Design and construction of the "Chaumény" footbridge in posttensioned UHPFRC

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Abstract

In 2020/21, the "Chaumény" footbridge was built in posttensioned UHPFRC over a railway line in the city of Montreux, Switzerland. UHPFRC stands for Ultra High Performance Fiber Reinforced Cementitious composite. UHPFRC shows high resistance both in tension and compression as well as excellent durability properties. The design and construction of the lightweight structure is described. The structure consists of a U-shaped trough girder with a span of 22.5m above the railway clearance, resting on one abutment and one pier, as well as a staircase leading from the pier down to the ground. The footbridge is composed of several precast elements that were assembled by posttensioning to achieve monolithically linked structure.

Keywords: UHPFRC, footbridges, design principles, dimensioning of UHPFRC structural elements, precast elements, mounting of 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. Today, the best UHPFRC have significant tensile strain hardening behaviour and relatively high resistance 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 very compact material and is thus waterproof and crack-free under service stresses due to the high fibre content, thus providing a robust protection against water and chloride ion ingress.

These properties allow for the design and construction of lightweight structures that are effectively durable and have enhanced structural resistance when compared to concrete and steel structures. In addition, the environmental impact of lightweight UHPFRC structures is limited.

UHPFRC does not comply with the definition of "concrete". UHPFRC is a fibre reinforced composite material and should thus not be called "concrete". It is fundamental to understand UHPFRC as an independent material with specific properties. This is the first basic principle when designing with UHPFRC to build new structures, as it is the language and the terminology that make a concept. The second 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.

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

This paper first describes the most important properties of UHPFRC for the design of structures. Then, the design and construction of the Chaumény footbridge is presented focussing on particular features and experience that could be useful for further projects.

2 UHPFRC properties for the design of structures

The required performance of currently available UHPFRC as stipulated in [1] is described in this chapter. Other fibre reinforced cement-based materials that show inferior performance, do not qualify for the design of structures similar to the Chaumény footbridge.

2.1 Tensile strength

The tensile behaviour of UHPFRC is of first importance for the intended structural behaviour under service stresses. The uniaxial tensile behaviour of plain UHPFRC has to comply with the indications given in Figure 1. 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.

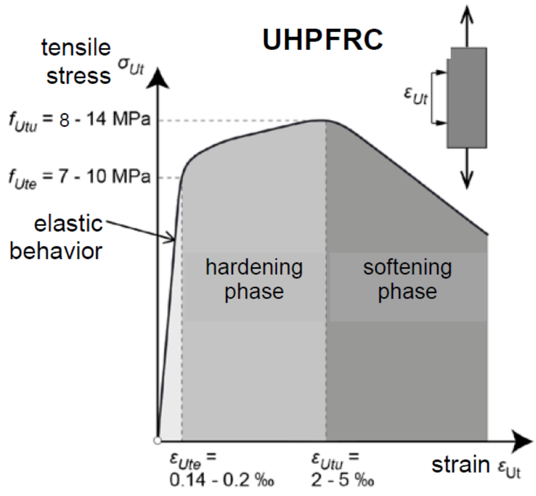


Figure 1. Tensile behaviour of UHPFRC

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} of UHPFRC. The mechanical response of UHPFRC depends on the fibre orientation due to the casting procedure and the dimensions (thickness) of the UHPFRC element. Possible anisotropic fibre orientation due to casting procedure is mitigated by the high fibre content, by the adding of reinforcing bars to the UHPFRC and by stringent mixing procedure with controlled adding of the fibres to the fresh UHPFRC matrix. For structural design, fibre orientation is considered according to [1] 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 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).

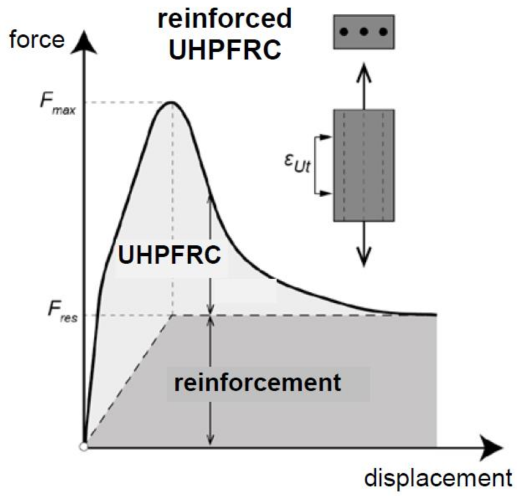


Figure 2. Tensile behaviour of R-UHPFRC

2.2 Compressive strength

The behaviour of UHPFRC under compression is characterized by a linear stress-strain relationship up to about 80% of the compressive strength. Beyond, a 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.

2.3 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.

2.4 Shrinkage and creep

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

2.5 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 [1].

2.6 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 a very low amount of 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.

3 Design principles

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

4 Chaumény Footbridge

4.1 Motivation and project objectives

The former footbridge had to be replaced for several reasons. First, it was a structurally deficient structure in steel with concrete slab elements in advanced deteriorated condition. Second, the requirement for railway clearance increased over the years. To comply with today’s clearance requirements, the level of the footbridge girder over the railway had to be raised by 1.0 m, and the girder length had to be modified from a 19 m long two span to a 22.5 m long single span girder.

Finally, a staircase of two flights leads to the ground. Due to its proximity to railway tracks and its difficult accessibility, the construction of the footbridge required special attention to construction sequence.

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

Figure 5. Chaumény Footbridge: view of completed bridge construction, before opening in June 2021.

The UHPFRC structure of the footbridge was designed using the Swiss UHPFRC Standard [1]. From the beginning, the project and its results were meant to become a showcase for a slender R-UHPFRC structure with original and pleasing appearance (Fig. 5).

4.2 Structural concept

The footbridge is composed of the girder, the Y-shaped pier and the staircase. These parts are all assembled by means of posttensioned bars and tendons to form a monolithic structure. This structure is fully fixed at the contact points with the ground, i.e. at the girder abutment as well as at the pier and staircase foundations (Fig. 6).

This structural concept allowed to obtain a structure that is (1) sufficiently stiff to avoid any issue with vertical and horizontal vibration, and (2) sufficiently flexible such that deformation due to temperature variation do not build up significant stresses in the structure. In addition, deformation due to shrinkage and creep only have minor effects.

The girder is composed of 5 precast elements (segments) that were cast upside-down in the plant and assembled by straight posttensioning tendons. The bottom plate of the girder is stiffened with ribs in the transverse direction providing the necessary stiffness to fix the webs such that lateral girder buckling is prevented.

The particular shape of the Y-shaped pier is the result of geometrical boundary conditions to respect the necessary clearance for the users of the footbridge. In order to guarantee compressive stresses for all load cases, the pier legs were posttensioned.

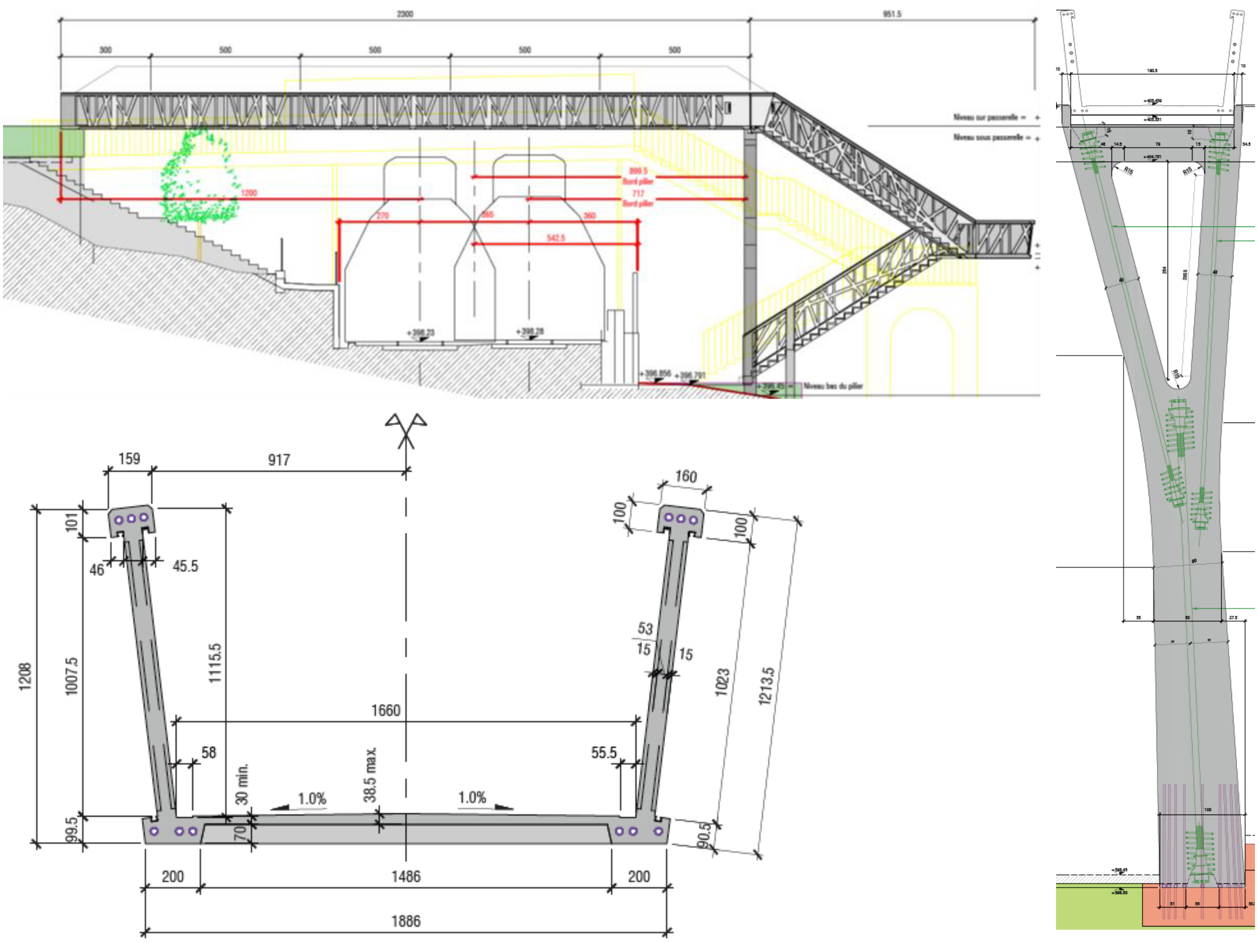


Fig. 6. Chaumény Footbridge: Elevation, cross section and pier (dimensions in mm).

The staircase is composed of three elements, i.e. two stair flights and the platform that were assembled by posttensioning tendons.

The webs of the U-shaped trough girder are slightly inclined outwards to create a more pleasant perception of the space for the users of the footbridge.

Same aesthetic design for the webs of the girder and staircase was developed to provide visual originality. The relief on the web, illuminated in the night by a lower and upper strip of Led light, shall be appealing for the user who should also perceive a material that is different to the traditional steel and concrete. The dark colour was obtained by adding black pigments to the fresh UHPFRC mix. The roughness of the walkway surface was cast by using a profiled steel sheet providing the required skid-proof surface; in this way, no pavement was needed.

4.3 Construction process

Each cast segment was demoulded 1 day after casting and cured in a plastic foil during at least five days in the plant. The girder was assembled in the plant and transported on a truck to the construction site. The butt joints between the segments were glued with epoxy resin (providing also water tightness of the joint), temporarily interlocked and pressed together.

On the construction site, the girder was first mounted by means of a large crane that had to be positioned on a street about 50 m away from the bridge site. The lever arm of the crane had to be sufficiently long to lift the girder over a multi-storey building nearby. After the levy, the bridge girder was positioned on its abutment and on a temporary scaffold. This operation was only possible because of the relatively low girder weight. It had to take place from 1 to 3 o'clock on a Sunday morning when complete railway service interruption was possible (Fig. 7).

During the same night shift, the pier was also lifted in, positioned and fixed in the ground foundation using fresh UHPFRC.

In a second stage, the three elements of the staircase were mounted, assembled and fixed to the girder and ground foundation.

Fig. 7. Mounting of the footbridge girder and pier.

Fig. 8. View of the girder in the morning after its mounting.

4.4 Dimensioning

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

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

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

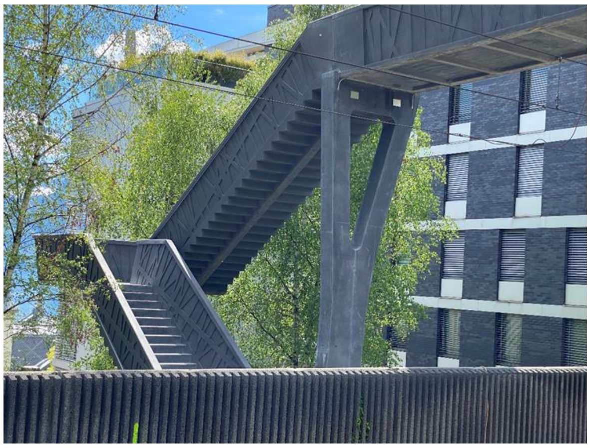
The rather complex structure has been analysed using a 3-dimensional FE-model to determine sectional forces. Design values for tensile and compression resistance of UHPFRC as well as the resistance models for bending and shear have been taken from [1].

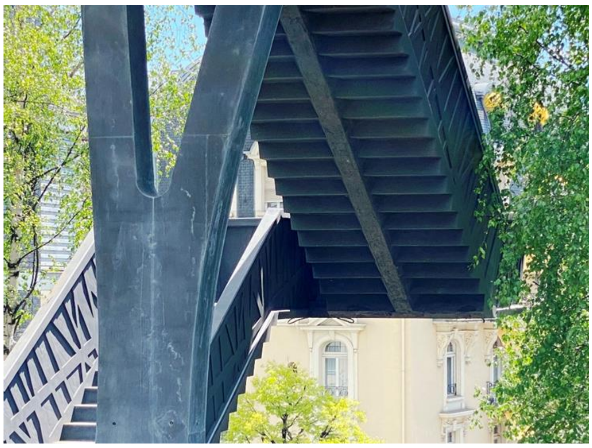
Results from calculations validated the structural dimensions at Ultimate Limit State. At the Serviceability Limit State, the calculated deflection of the girder at mid-span was significantly less than the allowable one confirming, as expected, the considerable stiffness of this lightweight structure.

The structure provides excellent durability properties because of (1) waterproof and crack-free UHPFRC material, (2) monolithic structural concept avoiding equipment like bearings, and (3) no coating (f.ex. on the walkway) is needed. Limited maintenance consisting in cleaning operations only can be expected over the service duration of the footbridge.

4.5 Validation

The following photos show some impressions of the UHPFRC structure, its various details and the interrelation with the built and natural neighbourhood of the footbridge (Fig. 9).





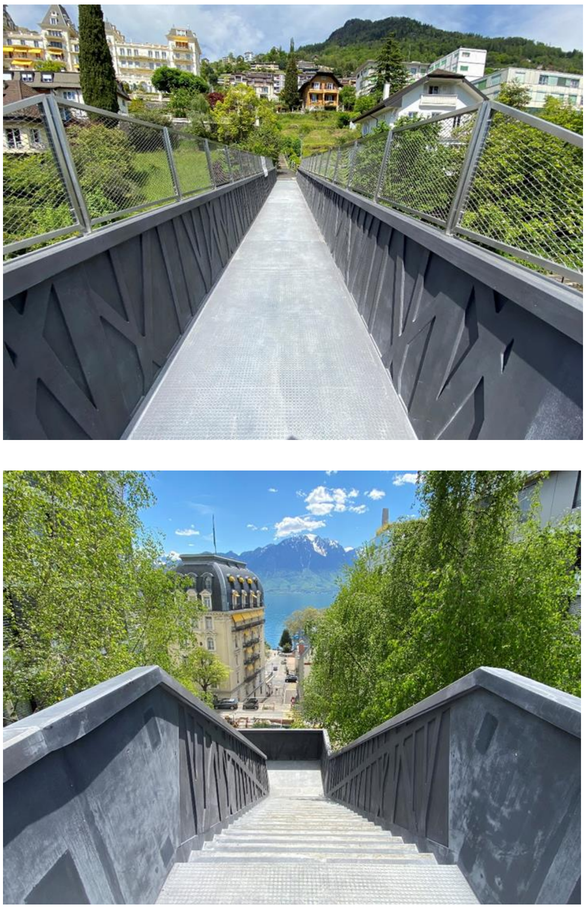


Fig. 9. Impressions of the Chaumény footbridge

The total construction cost was in the range of footbridges built in traditional construction considering difficult site conditions. The cost for the used UHPFRC material was less than 20% of the total construction cost. The prefabrication labour and the construction of the mould as well as the mounting using a large crane turned out to be most cost relevant.

5 Conclusion

The Chaumény footbridge demonstrates the potential of using R-UHPFRC to create, design and build new lightweight structures with enhanced durability and original aesthetics. The project was demanding in particular concerning the prefabrication of elements and segments as well as the construction procedure because of difficult site conditions in terms of access and the presence of the railway. These challenges could be successfully mastered.

The Chaumény footbridge and other recently built UHPFRC structures in Switzerland for footbridges, road and railway bridges show that R-UHPFRC structures increasingly replace traditional construction in reinforced concrete and in steel. This trend will be enhanced by the fact that the UHPFRC material is today readily available on the market in several countries and that an increasing number of construction companies gain knowledge in the UHPFRC Technology will enhance this trend.

In addition, the implementation of UHPFRC in structural engineering responds to the principles of sustainable construction as new lightweight structures use significantly less resources in terms of materials, energy and financial means (expressed as construction and life-cycle costs).

6 References

[1] Technical Leaflet SIA 2052 *UHPFRC – Materials, design and construction*, SIA – Swiss Society of Engineers and Architects, Zurich, March 2016. Currently under revision (in German and French; for English translation: eugen.bruehwiler@epfl.ch)