Short span UHPFRC railway bridge in Switzerland - from design to implementation

Ngoc Thanh Trinh

Project Manager, Deputy head of Leman Engineering Structure Department, Gruner Stucky Ltd, Switzerland

Numa Joy Bertola

Postdoctoral Researcher, Structural Maintenance and Safety Laboratory, EPFL, Switzerland

Enrique Garcia

Project Manager, TRAVYS Ltd, Switzerland

Eugen Brühwiler

Professor, Head of Structural Maintenance and Safety Laboratory, EPFL, Switzerland

Contact: ngoc-thanh.trinh@gruner.ch

Abstract

This paper presents the design and construction of the Aiguillon railway bridge in Switzerland, one of the first railway bridges completely made of Ultra-High-Performance Fiber-Reinforced Cementitious Composite (UHPFRC). The length and width of the trough girder are respectively 6.6 m and 5.7 m. It is designed for a narrow-gauge track and two walkways. The trough is composed of two prefabricated elements in UHPFRC with steel reinforcement bars. These elements are first built in the plant and then are assembled on site by a longitudinal cast-in-place joint.

The challenges and the experiences in this project are discussed and analysed in view of future projects. Furthermore, the full-scale suitability tests to validate the joint between the two prefabricated elements are described. The test results of the structural resistance of the joints are in good agreement with analytical results.

Keywords: UHPFRC; railway bridge; prefabrication; lightweight structure; laboratory experiment

1 Introduction

The Aiguillon bridge is part of a local narrow gauge railway line in Switzerland. The structure has a single span of 6.10 m. The existing bridge, built in 1978, had to be replaced as it did not meet the normative requirements for operating a railway line. The original masonry abutments, built when the railway line was created in 1893, were raised during the reconstruction of the existing bridge in 1978. The longitudinal slope of the existing structure is 4.4 %. The existing rails were directly fixed to the bridge deck without ballast and sleeper.

The railway track was also renovated and raised by 50 cm to obtain the necessary height to build the new bridge trough with the required ballast layer of at least 30 cm (under the sleepers) and two walkways for passengers. One of the key constraints of this project was that the clearance height of the existing road under the bridge had to be maintained. Due to this constraint, the maximum available height for the new deck thickness was limited to 24 cm. A conventional reinforced concrete deck was thus not feasible with this limited thickness, while a thin steel bridge deck would have had transportation difficulty, as the bridge is located in a mountainous area with limited access. Thus, a new thin bridge deck made from two UHPFRC prefabricated elements turned out to be the most suitable solution.

The new bridge trough, built in 2021, is designed for a narrow-gauge track and two walkways. The trough has a total length of 6.6 m and a total width of 5.7 m. The structure is composed of two precast elements in reinforced-UHPFRC with the thickness varying from 60 mm to 240 mm. These elements are first built in the plant and then assembled on-site by a longitudinal cast-in-place joint in UHPFRC. The connection between the precast elements is a key point of the bridge deck fabrication. For this reason, a full-scale laboratory experiment to analyse the behaviour of connection is performed to determine the maximum resistance and the failure mechanism.

UHPFRC has been used in structures worldwide for more than twenty years [1]. UHPFRC is made of a mix of cement, fine hard particles (with a maximum grain size of 1 mm), water, admixtures, additives, and a large amount of short slender steel fibers [2]. Steel fibers typically represent at least a 3 % in volume of the material [3].

The mechanical properties of UHPFRC are summarized in [4,5]. UHPFRC has significant mechanical properties, both in terms of tensile (up to 16 MPa) and compressive strengths (up to 150 MPa). The Young's modulus is 45 to 50 GPa, and the material has a strain-hardening behaviour until a strain of 1-2 ‰ in tension. The tensile strength is significantly improved by adding reinforcement bars (R-UHPFRC), similar to reinforced concrete (RC) structures [6].

Figure 1 The new Aiguillon railway bridge made of reinforced UHPFRC

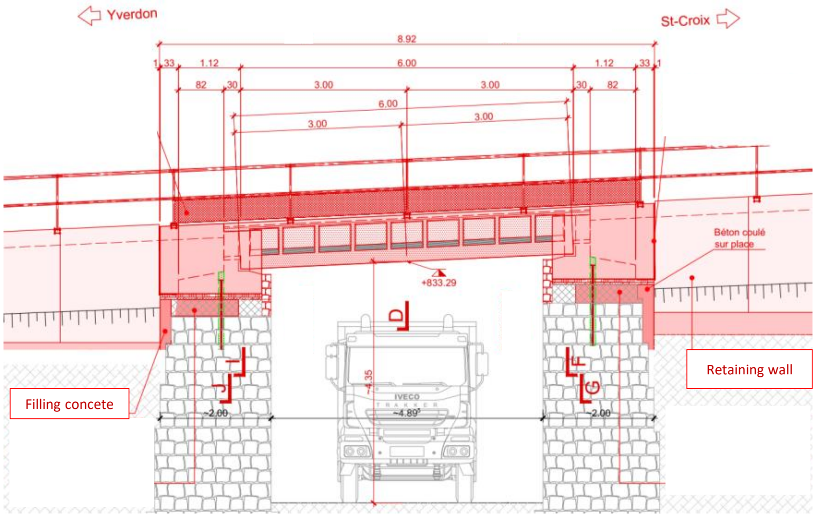

Figure 2 Bridge elevation

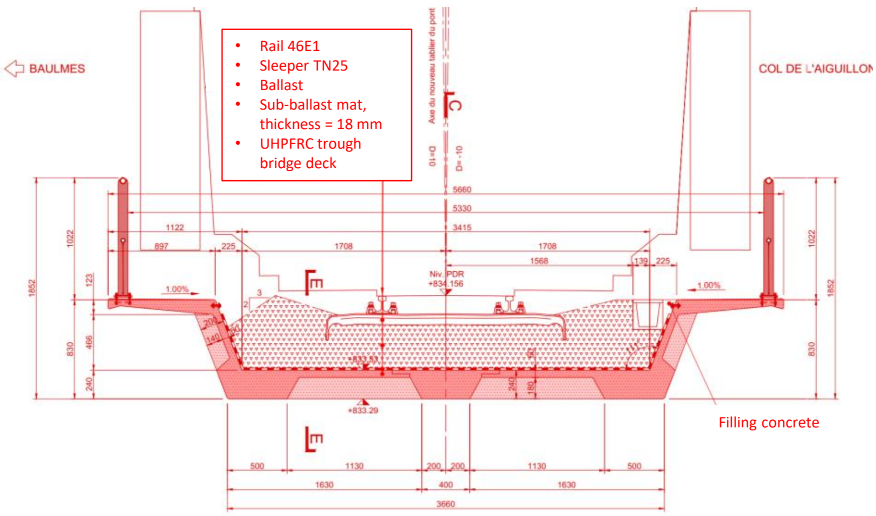

Figure 3 Bridge trough: cross-section

Due to its strain-hardening behaviour, UHPFRC structures typically remain crack-free under service conditions [7]. As this material is not porous, its surface is thus waterproof under service loads, providing robust protection again environmental actions over time [8].

Due to its specific structural properties, UHPFRC is an unique material and requires specific design codes and execution processes. The Standard on UHPFRC (SIA 2052) was introduced in Switzerland in 2016 [9]. Since the first UHPFRC application in 2004, more than 280 projects have involved UHPFRC in Switzerland [10]. This bridge is only the second railway bridge entirely made of UHPFRC worldwide after the railway underpass bridge Unterwalden [7].

2 Concept and design

2.1 Construction materials

The bridge trough is made of the UHPFRC Type UB according to the requirements defined in [9], and steel reinforcement bars with their mechanical properties presented in Table 1 and Table 2.

Table 1. Mechanical properties of UHPFRC (type UB)

Property	Design value	Characteristic value
Compressive strength (f_{Uc})	68 MPa	120 MPa
Tensile strength (f_{Utu})	6.4 MPa	12 MPa
Modulus of elasticity (E_U)	50 MPa	50 MPa
Ultimate tensile strain (ε_{Utu})		2 ‰
Density		26 kN/m^3

Table 2. Mechanical properties of reinforcing steel, B500B

Property	Design value	Characteristic value
Yield strength (f_s)	435 MPa	500 MPa

2.2 Actions

2.2.1 Permanent loads

The permanent loads consist of the self-weigh of the structural member (trough) and the non-structural elements (track ballast, sleepers, rails, barriers).

2.2.2 Live loads

The bridge is designed to support the following determining rail traffic loads:

- Loads due to narrow gauge rail traffic, the load model 7 according to Swiss standards (SIA 261) is determining and applied to design the trough. This load model consists of four axle loads with a characteristic value of 200 kN.
- Loads on the walkways with a characteristic value of 2.5 kN/m^2.

Furthermore, the loading caused by derailed vehicles are also considered using the derailment load models 6 and 7 in the Swiss Standard SIA 261 to prevent structural failure and retain the derailed vehicle in case of vehicle derailment.

2.3 Structural concept and analysis

2.3.1 Structural concept

The entire bridge trough is composed of two main girders, two walkways, cross-girders, web-stiffeners and 60 mm thin plates between cross-girders. All these components, presented in Figure 4, work together as a monolithic structural element. The dimensions of these components are found in the bridge deck cross-section in Figure 3.

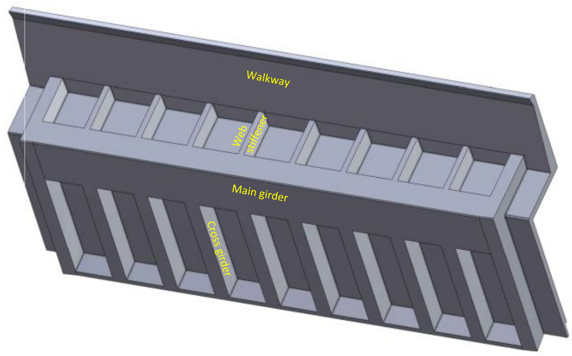

Figure 4. A prefabricated element in 3D of the bridge deck (extracted from the drawing made by the precasting contractor Element Ltd).

2.3.2 Structural analysis

The trough is dimensioned using a 3-D finite element model for structural analysis. The main girders work together with the walkway to create a “Z” beam in which the walkway is considered as the top flange in compression and the main girder as a bottom flange in tension. Four 20-mm diameter steel rebars are laid in the main girder to reinforce the tensile resistance. The UHPFRC tensile strength is also considered in the determination of the ultimate resistance of the main girder. The fatigue verification for reinforcing steel as well as UHPFRC is also carried.

The cross-girders between the two prefabricated elements are connected by a UHPFRC joint cast on-site. Due to the discontinuity of the steel fibers at the contacting surfaces between two fabrication stages, the UHPFRC tensile strength is neglected for the structural verification at these surfaces. This assumption is validated by the laboratory experiment presented in the next chapter.

Since the UHPFRC trough is carrying a heavy ballasted track and the service speed of the trains is relatively low (Vmax = 45 km/h), there is no issue regarding the dynamic behaviour. In projects with fixed railway track and high-speed trains, the dynamic behaviour would need to be analysed using dynamic models used for bridge structures in steel

3 Laboratory experiments

Due to the difficulty of accessing the bridge location, the bridge deck has been divided into two precast elements (Figure 3) and a cast-in-place keying joint. Thus, the crossbeams of the bridge include two precast elements and a keying joint. This design leads to particular structural properties as the fibers are not continuous in the UHPFRC at the interfaces between the precast elements and the keying joint.

The mechanical properties are expected to be different than a conventional beam cast in one element. For example, the tensile strength of UHPFRC is expected to be significantly lower at these interfaces. Two testing samples of crossbeams were prepared to be tested in the laboratory at full scale.

The beam has a total length of 3 meters (Figure 6) and the cross-section has a T-shape. The web has a squared area of 180 mm, and the flange has a height of 60 mm and a width of 650 mm. In each precast element, the reinforcement involves four rebars with a diameter of 26 mm. Reinforcements of both precast elements intersect within the keying joint.

In the analytical model, based on the Swiss Standard for UHPFRC (SIA 2052) [9], the maximum resistance of the joint detail was estimated equal to 204 kN using average values of mechanical properties of UHPFRC. The weakest section is at the interfaces between the precast elements and the keying joint, as the tensile strength of UHPFRC has not been considered due to the fiber discontinuity.

Two hydraulic jacks (capacity of 1000 kN each) are used to apply a force deformation on both sides of the beam (speed of 0.02 mm/s). The measurements are made using LVDTs (beam displacement), extensometers, and cracks have been detected using a Digital Image Correlation (DIC). A comprehensive article on the laboratory campaign is under preparation.

The force-displacement curves for each beam are shown in Figure 7. Since the experiment is controlled by an imposed displacement, the force measured by the load cell of each jack slightly varies for the same displacement due to the variability of material properties in the beam and slight asymmetry in the load introduction positions.

The average maximum resistance obtained from the two jacks and for each beam is 218 and 234 kN, respectively (Figure 7). These results agree well with the results of the analytical model.

The second goal of the test is to observe the failure mechanism. Both beams showed important post-peak deformation capacity. This result confirms that a brittle collapse of the beam is not plausible. Concerning the second test (Figure 7, on the right), a beam rotation was observed once the maximum resisting force was reached, explaining the difference in behavior between the hydraulic jacks. This rotation only affects results in the post-peak domain.

When examining at the test beams after the experiment, it has been observed that the failure mechanism is linked to crushing of UHPFRC rather than yielding of the reinforcement bars. The rupture occurred by pulling out of the reinforcement bars without affecting the ductility of the failure mechanism, as the anchorage length of rebars is parallel to the interface between precast and keying joint (i.e., the weakest section).

Altogether, the results of the experimental campaign have validated the design of the cross beam. The experimental results exhibit an elastic behavior under service-load conditions and a non-fragile collapse mechanism. Additionally, the predicted maximum resistance (structural performance) based on analytical models has been confirmed by the observed maximum load during the experiment. The shear resistance was predicted to be significantly larger than bending resistance by the analytical model, and this prediction has been validated by experimental results.

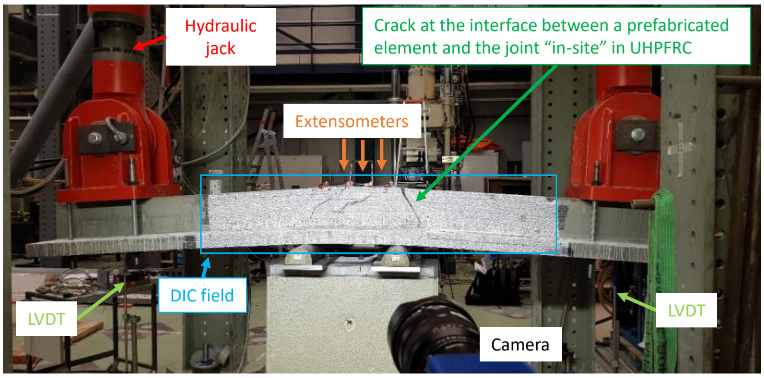

Figure 5. Laboratory experiment on the cross beam.

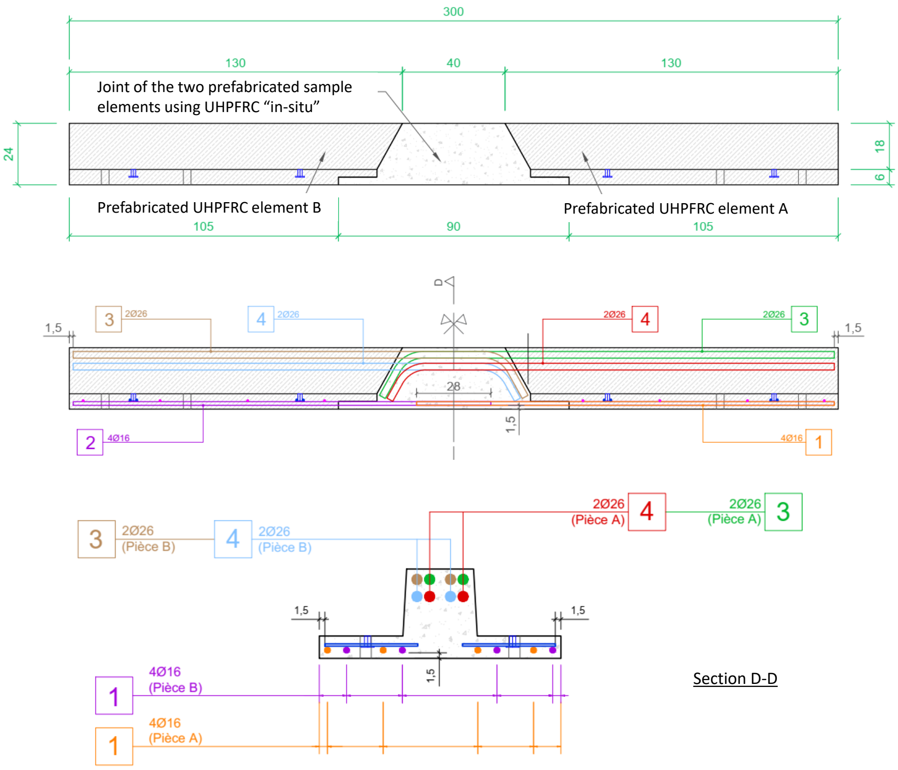

Figure 6. Elevation of the prefabricated sample and section with reinforcement rebars at the joint of the crossbeams.

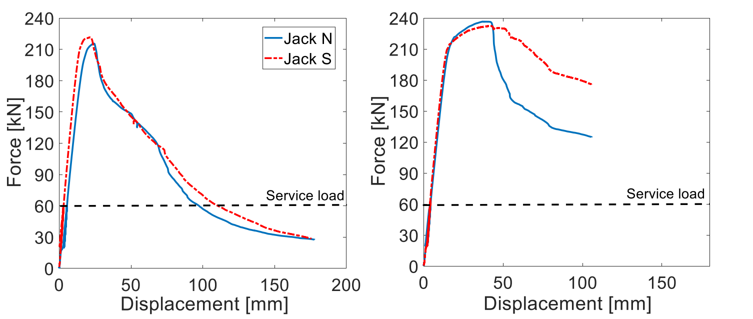

Figure 7. Force-displacement response for both crossbeams during the laboratory experiment.

4 Execution and installation

The two elements in UHPFRC of the bridge deck are prefabricated in the factory (Figure 8) before being transported to the construction site for assembling (Figure 9) The joint between the two elements is casted using the UHPFRC manufactured on-site by a special mixer. The precision of assembling these two elements is about some millimetres. The testing results of the samples extracted in the factory as well as on-site indicate that the characteristic value of the compressive strength of the UHPFRC at 28 days is more than 150 MPa. It is found that the effective compressive strength of the UHPFRC Type UB is much higher than the nominal value shown in Table 1.

The bridge trough was installed at night using a mobile crane Figure 10. This work took about 3 hours with a precision of the installation up to 3 mm.

Figure 8.Casting of one half of the trough

Figure 9. Casting of the longitudinal joint using UHPFRC fabricated in-situ

Figure 10.Installation of the bridge trough at night

5 Conclusion

The Aiguillon railway bridge was successfully built in reinforced UHPFRC in July 2021 confirming the potential and perspective of applying the UHPFRC material to build new structural elements for infrastructure projects. A few discussions and conclusions are drawn from this "pilot" project:

- The bridge trough thicknesses varied from 60 mm to 240 mm which are relatively thin thicknesses. The use of UHPFRC allows to significantly reduce the bridge element weight, compared to elements built in reinforced concrete.
- Slender elements allow for respecting more easily the limited available space and geometric constraints that often occur in rehabilitation projects of railway bridges.
- The high compressive strength (of more than 150 MPa) and high tensile strength (of more

than 10 MPa) allows to design lightweight elements. This is particularly advantageous in cases of difficult access to and limited space at the construction site.

- The experiment in the laboratory shows that the observed bending resistance of the crossbeams matches the analytical value in which the tensile strength at the interfaces between the concreting stage of UHPFRC is not taken into account.

6 Acknowledgements

The authors would like to sincerely thank the colleagues at Stucky Ltd and TRAVYS Ltd for their precious contributions to this challenging project. We would also like to acknowledge with gratitude the efforts and the great work being successfully carried out by the two construction companies: WALO Ltd and Element Ltd.

7 References

[1] Graybeal B, Brühwiler E, Kim B-S, Toutlemonde F, Voo YL, Zaghi A. International Perspective on UHPC in Bridge Engineering. Journal of Bridge Engineering 2020;25:04020094. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001630.

[2] Brühwiler E, Denarié E. Rehabilitation and Strengthening of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete. Structural Engineering International 2013;23:450–7. https://doi.org/10.2749/101686613X13627347100437.

[3] Brühwiler E. “Structural UHPFRC”: Welcome to the post-concrete era ! International Interactive Symposium on Ultra-High Performance Concrete, vol. 1, Des Moines, Iowa, USA: Iowa State University Digital Press; 2016. https://doi.org/10.21838/uhpc.2016.key.

[4] Brühwiler E. UHPFRC technology to enhance the performance of existing concrete bridges. Structure and Infrastructure Engineering 2020;16:94–105. https://doi.org/10.1080/15732479.2019.1605395.

[5] Yoo D-Y, Yoon Y-S. A Review on Structural Behavior, Design, and Application of Ultra-High-Performance Fiber-Reinforced Concrete. Int J Concr Struct Mater 2016;10:125–42. https://doi.org/10.1007/s40069-016-0143-x.

[6] Oesterlee C. Structural response of reinforced UHPFRC and RC composite members, Doctoral Thesis, EPFL - Swiss Federal Institute of Technology, 2010.

[7] Brühwiler E. Structural UHPFRC to enhance bridges. Proceedings of the 2nd International Conference on UHPC Materials and Structures UHPC 2018 - China 2018;129:140–58.

[8] Paul SC, van Zijl GP, Šavija B. Effect of Fibers on Durability of Concrete: A Practical Review. Materials 2020;13:4562.

[9] Swiss Society of Engineers and Architects. Technical Leaflet on UHPFRC: Materials, Design and Application. 2016.

[10] Bertola N, Schiltz P, Denarié E, Brühwiler E. A review of the use of UHPFRC in bridge rehabilitation and new construction in Switzerland. Front Built Environ n.d.:under review.