UHPFRC is ready to revolutionize existing and new structures

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Abstract

“Structural UHPFRC” stands for Ultra-High-Performance Fibre Reinforced Cementitious Composite material which is complemented by reinforcing and prestressing steel to enhance the resistance and durability of structural elements. Properties of impermeable, tensile strain hardening UHPFRC are discussed in view of structural applications. Two fundamental concepts to enhance concrete bridges have been developed by research and validated by numerous applications, mostly 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. UHPFRC also contributes in lowering the environmental impact of structures and thus improving sustainability. UHPFRC is at the beginning of a new construction era: the “post-concrete era”.

Keywords: UHPFRC, tensile properties of UHPFRC, rehabilitation and strengthening of reinforced concrete using UHPFRC, design of UHPFRC structural elements.

1 Introduction

“UHPFRC” stands for Ultra-High-Performance Fibre 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 fibres.

UHPFRC materials have been developed over the last 40 years. The pioneering development has been conducted by Hans-Henrik Bache in Denmark. Today, the best UHPFRCs have significant tensile strain hardening behaviour and high strength both in tension and compression. To enhance the structural behaviour and resistance, it is advantageous to complement UHPFRC with reinforcing bars and prestressing. UHPFRC is a dense material of optimized compactness and is thus waterproof and crack-free under service stresses, thus providing robust protection against water and chloride ion ingress.

UHPFRC does not comply with the definition of “concrete”, and therefore, UHPFRC should not be called “concrete” as is evidenced in Figure 1.

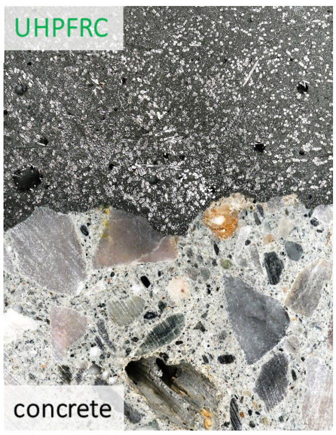

Figure 1. UHPFRC–concrete core showing the obvious difference between the two materials.

UHPFRC should 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, as it is the language and the terminology that make a concept.

The second design principle is that UHPFRC shall be complemented in a targeted manner with steel reinforcing bars and prestressing in order to enhance structural performance, safety and robustness as well as economy of structural applications. Subsequently, the term reinforced UHPFRC (or short: R-UHPFRC) is used.

This keynote paper focusses on aspects relevant for structural engineering using UHPFRC and summarizes experience gained by the author who was involved as designer, consulting engineer and expert in more than 100 realized UHPFRC projects, mostly in Switzerland [1]. After a short presentation of UHPFRC standards in Chapter 2, Chapter 3 summarizes the properties of UHPFRC and R-UHPFRC in terms of structural performance. Chapter 4 presents the design and execution of the strengthening of existing concrete bridges. Chapter 5 presents main aspects of the design and construction of new structures in R-UHPFRC.

This keynote paper is intended to for practising structural engineers. Scientific details are not discussed, and references only refer to standards and application-oriented papers by the author.

2 Standardization

Today, the state-of-knowledge is sufficient to establish rational design provisions for the application and implementation of R-UHPFRC in structural engineering. Several standards exist already, for example in Switzerland the Technical Leaflet SIA 2052 [2]. Two fundamental concepts are treated: (1) enhancement of existing concrete structures by adding a layer of UHPFRC, and (2) construction of new structures in UHPFRC. SIA 2052 focuses on tensile strain-hardening UHPFRC, and thus UHPFRC is classified with respect to tensile properties. UHPFRC properties are defined (including test methods for UHPFRC characterization), basic design provisions are formulated, structural detailing and main construction features, including quality assurance, are regulated. SIA 2052 has recently been revised and extended. SIA 2052 has been translated into Japanese, Chinese, Russian and probably other languages to be used in these countries.

The most well-known UHPFRC standards are the French Standards NF P18-470 [3] and NF P18-710 [4]. These standards are mostly based on the previous UHPFRC Recommendations published in France. They define material properties and testing methods and focus on the design of new UHPFRC structures.

One of the first UHPFRC standard was published in Japan. More recent recommendations and standards have been or are being elaborated in the USA, Canada, Germany and probably other countries.

3 UHPFRC properties for structural design

The required performance of currently available UHPFRC as stipulated in [2] is described in this chapter. Focus is thus given on tensile strain hardening UHPFRC of highest strengths. Other fibre reinforced cement-based materials and concretes (often denominated as “UHPC”) that show inferior performance, do not qualify for structural applications presented in this paper.

3.1 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 2. The significant strain hardening deformation ε_U 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 an aspect ratio of at least 65.

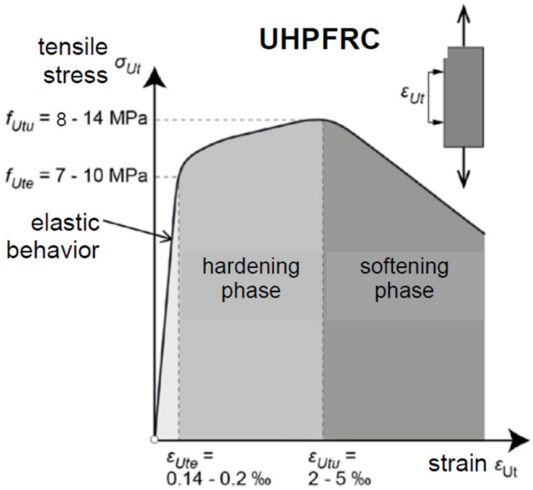

Figure 2. Tensile behaviour of UHPFRC

Tensile 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 f_{Ute}. 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. For structural design, fibre orientation is considered in [2] 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.

The main reason to complement UHPFRC with steel reinforcing bars (to obtain R-UHPFRC) is the significantly enhanced tensile resistance and reduced scatter of R-UHPFRC material properties. The rebars also improve the apparent deformation capacity and strain hardening of UHPFRC. The overall tensile behaviour of R-UHPFRC is described by linear superposition of reinforcing steel and UHPFRC tensile behaviours (Fig. 2).

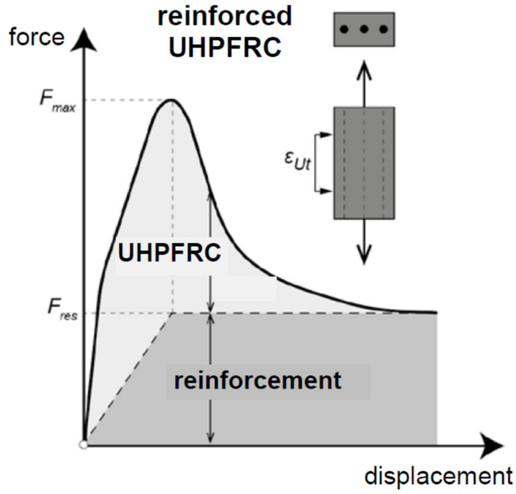

Figure 3. Tensile behaviour of R-UHPFRC

3.2 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 slightly non-linear relationship may be exploited for design purposes to describe the ascending branch up to the compressive strength. The required compressive strength typically is 150 MPa while higher compressive strength up to 200 MPa can be achieved reliably by thermal treatment.

3.3 Modulus of elasticity

The modulus of elasticity of UHPFRC in tension and compression is 45 to 50 GPa which is relatively low. Consequently, the stiffness of UHPFRC structural elements is of first importance in design. In the tensile strain-hardening domain, UHPFRC shows reducing apparent modulus of elasticity with increasing hardening strain.

3.4 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 also mechanical properties). 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.

3.5 Fatigue behaviour

The fatigue behaviour of UHPFRC under both tension and compression is characterized by the presence of a fatigue endurance limit higher than 50 to 60 % of the UHPFRC tensile and compressive strengths. Fatigue design is thus performed with respect to a fatigue limit stress, as given in [2].

3.6 Durability, abrasion and fire resistance

Regarding the durability performance, testing revealed that UHPFRC has extremely low air permeability and water conductivity, 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 relatively few capillary pores making strain-hardening UHPFRC impermeable for liquids, even under high tensile strains up to about 1.5 ‰.

Compared to other materials, UHPFRC show 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.

4 Rehabilitation and strengthening of existing concrete structures using R-UHPFRC

4.1 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.

Conventional "retrofitting" using concrete and repair mortar has shown insufficient performance, 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 4; they lead to the structural system of (monolithic) composite R-UHPFRC – RC elements.

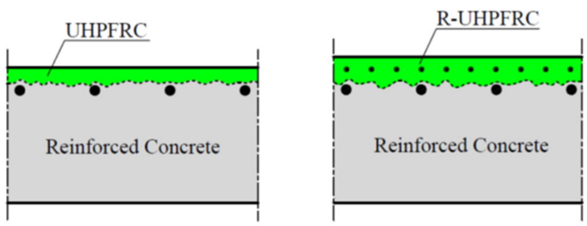

Figure 4. Basic configurations of structural elements combining UHPFRC and RC: left: UHPFRC layer has a protective function only; right: R-UHPFRC layer has structural resistance and protective functions.

4.2 Structural performance of R-UHPFRC – RC composite members

The author and his research team at EPFL have investigated the structural concept of composite R-UHPFRC – RC members over more than 20 years. The following is a brief summary of main findings of this research.

4.2.1 Behaviour in bending

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

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 has to be wetted and needs to be moist when the layer of UHPFRC is cast. This surface preparation provides a full bond between the UHPFRC and the concrete substrate. In fact, pull-out tests show the expected fracture in the concrete (and not at the interface). Therefore, 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. The structural behaviour in terms of moment – curvature relation and the ultimate bending resistance are calculated using the conventional sectional model, extended to account for the R-UHPFRC layer in the monolithic section (Fig. 5).

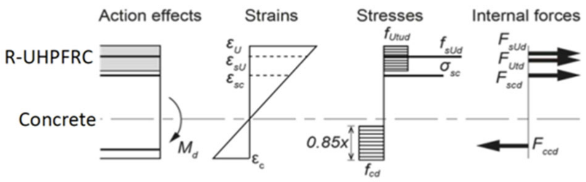

Figure 5. Plane section analysis for ultimate bending resistance.

When subjected to compressive stresses, the R-UHPFRC layer acts as a compression flange but the high UHPFRC compressive strength can usually not 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.

4.2.2 Behaviour in combined bending and shear

Testing of R-UHPFRC – RC composite beams revealed that the addition of a layer of R-UHPFRC delays the formation of the inclined shear crack in the concrete section. For many geometric configurations, the R-UHPFRC layer 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, the ultimate shear resistance is composed of the contributions due to concrete web crushing, vertical steel reinforcement yielding and a two hinge-bending mechanism of the R-UHPFRC layer. Accordingly, analytical expressions have been deduced to calculate the ultimate shear strength.

4.2.3 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. 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 5.

4.3 Selected applications

4.3.1 Introductory remarks

In Switzerland, the technology of enhancing the structural performance of existing RC structures by a layer of R-UHPFRC was applied for the first time in October 2004. Since then, more than 200 RC structures, mostly bridges, of various size have been rehabilitated and strengthened using tensile strain-hardening UHPFRC with a fibre content of more than 3% in volume [1].

Because of comparatively high labour and machine costs, the UHPFRC material cost is only in exceptional cases higher than 30% of the total project cost. Obviously, the cost for high fibre content is largely outbalanced by the superior technical performance, often leading to slenderer UHPFRC element thickness.

The main reason for the high number of applications is the cost effectiveness of the UHPFRC Technology compared to traditional methods. (Obviously, it is meaningless to compare the material cost only of concrete or steel and UHPFRC.)

4.3.2 Chillon Viaducts

The 2.1 km long Chillon Viaducts are two parallel posttensioned concrete highway viaducts built in the late 1960s (Fig. 6). To ensure structural safety for future traffic demands, it was decided to strengthen the deck slab by adding a layer of R-UHPFRC acting as an external tensile reinforcement for the slab and main girder.

Figure 6. Chillon Viaducts along Lake Geneva with Chillon Castle.

The *concept* (Fig. 7) implemented in 2014/15 had 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.

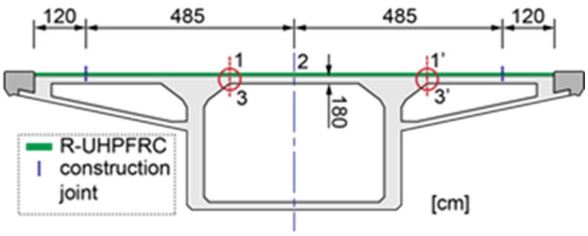

Figure 7: Geometry of the box girders cross-section (thickness of R-UHPFRC layer: 50 mm over piers and 40 mm in the spans).

The deck slab had originally a small thickness. Transversal steel rebars are thus positioned in the UHPFRC layer. Over the piers, the thickness of the UHPFRC layer was increased, and rebars were also placed in the longitudinal direction (in addition to the transverse rebars) to increase the 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 introduced above. The calculated ultimate hogging moment resistance of the strengthened slab is 73% higher than the resistance of the RC section alone. For sagging moment resistance, 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 resulting resistance increase is 33%.

The deck slab does not have any shear reinforcement. Ultimate shear resistance of the composite element was thus calculated as the sum of the concrete and UHPRRC contributions. Due to the R-UHPFRC reinforcement, the increase in ultimate shear resistance is 40%. The increased shear resistance is significant such that theoretically the flexural failure mode is now predominant even in shear prone loading situations.

Execution: All listed requirements and structural functions were realized by the casting of one layer of R-UHPFRC using a machine (Fig. 8) on the concrete surface prepared by removal of 10 mm by hydro-jetting. The large volume of 2'350 m^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 less than 30 working days.

Figure 8. UHPFRC casting machine (top) and fresh UHPFRC layer after casting (bottom).

Quality testing confirmed that the built-in 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 significantly.

4.3.3 Boli-Mettlen-Linden Viaducts

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. 9). 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 form a continuous girder.

Figure 9. View of one of the three twin viaducts

The hogging moment capacity (over the piers) was originally relatively low. In view of future traffic demands, the viaducts were strengthened to increase the load bearing capacity.

The basic concept of strengthening of the superstructure consists in increasing significantly the hogging moment capacity by adding a strong R-UHPFRC layer on top of the slab (Fig. 10).

Allowing for plastic moment redistribution from mid-span (sagging moment region) to the piers (hogging moment region) at ULS, the required load bearing capacity of the superstructure is obtained. This moment distribution was possible because the relevant cross sections allow for sufficient ductility. The 100 mm thick R-UHPFRC strengthening chord containing a high amount of steel rebars 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.

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 concentrated wheel loads in the transverse direction of the cross section while also reducing moment peaks.

In addition, the UHPFRC layer on the deck slab provides the waterproofing and protection of the reinforced concrete. UHPFRC (instead of repair mortar) was also used to rehabilitate common local rebar corrosion damage on the outer girders and bottom flanges.

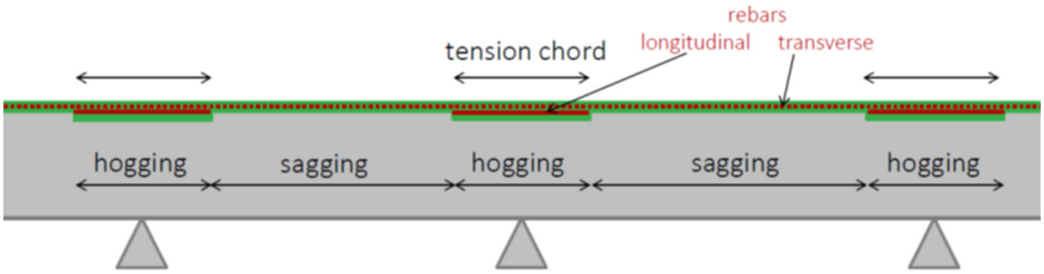

Figure 10. Concept of strengthening: increasing the hogging moment and shear resistance over the piers by a strong R-UHPFRC chord.

Pre-dimensioning using analytical models given in SIA 2052 validated the chosen strengthening concept. Detailed non-linear FE analyses gave deeper insight into the structural performance of the R-UHPFRC strengthening concept.

In 2018 and 2019, UHPFRC layer was cast on the deck slab of the viaducts following a similar procedure and using a casting machine.

4.3.4 Riddes Viaduct

The 1.2 km long road viaduct (Fig. 11) consisting of a twin continuous box girder in posttensioned concrete built in 1976 is an overpass over a railway line, highway and a river.

Figure 11. UHPFRC ready mix plant next to the Riddes Viaduct.

RC damage including corrosion of prestressing tendons and steel rebars as well as alcali-aggregate reaction lead to a significant lack of 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) a loss of 1/3 of post-tensioning, (2) 30% AAR-related concrete strength reduction and (3) local damage of the deck slab.

Figure 12. UHPFRC casting on 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 10 and the design provisions of SIA 2052 including detailed non-linear FE analyses. The UHPFRC layer was cast in 2021 on the deck slab of the viaduct using again a casting machine (Fig. 12).

4.3.5 Other applications

Other realized applications using the UHPFRC technology include the rehabilitation and strengthening of:

- many road and rail bridges as well as pedestrian bridges of short and medium lengths in reinforced concrete and steel-concrete composite construction
- several slabs in buildings to increase flexural, shear and punching resistance
- one tunnel lining and several wall-like elements
- one fixed railway track of a railway station
- several concrete surfaces exposed to hydro-abrasion, mechanical abrasion and aggressive chemical substances.

In addition, the author was also involved in several UHPFRC projects outside Switzerland, implementing the "Swiss Method".

5 Construction of new structures in R-UHPFRC

5.1 Design principles

The basic approach (and <u>forth UHPFRC principle</u>) in designing new R-UHPFRC structures is to combine the advantageous 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 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 at a competitive level.

The design of R-UHPFRC structures is inspired by steel construction, prestressing technology and cast connections. Dimensions are expressed in

[mm] as the fabrication precision is in the millimetre domain. UHPFRC structural elements are designed as monolithic elements 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.

These properties allow for the design and construction of lightweight structures that are durable and have enhanced structural resistance when compared to traditional concrete and steel structures.

5.2 Structural performance of R-UHPFRC members

5.2.1 General

R-UHPFRC structures are lightweight structures. Consequently, verification of serviceability and fatigue limit states are often determinant when dimensioning elements and structures made of R-UHPFRC. Verification of the ultimate limit state of structural safety can thus be carried out with relatively simple and conservative resistance models.

Most important, R-UHPFRC members subjected to loading under service conditions remain uncracked as the highest acting tensile strains rarely are larger than 1 ‰. Thus, highly stressed UHPFRC is taking significant tensile stress according to the tensile strain hardening behaviour. Consequently, the R-UHPFRC member is preserving largely its initial rigidity. Providing sufficient rigidity in the design of R-UHPFRC structures may thus be considered as fifth design principle.

5.2.2 Modelling under service conditions

The real goal in verifying serviceability limit states is to demonstrate that the structure has sufficient rigidity. As a rule, the limit values of serviceability for functionality and user comfort are verified as specified in standards.

Deformations (deflections) and the dynamic behaviour (vibrations) of the R-UHPFRC structure are analysed assuming elastic structural behaviour (Figure 13).

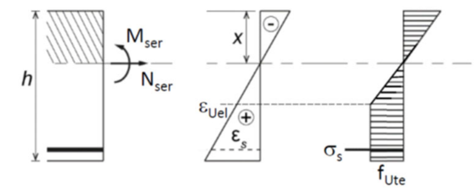

Figure 13. Model for the elastic structural analysis of R-UHPFRC.

5.2.3 Ultimate resistance models

Bending resistance: The design value of ultimate resistance under pure bending and bending with normal force is determined applying the resistance model according to Figure 14:

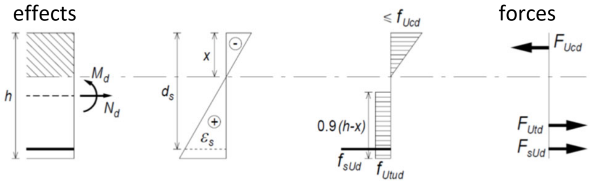

Figure 14. Resistance model for the determination of the ultimate bending resistance of a cross section in R-UHPFRC.

Thus, it is assumed that plane cross sections remain plane with linear strain distribution. Stress values in the materials are determined using the respective constitutive material laws. The resulting internal forces in the UHPFRC and reinforcing steel in the cross-section must be in equilibrium. The position of the neutral axis is found by iteration. The ultimate bending resistance results from the equilibrium of moments in the cross-section.

The resistance model applies analogously to cross sections with prestressing steel or a combination of reinforcing and prestressing steel.

Shear resistance: When determining the design value of the shear force resistance of a beam, it is assumed that the shear force is transmitted by the web alone. This is a conservative assumption, because tests revealed that the contribution of the beam flanges to the resistance of a shear prone zone is significant.

The shear force resistance model is analogous to a truss model and consists of the girder web with stress fields of variable inclination of the compression field and the tensile field acting perpendicular to it.

Shear resistance is rarely determinant in the design of structural members.

5.3 Selected applications

The following selected examples were all designed and built based on the principles and provisions of SIA 2052 [2].

Since 2015, several pedestrian bridges in R-UHPFRC have been designed and built in R-UHPFRC [5]. The following selected applications concentrate on rail and road bridges.

5.3.1 Railway Underpass Unterwalden

The Railway Underpass Unterwalden located in Central Switzerland (Fig. 15) replaced a deteriorated slab structure on a busy main railway line. Important geometric constraints related to both clearance of the underpassing road and the railway track imposed a limited construction height of the new structure.

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 ribbed plate girder consists 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 are in each rib as bending reinforcement allowing for a rebar cover, which is more than the 15 mm required by [2]. The ribs provided enough cross section to resist the design shear force without placing vertical rebars. No transverse diaphragm was necessary.

Figure 15. Railway underpass consisting of two ribbed plate girders and edge girders in R-UHPFRC resting on concrete abutments.

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 the design impact force of underpassing vehicles. Moreover, the shape of the edge girder should have an appearance that is characteristic for UHPFRC structural elements.

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 and detailed FE structural analysis.

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.

The installed monitoring system confirms the expected deformation values that lie significantly below the calculated values as obtained using the railway load model according to the standard.

The prefabrication of the R-UHPFRC elements claimed for 15% of the total project costs, in which the UHPFRC material cost is thus only a minor part.

This first pilot application on a small structure also provided valuable experience for future applications in the domain of railway bridges [6].

5.3.2 Road bridge Walo

In November 2020, the first road bridge made of R-UHPFRC was built in Switzerland as a two-lane access bridge to an industrial site (Fig. 16). The bridge crosses a river. The height of the construction had to be kept to a minimum due to the clearance requirements for flood water and the level of adjacent roads. The most important project goal was to realize a bridge with least maintenance need and at lowest possible construction costs.

Figure 16. View of the R-UHPFRC road bridge

The bridge girder is a 25.0 m span T-beam with variable girder height, consisting of a cross-section with four precast girders (Fig. 17). At mid-span, the girder height is 1.25 m, which tapers towards the abutments to 0.75 m. The four precast girders have a conventional T-shaped cross section, but with greatly reduced element thicknesses compared to traditional RC girders.

The precast beams were placed on neoprene bearings of the two abutment benches. A 50mm thick layer of R-UHPFRC was then cast in-situ to link the girders and to complete the deck slab to obtain a monolithic structure. The in-situ UHPFRC layer was pulled over the abutment as a transition slab to create a semi-integral abutment and to avoid dilation joints. The driveable UHPFRC surface of sufficient skid-resistance was obtained by spraying quartz sand during surface finishing.

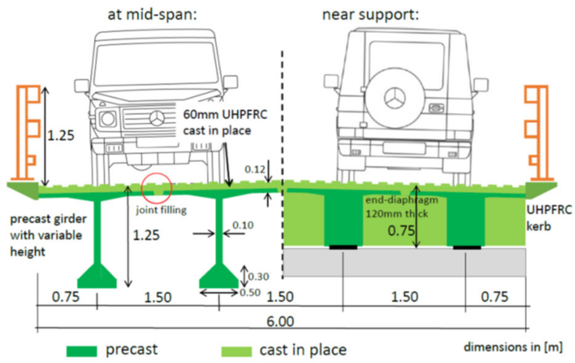

Figure 17. R-UHPFRC road bridge: cross-sections at mid-span and support.

The on-site construction works took 1 week until the bridge was opened to traffic. The construction cost was significantly lower than the estimated cost for variants in traditional construction.

5.3.3 Road bridge Fruttli

With the advent of UHPFRC, traditional composite construction in steel-concrete and timber-concrete should be challenged since reinforced concrete is a comparatively inferior partner to steel and timber.

Reinforced concrete deck slabs of composite bridges are prone to cracking and show durability issues. In addition, the relatively heavy reinforced concrete slab dominates the design of composite bridges and thus the consumption of steel and timber. In contrast, UHPFRC is a more effective partner for steel and timber. UHPFRC deck slabs are about 3 to 4 times lighter than traditional RC slabs which leads to more efficient composite strucrures.

Several timber-UHPFRC composite bridges have been built recently in Switzerland, in particular in rural areas. The Fruttli Bridge with a span of 10 m was built in 2020 (Fig. 18). The timber-UHPFRC composite structure was designed for road traffic. The surface of the 3.5 m wide and 80 mm thick UHFB roadway slab is driveable. The construction cost was slightly lower than those for an initially designed conventional RC bridge. Additionally, the construction duration was significantly shorter.

Figure 18. Road bridge Fruttli: timber – UHPFRC composite bridge (photo by E.Kälin)

Further argument for building the timber-UHPFRC composite bridge was the advantageous ecological balance. An important part of the CO_2 emitted for the cement and steel used for the UHPFRC slab is actually contained in the used timber [7].

5.3.4 Further concepts and project designs

UHPFRC and its specific properties offer the potential of novel design concepts, for example:

- elements for buildings like lightweight slabs (including punching reinforcement), slender columns and cladding panels of original design
- tunnel construction (lining of relatively small thickness) with the objective to reduce excavation and to accelerate construction
- road construction and fixed railway tracks to improve durability and reduce material use
- R-UHPFRC elements (slabs) on riveted steel bridges, often of high cultural values, to increase the structural capacity by steel-UHPFRC composite action [8].

Integrated designs with UHPFRC fulfilling several functions may provide technically and economically effective solutions such as, for example, the railway bridge girder (for long viaducts with spans of 30 m) with integrated fixed railway track (Fig. 19):

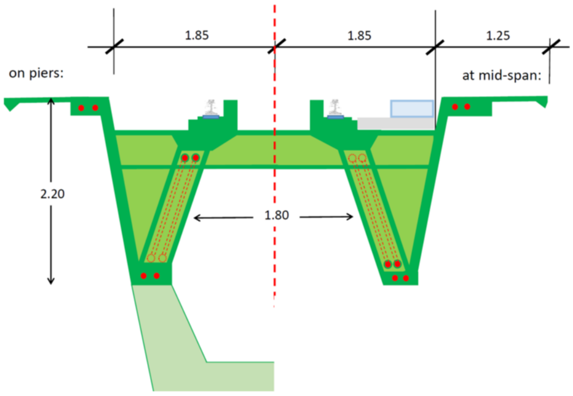

Figure 19. Integrated bridge girder – fixed railway track design in segmental posttensioned R-UHPFRC construction.

6 Conditions for the introduction of the novel UHPFRC Technology

Since 2004, the author is involved in numerous projects to implement UHPFRC in the Swiss construction practice. Based on this experience, some conditions for the introduction of the UHPFRC Technology in the construction practice are highlighted.

Obviously, competitive construction costs compared to traditional construction methods are the main reason for UHPFRC applications. The increased technical efficiency and improved durability of UHPFRC structures are just an additional asset which has a beneficial effect on (life-cycle) cost during the service.

Equally important are the following three conditions:

- High-quality education of both engineers and craftspeople provide the necessary competence and confidence to follow and implement novel technological developments.
- An accepted standard provides a regulatory framework that sets the essence in a concise and easy-to-understand form while leaving enough room for further developments.
- Incentives of personal and financial nature are stimulating. Application of the UHPFRC Technology should be personally rewarding !

7 Conclusions and future developments

Application of UHPFRC as building material is increasing over recent years, and this trend is likely to prevail worldwide.

In Switzerland, the strengthening method using a layer of strain-hardening UHPFRC has made its proof as an effective method in terms of technical and economic performance. This technology is now also implemented in countries like Japan, France, USA and China. Enhancement of existing bridges and other structures by UHPFRC is also more economic and sustainable, compared to replacement of bridge decks or entire bridges and structures.

Today, the UHPFRC technology offers a validated potential for eliminating weak points of the still dominant reinforced concrete construction. This potential shall be exploited for new R-UHPFRC structures. In addition, composite steel – UHPFRC and timber – UHPFRC members for bridges and other structures represent an interesting opportunity.

The "next generation" of UHPFRC materials will significantly reduce CO_2 emissions and energy consumption. Novel UHPFRC mixes are developed by replacing a significant part of cement by other powders like limestone filler and by using synthetic fibres with highest modulus of elasticity.

In addition, the implementation of UHPFRC in structural engineering complies with 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).

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