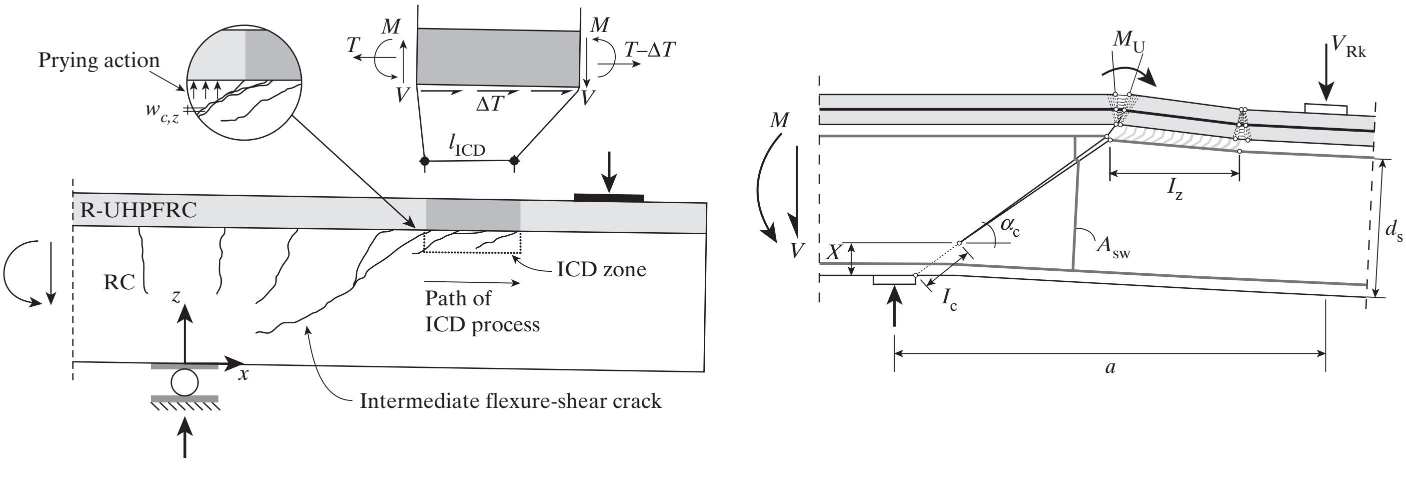

Fig. 5: Intermediate-crack-induced delamination (ICD) in R-UHPFRC–RC elements subjected to combined bending and shear

a so-called intermediate crack induced delamination (ICD) zone (*Fig. 5*). This ICD zone is, in fact, the softening of the connection between the two elements.[8] The relative vertical movement of the RC segments separated by inclined flexure-shear cracks generates prying stresses on the R-UHPFRC layer. These stresses are resisted by the R-UHPFRC tensile element bending in double curvature and forming two hinges above the end zones of the ICD.

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 the formation of the flexure-shear collapse mechanism.

The ultimate resistance of R-UHPFRC–RC beams and slabs subjected to combined bending and shear depends on the shear span–depth ratio (*a/d*), the ratio of shear reinforcement (stirrups) in the RC element, the longitudinal reinforcement, namely, the steel rebars and the UHPFRC section and finally the bond characteristics of each reinforcement, including that of the UHPFRC layer, which is influenced by the ICD zone.

The contribution of the tensile R-UHPFRC element is twofold: first, the element resists the out-of-plane prying stresses by bending in double curvature. Second, by acting as an external tensile reinforcement, the element controls the width of cracks in concrete, thus increasing the shear resistance.

Both mechanisms are inversely related to the length of the ICD zone between the RC and the R-UHPFRC elements. While the former mechanism contributes to the shear resistance after a flexure-shear failure, the latter is then replaced by the tensile membrane action of the R-UHPFRC reinforcement. Analogous to the longitudinal tensile rebars, the vertical component of the tensile force in the deformed R-UHPFRC element contributes to the shear resistance of the member. The post-peak flexure-shear failure mechanism is of interest in the design of structures that require structural redundancy and the ability to redistribute loading after a local failure, thus preventing progressive collapse.

Models were developed to predict the ultimate resistance and the pre-peak deformation capacity of the beams.[9,10]

Fatigue Behaviour

Series of experiments were performed on plain UHPFRC and R-UHPFRC specimens as well as R-UHPFRC–RC composite beams. Tensile fatigue tests with constant amplitude cycles were conducted on plain UHPFRC specimens up to 10 million cycles. The objective was to determine the endurance limit of UHPFRC. These fatigue tests revealed that this limit exists in all three domains of the UHPFRC tensile behaviour (i.e. elastic, hardening and softening) at S-ratios ranging from 0,70 to 0,45, *S* being the ratio of the maximum fatigue stress to the elastic limit strength of UHPFRC.[11] Rather large variations in local specimen deformations were measured during the tests, which indicates significant stress and deformation redistribution capacity of the UHPFRC bulk material.

The fatigue fracture surface of UHPFRC showed features of fatigue fracture surfaces known from steel, i.e. fatigue crack propagation is identified by a smooth surface while final fracture leads to a rather rough surface. Various fatigue damaging mechanisms due to fretting and grinding as well as tribocorrosion were identified.

The fatigue tests on R-UHPFRC showed internal stress distribution. The measured growth of the deformation of R-UHPFRC was attributed to the stiffness degradation of UHPFRC caused by microcracking in the hardening domain. The fatigue fracture process of R-UHPFRC specimens was finally determined by fatigue fracture of steel rebars.

The results of bending fatigue tests on 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 seemed to exist.

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.

Applications

Introduction

Since 2004, UHPFRC was applied more than 20 times in Switzerland (and in one case in Slovenia[12]) on existing RC structures: on bridge deck slabs as thin watertight overlays (in replacement of currently used waterproofing membranes) as well as on bridge and building slabs as reinforcement layers in R-UHPFRC. This layer provides structural resistance capacity for bridge elements and slabs in buildings without increasing the dead load of the structure.

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

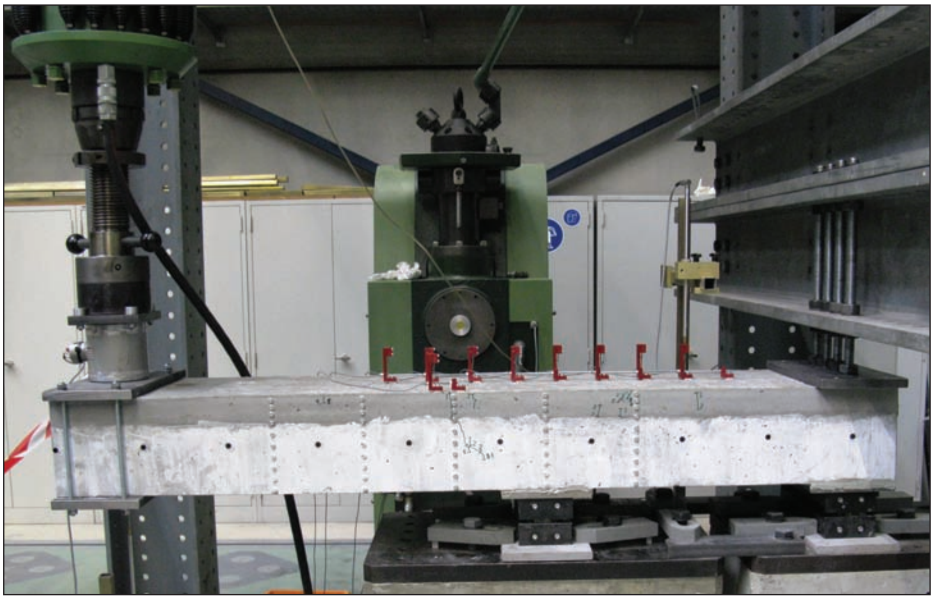

Fig. 6: Bending fatigue test set-up on R-UHPFRC–RC composite beams (beam length: 1900 mm, depth: 220 mm)

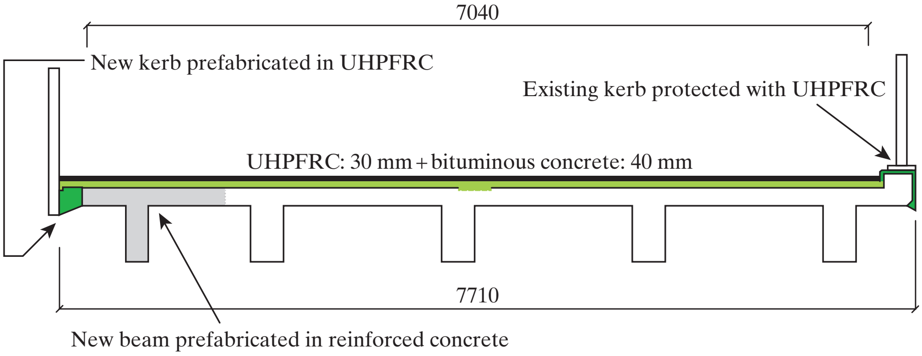

Fig. 7: Bridge cross section after rehabilitation (Units: mm)

Fig. 8: UHPFRC casting and handling of UHPFRC using simple tools

Fig. 9: Rehabilitation of a bridge deck of an underpass with UHPFRC: slope 5%, average external temperature of 5°C

substances such as de-icing salts and impact-like action. Such elements usually show insufficient durability when built with conventional reinforced concrete. Again, UHPFRC is suitable to establish the required durability and mechanical performance of such structural elements.

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.[13,14] The entire deck surface of the bridge was rehabilitated in three steps (*Fig. 7*).

Firstly, the downstream curb was replaced by a 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 30 mm of UHPFRC in two consecutive steps so that one traffic lane could stay open. Finally, the concrete surface of the upstream curb was replaced with 30 mm 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 with high-pressure water jetting (*Fig. 8*). The UHPFRC was easy to produce and to place with standard tools and very robust and tolerant to the unavoidable, peculiar site conditions.

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 1 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.

One challenging application of UHPFRC took place in late fall 2010 on a heavily trafficked road with 20000 vehicles per day and per lane and with slopes of 5% on the bridge deck (*Figs. 9 and 10*). The UHPFRC mix is self-compacting and can be cast on slopes with 5% inclination. This application helped the owner to save about 30% on construction costs when compared to conventional intervention methods by avoiding an expensive and long re-profiling procedure of the concrete road in front of and behind the bridge to accommodate the position of the rebars unexpectedly close to the road surface in the upper face of the deck and to reduce the duration of intervention (and thus traffic restriction) to only 14 days per lane.

Several more applications following the same principle have been conducted under various weather

Fig. 10: Rehabilitation of a bridge deck with UHPFRC: tight geometrical constraints for rebars

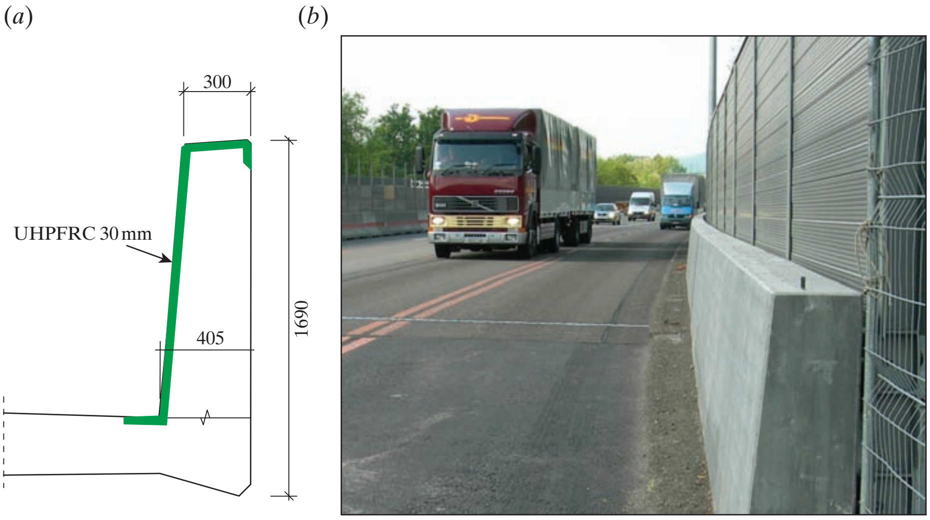

Fig. 11: (a) Typical cross section of the crash barrier wall and (b) view after rehabilitation (Units: mm)

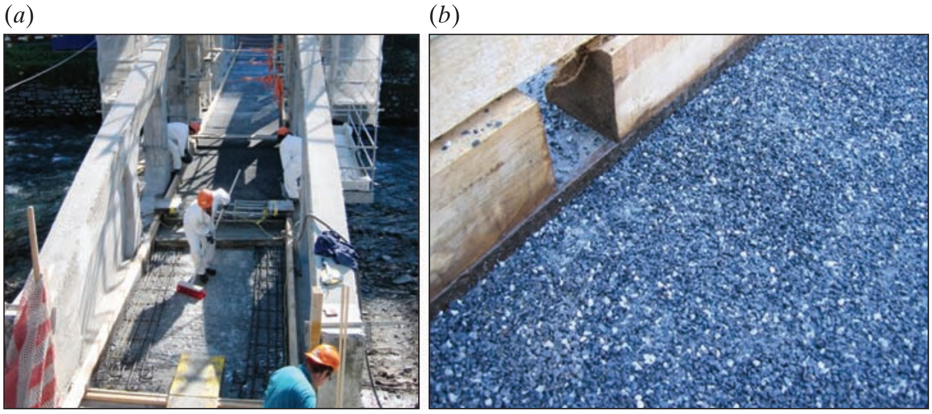

Fig. 12: (a) Rehabilitation and strengthening of a bridge deck slab with reinforced UHPFRC; (b) drivable UHPFRC surface

conditions and construction site constraints. Fresh UHPFRC has also been mixed at the construction site. By optimizing additives, maximum slopes of up to 10% could be cast with this self-compacting material.

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 because of 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 the UHPFRC layer to ingress of water and chloride ions is extremely low.

The rheological properties of UHPFRC were adapted for easy pouring into the 30 mm wide by 1,20 m high formwork.

The UHPFRC is bonded to the existing reinforced concrete wall, and the early-stage deformations of the material (mostly due to thermal and autogenous shrinkage) are restrained. Consequently, an internal stress state builds up in the composite element with tensile stresses in the UHPFRC layer reaching maximum values of 7 to 9 MPa, obtained from numerical analysis.[15,16] These tensile stresses are resisted by the UHPFRC without crack formation as confirmed by visual inspections after the application.

The next application consisted in fabricating 40 mm thick UHPFRC shell elements to form an outer protection shield for an existing 40-year-old reinforced concrete bridge pier 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.

Strengthening of Slabs

As a first example, the deck slab of a over 70-year-old reinforced concrete bridge of high cultural value had to be rehabilitated and strengthened to accommodate 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 of improving the durability and restoring the structural safety (*Fig. 12*). Gravel was dispersed on the fresh UHPFRC to obtain the level of roughness of the surface required to make it fit for road traffic.

As a second example, 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

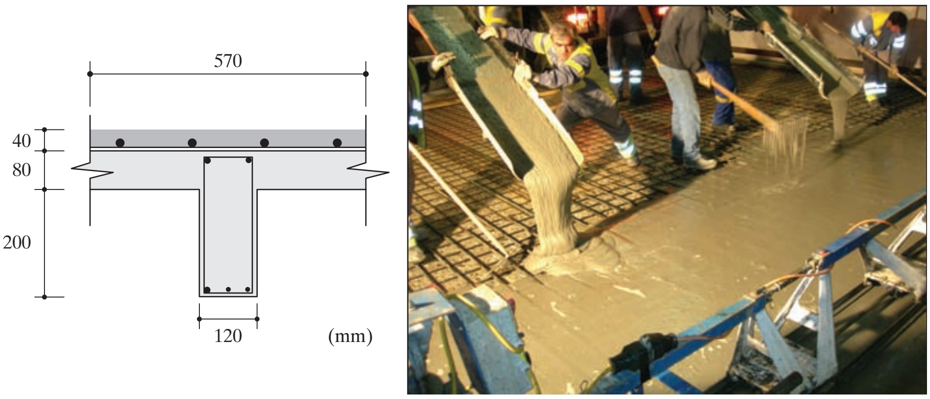

Fig. 13: (a) Cross section with R-UHPFRC layer (in dark grey) and (b) a view of UHPFRC casting

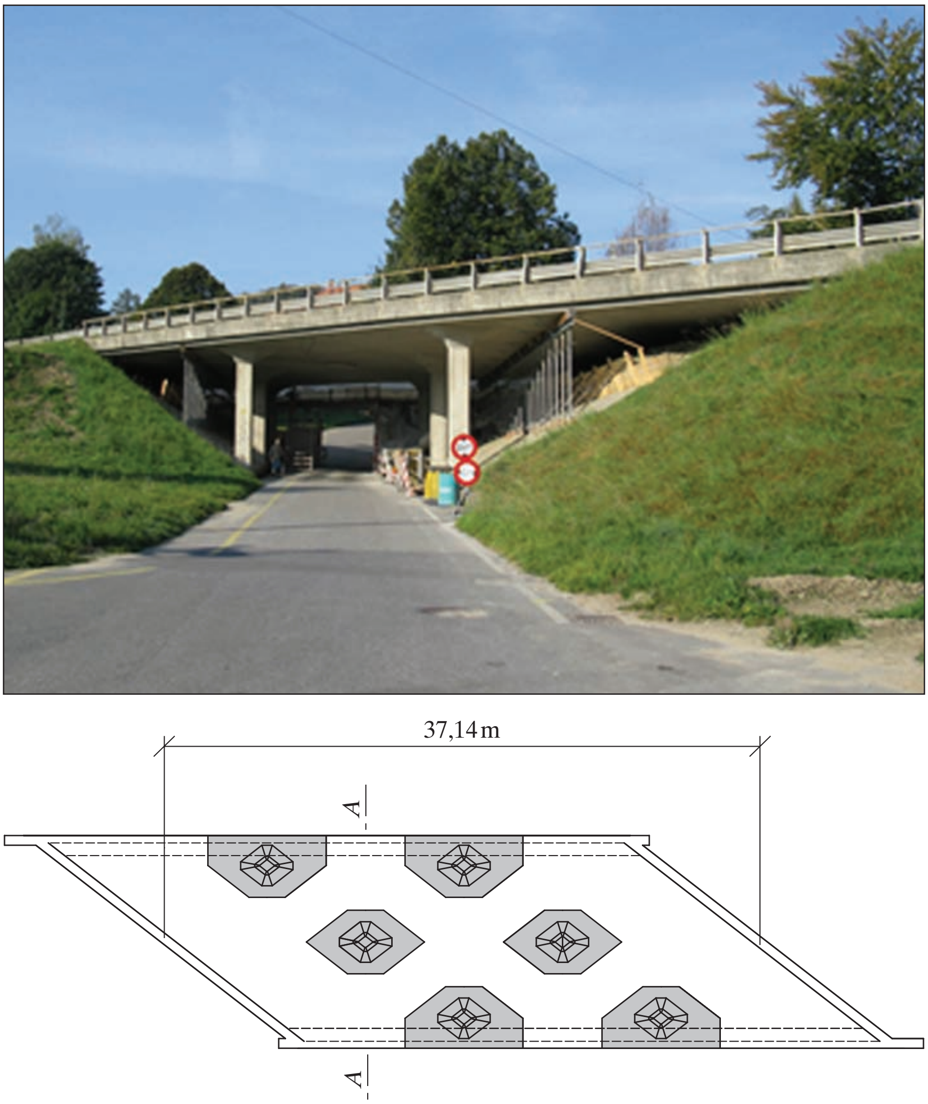

Fig. 14: Massive slab bridge strengthened using R-UHPFRC over piers (dark areas)

concept for increasing the structural capacity of the existing slab of 720 m^2 was to pour a 40 mm thick UHPFRC layer on top of the existing RC slab in replacement of the existing cementitious overlay (*Fig. 13*). The UHPFRC layer leads to a thicker load-carrying slab providing better distribution of local wheel loads, increase in static height and high strength material to resist both compression and tension stresses.

The use of UHPFRC turned out to be a very economic solution (compared to the conventional solution of slab demolition and reconstruction). In addition, the utilization of the fire workers building was only slightly restricted during the intervention and thus user costs could be kept minimal.

As a third example, a 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. 14*). Load-bearing capacity of the bridge was found to be insufficient for the present and future vehicles. Besides, its deck slab had deteriorated because of chloride-induced rebar corrosion.

A UHPFRC layer that is 25 mm thick was cast for waterproofing of the whole deck. The areas above the columns were strengthened by a 65 mm thick R-UHPFRC layer in order to increase bending and punching shear resistance. The UHPFRC material was prepared on site, and about 300 l were mixed per batch. The RC top surface was first treated with high pressure water jet to remove the concrete up to a depth of 20 to 40 mm. UHPFRC was then cast with standard and simple tools (*Fig. 15*).

Bituminous pavement was finally applied with a bituminous emulsion on the UHPFRC surface after more than 3 days of curing. Traffic in both directions was maintained on one traffic lane during the work.

Economic Aspects

The relatively high material cost restricts the use of UHPFRC to only where maximum benefit of the outstanding mechanical properties can be exploited. Obviously, the more requirements (regarding durability, structural and fatigue safety, 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 similar and in some cases significantly less expensive than using conventional methods (which, however, provide lower quality in terms of durability and life-cycle costs).

In addition, the UHPFRC technology allows for significant gains in terms of long-term durability when compared to conventional methods. Also, depending on the given site conditions, it provides important reduction of traffic disruptions (and subsequent user costs) due to multiple interventions

Fig. 15: *UHPFRC casting for R-UHPFRC strengthened zone over a pier*

(required in the case of conventional methods).

Conclusions

An original concept using UHPFRC for the rehabilitation and strengthening of concrete structures has been developed and validated by means of site applications.

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

Numerous 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.

This original concept may also be applied for the construction of durable new reinforced concrete structures by assembling prefabricated elements in conventional concrete with UHPFRC and by complementing with a UHPFRC layer those areas that are subjected to severe environmental and mechanical exposure.[17]

Acknowledgements

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.

References

[1] Charron J-P, Denarié E, Brühwiler E. Permeability of ultra high performance fiber reinforced concretes (UHPFRC) under high stresses. *Mater. Struct.* 2007; **40**(3): 269–277.

[2] Denarié E, Brühwiler E. Strain hardening of ultra-high performance fibre reinforced concrete: deformability versus strength optimization. *Int. J. Restor. Build. Monum.* 2011; **12**(6): 397–410.

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

[4] Wuest J. *Structural Behaviour in Tension of Ultra-High Performance Fibre Reinforced Concrete in Composite Elements*. Doctoral Thesis No. 3987, Swiss Federal Institute of Technology, Lausanne (EPFL), 2007 (in French).

[5] Oesterlee C. *Structural Response of Reinforced UHPFRC and RC Composite Members*. Doctoral Thesis No. 4848, Swiss Federal Institute of Technology Lausanne (EPFL), 2010.

[6] Habel K. *Structural Behaviour of Elements Combining Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) and Reinforced Concrete*. Doctoral Thesis No 3036, Swiss Federal Institute of Technology Lausanne (EPFL), 2004.

[7] Habel K, Denarié E, Brühwiler E. Structural response of elements combining ultra-high performance fiber reinforced concretes (UHPFRC) and reinforced concrete. *ASCE Struct. J.* 2006; **132**(11): 1793–1800.

[8] Noshiravani T, Brühwiler E. Experimental investigation on R-UHPFRC – RC composite beams subjected to combined bending and shear, *ACI Struct. J.* 2013; **110**(2): 251–261.

[9] Noshiravani T, Brühwiler E. Analytical model for predicting the response and flexure-shear resistance of R-UHPFRC–RC composite beams. *ASCE J. Struct. Eng.* (in press).

[10] Noshiravani T, Brühwiler E. Rotation capacity and stress redistribution ability of R-UHPFRC - RC composite continuous beams: an experimental investigation. *Mater. Struct.* 2013. DOI: 10.1617/s11527-013-0033-5 [Epub 24 February 2013].

[11] Makita T, Brühwiler E. Tensile fatigue behaviour of ultra-high performance fibre reinforced concrete. *Mater. Struc.* 2013. DOI: 10.1617/s11527-013-0073-x [Epub 23 April 2013].

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

[13] Denarié E, Brühwiler E. Structural rehabilitations with ultra high performance fibre reinforced concretes. *Int. J. Restor. Build.Monum.* 2006; **12**(5 and 6) : 453–467.

[14] SAMARIS. *Full Scale Application of UHPFRC for the Rehabilitation of Bridges, European Project 5th FWP/SAMARIS – Sustainable and Advanced Materials for Road Infrastructures – WP 14: HPFRCC.* SAMARIS Report D22, 2005, http://samaris.zag.si/.

[15] Oesterlee C, Denarié E, Brühwiler E. 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: Stuttgart, Germany.

[16] 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*, Kassel, Germany, 2008.

[17] Brühwiler E, Fehling E, Bunje K, Pelke E. Design of an innovative composite road bridge combining reinforced concrete with ultra-high performance fibre reinforced concrete. *Proceedings, IABSE Symposium "Improving Infrastructure Worldwide",* Weimar, Germany, 2007; 80–81.