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Combining monitoring information and UHPFRC strengthening to extend bridge service duration

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ABSTRACT: As many bridges are approaching the end of their supposedly theoretical service duration, finding novel technical solutions to extend their service duration is crucial, also for reasons of sustainability. In this article, two strategies (structural performance monitoring, and strengthening with ultra-high-performance fiber-reinforced cementitious composite (UHPFRC)) are introduced to avoid prematurely replacing structures. The case study of the Ferpècle road bridge (Valais, Switzerland) is presented since the two strategies were combined in 2023 to extend its service duration. This bridge is one of the first prestressed concrete bridges in Switzerland. Built in 1958, the structure consists of a single girder with a 34.5-meter span resting on abutments in the form of reinforced concrete piers. As the deck has a width of only 5.3 meters, bridge owners have decided to widen it to 7.9 meters in order to include two road lanes and a pedestrian way. Despite its good condition, the bridge must be strengthened as its load-bearing capacity (bending moment at mid-span) would be largely insufficient with the new deck width. To increase its load-bearing capacity while widening the bridge deck by 50%, an intervention with UHPFRC has been made. The innovative intervention enables clamping the abutments with the bridge deck to modify the static system to obtain a semi-rigid frame to reduce the bending moment at mid-span. Two load tests using the latest sensing technologies, before and after the intervention, have enabled the quantification of the design capacity and the validation of this pioneering intervention. This case study demonstrates the potential of novel technologies to extend bridge service duration, thereby improving the sustainability of the construction sector.

1 INTRODUCTION

High-performance fiber-reinforced cementitious composite (UHPFRC) has been used in structural designs for over twenty years in many countries (Graybeal et al., 2020). The UHPFRC mix consists of a matrix composed of fine-coarse particles (cement, sand, and silica fumes up to 1 mm in size), water, additives, and a large number of short and slender steel fibers (Brühwiler and Denarié, 2013). Steel fibers (accounting for at least 3 vol-%) give this material its specific mechanical properties and high durability due to its impermeability in service (Brühwiler, 2016).

The mechanical properties of UHPFRC are summarized by (Brühwiler, 2020). UHPFRC has significant characteristic tensile strength (up to 16 MPa) and compressive strength (up to 150 MPa). The elastic modulus is 45-50 GPa, and the material exhibits strain-hardening behavior in tension until 2 ‰. Tensile strength is usually increased by the addition of reinforcing bars (called R-UHPFRC), as for traditional reinforced-concrete structures (Oesterlee, 2010). Technical specification SIA 2052 (“Technical Leaflet on UHPFRC: Materials, Design and Application,” 2016) is used to design UHPFRC elements, as well as reinforced concrete (RC) - R-UHPFRC composite elements.

With over 350 applications, Switzerland is a forerunner in using R-UHPFRC both for the construction of strengthening existing structures and new structural designs (Bertola et al., 2021b).

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Regarding the strengthening of existing structures, R-UHPFRC has been used on numerous occasions to improve the load-bearing capacity of bridges, such as the Chillon Viaduct (Brühwiler and Bastien Masse, 2015), the Guillermaux Bridge (Hajiesmaeili et al., 2019) and, more recently, the Riddes Viaduct (El Jisr et al., 2023).

This article presents a recent application of R-UHPFRC for the rehabilitation, strengthening, and widening of a prestressed concrete bridge in Switzerland. The project involves widening the simply-supported bridge deck from 5.3 m to 7.9 m (+50%) by only intervening on the deck. The idea behind the reinforcement is to modify the static system by clamping the abutments to form a monolithic structure. This elegant intervention significantly strengthens the bridge through the parsimonious use of R-UHPFRC while preserving the existing structure. Monitoring campaigns before and after the intervention have enabled the validation of the intervention design.

2 BRIDGE EXAMINATION

2.1 *Presentation*

The Ferpècle Borgne Bridge is a prestressed reinforced concrete double-girder structure (TT cross-section) located in the Swiss Alps in the small village of Les Haudères (Valais) at an altitude of 1450 meters. The bridge was built in 1958 according to the plans drawn up by the engineering firm B.Deléglise - P.Tremblet in Sion, who took over Robert Maillart's engineering office in Geneva, which became Bureau Tremblet, now T Groupe.

The static system is a simply-supported beam with a 34.5-meter span, resting on abutments with side walls approximately 7 meters long (Figure 1). With a beam height of 1.75 meters, the slenderness of 1/20 is audacious for a simple beam. Visual inspection of the structure using the risk approach (Bertola and Brühwiler, 2021) showed that the bridge was in "defective" condition (rating of 3 out of 5), while structural elements are in "acceptable" condition.

2.2 *Structural examination*

With regard to the strength of materials, a C45/55 concrete grade (updated from the C30/37 at the construction) has been selected, leading to a compressive strength of $f_{cd} = 26\ MPa$. The tensile strength of the "Box-Tor-Caron" reinforcing steel was accepted at $f_{sd} = 300\ MPa$. For prestressed bars, an ultimate strength of $f_{pd} = 730\ MPa$ was assumed. Load levels are defined in the Swiss standards for existing structures SIA 269 (Swiss Society of Engineers and Architects, 2011). Structural safety is evaluated based on the concept of the degree of compliance n (Brühwiler et al., 2012) using design values of both structural resistance R_d and action effects E_d.

$$n = Capacity/Demand = \frac{R_d}{E_d} \tag{1}$$

A three-dimensional finite-element model was made in DIANA software to examine the structural safety. This modeling was carried out as realistically as possible, taking into account non-structural elements such as curbs and the asphalt pavement. In addition, each rebar and prestressing tendon have been included in the model. Prestressing is taken from the resistance side.

This model allows the calculation of stresses directly in reinforcing bars and prestressing tendons (Figure 3). For the ultimate limit state (ULS), traffic loads are placed at the most unfavorable locations (at mid-span for bending verifications and close to supports for shear verifications). The stresses in critical prestressing tendons are almost equal to their yield point. Using the numerical model, it is possible to determine the overall degree of compliance by progressively increasing the live-load until failure. A degree of compliance for the mid-span bending verification n_M equal to 1.05 was obtained, showing that the structural safety of the structure in its current state is guaranteed. Analogously, the degree of compliance for the shear verification n_V is equal to 1.10.

Nonetheless, it can be anticipated that after widening (from 5.3 m to 7.9 m), this structural safety will no longer be satisfied. A strengthening scheme will be necessary.

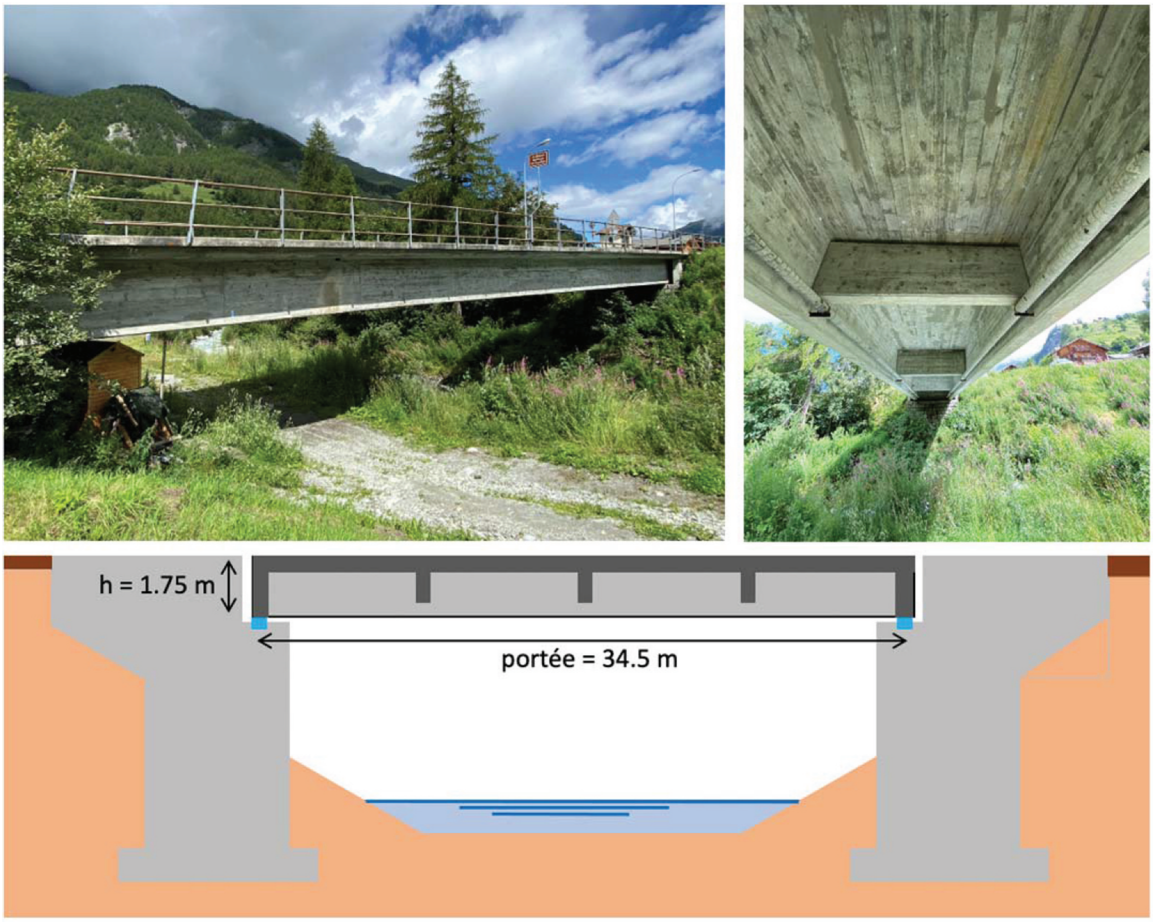

Figure 1. Presentation of the Ferpècle Bridge.

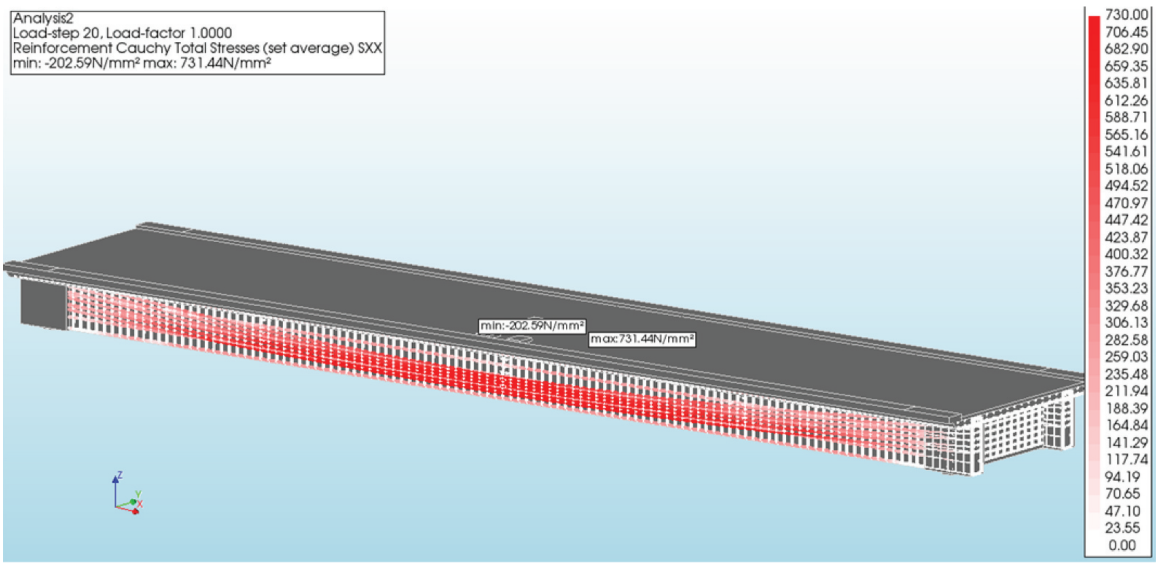

Figure 2. Finite element model and stress in prestressing tendons at ELU 2 (maximal bending at midspan).

3 INTERVENTION SCHEME

The widening of the deck from 5.3 m to 7.9 m, is made through a cantilevered full slab with a variable thickness, in R-UHPFRC (type UB; $f_{Utud} = 6.9MPa$, $E = 45\ GPa$), that is anchored in the existing structure. At midspan, the deck thickness is increased from 25 to 27.5 cm (Figure 3). 20 mm of concrete from the existing slab is hydro-jetted, and the UHPFRC layer of 45 mm is poured on site. Transverse and longitudinal reinforcing bars (ϕ14 @ 150 mm) have been included in the UHPFRC layer. The RC – R-UHPFRC structure works as a composite element.

At the bridge supports, a thicker layer of R-UHPFRC (70 mm) is cast. Moreover, significant reinforcement steel bars (ϕ22 @100 mm) are included to increase the positive bending capacity. To achieve a monolithic structure, the abutments are clamped with traditional reinforced concrete to the superstructure, connecting the two prestressed beams with the deck, the abutment bottom wall the side walls (Figure 4). This intervention thus eliminates the need for expansion joints. The concept behind this clamping in the longitudinal intervention is (1) to create a semi-integral structure and (2) (partially) connect the beam in the abutments. These abutments also act as “counterweights” to take up the positive bending moment at supports.

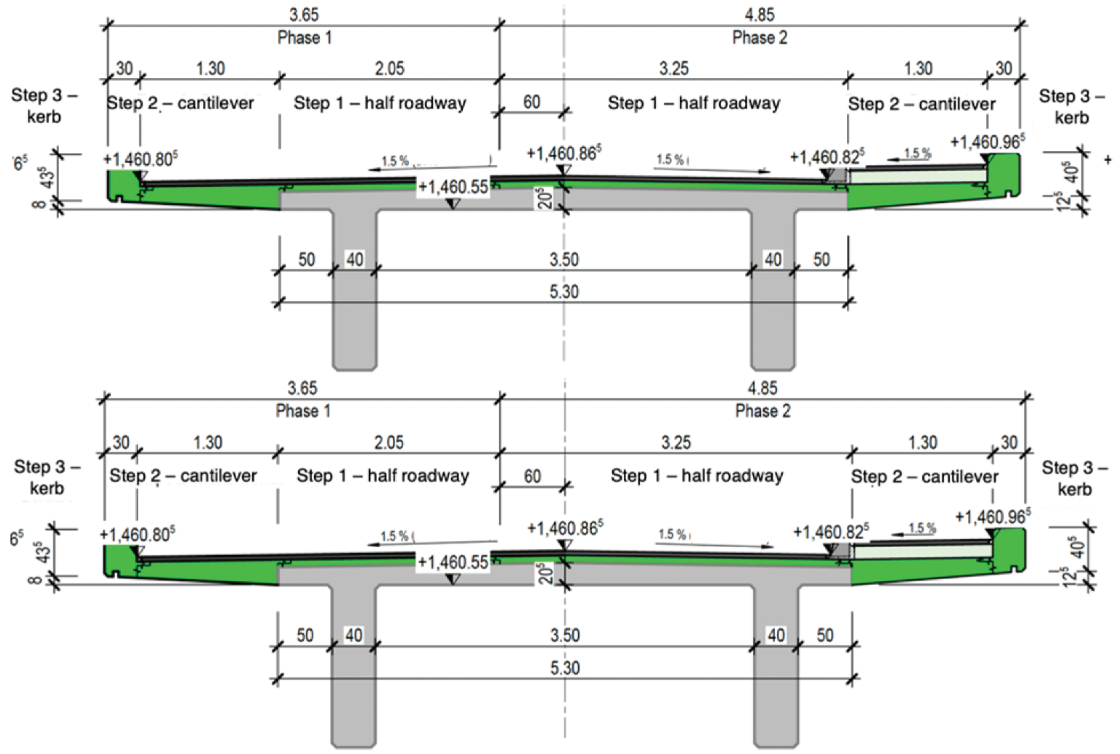

Figure 3. Cross-sections (in span and on supports) with new UHPFRC shown in green.

The concept of the intervention is to redistribute the bending-moment deficit at midspan to the supports. In this way, the static system is modified to form a semi-integral bridge with flexural rigidity at the supports, enabling it to take up this action. The new layer of reinforced UHPFRC (70 mm with (ϕ22 @100 mm) is used to create the necessary bending resistance at supports.

The numerical model is modified to predict the structural behavior after the intervention (Figure 5). For reliable predictions, the abutments are modeled and linked to the superstructure with UHPFRC. This model is used to verify the stresses in the UHPFRC tensile chord, beam compressive action, and abutment tensile reinforcements. Non-linear analyses are needed to effectively predict the strain-hardening behavior of UHPFRC in tension.

This new numerical model is used to evaluate structural safety. The overall degree of compliance obtained is 1.15. Model predictions show that the maximum stress in the new rebars at support is around 280 MPa, well below the yield point. However, some of the rebars in the abutment have stresses up to their yield stress at ULS, showing that this is a decisive factor in the design. In addition, the stresses in the UHPFRC (tension) and in the girder reinforced concrete

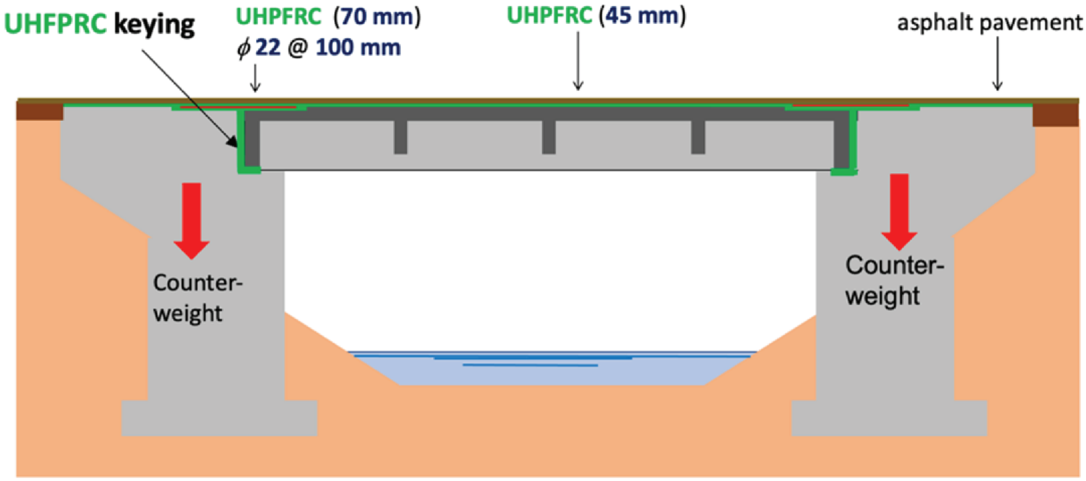

Figure 4. Scheme of the intervention (strengthening in the longitudinal direction).

(compression) are lower than their respective strengths. This difference is due to a greater participating width according to the numerical model than according to an analytical model.

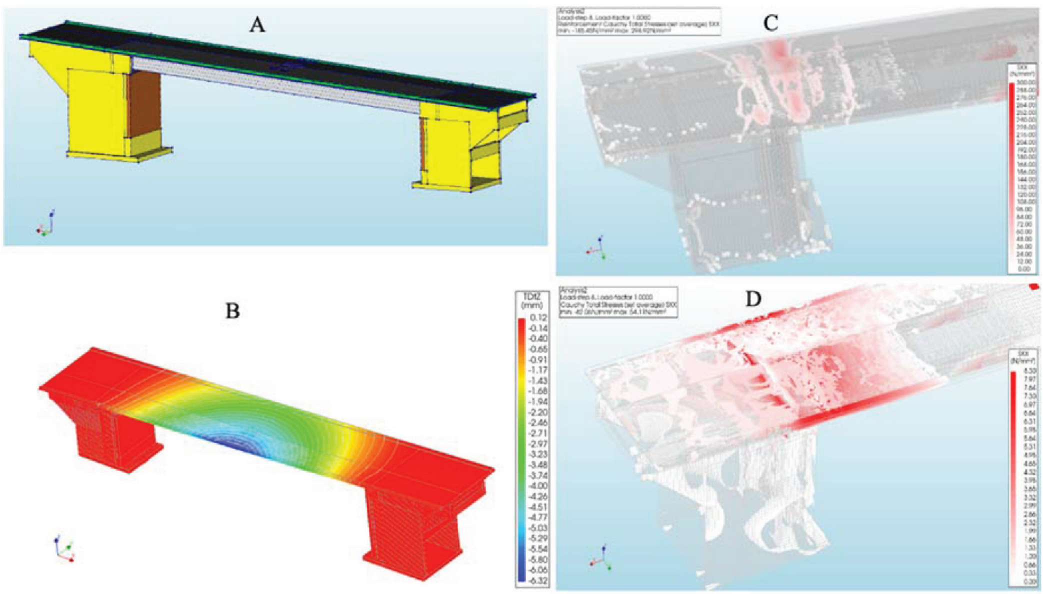

Figure 5. A) Finite element model of the bridge structure after intervention, B) Deformation under SLS load level; C) Tensile stresses in slab reinforcing bars at ULS; D) Tensile stresses in UHPFRC at ULS.

4 INTERVENTION WORK

The intervention was completed between April and November 2023. The work was carried out in two phases (upstream and downstream), enabling alternating traffic flow throughout the work.

In the first stage, scaffolding was erected, the asphalt pavement was removed from the entire deck, and the upstream curb was cut. Then, the formwork for the UHPFRC cantilever and the new curb was installed, and a new RC transition slab was poured. The UHPFRC is prepared directly on site. The deck and the new cantilever were cast in 3 stages (Figure 6), then the curb was cast in a single stage. Finally, the abutments were clamped. The work was then repeated on the downstream part of the structure.

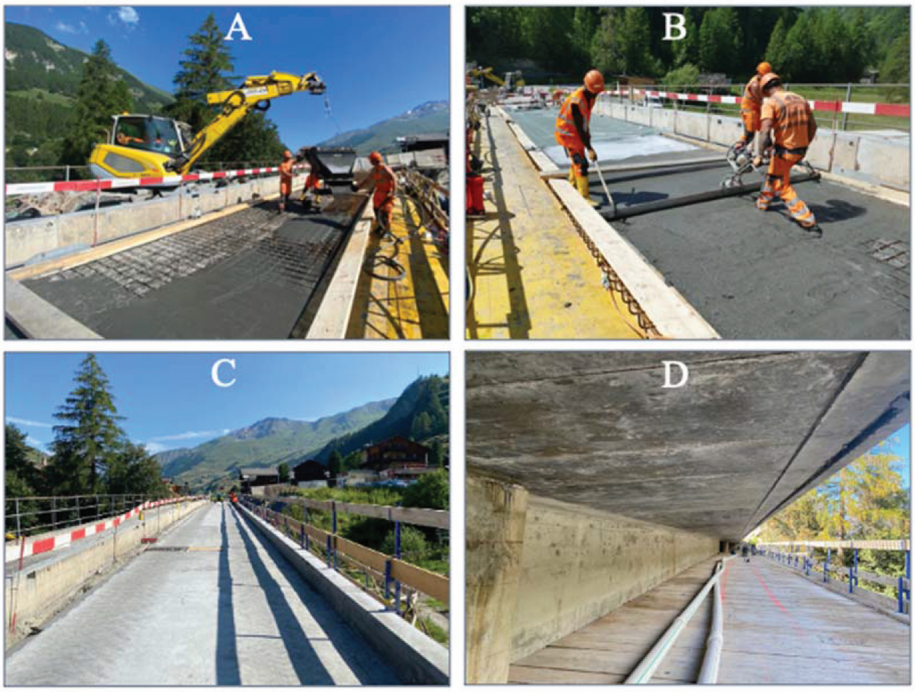

Figure 6. Photographs of the construction work. A, B) UHPFRC casting, C,D) results of the UHPFRC interventions.

5 VALIDATION THROUGH MONITORING

Two monitoring campaigns were performed prior to and after the structural intervention. The aim is to validate the change of the static system (from a simply supported beam to a fixed beam) and to update the material properties, such as the material elastic moduli. Each monitoring involves both static and dynamic excitations that are combined to model updating.

The first monitoring campaign (Phase 1) involved 3 static load tests with a 3-axle truck of 26,5 tons placed at quarter-spans and midspan. The second monitoring campaign (Phase 2) involved 5 static load tests with either one truck (to reiterate previous load tests of Phase 1) or two trucks to maximize the deflections. Additionally, dynamic load tests, which consist of a truck passing over the bridge at a given speed, were performed on both phases of the monitoring campaign.

In Phase 1, the monitoring system involved 10 deflection measurements made from the deck with a total station and targets on the bridge (supports, quartier spans, and midspan), and 10 accelerometers at the same locations. In Phase 2, the monitoring system involved 6 LVDT sensors on one side of the bridge on both girders.

Table 1. Measurements collected during monitoring campaigns.

Measurement	Before intervention	After intervention
1st modal frequency [Hz]	3.42	5.58 (+63 %)
Maximum deflection (extrapolation) [mm]	7.82	2.01 (-38.7 %)

Main data collected during these monitoring campaigns are shown in Table 1, where measurements prior to and after intervention are compared. As the first modal frequency is increased and deflections are reduced, it can be concluded that the rigidity of the structure has been increased significantly. After performing model updating (developed in later studies), it is shown that the global bridge behavior is significantly modified (Figure 7). Deformations predicted by the numerical models prior to and after monitoring match the measurements collected during load tests.

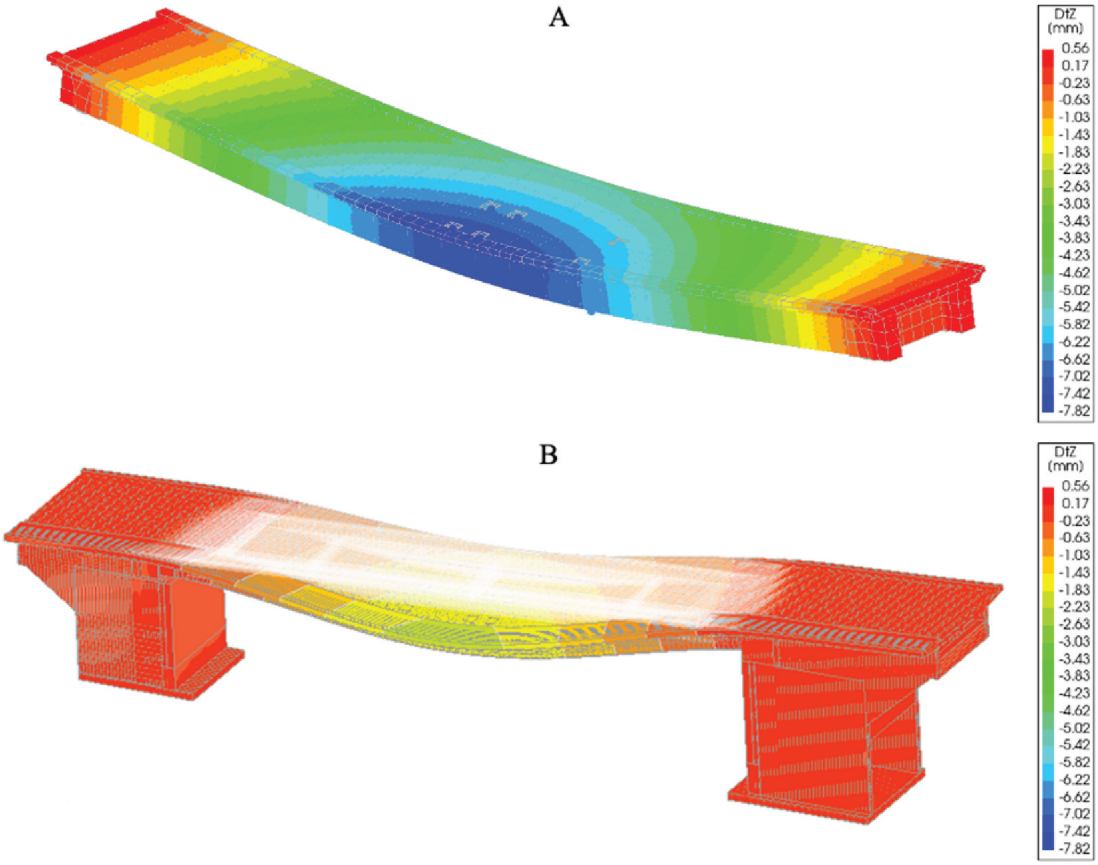

Figure 7. Bridge deflection behavior. A) Prior to monitoring; B) After monitoring.

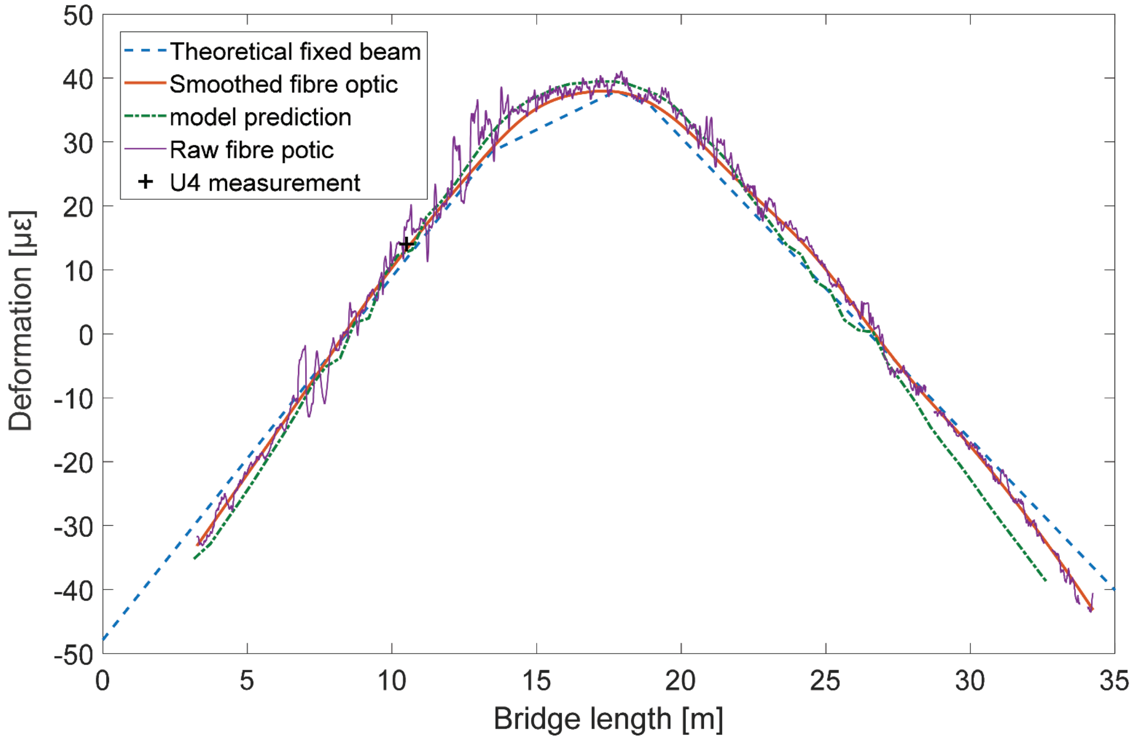

Figure 8. Comparison of model predictions, optical fiber strain measurements, and deformation of a theoretical fixed beam.

Two 32m-long optical fibers (SMARTprofile II from Smartec and a LUNA data acquisition system) were glued along both girders to validate the change of the static system. These optical fibers measure strain every approx. 3 mm along virtually the entire length of the structure. This corresponds to the equivalent of around 11,000 strain gages installed in series on each girder, enabling a much more detailed analysis than is usually the case where only a few strain gages are placed along the length of the bridge. Measurements are taken at a frequency of 5 Hz.

Strain predictions are compared with fiber optic measurements in Figure 8. The values in the cracks are removed from the fiber measurements ("raw fiber optic"). These values are then smoothened ("smoothed fibre optic") to remove local variations in the measurements and enable easier comparison. The theoretical deformation of a fixed beam with three concentrated loads (corresponding to the truck's three axles) is also presented. It can be seen that the predictions are very close to both the fiber optic measurements and the theoretical deformation. The average error is around 2 $\mu\varepsilon$. It can thus be concluded that the intervention resulted in the modification of the static system, where the bridge superstructure is being clamped to the abutments, creating a monolithic behavior of the structure. More in-depth analyses of the fiber-optic data will be made in future work.

6 CONCLUSIONS

This article presents the design, execution, and monitoring of the UHPFRC intervention on the Ferpècle bridge, one of the first prestressed concrete bridges in Switzerland. The project involved widening the bridge deck from 5.3 to 7.9 m (increase of about 50 %). The resulting need for reinforcement was met by redistributing actions (from midspan to the supports) based on the theory of plasticity at ULS. Strengthening only the top of the deck increases the structure's flexural load-bearing capacity by 44 %, while widening and rehabilitating the bridge. This case study demonstrates that UHPFRC can effectively strengthen existing structures by changing the static system. Compared with the demolition-reconstruction initially envisaged, the project is considerably less costly (-75 %) and has smaller associated carbon-dioxide emissions (- 55 %). The intervention was validated through an innovative monitoring scheme involving strain, acceleration, and deflection data. Measurements collected during load tests match the predictions of the finite-element models and correspond to the behavior of a fixed beam.

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REFERENCES

Bertola, N., Brühwiler, E., 2021. Risk-based methodology to assess bridge condition based on visual inspection. Structure and Infrastructure Engineering 0, 1–14. https://doi.org/10.1080/15732479.2021.1959621

Bertola, N., Küpfer, C., Kälin, E., Brühwiler, E., 2021a. Assessment of the Environmental Impacts of Bridge Designs Involving UHPFRC. Sustainability 13, 12399. https://doi.org/10.3390/su132212399

Bertola, N., Schiltz, P., Denarié, E., Brühwiler, E., 2021b. A Review of the Use of UHPFRC in Bridge Rehabilitation and New Construction in Switzerland. Frontiers in Built Environment 7, 155. https://doi.org/10.3389/fbuil.2021.769686

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

Brühwiler, E., 2016. "Structural UHPFRC": Welcome to the post-concrete era !, in: International Interactive Symposium on Ultra-High Performance Concrete. Iowa State University Digital Press, Des Moines, Iowa, USA, pp. 1–16. https://doi.org/10.21838/uhpc.2016.key

Brühwiler, E., Bastien Masse, M., 2015. Strengthening the Chillon viaducts deck slabs with reinforced UHPFRC [WWW Document]. IABSE Conference Geneva 2015 "Structural Engineering: Providing Solutions to Global Challenges." URL http://infoscience.epfl.ch/record/212773 (accessed 12.4.20).
Brühwiler, E., Denarié, E., 2013. Rehabilitation and Strengthening of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete. Structural Engineering International 23, 450–457. https://doi.org/10.2749/101686613X13627347100437
Brühwiler, E., Vogel, T., Lang, T., Lüchinger, P., 2012. Swiss standards for existing structures. Structural Engineering International 22, 275–280.
El Jisr, H., Moreillon, L., Menétrey, P., 2023. Strengthening of the Riddes Viaduct Through UHPFRC-Based Rehabilitation. Structural Engineering International 0, 1–9. https://doi.org/10.1080/10168664.2023.2194898
Géhin, D., Brühwiler, E., Bertola, N., Widmer, L., 2022. Design and Construction of the" Chaumény" Footbridge in Posttensioned UHPFRC, in: IABSE Symposium Prague 2022. IABSE, pp. 285–292. https://doi.org/10.2749/prague.2022.0285
Graybeal, B., Brühwiler, E., Kim, B.-S., Toutlemonde, F., Voo, Y.L., Zaghi, A., 2020. International Perspective on UHPC in Bridge Engineering. Journal of Bridge Engineering 25, 04020094. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001630
Hajiesmaeili, A., Pittau, F., Denarié, E., Habert, G., 2019. Life Cycle Analysis of Strengthening Existing RC Structures with R-PE-UHPFRC. Sustainability 11, 6923. https://doi.org/10.3390/su11246923
Oesterlee, C., 2010. Structural response of reinforced UHPFRC and RC composite members. EPFL, Lausanne, Switzerland.
Swiss Society of Engineers and Architects, 2011. Existing structures, SIA 269, 269/1-269/7. Swiss Society of Engineers and Architects, Zurich, Switzerland.
Technical Leaflet on UHPFRC: Materials, Design and Application, 2016.
Trinh, N.T., Bertola, N., Garcia, E., Brühwiler, E., 2022. Short Span UHPFRC Railway Bridge in Switzerland-From Design to Implementation, in: IABSE Symposium Prague 2022. IABSE, pp. 277–284. https://doi.org/10.2749/prague.2022.0277