“STRUCTURAL UHPFRC” TO ENHANCE BRIDGES

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Abstract

“Structural UHPFRC” stands for Ultra-High Performance Fiber Reinforced Cementitious Composite material that is complemented by reinforcing and prestressing steel to enhance the resistance and durability of structural elements. Properties of impermeable, tensile strain hardening UHPFRC are outlined in view of structural applications. Two fundamental concepts to enhance concrete bridges have been developed by research and validated by applications in Switzerland: 1) Rehabilitation and strengthening of existing concrete structures by adding a layer of structural UHPFRC, and 2) Construction of new structures in Structural UHPFRC, often composed of precast elements. These applications show that Structural UHPFRC has made its proof as a novel building material and technology to enhance bridges and structures in general. Structural UHPFRC is the advent of a new construction era.

1. INTRODUCTION TO THE UHPFRC TECHNOLOGY

“UHPFRC” stands for Ultra-High Performance Fibre Reinforced Cementitious Composite material produced from cement and other reactive powders, additives, fine hard particles (maximum grain size of 1mm), water, admixtures and a large amount of slender short steel fibres. UHPFRC materials have been developed over the last 30 years. Today, the best UHPFRC have significant tensile strain hardening behaviour and high resistance both in tension and compression. UHPFRC is a compact material that is waterproof and crack-free under service stresses, thus providing a robust protection against water and chloride ion ingress. These properties allow for the design and construction of lightweight structures that are effectively durable and have enhanced structural resistance when compared to reinforced concrete and steel structures. In addition, the environmental impact of lightweight UHPFRC structures is limited.

UHPFRC does not comply with the definition of “concrete”, and therefore, UHPFRC should not be called “concrete” as is evidenced in Figure 1. UHPFRC must be understood as an individual material with specific properties implying a technology with its own features. This is the first basic principle when designing with UHPFRC to enhance existing structures and build new structures.

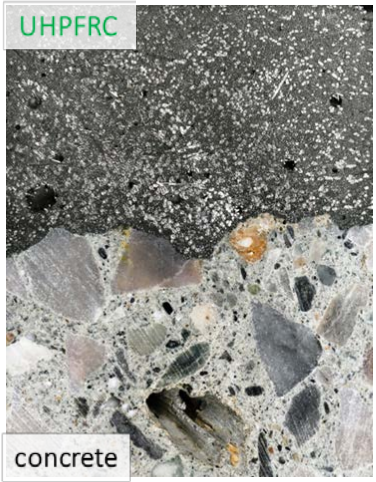

Fig. 1. UHPFRC – concrete core showing the obvious difference between the two materials.

The second principle is that UHPFRC is complemented in a targeted manner with reinforcing steel in order to enhance structural performance and economy of applications. Subsequently, the term Reinforced UHPFRC (or short: R-UHPFRC) is used.

Today, the state-of-knowledge is sufficient to establish rational design rules for the application and implementation of “Structural UHPFRC” in structural engineering. Several standards exist already, for example, in Switzerland the Technical Leaflet SIA 2052 [1].

Two fundamental concepts treated in the Swiss Technical Leaflet SIA 2052, have been developed by research and validated by applications in Switzerland:

- enhancement of existing concrete structures by adding a layer of structural UHPFRC, and
- construction of new structures in Structural UHPFRC often composed of precast elements.

This keynote paper focusses on aspects relevant for the structural engineering design using Structural UHPFRC. Part 1 summarizes the properties of UHPFRC and R-UHPFRC in terms of structural performance. Part 2 presents the design and execution of the strengthening of a (1) box girder and (2) multiple beam girder of existing concrete bridges using analytical formulas allowing to determine the increase in structural resistance. Part 3 presents main aspects of the design and construction of two pedestrian bridges and one short span railway bridge.

PART 1

2. STRUCTURAL PERFORMANCE OF UHPFRC AND R-UHPFRC

Remark: The required performance of currently used strain-hardening UHPFRC is summarized in [1-3]. Other fibre reinforced cementitious materials with lower performance – also designated as “UHPC” or high-strength concrete – do not qualify for the designs and applications described in this paper.

2.1 Tensile strength

The tensile behaviour of UHPFRC is of first importance for the intended structural behaviour under service stresses. The uniaxial tensile behaviour of plain UHPFRC has to comply with the indications given in Figure 2a. The significant strain hardening deformation ε_{Utu} of more than 2‰, while the tensile strength f_{Utu} reaches values ranging from 8 to 14MPa, can only be obtained with fibre contents of more than 3 volume-% of straight steel fibres with a slenderness of at least 65.

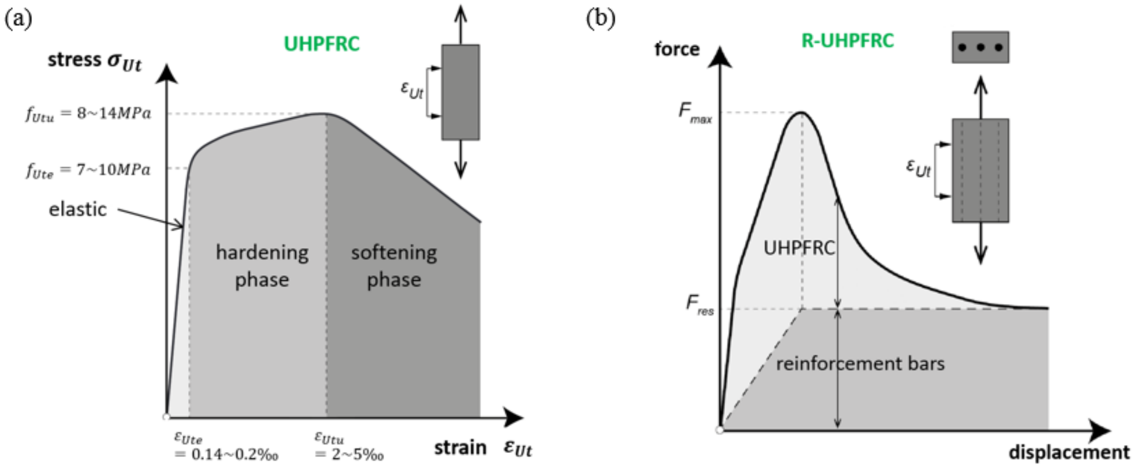

Figure 2. Characteristic tensile behaviour of a) plain UHPFRC and b) R-UHPFRC.

Significant strain hardening provides ductility. Built-in stresses and deformation due to shrinkage and creep as well as stresses due to external loads and forces may be absorbed without detrimental crack formation, even when stresses under service loading exceed the elastic limit stress of UHPFRC. The mechanical response of UHPFRC depends on the fibre orientation due to the casting procedure and the dimensions (thickness) of the UHPFRC element. Possible anisotropic fibre orientation due to casting procedure is mitigated by the high fibre content, by the adding of reinforcing bars to the UHPFRC and by stringent mixing procedure with controlled adding of the fibers to the fresh UHPFRC matrix. For structural design, fibre orientation is considered by a coefficient that decreases from 1.0 for a thickness of 30 mm to a value of 0.80 for increasing element thicknesses up to 80 mm and beyond.

The main reason to complement UHPFRC with steel reinforcing bars (to obtain R-UHPFRC) is the significantly improved tensile resistance and reduced scatter of material properties [4, 5]. 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. The rebars also improve the apparent deformation capacity and strain-hardening of UHPFRC. The mechanical behaviour in tension of R-UHPFRC is described by superposition of the reinforcing steel and the UHPFRC tensile behaviours (Fig. 2).

2.2 Compressive strength

The behaviour of UHPFRC under compression is characterized by a linear stress-strain relationship up to about 80% of the compressive strength. Beyond, a slight non-linear relationship may be taken into account for design purposes to describe the ascending branch up to compressive strength. The compressive strength of current UHPFRC is 150 to 200 MPa.

2.3 Modulus of elasticity

The modulus of elasticity of UHPFRC in tension and compression is 45 to 50 GPa which is relatively low. This is an advantage when UHPFRC is used to enhance RC structures since concrete has a modulus of elasticity of 30 to 45 GPa; early age deformation-induced stress due to temperature and shrinkage effects is thus limited. In the case of the design of new structures, the stiffness of UHPFRC structural elements is of first importance.

When UHPFRC is deformed in the tensile strain-hardening domain, UHPFRC shows reducing apparent modulus of elasticity with increasing hardening strain.

2.4 Shrinkage and creep

Final shrinkage and creep values of UHPFRC are similar to other cementitious materials, but may be considerably reduced by thermal treatment thereby increasing mechanical strength.

Shrinkage develops rapidly and about 60 to 90 % of total shrinkage has completed already after 50 days. The largest part of shrinkage of UHPFRC results from endogenous shrinkage.

2.5 Fatigue behaviour

The fatigue behaviour of UHPFRC under both tension and compression is characterized by the presence of a fatigue endurance limit at 50 to 60 % of UHPFRC tensile and compressive strength. Fatigue design verification is thus performed with respect to a fatigue limit stress.

2.6 Durability, abrasion and fire resistance

Regarding the durability performance, testing revealed that UHPFRC has extremely low air and water permeability, very high resistance against freeze-thaw-cycles, sulphates and AAR. In addition, increased resistance against acid liquids has been determined. This performance is explained by the extremely dense matrix showing a very low amount of capillary pores making strain-hardening UHPFRC impermeable for liquids, even under high tensile strains up to about 1.5 ‰. Under service stress, strain-hardening UHPFRC remains crack-free.

Compared to other materials, UHPFRC also shows very high resistance against mechanical abrasion and hydro-abrasion.

Adding polypropylene fibres to the UHPFRC mix improves the fire resistance and can avoid the spalling of UHPFRC providing thus sufficient fire safety for most applications.

PART 2

3. STRUCTURAL RESPONSE OF R-UHPFRC – RC COMPOSITE BEAMS

3.1 Motivation and basic concept

Reinforced concrete (RC) structures like bridges, retaining walls or buildings often show insufficient performance in terms of structural resistance and durability when exposed to severe environmental influences and high mechanical loading. Interventions to improve deteriorated concrete structures are a heavy burden from a socio-economic viewpoint, since they lead to significant intervention costs and user costs. (RC structures are cheap at construction but turn out to be costly during their use because of premature damage calling for costly interventions.) Much conventional “retrofitting” using concrete and repair mortar is not durable, and therefore, novel concepts for the improvement of RC structures must be developed.

This leads to the third principle of the UHPFRC technology. The targeted addition of a thin layer of strain-hardening UHPFRC to an existing member in reinforced concrete (RC) enhances the structural resistance and durability of existing RC structures. The two basic concepts are shown in Figure 3; they lead to the structural system of (monolithic) composite R-UHPFRC – RC elements.

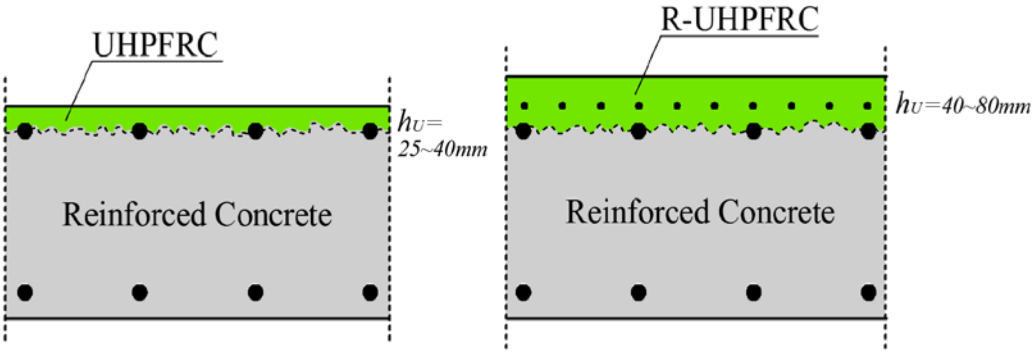

Figure 3. Basic configurations of structural elements combining UHPFRC and RC: left: UHPFRC layer has a protective function only; right: R-UHPFRC layer has structural resistance and protective functions.

The author and his team have investigated the structural concept of composite R-UHPFRC – RC elements (Fig. 1b) over more than 18 years (see [1] and references in [2, 3]). In the following, the most important findings of this research are outlined and two applications cases are described.

3.2 Behavior in bending

When in tension, the R-UHPFRC layer principally acts as an added flexural reinforcement chord for the RC element. Both the steel rebars and the UHPFRC contribute to the resistance. RC beams strengthened with an R-UHPFRC layer are characterised by a significant increase in elastic stiffness and ultimate resistance when compared to the initial concrete element.

The bond between UHPFRC and concrete is obtained by preparing the concrete substrate surface by high pressure water jetting or sand blasting. The concrete substrate is wetted and has to be wet when the layer of UHPFRC is cast. This surface preparation provides full bond between the UHPFRC layer and the concrete substrate. In fact, pull-out fracture tests (force is applied perpendicular to the UHPFRC surface) show the expected fracture within the concrete substrate (and not at the interface or in the UHPFRC). Thus, the composite R-UHPFRC – RC section behaves monolithically.

The plastic post-peak rotation capacity of strengthened RC beams is maintained with an appropriate design of the rebars in the UHPFRC layer. Also, smooth high yield strength reinforcing bars in the UHPFRC layer offer high increase in resistance while the post-peak rotation capacity remains ductile. The structural behaviour in terms of moment – curvature relation and the ultimate bending moment are calculated using the conventional sectional model with the extension to account for the R-UHPFRC layer in the monolithic section (Figure 4).

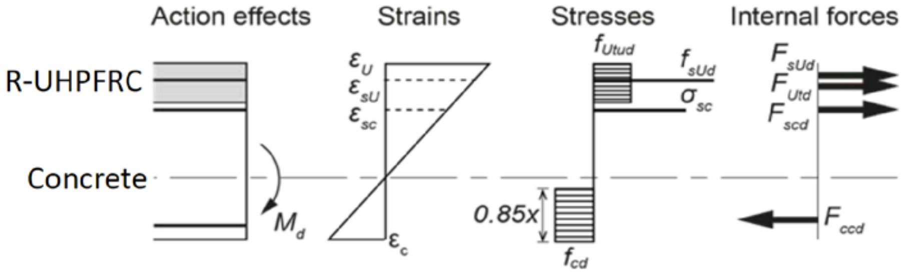

Figure 4. Plane section analysis for bending resistance at Ultimate Limit State ULS.

When subjected to compressive stresses, the R-UHPFRC layer acts as a compression flange but the high UHPFRC compressive strength cannot be fully exploited. This is because the compressive strength of the adjacent concrete below the UHPFRC layer often is three to six times lower, and thus concrete would crush prior to the UHFPRC reaching its compressive strength.

3.3 Behavior in combined bending and shear

As was shown by tests on composite beams, the addition of a layer of UHPFRC delays the formation of the inclined critical shear crack in the concrete section. For many geometric configurations, the layer of UHPFRC modifies the failure mode from shear failure with little deformation to a ductile flexural failure mode.

A shear failure is observed in a composite section only for specific geometric and material configurations. Due to the experimentally observed failure mechanism (Fig. 5), the ultimate shear strength is composed of the contributions due to (1) concrete web crushing V_{Rc}, (2) vertical steel reinforcement yielding V_{Rs} and (3) the two hinge-bending mechanism of the R-UHPFRC layer V_{RU}. Accordingly, analytical expressions have been deduced to calculate the ultimate shear strength [6, 7].

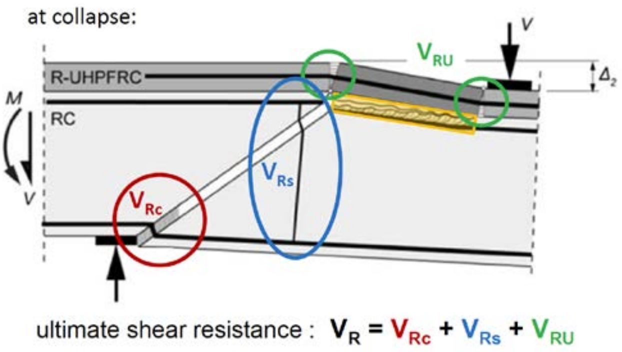

Figure 5. Shear failure mechanism at ULS.

3.4 Fatigue behaviour

The results of bending fatigue tests on R-UHPFRC – RC beams revealed the existence of a fatigue limit at 10 million cycles at a fatigue stress level of about 50 % of the ultimate static resistance of the R-UHPFRC – RC beams [8]. Consequently, fatigue design rules for R-UHPFRC – RC members under bending fatigue need to account for steel rebar and UHPFRC fatigue resistances. Fatigue stresses are calculated using an elastic sectional model similar to the one shown in Figure 4 but for elastic stresses under service conditions.

4. ENHANCEMENT OF TWO HIGHWAY VIADUCTS

4.1 Introduction

In Switzerland, the technology of enhancing the structural performance of existing RC structures by adding a layer of R-UHPFRC was applied for the first time in October 2004. Since then, more than 50 structures have been strengthened using the UHPFRC technology. In the following, the conceptual design for the enhancement of two large highway viaducts is presented.

4.2 Chillon Viaducts, a twin box-girder structure

Aim and objectives: Located in Switzerland, the Chillon viaducts are two parallel posttensioned concrete highway structures built in the late 1960s (Fig. 6). To ensure structural safety for future traffic demands, it was decided to strengthen the slab and the box girder by adding a layer of R-UHPFRC acting as an external tensile reinforcement [9].

Figure 6. Chillon Viaducts along Lake Geneva.

Motivation and objective: The concept implemented in 2014/15 consisted of casting one layer of R-UHPFRC on the deck slab (Fig. 7) to achieve the following beneficial effects:

- increase the slab’s ultimate (bending and shear) resistance in the transverse direction
- increase the slab’s stiffness to reduce fatigue stresses in steel rebars in the concrete
- increase the hogging bending moment resistance and the stiffness of the box girder
- provide waterproofing to protect the existing concrete of the slab from water and chloride ingress, thus improving durability
- limit duration of the intervention.

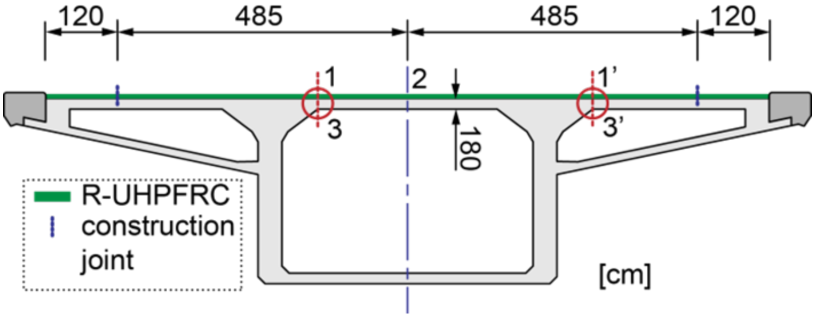

Figure 7: Geometry of the box girders cross-section (thickness of R-UHPFRC layer: 50mm over piers and 40mm in the spans).

Dimensioning:

As illustrated in Figure 6, the concrete bridge deck slab has a total thickness h_c of 180 mm. The transversal 16-mm diameter top steel rebars are positioned at a height d_{sc} of 152 mm from the intrados and spaced at 125 mm. There is no transversal pre-stressing in the bridge deck slab. The layer of UHPFRC has a thickness of h_U of 40 mm and is reinforced transversally with 12-mm diameter rebars also spaced at 125 mm. The centre of these rebars is at 16 mm from the top of the concrete. Over the piers, the thickness of the UHPFRC layer was increased to 50mm, and 12 mm rebars spaced at 125mm were placed in the longitudinal direction (in addition to the transverse rebars) to increase the negative (hogging) moment resistance of the box girder in the longitudinal direction.

The *transversal bending resistance of the deck slab* was calculated using the resistance model according to 3.2. For negative bending moment, the ultimate bending resistance m_{Rd} for sections 1 and 1' (Fig. 7) is equal to 165.5 kNm/m. The ultimate bending resistance of the strengthened slab is 73% higher than the resistance of the RC section alone. For positive bending moments, the layer of UHPFRC is in compression and mainly contributes to the resistance by reducing the height of the compression zone and thus increasing the static height. The ultimate positive bending resistance at section 2 is increased by 33%.

The deck slab does not have any shear reinforcement. *Ultimate shear resistance* v_{Rd} of the composite element was thus calculated as the sum of the concrete contribution v_{Rc} and the UHPRRC contribution v_{RU} according to 3.3. With an angle of the inclined crack estimated at 35°, the shear resistance of the composite slab section is 265 kN/m. The UHPFRC layer contributes to 33% of the total shear resistance. Due to the R-UHPFRC reinforcement, the increase in shear resistance is 40% according to the resistance model presented in [7].

The increased shear resistance is significantly higher than for the flexural failure mode, and the flexural failure mode is predominant even in shear prone loading situations.

Execution:

All listed requirements and structural functions were realised by the casting of just one layer of R-UHPFRC using an adapted finisher (Fig. 8) on the concrete surface prepared by removal of 10mm by high pressure water jetting. The large volume of 2,350m^3 of fresh UHPFRC was produced on-site in a ready-mix plant. During the summers 2014 and 2015, the UHPFRC layer was cast over the two 2,120 m long viaducts, each in 25 working days.

Figure 8. UHPFRC casting finisher (left) and fresh UHPFRC layer after casting (right).

Testing according to quality assurance requirements given in [1] revealed that the UHPFRC complied with the requirements for strain-hardening UHPFRC. The fresh UHPFRC had to show thixotropic behaviour as it was cast on slopes of up to 7%. An asphalt layer and bituminous pavement, overall 6-cm thick, were finally placed on the UHPFRC surface to obtain the drivable road surface. The overall self-weight of the structure was not increased and thus strengthening of the piers and foundations could be avoided.

4.3 Improvement of three highway viaducts consisting of multiple PC precast girders

Motivation and objective: Three 45-year-old highway twin viaducts of identical construction follow each other in a hilly area in Central Switzerland to form a total length of 1,050m (Fig. 9a). The superstructure of the viaducts is composed of four slender precast prestressed girders with lengths of 40m. These girders have been designed as simple span beams, but during construction, they were monolithically joined over the piers (to avoid joints) to form a continuous girder. The hogging moment capacity (over the piers) is relatively low. In view of future traffic demands, the viaducts need to be strengthened to increase the load bearing capacity. They also need to be rehabilitated because of rebar corrosion damage.

Conceptual design:

The basic idea of the strengthening of the superstructure is the following: since the original hogging moment capacity is low, it can be increased significantly by adding a strong R-UHPFRC layer on top of the slab (Fig. 9b). Allowing for plastic moment redistribution from mid-span (sagging moment range) to the piers (hogging moment range) at ULS, the required load bearing capacity of the superstructure is obtained (Fig. 9c). This moment redistribution is however only possible if the relevant cross sections allow for plastic rotation capacity of hinges with sufficient ductility. This condition has been verified in the present case.

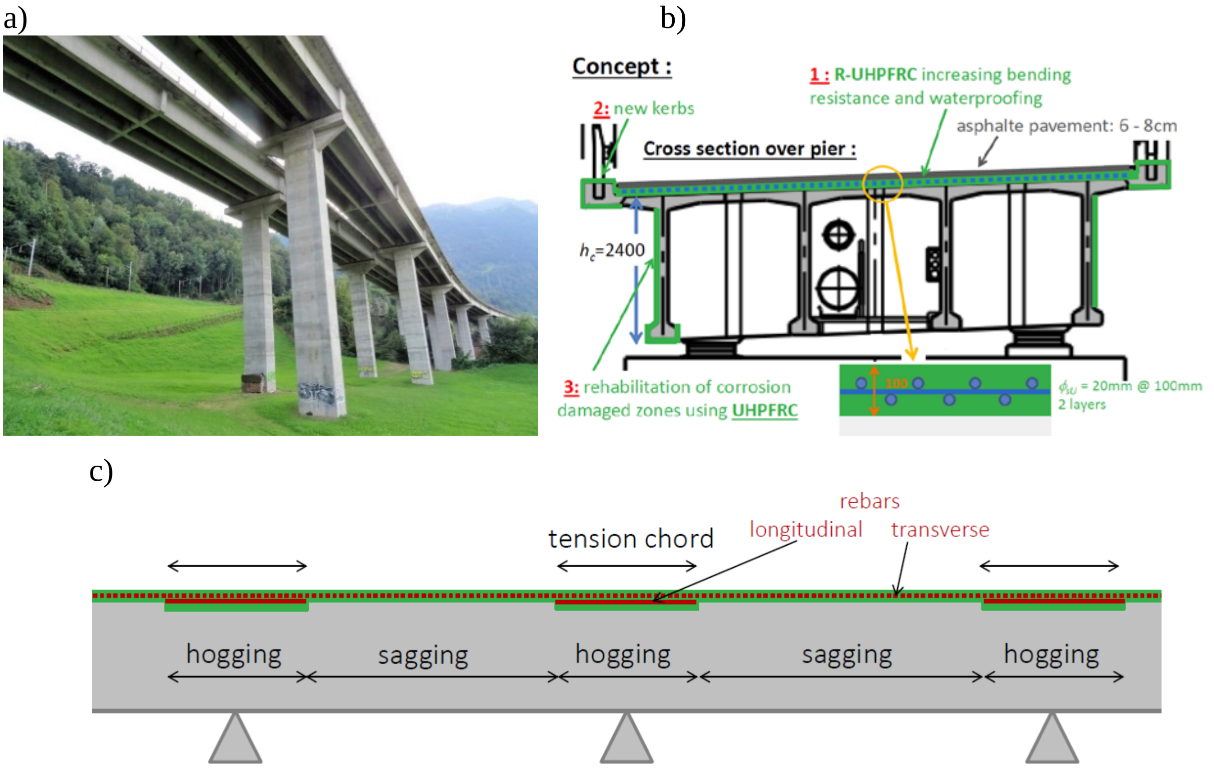

Fig. 9 a) View of one of the three twin viaducts; b) Intervention concept (cross section at pier); c) concept of strengthening: increasing the hogging moment capacity.

The 100 mm thick R-UHPFRC flange extends by 6 m on each side of the pier such that the strong R-UHPFRC layer also increases the shear resistance of the girder near the piers according to the mechanism shown in Fig. 5.

The rest of the deck slab (sagging moment region) is strengthened by a 45 mm thick UHPFRC layer with rebars in the transverse direction such as to increase the torsional stiffness of the open cross section allowing for more effective distribution of high concentrated (wheel) loads in the transverse direction of the cross section, thus reducing moment peaks.

In addition, the UHPFRC layer on the deck slab provides the waterproofing protection for the reinforced concrete, and UHPFRC is also used to rehabilitate local rebar corrosion damage on the outer girders and bottom flanges because of superior performance compared to repair mortars.

Dimensioning:

Bending moment capacity: With design values for the tensile strength of UHPFRC and steel rebars of respectively 8 MPa and 435 MPa, and the UHPFRC cross section and rebar area as given in Figure 9b, the tensile force developed at ULS by the R-UHPFRC flange is F_{RUd} = 3’480 kN per metre width. (78% of this tensile force is due to the steel rebars; 22% is due to the UHPFRC.) The internal lever arm y_U of the cross section (i.e. distance between the resultant tensile force and compression force) that is plasticized at ULS, is about 1.8 m, and thus, the additional hogging (negative) moment capacity in the longitudinal direction is: $\Delta M_{RUd} = y_U \cdot F_{RUd} = 1.8m \cdot 3.48MN = 6.3MNm/m$

This additional moment capacity is sufficient to obtain the required moment bearing capacity of the superstructure. Obviously, increasing the tensile reinforcement leads to higher compressive stresses in the lower part of the cross section over the pier. In the present case, the compression zone was not fully exploited before strengthening and the compressive strength increased over time to reach after 45 years a compressive strength about 30% higher than the 28-day-compressive strength assumed in the initial design. These are the reasons why the dimensions of the compression zone are sufficient also after strengthening.

Shear resistance: The resistance model given in 3.3 was applied to the 2.5m high PC girder. The following contributions to the ultimate shear resistance of one strengthened girder were obtained: (1) concrete web crushing V_{Rc} = 426 kN; (2) two hinge mechanism of the R-UHPFRC layer V_{RU} = 305 kN; (3) steel reinforcement: vertical rebars (stirrups) and vertical component of two inclined post-tensioning cables in the concrete girder web: V_{Rs} = 813 kN. Thus, the ultimate shear resistance of the strengthened girder is the sum of (1) to (3): V_{Rd} = 1’544 kN. This ultimate shear resistance is 90% higher than the shear resistance before strengthening and 34% higher than the acting shear force. Actually, the shear resistance is enhanced to such an extent that bending failure will prevail. In addition, non-linear FE analysis was performed confirming the formation of the expected failure mechanism and the analytically determined ultimate shear resistance.

Slab strengthening in the transverse direction: The R-UHPFRC layer leads to a thicker slab of higher stiffness allowing for more effective transverse distribution of concentrated wheel loads. This favourable effect was considered and precisely determined in the detailed dimensioning. This dimensioning was used to validate the feasibility of the intervention concept. Detailed design by means of non-linear FE analyses gave deeper insight into the performance of the R-UHPFRC strengthening concept.

Execution: In 2017, chloride induced rebar corrosion damage at outer girder webs and bottom flanges were rehabilitated using UHPFRC. In addition, suitability tests have been performed to validate the UHPFRC material and the UHPFRC casting using the adapted finisher. In June and July 2018, the UHPFRC was cast over a period of 30 working days on the three viaducts in one direction of the highway (Fig. 10). In 2019, the second series of three viaducts of the second highway direction will be enhanced by casting the UHPFRC layer.

Figure 10. General view of construction site on 12th of July 2018 (left; Photo A.Wey keystone), and UHPFRC casting using a finisher (right).

5. VALIDATION

The UHPFRC technology for the enhancement of existing concrete bridges presented here is validated by qualitative comparison with the traditional method using concrete, instead of strain-hardening UHPFRC, leading to the following arguments:

UHPFRC has an optimised compact matrix consisting of particles and a water/binder ratio typically lower than 0.20, which results in a material that has no free water, and no (communicating) capillary pores; consequently, UHPFRC is waterproof and thus durable. On the contrary, concretes show significant amounts of communicating capillary pores because of the relatively high w/c-ratio larger than 0.40; consequently, concrete cannot be considered as durable, i.e., durability problems like rebar corrosion, frost damage or alkali-aggregate reaction are likely to occur even for improved concrete mixes.

UHPFRC shows much higher tensile strength with significant deformation capacity (ductility) compared to concretes; consequently, the tensile strength of UHPFRC is considered in the design of strengthening interventions (as the ones presented in this paper). This significantly enhances the ultimate resistance and the stiffness of strengthened R-UHPFRC – RC structural members. On the contrary, the tensile strength of concrete must not be taken into account in the determination of structural resistance, also because of brittleness. The compressive strength of UHPFRC is about three to five times higher than that of high strength concretes. This is a further reason why relatively thin additional layers in UHPFRC are sufficient.

Because of the aforementioned significant differences in mechanical performance of the two materials, a strengthening layer in concrete (following similarly the concept presented in this paper) would result in a thicker concrete cover and overall layer thickness, more rebars and additional measures (like waterproofing membranes) to guarantee durability. Overall, the additional relatively thick layer in high strength concrete would lead to an important increase in dead weight of the bridge structure which is likely to trigger additional (costly and time consuming) strengthening interventions.

In addition, additional measures, f.ex. to guarantee durability, and more complex works in the case of traditional methods are time-consuming and offer more sources of errors. This leads to more important restrictions for the user of the structure and thus significantly higher (indirect) user costs.

Overall, despite the fact that concrete is a cheap material compared to UHPFRC, the overall cost of a UHPFRC strengthening intervention on existing structures is significantly lower … which is actually the main reason why numerous applications have already been carried out in Switzerland. Obviously, it is erroneous to compare the material cost only of concrete and UHPFRC, since in many countries labour and machine costs are significantly higher than material costs. The cost for the overall intervention finally counts, and the material cost is only a (minor) part of it.

6. CONCLUDING REMARKS

In The strengthening method using a layer of strain-hardening UHPFRC is an effective method in terms of technical performance. Significant tensile strain-hardening and high tensile strength of the UHPFRC is decisive for the successful implementation of the enhancement concept of concrete bridges.

The design of the strengthening intervention is based on a clear concept with a targeted consideration of the structural behaviour and performance of the given structure to be improved as well as the UHPFRC material properties.

The UHPFRC strengthening concept has been demonstrated in this paper by means of two large viaducts of common design, i.e. box girder and multiple beam cross sections. Simple analytical formulas are sufficient to validate this intervention concept.

The R-UHPFRC technology to improve the resistance and durability of existing concrete structures discussed here is cost-effective at execution and economic in the long term. Actually, lower intervention costs (when compared to traditional methods) are the main reason for the increasing number of applications of the UHPFRC Technology in Switzerland. Further countries are at the beginning or will soon start the application of the technology.

PART 3

7. DESIGN AND CONSTRUCTION OF NEW LIGHTWEIGHT BRIDGES

7.1 Introduction

Persistent over-conservatism in structural engineering, over-regulated design and construction procedures and lack of incentives for structural engineers are the reasons why worldwide only relatively few R-UHPFRC structures have been built until now.

Among them, there are several footbridges like the pioneering footbridge in Sherbrooke, Canada (1997), the Seonyu Peace Bridge (2002), an arch footbridge over the Han River in Seoul, South Korea, or the elegant Sakata Mirai Bridge in Japan (2002). Three UHPFRC road bridges have been built between 2006 and 2012 in remote areas in the State of Iowa in the USA. Several UHPFRC structures for both bridges and buildings have been realised in

France. In addition to Japan and France, the only country so far with an impressive record of UHPFRC construction is Malaysia with more than 20 segmental short and medium span road bridges built since 2010 [10].

7.2 Design principles

The basic approach in designing new R-UHPFRC structures is to combine assets of steel construction and reinforced concrete construction in order to realize cost-effective lightweight structures. The dead load of R-UHPFRC structures typically is at least three to four times lower than the dead load of a RC structure fulfilling the same structural function. Targeted use of rebars and prestressing, optimized prefabrication and rapid construction methods (adapted to lightweight elements) lead to this goal and limit the construction cost to a level that is competitive with traditional construction methods.

The design of R-UHPFRC structures is inspired by steel construction, prestressing technology and cast connections. Dimensions are expressed in [mm] because the fabrication precision is in the millimetre domain. UHPFRC structural elements are designed with the objective to maximise their stiffness while minimising their sections, dead weight and thus the amount of the precious building material.

Structural UHPFRC elements are designed as profiled elements consisting of plates (sheets) stiffened by ribs with thicknesses typically of 30 to 100 mm. “Linear” elements like beams or stiffeners contain reinforcing bars and/or prestressing steel. Plate elements like slabs, webs as well as wall and façade elements may be designed without rebars.

R-UHPFRC structures are monolithic, and thus a further source of inspiration are the slender monolithic structures in early reinforced concrete (19th Century) like the ones by Hennebique. For curved plates and shells, wire mesh in steel or synthetic fibres (fabrics, mesh wires) may be suitable to increase resistance, as inspired by ferrocement structures.

In the following, three recently built R-UHPFRC structures recently built in Switzerland are briefly described.

8. THREE R-UHPFRC STRUCTURES RECENTLY BUILT IN SWITZERLAND

8.1 Martinet Footbridge in Lausanne

Motivation and project objectives: The Martinet Footbridge is part of a new pedestrian and bike path following the main railway line in the agglomeration of Lausanne, Switzerland (Fig. 11). The UHPFRC structure is a girder of 15.3 m single span resting on two RC abutment walls.

The project objectives were: i) construction cost not higher than for a conventional structure, ii) original aesthetic expression, iii) minimum maintenance, iv) minimum use of resources, while obviously respecting code requirements.

The UHPFRC structure of the Martinet Footbridge was designed using drafts of the Swiss UHPFRC Standard [1]. From the beginning, the project and its result were meant to become a showcase for the design and construction of a slender R-UHPFRC structure with original and pleasing appearance.

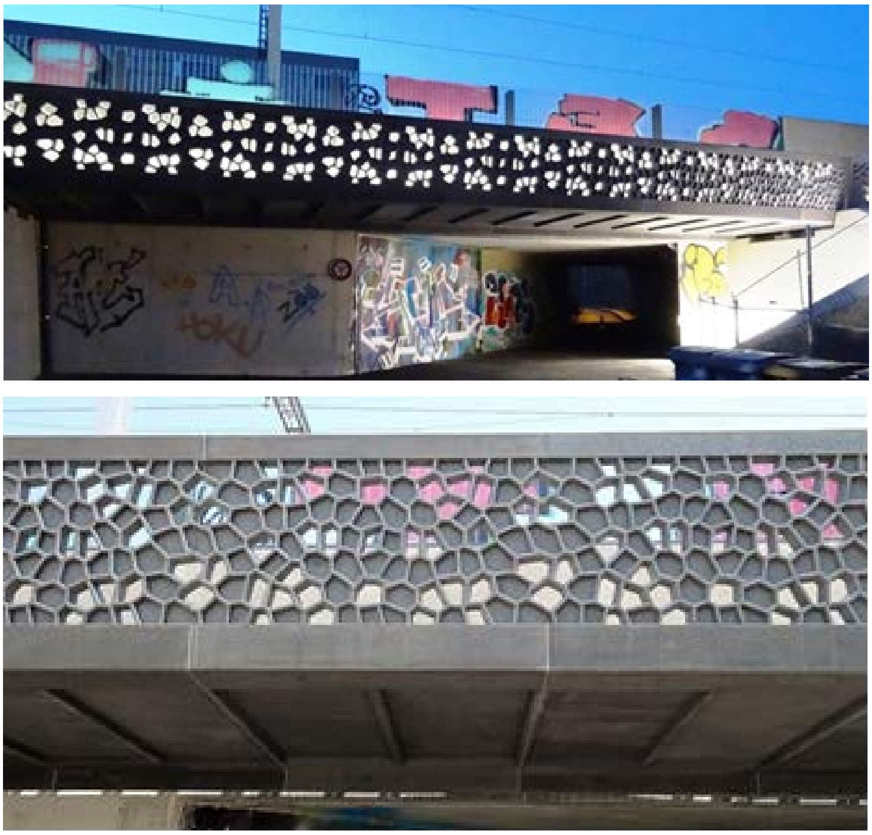

Figure 11. Martinet Footbridge: view of illuminated bridge at dusk, after opening in July 2015 (left), and view of the “organic” web and underside of the ribbed slab (right).

Structural concept: The asymmetric U-shaped cross section in the form of a trough consists of two main girders, an "organic" one with the required railing height and a lower one with full web next to the retaining wall and underpath of the neighbouring railway line (Fig. 12). Both girders form a half-frame with the bottom plate that is stiffened with ribs in the transverse direction. In the longitudinal direction, the structure consist of nine segments that were cast upside-down in the plant using a mould in steel with an element in plastic for the “organic” web.

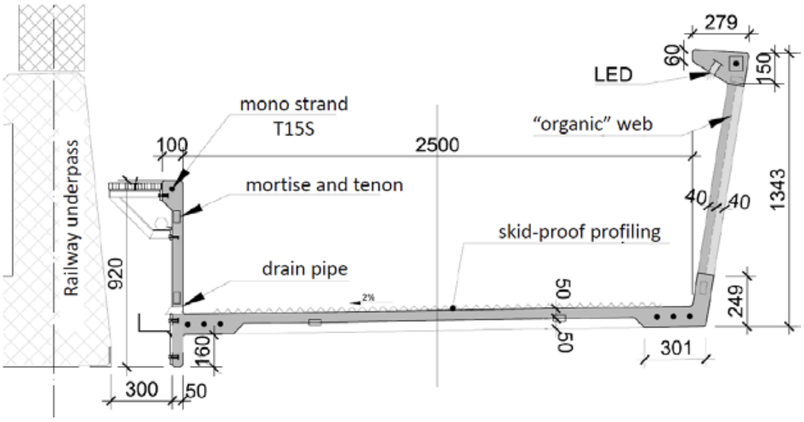

Fig. 12. Martinet Footbridge: asymmetric cross section (dimensions in mm).

The “organic” web was developed by optimizing aesthetic, static and casting requirements; it provides visual originality and is appealing for the user who shall perceive an original material. The dark colour was obtained by adding black pigments to the fresh UHPFRC mix. The roughness of the walkway surface was cast by using a profiled steel sheet providing the required skid-proof surface; in this way, no pavement was needed.

Construction process: Each cast segment was demoulded 15 hours after casting and cured in a plastic foil during seven days in the plant. During one morning, all nine segments were transported on trucks to the construction site where each segment of a relatively low weight of 1.7 tons was lifted and arranged on a light scaffold using the crane fixed to the truck. The butt joints between the segments were glued with epoxy resin (providing also water tightness of the joint), temporarily interlocked and pressed together.

A few days after mounting of all segments, the post-tensioning mono-strands were inserted in the ducts and tensioned in stages. Afterwards, the post-tensioned structure was lowered on the elastomer bearings using hydraulic jacks.

Dimensioning: The straight post-tensioning cables provide in the longitudinal direction a force-fit connection of the segments under a compressive stress of 3 MPa (uniformly distributed over the cross section under permanent loads) such that, at serviceability limit state, no zone of the cross section is decompressed.

At Ultimate Limit State, the post-tensioning tendons act as main reinforcement in the longitudinal direction. The shear force in the “organic” and full webs is carried by the UHPFRC including single vertical rebars and in the segment joints by interlocking shear keys. In the transverse direction, the 50 mm bottom plate with transverse 100 mm high ribs in R-UHPFRC mainly carries sectional forces.

Due to the relatively high tensile strength and strain hardening of the UHPFRC, the structure remains crack-free under service stresses and hence, given the water tightness of the UHPFRC, the severe requirements regarding durability (i.e., significant amounts of deicing salts are spread in winter season) are fulfilled without particular measures.

Validation and construction cost: Validation by testing was important for the success of the project: i) casting procedure, colour and surface finish could be optimized; ii) fracture tests on a prototype segment allowed to verify the design and dimensioning; iii) in-situ load tests using a 5 ton vehicle provided valuable information about the structural behaviour: measured first basic frequency of the relatively stiff structure was 6.6 Hz which matched with the calculated value. At the serviceability limit state, the calculated deflection of the girder at mid-span is 11 mm, significantly less than the allowable 26 mm. For visual reasons, a camber of 40mm was realized.

The total construction cost was 4’200 Euro per m^2 of walkway surface that is about 10% higher than the estimated cost for a RC structure (though with limited durability). The cost for the used UHPFRC material (in total of 15 tons) was only 5.5% of the total construction cost; the prefabrication labour as well as the construction of the mould turned out to be most cost relevant.

8.2 Footbridge in Le Bouveret

This footbridge is located in the village of Le Bouveret adjacent to the entry of the Rhone River into Lake Geneva in Switzerland. It overspans the main road of the village and establishes a new pedestrian access to the local school and the lower part of the village (Fig. 13). The UHPFRC structure is a single span girder of 26.5m span and is composed of precast segments that are posttensioned in the longitudinal direction to form the monolithic structure.

Figure 13. Footbridge at Le Bouveret: 25m span girder spanning over a road (left); symmetric cross section with inclined webs (right), before opening in June 2018.

The main reason for the use of UHPFRC was the aesthetic expression of the structure while the cost was estimated to be lower than for a conventional structure. The Martinet Footbridge inspired the design but the following simplifications have been made: symmetric cross section, simplified web design (and thus simplified mould) and reduction in number of posttensioning cables (consisting of several strands). For aesthetic reasons, the girder was slightly bent with a rise of 215mm at mid-span. The UHPFRC structure was dimensioned using the Swiss UHPFRC Standard [1].

The precast elements were fabricated and assembled in the plant. Then, the whole girder was transported by truck over a distance of 80km to the construction site where it was lifted and placed by two cranes in its final position resting on the two abutments (Fig. 14).

Figure 14. Precast UHPFRC element in the plant (left); lifting of the assembled girder by two cranes in the night of May 25, 2018.

8.3 Railway Underpass Unterwalden at Sempach

The Railway Underpass Unterwalden at Sempach in Central Switzerland is probably the first R-UHPFRC railway structure worldwide on a main railway line (Fig. 15). It replaced a deteriorated slab structure. Important geometric constraints related to both clearance of the underpassing road and the railway track imposed a limited construction height of the new structure. The responsible structural engineers of the Swiss Federal Railways, the owner, consider UHPFRC as a construction material of high mechanical resistance and superior durability providing a high potential for UHPFRC to be used for railway structures.

In the present case, the main reasons for the use of UHPFRC for the double-track railway slab was the possibility to design a relatively stiff lightweight structure composed of lightweight precast elements that accelerate and simplify the construction process. This leads to minimum service restrictions on this main railway line with a busy traffic. In addition, the expected high durability of the UHPFRC structure results in low life-cycle costs. This first pilot application on a small structure also provided valuable experience for future applications of the UHPFRC Technology in the domain of railway structures.

Figure 15. Railway underpass Unterwalden with a structure in R-UHPFRC resting on concrete abutments (left); edge girder and ribbed plate girder of the structure in reinforced UHPFRC.

These project constraints and the design rules for UHPFRC structures led to an R-UHPFRC structure consisting of one single span ribbed plate and one edge girder per rail, altogether 2 times two identical prefabricated elements.

The dimensions of the ribbed plate consisting of a 50mm thick upper plate acting as compression chord of the single span structure with a span of 6.0m and ribs spaced by 250mm with a thickness varying from 80mm at the bottom to 100mm at the top. Two steel reinforcing bars of 26mm diameter were placed in each rib as bending reinforcement allowing for a rebar cover of at least 26mm, which is more than the 15mm required by [1]. The ribs provided enough cross section to resist the design shear force without placing a vertical rebar. No transverse diaphragm was necessary.

The edge girder consists of an edge board to hold back the ballasted bed of the railway and of a massive beam (incorporating steel reinforcing bars) to resist impact force of underpassing vehicles. Moreover, the shape of the edge girder should have an appearance that is characteristic for UHPFRC structural elements.

The UHPFRC structure was dimensioned using the Swiss UHPFRC Standard [1]. The requirements for stiffness (with respect to an allowable deflection at mid-span of 3.0mm) as well as for fatigue safety governed the dimensioning. The design of the structure was verified by means of two full-scale tests on girders with TT-cross section.

During the nights of November 11/12 and 12/13, 2017, respectively, the UHPFRC elements were mounted on each railway track, and put in service immediately after installation. A monitoring system was installed to validate the expected structural behaviour. The first results of the measurements confirm the expected values that lie significantly below the calculated values as obtained using the railway load model according to the European Codes.

The production of the UHFB finished parts claimed 15% of these expenses and the obstructed 24m3 UHFB put out possibly half or 7.5% of the whole costs of construction. The building material expenses for the UHFB put out therefore an insignificant interest in the whole project expenses.

9. CONCLUDING REMARKS

The state-of-knowledge and diversity of applications confirm the potential of using R-UHPFRC to create, design and build new lightweight structures with enhanced durability and original aesthetics. R-UHPFRC structures will complement and replace step-by-step traditional construction in concrete and steel. In principle, R-UHPFRC is suitable for a large variety of structures and structural elements and also for large scale structures that are nowadays still built in reinforced concrete and steel.

UHPFRC showing significant tensile strain hardening and high tensile strength will prevail in the near future as it has important advantages in structural applications in terms of structural behaviour under service conditions and durability.

The implementation of Structural UHPFRC responds to the principles of sustainable construction as new lightweight structures use significantly less resources in terms of materials, energy and financial means (expressed as construction and life-cycle costs). Additionally, cost-benefit analysis (or life-cycle costs) is beneficial. Because of the significantly enhanced durability, it may be expected that UHPFRC structures (contrary to steel and concrete structures) do not require any rehabilitation interventions.

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