"Structural UHPFRC": Recent applications in rehabilitation and strengthening of bridges in Switzerland

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Abstract

"Structural UHPFRC" stands for Ultra-High-Performance Fiber Reinforced Cementitious Composite material which is complemented by reinforcing and prestressing steel to enhance the resistance and durability of structural elements. Structural application of impermeable, tensile strain hardening UHPFRC follows two fundamental concepts including: 1) Rehabilitation and strengthening of existing bridges by adding a layer of structural UHPFRC, and 2) Construction of new bridges in Structural UHPFRC, often composed of precast elements.
This paper presents basic principles and three recent project realizations in rehabilitation and strengthening of existing RC bridges in Switzerland using Structural UHPFRC. The underlying design concepts and issues of dimensioning and detailing are explained, and experiences in casting UHPFRC onsite are described. The UHPFRC Technology has made its proof as a technology to enhance existing bridges and structures in general. UHPFRC also contributes in lowering the environmental impact of structures as existing structures are improved to remain in service.

Keywords: Structural UHPFRC, bridges, rehabilitation, strengthening, applications.

1. Introduction

Construction of reinforced concrete bridges is very successful because it is cheap. However, the problems of insufficient durability are known for several decades already. Rehabilitation of bridges in reinforced concrete using traditional methods implies high intervention and user costs which represent a heavy burden for national economies and the environment. Novel intervention methods are urgently needed to improve existing reinforced concrete bridges.

UHPFRC stands for Ultra-High-Performance Fiber Reinforced Cementitious Composite materials. UHPFRC is composed of cement and other reactive powders, additions, hard fine particles, low amount of water, admixtures and very high amount of relatively short and slender steel fibers. The composition of UHPFRC is optimized with respect to compaction of particles leading to a waterproof material up to a tensile strain of about 0,1 %. The tensile strength of UHPFRC typically is about 12 MPa and the material shows significant strain-hardening behavior in tension. UHPFRC has compressive strength higher than 140 MPa. UHP(FR)C is nowadays used in many countries, mostly in the domain of new construction (Graybeal et al. 2021).

The author and his team have developed the UHPFRC rehabilitation and strengthening technology over the last 25 years by means of scientific research and applications (Bertola et al. 2021, Brühwiler 2020). In Switzerland (8,7 million inhabitants, area of 41'000 km2) there are currently more than 350 reinforced concrete structures, mainly bridges, that have been improved using the UHPFRC Technology, since 2004. This is the by far highest UHPFRC application rate in the world with respect to the size of the country.

The main reason for this successful implementation of a new technology in practice is that compared to traditional methods using concrete, mortar and epoxy coatings, the UHPFRC Technology is economic in terms of costs and material use, allows for an accelerated construction process and provides durable structures for further use reducing or eliminating maintenance costs. By applying a UHPFRC reinforcement and waterproofing layer, the use of an existing RC bridge can continue. In this way, new requirements of use are accommodated in an economical, environmentally friendly and socially responsible manner. The UHPFRC Technology is also particularly suitable for bridges of high cultural values, since interventions are usually not visible.

2. Design concepts to improve bridges

UHPFRC is used as a high-performance building material to improve existing bridges in traditional reinforced concrete with the aim of remedying, through a targeted supplement with UHPFRC, the known deficiencies of reinforced concrete.

2.1. Basic principle of UHPFRC-concrete composite elements

The basic idea of reinforcing structural RC bridge elements with UHPFRC is to monolithically connect a 25 to 80 mm thick UHPFRC layer with the RC cross-section. The resulting UHPFRC-concrete composite element consists of a RC cross-section and a layer of UHPFRC or R-UHPFRC (incorporating steel reinforcement bars) according to Figure 1.

The term "strengthening" used here includes the increase in resistance and rigidity of structural bridge elements. At the same time, the UHPFRC layer also provides the protection function by a watertight barrier to shield reinforced concrete from direct contact with water and chloride ions.

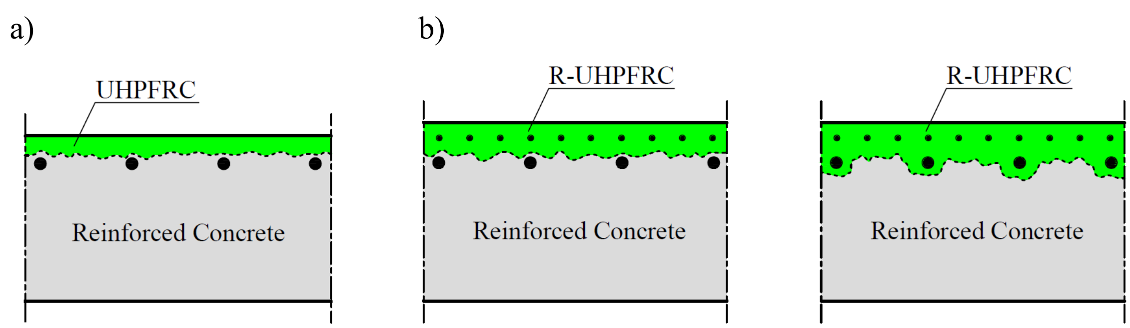


Figure 1 Basic configurations of the UHPFRC-concrete composite construction: a) protective function and increase in rigidity under service conditions, b) protective function and increase in element rigidity and ultimate resistance.

The essentials of UHPFRC-concrete composite behavior and required relevant UHPFRC material properties are summarized in (Brühwiler 2020). UHPFRC should generally be used as material to rehabilitate and restore damaged reinforced concrete elements, thereby replacing inferior materials like repair mortars or epoxy coatings.

In the following, concepts are presented to increase structural resistance of R-UHPFRC improved RC bridges:

2.2. Project objective 1: Restoring and increasing the resistance of bridge deck slabs

Bridge deck slabs made of reinforced concrete are subject to particularly high loading due to environmental influences and traffic loads. Accordingly, there is a high demand for intervention to restore and increase the structural resistance of deck slabs.

Figure 2 shows the basic strengthening concept of bridge deck slabs by applying a R-UHPFRC layer to the existing concrete slab. Bridge deck slabs carry loads and forces mainly in the transverse direction. Correspondingly, a distinction is made between the sagging moment zone (positive bending moments) and the hogging moment zone (negative bending moments) above the webs of beams or box girders.

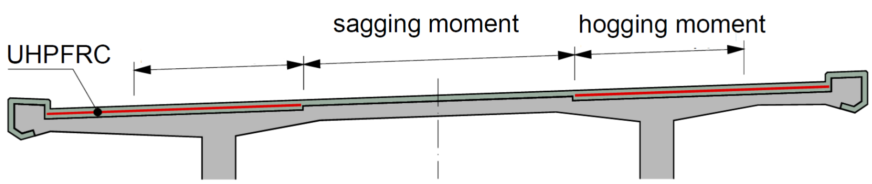


Figure 2 Concept of increasing the resistance of the original RC deck slab by means of the R-UHPFRC layer forming a strong R-UHPFRC tension chord in the hogging moment zone.

The concept is to significantly increase the flexural resistance in the hogging moment zone by forming a strong R-UHPFRC tension chord allowing for moment redistribution from the sagging to the hogging moment zone at ULS (ultimate limit state) according to the plasticity theory, given that the UHPFRC layer under compression in the sagging moment zone only leads to a comparatively small increase in flexural resistance.

The R-UHPFRC tension chord must be compensated by a correspondingly strong compression zone. In order to ensure the balance of the tensile and compressive forces resulting in the bending cross-section, the effective concrete compressive strength is exploited, which has usually increased considerably (i.e. by 20 to 50 % compared to the 28-day compressive strength) during the bridge's service duration, often of several decades. This well-known time-dependent increase in strength is estimated using analytical expressions given in scientific literature and standards, and verified by means of non-destructive testing on the structure. In this way, strengthening of the compression zone can usually be avoided.

By creating a R-UHPFRC tension chord, the ultimate shear resistance is also greatly increased in the hogging moment zone, such that the shear force check is usually fulfilled easily. By the R-UHPFRC reinforcement, the slab rigidity is significantly increased, which greatly reduces fatigue stresses in the existing steel reinforcement bars and concrete. The fatigue safety check is therefore usually fulfilled without problems.

2.3. Project objective 2: Increasing the resistance of bridge girders

The targeted use of R-UHPFRC, in particular as a R-UHPFRC tension chord, enables a significant increase in the load-bearing capacity of bridge girders in the longitudinal direction without significantly increasing permanent actions (by the additional R-UHPFRC layer) and without the intervention becoming visible. For this purpose, a modification of the static system is usually appropriate. Two basic principles are described as follows.

2.3.1. Principle 1: Reinforcement of continuous beams by means of a R-UHPFRC layer

In statically indeterminate systems such as continuous beams, the bending resistance in the hogging moment zone is greatly increased by the formation of a strong R-UHPFRC tension chord in order to be able to carry out a plastic moment redistribution from the sagging to the hogging moment zones at ULS, similar to the concept related to deck slabs (Fig. 3). However, this moment redistribution is only possible if the bending cross-sections are sufficiently ductile, which must be verified. For this purpose, a non-linear finite element analysis is often useful if the empirical rules of standards are not satisfactory.

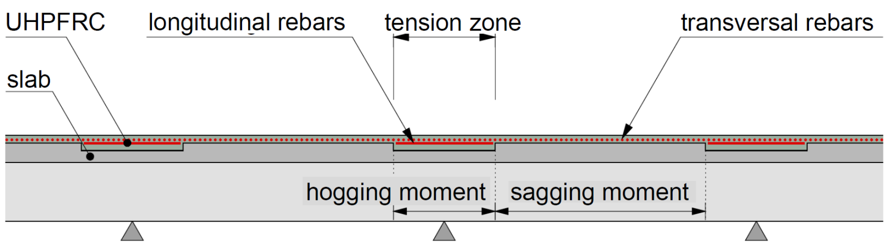


Figure 3 Principle of increasing the ultimate resistance of reinforced concrete bridge girders using a R-UHPFRC layer with the formation of a strong R-UHPFRC tension band in the support area.

This principle is efficient in that an increase in the load-bearing capacity (ultimate resistance) of 15 to 30% (and in extreme cases up to 50%) can be obtained. In this way, for example, even severe damage such as failure of prestressing cables due to corrosion can be compensated without having to install costly additional tendons.

As in the sagging moment zone of a bridge girder, the R-UHPFRC layer only leads to a small increase of the flexural resistance, a need for additional reinforcement of the tension zone at the bottom side of simple and continuous beams can be accommodated for by CFRP (carbon fiber reinforced plastics) lamellas on the underside of the bottom flange or by additional external posttensioning tendons.

2.3.2. Principle 2: Creation of hyperstatic systems by force-locked closure of dilation joints

For existing short and medium span RC bridges with lengths up to 80 m, all dilatation joints can be eliminated using UHPFRC. Force-fit joint closure leads to hyperstatic systems. Particularly, the structural behavior of the modified abutments needs to be investigated applying recent knowledge in the area of integral RC bridge structures. In the case of existing bridges, the dilatation movement to be considered is limited to that due to changes in temperature alone, since girder deformation due to final shrinkage and creep of the existing concrete is negligible.

Bridges consisting of a series of simple beams that are force-fitted monolithically in the support zone by R-UHPFRC, are converted into a continuous beam and are thus analyzed like continuous beams according to Principle 1.

Figure 4a shows the concept of joint closure in the abutment area of a single span beam. In the case of pier-like abutments with large dimensions, a frame structure can be created. By modifying the end zones of the beam to frame corners, the bending stress is redistributed from the sagging zone to the frame corners and thus relieved. By installing the R-UHPFRC tension chord in the abutment zones and a UHPFRC layer over the entire deck, the dilatation joints are eliminated and the reinforced concrete is protected from chlorides and water.

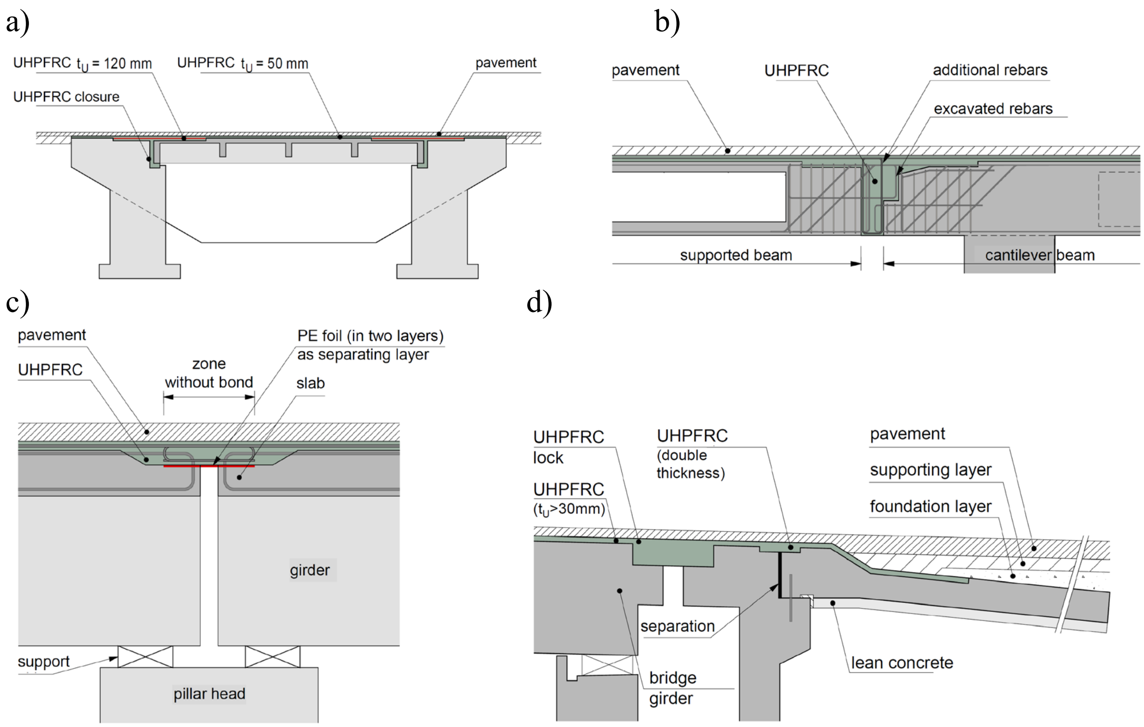


Figure 4 Principle of UHPFRC joint closure: a) in the abutment zones of a single span bridge to create a half-frame, b) force-locked Gerber joint, c) partial joint closure for beam chains, also called "link slab", and d) creation of a semi-integral bridge end.

Figure 4b shows the constructional detail of a force-locked Gerber joint, which is bending and shear resistant. The UHPFRC lock is anchored into the existing RC bridge structure with rebar inserts on both sides. In the case of single span girders in series, the partial joint closure at the level of the deck slab shown in Figure 4c can be suitable. A relatively massive unbonded slab in R-UHPFRC, called “link slab”, is anchored in the adjacent RC deck slabs to connect two adjacent bridge girders by a continuous deck slab. The length of the connecting UHPFRC slab is designed such that temperature related deformations are absorbed by deformation of the “link slab”. The static functioning of the original simple beams is not modified by this intervention. This “link slab” principle can also be implemented in the transition from the bridge to the road for dilations up to ±10 mm.

Figure 4d shows the design of a semi-integral abutment by means of a R-UHPFRC lock connecting the bridge deck slab to the transition (or approach) slab, thereby waterproofing the bridge end zone and eliminating the dilation joint above the bridge bearing.

By forming force-locked UHPFRC connections, the structure is stiffened, which usually increases structural resistance. Obviously, the entire strengthened structure and in particular the UHPFRC-locked zone must be analyzed accordingly and the force flow in the modified structure must be carefully verified.

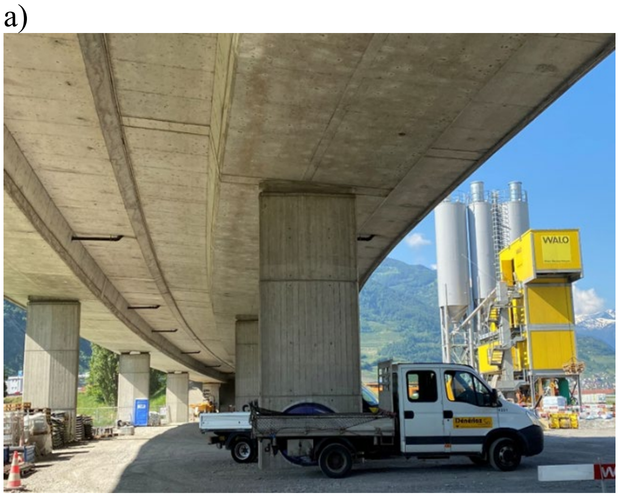
3. Three selected recent applications

Among numerous UHPFRC application projects (Bertola et al.) with involvement of the author in conceptual design, dimensioning, project proof and quality control, three recent projects are selected and briefly described in the following:

3.1. Riddes Road Viaduct

The 1.2 km long road viaduct (Fig. 5a) consisting of a twin continuous box girder in posttensioned concrete built in 1976 is a major road overpass over a railway line, highway and a river.

a)



b)

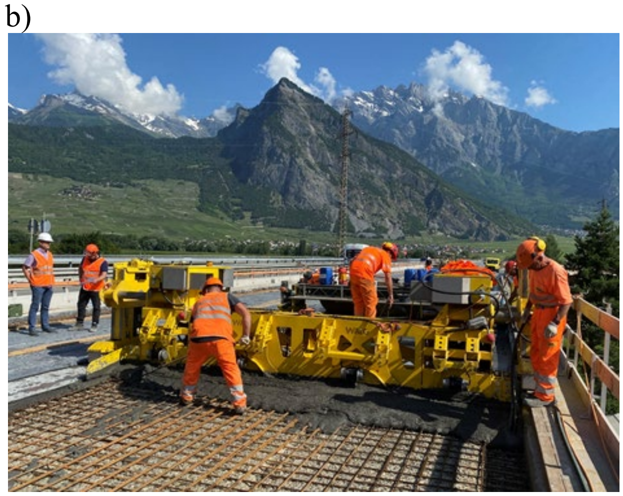


Figure 5 a) UHPFRC ready mix plant next to the Riddes Viaduct, b) UHPFRC casting on the deck slab.

RC damage including corrosion of prestressing tendons and steel rebars as well as alkali-aggregate reaction lead to a significant deficit in structural resistance. Strengthening intervention was urgently needed. The objective of the intervention was to over-strengthen the girder for flexural resistance to accommodate for (1) potential loss of 1/3 of post-tensioning, (2) 30% AAR-related and forecasted concrete strength reduction as well as (3) local damage of the deck slab.

The R-UHPFRC intervention method was found to be most cost-effective and rapid to rescue the viaduct's post-tensioned concrete structure. The concept and design of strengthening was following the principle shown in Figure 6 and the design provisions of the Swiss UHPFRC standard (SIA 2052) including detailed non-linear FE analyses. The UHPFRC layer was cast in 2021 on the deck slab of the viaduct using a casting machine (Fig. 5b).

3.2. Aare Bridge Schinznach

This 120 m long three span road bridge for bi-directional road traffic and with a pedestrian walkway was built in 1954. This bridge belongs to the first generation of steel-concrete composite bridges and has significant cultural and aesthetic values (Fig. 6a).

The cross section consists of two main steel girders and the RC deck slab. The RC slab showed ordinary steel rebar corrosion damage, and the pedestrian walkway had to be widened to accommodate for future user demand. In addition, examination of the composite structure and the deck slab revealed deficits in structural capacity and thus structural strengthening was required.

a) b)

Figure 6 a) View of the steel-concrete composite bridge after R-UHPFRC strengthening, b) casting of UHPFRC with immediate application of curing compound.

The realized strengthening consisted in adding a 60 mm thick layer of UHPFRC incorporating steel reinforcement bars in orthogonal directions to waterproof and protect the RC slab as well as to increase the resistance of the slab in the transverse direction and the hogging moment capacity over the piers in the longitudinal direction. The UHPFRC casting works of the roadway were realized in two days in Summer 2022 (Fig. 6b).

The R-UHPFRC strengthening was optimized such that strengthening of the two steel girders could be avoided, reducing the intervention on the main structure in steel to the renewal of the corrosion protection coating only.

3.3. Viaducts Pont d'Ouche

Built as part of a vast motorway program in the 1960s, the 504 m long Pont d'Ouche twin viaducts are one of the major elements of the A6 motorway in France (Fig. 7a). At the time of their construction, they were unique by its geometric characteristics, since built entirely in curves and in slope, and by the structure being made up of prestressed prefabricated isostatic beams with spans of 36 m with cast-in-place connecting slabs. This rational structural system for RC viaducts, which was very often realized in France and worldwide, allowed realization in a record time of 20 months and the inauguration of the viaducts in October 1970.

Installation of a robust water proofing layer in UHPFRC, repair of rebar corrosion damage and structural strengthening of the slab zone near the curbs to resist possible vehicle impact forces on the new vehicle retaining system, were the main reasons for realizing the UHPFRC project. The UHPFRC layer on the deck slab of the first viaduct was cast in 2022 using a casting machine (Fig. 7b). The same UHPFRC intervention will be realized in 2023 on the adjacent viaduct.

a)

b)

Figure 7 a) View of the twin viaduct structure with triple PC-girder cross section, b) casting of UHPFRC and curing with a plastic foil.

4. Conclusions

The UHPFRC Technology provides effective solutions to rehabilitate and strengthen existing bridges with little use of materials to upgrade them for future utilization. When dealing with existing bridges, the use of UHPFRC leads to: *"Improve instead of replace!"* UHFB technology is able to rehabilitate and strengthen, actually to salvage, existing RC structures. In this way, already used material resources are further utilized. The existing bridge is valorized and upgraded in an economic manner. This follows the principle of sustainability to preserve material resources and their grey energy that are already in use, thereby limiting greenhouse gas emissions to a minimum and thus making bridges sustainable.

The UHPFRC Technology has already been implemented in practice. Recently, the Swiss Federal Roads Office has published a documentation to facilitate the use of the UHPFRC Technology for the preservation existing and the construction of new engineering structures of the road infrastructure (FEDRO 2023).

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