

# “Structural UHPFRC” :

## *Welcome to the post-concrete era !*

### Eugen Brühwiler

Professor, Dr Structural Engineer

EPFL – Swiss Federal Institute of Technology in Lausanne, Switzerland

**Abstract:** “Structural UHPFRC” stands for Ultra-High Performance Fiber Reinforced Cement-based composite material which is complemented by reinforcing and prestressing steel to enhance structural resistance and durability. First, properties of impermeable, tensile strain hardening UHPFRC are described in view of structural applications. Then, two fundamental concepts are presented and validated by means of research results and practical applications: i) Rehabilitation and strengthening of existing concrete structures by adding a layer of structural UHPFRC, and ii) Construction of new structures in Structural UHPFRC, often composed of precast elements. Many applications show that Structural UHPFRC has made its proof as a novel building material and technology to improve structures which may be seen as the advent of a new construction era: *the post-concrete era has begun !*

**Keywords:** UHPFRC, Structural UHPFRC, tensile strain hardening, impermeability, composite elements, strengthening, rehabilitation, lightweight structures, applications.

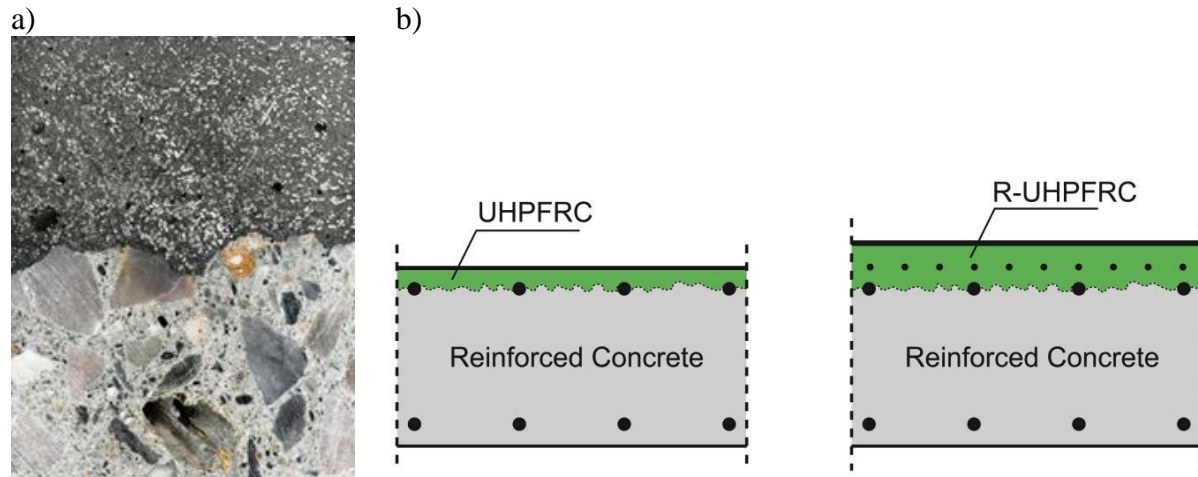
### 1. Introduction

“UHPFRC” stands for Ultra-High Performance Fiber Reinforced Cement-based Composite material produced from cement, additions (powders), hard fine particles, water, admixtures and high amount of relatively short steel fibers. The required performance of currently used UHPFRC is described below in Chapter 2. Other fiber reinforced cement-based materials that do not present this performance may not be compatible with the designs and applications described in this keynote paper.

UHPFRC does not comply with the definition of “concrete”, and therefore, UHPFRC should not be called “concrete” as is also clearly shown in (Fig. 1a). It is fundamental to understand UHPFRC as an independent material with specific properties. This is actually the first basic principle when designing with UHPFRC to improve existing structures and to build new structures.

The second basic principle is that UHPFRC shall be complemented in a targeted manner with reinforcing and prestressing steel in order to enhance structural performance and thus economy of structural applications. Subsequently, the terms reinforced UHPFRC (or short: R-UHPFRC) and prestressed (or post-tensioned) UHPFRC will be used.

“Structural UHPFRC” is UHPFRC, R-UHPFRC and prestressed UHPFRC used for structural applications to enhance structural resistance as full members or as integral parts of (existing) structures in composite action, for example, composite R-UHPFRC – RC structures. Structural UHPFRC has the potential i) to improve the resistance and durability of RC structures (Fig. 1b), and ii) to build UHPFRC structures, a novel generation of structures.



**Figure 1. a) UHPFRC – concrete core showing the obvious difference between the two materials; b) Basic configurations of composite structural elements combining R-UHPFRC and RC: left: UHPFRC layer (thickness 25 to 40mm) has a protective function only; right: R-UHPFRC layer (thickness of 40 to 80mm or more) has both structural resistance and protective functions.**

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 Standard SIA 2052 [1]. This is seen as the advent of a new construction method complementing and steadily substituting RC construction: *the post-concrete era has begun!*

This keynote lecture contains first a description of mechanical performance of current UHPFRC as required for structural applications. Then, two fundamental concepts are presented and validated by means of research results and practical applications: i) improvement (i.e., rehabilitation and strengthening) of existing concrete structures, by means of a layer of structural UHPFRC [2], and iii) design and construction of new structures in structural UHPFRC.

## 2. Performance of UHPFRC

### 2.1. Mix design and fresh UHPFRC properties

UHPFRC mixes typically contain 650 to 900kg/m<sup>3</sup> cement as well as micro-silica and fine particles (quartz, basalt, etc.) with a maximum grain size not exceeding 1 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 is 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 fibers of 13 to 15mm length and an aspect ratio of more than 65, with a dosage of at least 3% in volume (or 240kg/m<sup>3</sup>), in order to obtain high tensile strength and significant tensile strain hardening behavior, a most important property for applications, in particular for composite R-UHPFRC – RC members.

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. Additions may be added to the mix in order to obtain thixotropic behavior of the fresh UHPFRC in view of casting UHPFRC on slopes (up to 12%).

The evolution of mechanical properties of UHPFRC as a function of time depends on the composition, thermal treatment and curing of UHPFRC.

## 2.2. Tensile behavior of plain UHPFRC and R-UHPFRC

### 2.2.1. Plain UHPFRC

As illustrated in Figure 2a, the uniaxial tensile behavior of UHPFRC is described by three phases:

- First, the material is elastic up to the elastic limit stress  $f_{Ute}$ , with typical values of 7 to 11MPa.
- Second, it goes into a strain hardening phase characterized by fiber activation accompanied by (non-visible) multiple fine micro-cracking of the matrix; the material still behaves like a continuum. Significant strain hardening behavior is only obtained with (straight) steel fibers having an aspect ratio larger than 65 and a fiber content of at least 3% in volume. Strain hardening domain shall reach strains  $\epsilon_U$  more than 2‰ and while the (uniaxial) tensile strength  $f_{Ut}$  reaches values ranging from 9 to 15MPa.
- The third phase starts upon the formation of a discrete macro-crack at ultimate resistance and strain softening begins. The maximum crack opening  $w_{Ut,max}$  equals about half of the fiber length, i.e. 6 to 8mm. At these crack openings, no more tensile stress is transferred.

The tensile hardening and softening behavior of UHPFRC depends on the bond, aspect ratio, content and random orientation of the straight steel fibers [4,5]. The specific fracture energy GFU of UHPFRC typically ranges from 20 to 30kJ/m<sup>2</sup>. A significant part of the work of fracture of UHPFRC is dissipated in the bulk of the material, during the strain hardening phase.

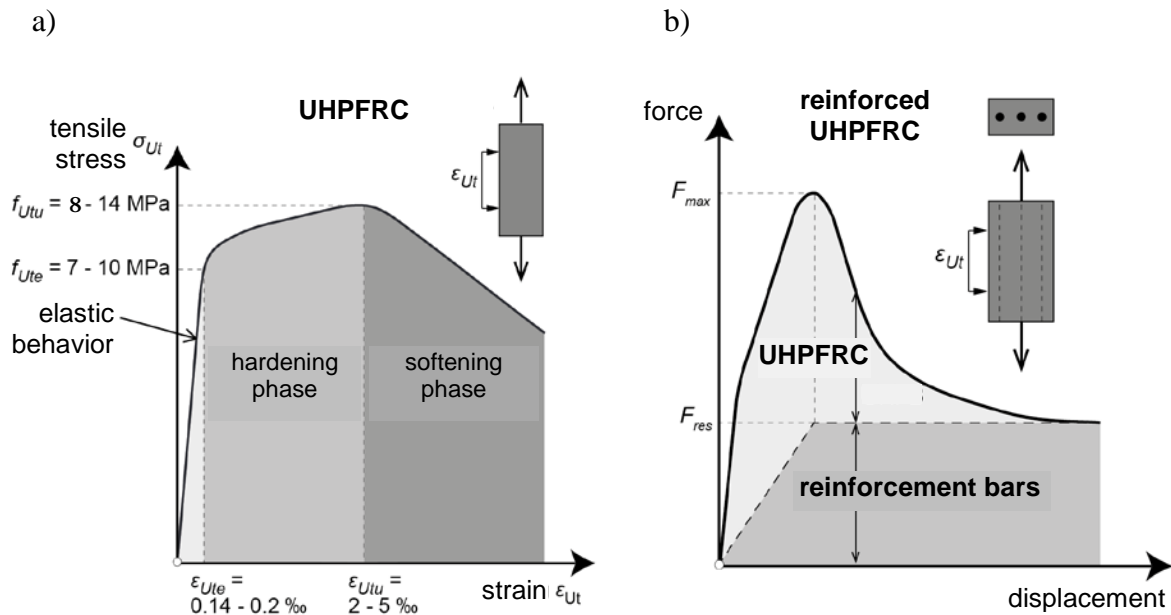


Figure 2. Characteristic tensile behavior of a) UHPFRC and b) R-UHPFRC

The mechanical response of fibrous materials such as UHPFRC depends on the fiber orientation due to the casting procedure and the dimensions (thickness) of the UHPFRC element or layer [4,6]. Anisotropic fiber orientation is mitigated by high fiber content and by adding of reinforcing bars to the UHPFRC. For structural design, fiber orientation may be taken into account by a coefficient that decreases to a value of 0.80 for increasing element thicknesses up to 80 mm [1].

### *2.2.2. Reinforced UHPFRC (or short: R-UHPFRC)*

The main reasons to complement UHPFRC with steel reinforcing bars are a significantly improved tensile behavior and a reduction of the scatter in the material properties [7]. 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 [7,8]. The rebars not only significantly increase the resistance but also improve the deformation capacity and strain hardening behavior of UHPFRC. Thus the reinforcing bars enhance the apparent UHPFRC tensile behavior.

The global tensile behavior of R-UHPFRC can be described by linear superposition of the reinforcing steel and the UHPFRC tensile behaviors (Fig. 2b). Localization of the deformation in one macro-crack occurs at the start of yielding of the reinforcing steel. This was observed to be independent of the steel grade of the reinforcement [7]. 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 the pre-peak behavior is independent of the bond strength and that the crack spacing is controlled by the fibers. Compared to ribbed reinforcing bars, smooth rebars have lower bond strength and allow for larger post-peak deformations while avoiding localized stress concentration in the softening UHPFRC macro-crack [7].

### *2.3. Compressive behavior*

The behavior of UHPFRC under compression is characterized by a rather linear stress-strain relationship until the compressive strength of typically 130 to 180 MPa is reached. A slightly non-linear relationship may be used for design purposes to describe the ascending branch of the stress-strain diagram.

### *2.4. Elastic modulus and stiffness*

The modulus of elasticity of UHPFRC in tension and compression is 45 to 50 GPa which is a relatively low value in view of the stiffness of new structures in structural UHPFRC. However, for composite R-UHPFRC – RC members, similar moduli of elasticity of UHPFRC and concrete is advantageous with respect to deformation induced stresses such as temperature and shrinkage effects. In the tensile strain hardening domain, UHPFRC shows reducing apparent modulus of elasticity with increasing hardening strain.

### *2.5. Shrinkage and creep*

Evolution of shrinkage and creep of UHPFRC is similar to other cement-based materials, but by thermal treatment at early age, creep and shrinkage of UHPFRC is considerably reduced.

Also, shrinkage develops rapidly and about 60 to 90 % of total shrinkage has completed already after 50 days. This is because the largest part of shrinkage of UHPFRC results from endogenous shrinkage and a smaller part from drying shrinkage [9,10].

## **2.6. Fatigue behavior**

The fatigue behavior of UHPFRC under both tension and compression is characterized, in view of fatigue design, by a fatigue endurance limit that is about 50 to 60 % of the tensile and compressive strengths. Above this limit, significant fatigue damage occurs and the fatigue strength is relatively low [11].

## **2.7. Durability: resistance against ingress of liquids**

Testing using methods commonly used for concrete, revealed the following UHPFRC properties related to durability: extremely low air permeability and water conductivity, very high resistance against freeze-thaw-cycles, sulfates 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 UHPFRC impermeable for liquids, even under high tensile strains up to about 1.5 ‰ [12].

## **2.8. Abrasion resistance**

Compared to other materials, UHPFRC shows a very high resistance against mechanical abrasion and hydro-abrasion [13].

## **2.9. Fire resistance**

The fire resistance of UHPFRC is relatively low and similar to concrete, although there is no free water in UHPFRC. Adding polypropylene fibers can however avoid the spalling of UHPFRC providing thus sufficient fire safety for most applications.

# **3. Improvement of existing RC structures by strengthening with a layer of R-UHPFRC**

## **3.1. Introduction**

Reinforced concrete (RC) structures show satisfactory performance in terms of structural behavior and durability except for the zones that are exposed to severe environmental influences and high mechanical loading. Interventions to improve deteriorated concrete structures are a heavy burden from the socio-economic viewpoint since they lead to significant direct and user costs. RC structures are cheap at construction but costly during service life because of insufficient durability that often leads to important premature rehabilitation.

As a consequence, novel concepts for the improvement of RC structures must be developed. In the future, sustainable structures will be those requiring just minimum interventions for preventive maintenance with no or little service disruptions. UHPFRC provide the structural engineer with material properties that can be exploited to significantly improve structural resistance and durability of concrete structures.

## **3.2. Conceptual idea**

The basic conceptual idea is to use UHPFRC only in the zones of the structure where the 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, aggressive liquids) and high mechanical loading (e.g. concentrated forces, fatigue, impact, abrasion). Parts of the structure that are subjected to relatively moderate exposure remain in conventional structural concrete. This concept is applicable both to improve

existing structures and to build new structures. It necessarily leads to composite structural elements combining conventional RC and UHPFRC (Fig. 1b).

The original conceptual idea (developed in 1999) has been investigated by means of extensive research activities over more than 16 years, aimed at characterizing the properties of UHPFRC and the structural behavior of R-UHPFRC – RC composite structural members, combining material and structural engineering sciences.

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

#### *3.3.1. Built-in tensile stresses in the R-UHPFRC*

The manufacturing of a composite element consisting of a UHPFRC layer on a RC substrate leads to built-in stresses in this element. In the UHPFRC, strains induced by shrinkage and other processes linked to temperature are restrained due to bond of UHPFRC with the concrete and induce tensile stresses in the UHPFRC in the range of 3 to 6 MPa (or 40 to 80% of the elastic limit stress  $f_{Ute}$ ); subsequently, the creep of UHPFRC however considerably reduces these stresses.

The state of built-in stresses depends on the specific UHPFRC properties and structural properties (stiffness of UHPFRC layer with respect to the stiffness of the RC substrate). It may be described by the degree of restraint. These built-in stresses need to be analyzed and evaluated under service conditions but are usually resisted by the strain hardening UHPFRC without crack formation [14]. At the ultimate limit state, stresses in the composite system due to restrained deformations at early stage may be neglected, in particular tensile strain in the UHPFRC.

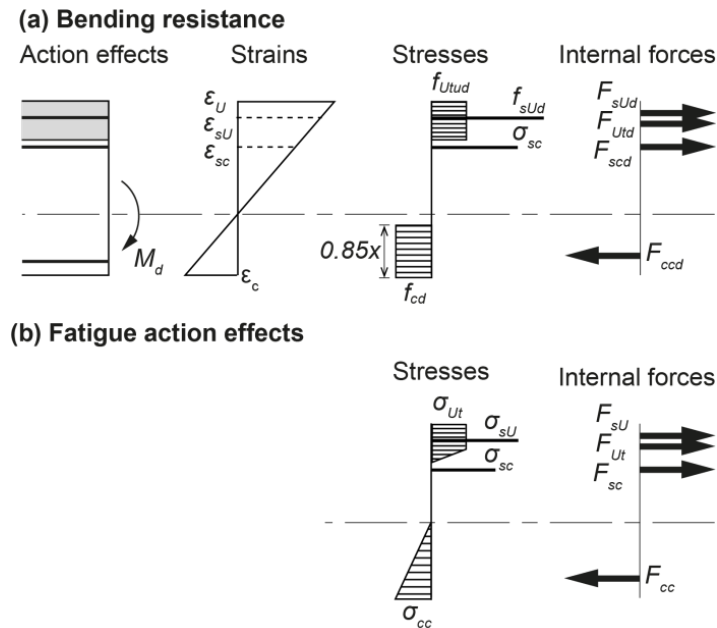
#### *3.3.2. Behavior in bending*

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 of the stiffness and the ultimate resistance. This increase depends on the type and strength of the steel reinforcement [7,8].

The bond between UHPFRC and concrete is obtained by preparing the concrete substrate surface by high pressure water jetting or by sand blasting. This surface preparation is sufficient to avoid separation between UHPFRC and concrete. In fact, in all fracture tests there was no separation along the interface zone, and as there is no slip between the two layers, shear connectors would not be effective. The R-UHPFRC – RC section is monolithic.

The plastic post-peak rotation capacity of strengthened RC beams is reduced by the UHPFRC layer. With an appropriate design of the rebars in the UHPFRC layer, the reduction of plastic rotation capacity can be controlled. Smooth high yield strength reinforcing bars in the UHPFRC layer offer a large increase in resistance while the post-peak rotation capacity remains high [7,15]. The structural behavior in terms of moment – curvature relation of composite sections subjected to bending as well as the ultimate bending moment are calculated using the conventional sectional model for RC with the extension to account for the R-UHPFRC layer in the monolithic section (Fig. 3a).

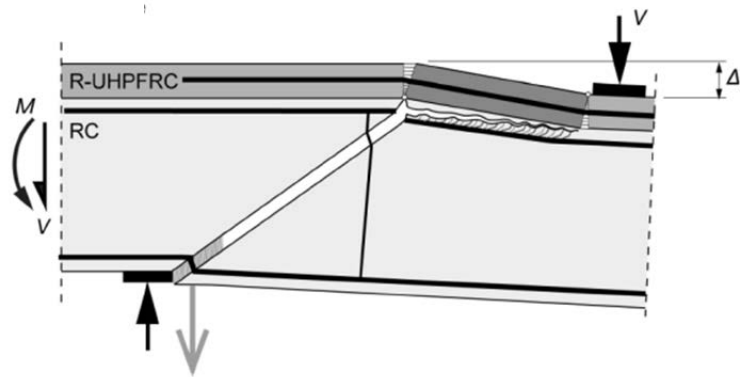
When subjected to compressive stresses, the R-UHPFRC layer acts as a compression chord but the high UHPFRC compressive strength of up to 180 MPa cannot be fully exploited in R-UHPFRC – RC members. This is because the compressive strength of the adjacent concrete below the UHPFRC layer often is about 5 times smaller than the compressive strength of UHPFRC, and thus concrete would crush before UHPFRC reaches its strength.



**Figure 3. Plane section analysis: (a) bending resistance; (b) fatigue action effects.**

### 3.3.3 Behavior due to combined bending and shear

When subjected to combined bending and shear, R-UHPFRC – RC members develop, when approaching the ultimate resistance, multiple cracking in the concrete volume below the interface allowing for the formation of a specific failure mode [16] as shown in Figure 4. The relative vertical movement of the RC segments separated by inclined main shear crack 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 multiple concrete cracking.



**Figure 4. Flexure-shear crack failure mode of a R-UHPFRC – RC composite member.**

In addition, the tensile R-UHPFRC layer acts as an external tensile reinforcement, leading to confinement of the composite member resulting in control of the width of cracks in concrete. A web crushing type failure mode develops in the concrete of the lower beam part subjected to compressive stresses, thus increasing the ultimate resistance.

The ultimate resistance is thus the sum of the resistances provided by the R-UHPFRC layer, crushing of the lower part of the concrete web and, if available, vertical steel reinforcement. Analytical models were developed to predict the ultimate resistance and the pre-peak deformation capacity of the beams [17]. Failure mechanism is similar in the case of punching shear strengthening of slabs (supported by columns) using a layer of R-UHPFRC [18].

### *3.3.4 Fatigue behavior*

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 strength of the R-UHPFRC – RC beam. At fatigue solicitation levels above this value, the fatigue life was rather short and fatigue strength was not significant. Fatigue fracture process of R-UHPFRC – RC beams was determined by fatigue fracture of steel rebars in the R-UHPFRC layer [19].

Consequently, fatigue design rules for R-UHPFRC – RC members under bending fatigue need to account for steel rebar and UHPFRC fatigue resistances. Cross sectional fatigue stresses are calculated using the model shown in Figure 3b.

## **3.4. Applications**

### *3.4.1. Domains of application*

In Switzerland, the technology of improvement of existing RC structures by strengthening with a layer of R-UHPFRC was applied for the first time in October 2004. Since then, more than 50 structures have been improved using this technology to establish the required durability and mechanical performance.

These applications are based on principles and provisions according to the Swiss Standard SIA 2052 for UHPFRC [1] and include the following issues (f.ex. [13]):

- Protection (waterproofing) and strengthening of bridge deck slabs: UHPFRC was used as thin watertight layers (in replacement of currently used waterproofing membranes) and as reinforcement layers in R-UHPFRC. This layer provides structural resistance in bending, shear and fatigue without increasing the dead load of the structure (hence avoiding strengthening of primary structural elements).
- Rehabilitation and protection of severely (chloride) exposed kerbs, parapets, crash barrier walls and piers of bridges showing heavy rebar corrosion damage. UHPFRC was used as reprofiling material. The impermeability against water and chloride ions as well as the tensile resistance presented significant advantages compared to conventional repair materials.
- Strengthening of building slabs by a layer in R-UHPFRC providing the required increase in structural resistance in bending, shear and punching shear. Often, the overlay on the slab was replaced by the UHPFRC layer, avoiding increase in dead load and reduction of clearance height.
- Wearing layer in UHPFRC of industrial floors and one river weir. In the case of two pedestrian bridges, in order to obtain directly walkable and drivable surface in UHPFRC, pea gravel coating was cast on the 25 mm thick UHPFRC layer by means of a 3 mm thin film of UHPFRC matrix that allowed for incorporating pea gravel.
- Protection of concrete structures such as containers against chemical attack and aggressive wastewater. The UHPFRC coating of the walls was realized using a formwork. An important advantage of using UHPFRC is the relatively thin layer which allows to limit the reduction of storage volume in the containers.



In the following, the up to now most important application is briefly described.

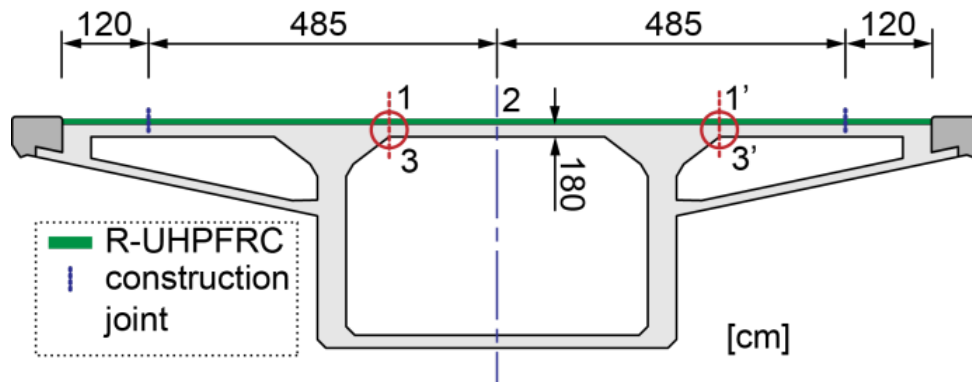
### 3.4.2. Improvement of the Chillon Viaducts [20]

Located in Switzerland, the Chillon viaducts are two parallel posttensioned concrete highway bridges built in the late 1960s (Fig. 5). The concrete of the deck slabs of these bridges shows signs of early alkali-aggregate reaction (AAR) which will induce in time a decrease of the concrete strength leading to insufficient structural safety.



**Figure 5. Chillon Viaducts along Lake Geneva.**

To insure structural safety for future traffic demands, it was decided to strengthen the slab by adding a layer of 45 mm of reinforced UHPFRC acting as an external tensile reinforcement for the slab and main girder (Fig. 6).



**Figure 6. Geometry of the box girders cross-section.**

By casting one layer of R-UHPFRC on the deck slab, the following beneficial effects were achieved:

- increase the deck slab's ultimate resistance in the transverse direction in bending and shear
- increase the deck slab's stiffness to improve the serviceability of the slab and the fatigue safety of the steel rebars in the existing concrete in view of future higher traffic loading
- increase the hogging bending moment resistance and the stiffness in the longitudinal direction of the box girder
- provide waterproofing to protect the existing concrete of the slab from ingress of water (and chloride ions), thus limiting further development of the AAR
- limit duration of the intervention.

All listed requirements and structural functions were realized (by the casting of just one layer of R-UHPFRC) using a machine that was developed specifically for this casting application. The large volume of 2'350m<sup>3</sup> 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 less than 30 working days (Fig. 7).



**Figure 7. UHPFRC casting machine (left), and fresh UHPFRC layer after casting (right).**

Testing according to quality assurance given in [1] revealed that the UHPFRC complied with the requirements for strain hardening UHPFRC (as described in Chapter 2). The fresh UHPFRC had to show thixotropic behavior as it was cast on slopes of up to 7%. An asphalt layer and bituminous pavement, overall 8-cm thick, were finally placed on the UHPFRC surface to obtain the drivable road surface.

The overall cost of the UHPFRC intervention (including hydro-jetting surface preparation) was 235 Swiss Francs per m<sup>2</sup> road surface (or about 235 US \$ per m<sup>2</sup>) which turned out to be an order of magnitude lower than the estimated cost of conventional strengthening methods.

### 3.4.3. Current projects and outlook

Most typical problems of rehabilitation projects can be solved by the strengthening method using Structural UHPFRC. Currently the following projects are under investigation or in the tendering phase in Switzerland and other countries:

- several bridges of medium and larger size
- use of UHPFRC for rehabilitation of RC bridge piers and wall elements of abutments and retaining walls damaged by chloride induced steel rebar corrosion
- continuous UHPFRC topping of the runway of an airport
- strengthening of the top layer of bus stops, in particular when they are in slopes, and roundabouts using UHPFRC
- strengthening of wearing surface of hydraulic structures subjected to severe hydro-abrasion .

Obviously, and since reinforced concrete will remain a low cost building material, the concept of composite R-UHPFRC – RC construction should be implemented to the design and construction of new RC structures with severely exposed elements such as deck slabs of bridges or walls strengthened using Structural UHPFRC. In this way, important rehabilitation works 20 to 30 years after construction could be avoided while the targeted application of Structural UHPFRC would increase the initial construction cost only by some percent [21].

## 4. New structures in Structural UHPFRC

### 4.1. Introduction

The basic principle in designing new structures in Structural UHPFRC is to combine assets of steel construction and reinforced concrete construction in order to realize cost-effective lightweight structures of original aesthetic expression. The dead load of structures in Structural UHPFRC typically is at least three 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.

Structural UHPFRC elements contain reinforcing bars and/or prestressing steel and are designed as profiled elements consisting of plates (sheets) stiffened by ribs with thicknesses typically of 30 to 100 mm. The design of structures in Structural UHPFRC is inspired by steel construction, post-tensioning technology and cast connections (such as the ones in cast iron). For thin plates (as parts of slabs or façade elements), steel reinforcing bars are not always needed. For curved plates and shells, wire mesh in steel or synthetic fibers (fabrics, mesh wires) may be suitable to increase resistance, as inspired by ferrocement structures and similar designs from the origin of reinforced concrete in the 19th Century.

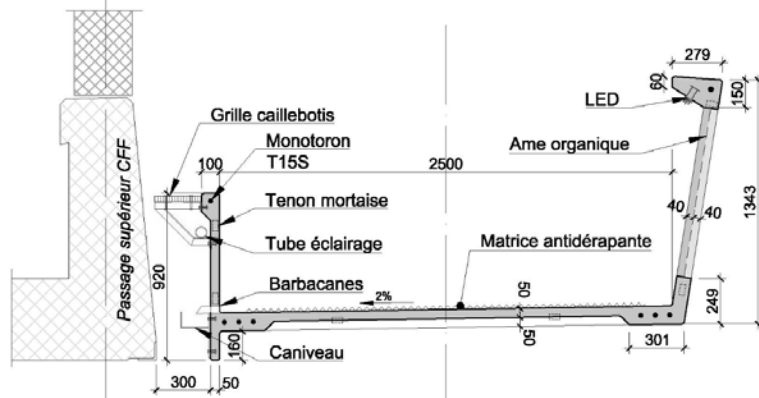
### 4.2. *Martinet pedestrian bridge in Lausanne Switzerland [22]*

The Martinet pedestrian bridge is part of a new pedestrian and bike path following the main railway line in the agglomeration of Lausanne, Switzerland (Fig. 8). The UHPFRC structure is a girder of 15.3 m single span resting on two RC abutments. The project objectives were: i) construction cost not higher than for a conventional structure in RC or steel, ii) original aesthetic expression, iii) minimum maintenance, iv) minimum use of resources, while obviously respecting usual code requirements.

The UHPFRC structure of the Martinet pedestrian bridge was designed using the drafts of the Swiss Standard on UHPFRC [1]. From the beginning, the project and its result were meant to become a showcase for the design and construction of a slender structure in Structural UHPFRC and with original and pleasing expression.

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 neighboring railway line (Fig. 8). Both girders form a rigid half-frame with the bottom plate that is stiffened with ribs in the transverse direction. The structure consists, in the longitudinal direction, of 9 segments that were cast upside-down in the plant using a mold in steel.

The "organic" web was found by optimizing aesthetic, static and casting requirements; it provides visual originality and is appealing for the user who shall perceive a material that is different to concrete or steel. The dark color 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.



**Figure 8. Martinet Pedestrian Bridge in Lausanne, Switzerland; Top: overall view of illuminated bridge at dusk, Middle: “organic” web and bottom plate with ribs, Bottom: asymmetric cross section (dimensions in mm).**

Each cast segment was demolded 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 track. The butt joint between the segments was glued with epoxy resin (providing also water tightness of the joint) and temporarily interlocked and pressed together. A few days after mounting of all segments, the

mono-strands for the prestress were inserted in the ducts and tensioned by stages. Afterwards, the post-tensioned structure was lowered on the elastomer bearings using hydraulic jacks.

The straight post-tensioning provides in the *longitudinal direction* a force-fit connection of the segments under a compressive stress uniformly distributed over the cross section of only 3 MPa under dead load such that at serviceability limit state, no zone of the cross section is decompressed. At the ultimate limit state, the prestressing tendons act as main reinforcement in the longitudinal direction. The shear force in the “organic” and full web is carried by the UHPFRC including single vertical rebars and in the segment joints by interlocking mortise and tenon.

In the *transverse direction*, internal forces are mainly carried by the 50mm bottom plate with transverse ribs in R-UHPFRC.

Due to the relatively high tensile strength and strain hardening of the UHPFRC, the construction remains crack-free under service stresses and hence, given also the water tightness of the UHPFRC, the severe requirements regarding durability (significant amounts of deicing salts are spread in winter season) could be fulfilled without particular measures. (Minimum rebar cover was 10mm.)

Validation by testing was important for the success of the project: i) casting procedure, color 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 vehicle of 5 tons weight provided valuable information about the structural behavior: 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 at mid-span is 11mm, significantly less than the allowable 26mm. For visual reasons, a camber of 40mm was realized.

The total construction cost was 5'000 Swiss francs (or about 5'000 US \$) per m<sup>2</sup> of walkway surface which is about 10% higher than the estimated cost for a cheap RC structure (of limited durability and thus high maintenance demand). The cost for the used UHPFRC material (of 15 tons) was only 5.5% of the total construction cost; the prefabrication labor as well as the construction of the mold turned out to be cost relevant.

### 4.3. Outlook

Experiences with the design, dimensioning and construction of the Martinet pedestrian bridge are now an important basis in the design of next lightweight structures in Structural UHPFRC by the author and his team:

- Smaller structures such as roof structures for houses and next pedestrian bridges are currently in the tendering process or were recently built.
- A short span railway bridge design has been recently validated and will be built in 2017, and a 100m-long curved single track narrow gauge railway bridge structure in Structural UHPFRC has been recently designed.
- improvement of (fatigue) strength and durability of railway sleepers of fixed and ballasted railway tracks
- The design of wind turbine towers in Structural UHPFRC of increased height (150 to 200 m) is currently developed.

These projects and case studies show that there is a wide scope for the design of original structures. In principle, Structural UHPFRC is suitable for a large variety of structures.

## 5. Conclusions and outlook

The state-of-knowledge and the diversity of applications using Structural UHPFRC confirm the potential of the two basic implemented structural concepts:

- i) existing structures are significantly and economically improved providing them a next service life cycle while responding to the requirements of modern use;
- ii) new lightweight structures with enhanced durability and original aesthetics will complement and replace step by step traditional construction in concrete and steel.

UHPFRC showing the performance described in Chapter 2 will prevail in the near future over other fiber reinforced cement-based materials. Significant tensile strain hardening and high tensile strength of the UHPFRC have important advantages in structural applications in terms of structural resistance and durability. Implementation of UHPFRC materials relies on the state-of-knowledge in material science and structural engineering, combining the knowledge of production and process technologies.

The sometimes raised cost issue related to relatively high fiber contents of UHPFRC is insignificant as the pure material cost for UHPFRC often is less than 20 to 30% of the total intervention or construction cost. Labor costs and project condition related costs usually dominate compared to material costs.

The implementation of Structural UHPFRC responds to the principles of sustainable construction : i) improving existing structures to provide a next service life cycle (rather than replacing them), as well as ii) new lightweight structures use significantly less resources in terms of materials [23], energy and financial means (expressed as intervention or construction costs and life-cycle costs).

UHPFRC is not a concrete, and thus structural engineering, design and construction in Structural UHPFRC is not just a “niche” of concrete construction but may soon become a specific discipline with an own industry. *The post concrete era has begun !*

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