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BRIDGE REHABILITATION WITH USE OF UHPFRC IN SWITZERLAND

Abstract:

This article provides a practical framework for the application of ultra-high-performance fiber-reinforced concrete (UHPFRC) in road bridges. Most of these bridges, constructed with reinforced or prestressed concrete according to mid-20th-century European practices, now face significant durability challenges. The rehabilitation of existing bridges using UHPFRC began in Europe in the early 2000s and was quickly implemented in Switzerland. Since then, more than 350 projects have been completed in Switzerland, official guidelines for the maintenance and construction of structures using UHPFRC have been published, and several examples of rehabilitation and strengthening from these guidelines are presented. The case study of strengthening the Ferpècle road bridge is presented.

Keywords: UHPFRC, UHFB, bridge strengthening, bridge rehabilitation, bridge durability,

САНАЦИЈА МОСТОВА У ШВАЈЦАРСКОЈ ПРИМЈЕНОМ МИКРОАРМИРАНИХ БЕТОНА УЛТРА-ВИСОКИХ ЧВРСТОЋА

Сажетак:

Овај рад пружа практичан оквир за примјену микроармираних бетона ултра-високе чврстоће (UHPFRC) на друмским мостовима. Већина ових мостова, изграђених од армираног или преднапрегнутог бетона у складу са европском праксом из средине, 20. вијека, данас се суочава са значајним изазовима у погледу трајности. Санација постојећих мостова примјеном UHPFRC-а започета је у Европи раних 2000-их година и у Швајцарској је брзо примијењена у праксу. Од тада је у Швајцарској реализовано више од 350 пројеката, објављене су званичне смјернице за одржавање и изградњу објеката примјеном UHPFRC-а, а у овом раду приказано је и неколико примјера санације и ојачања из ових смјерница. Такође, приказан је и практичан примјер ојачања друмског моста Ferpècle.

Кључне ријечи: UHPFRC, UHFB, ојачање мостова, санација мостова, трајност мостова
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1. INTRODUCTION

Reinforced concrete bridges, have been extensively constructed worldwide since the mid-20th century, when labor cost was not significant. Over time, however, they frequently exhibit durability issues, which were not considered in earlier designs. Mainly due to inadequate sealing of the deck, which allows chloride ingress. These chlorides typically originate from de-icing salts applied to the deck during winter conditions. Chloride contamination frequently leads to corrosion of the steel reinforcement, which in turn causes concrete cracking, delamination, and spalling. Other contributing factors include freeze–thaw cycles, cracking due to overloading, and, in rare cases, alkali–aggregate reactions, or a combination of these mechanisms. These forms of deterioration can substantially compromise their structural performance [1].

2. UHPFRC:MATERIAL PROPERTIES

Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) is an advanced cement-based composite material, also referred as UHPFR Cementitious Composite, as more accurate term [2]. It typically combines a water-to-cement ratio lower then 0.25 , optimized particle packing, high cement content, and large amount of slender discontinuous steel fibers, more than 150 kg/m^3 [3]. With a cement matrix of a characteristic compressive strength in excess of 150 MPa, and tensile resistance higher than 8 MPa, UHPFRC is distinguished from ordinary concrete (OC) or fiber-reinforced concrete (FRC) [3].

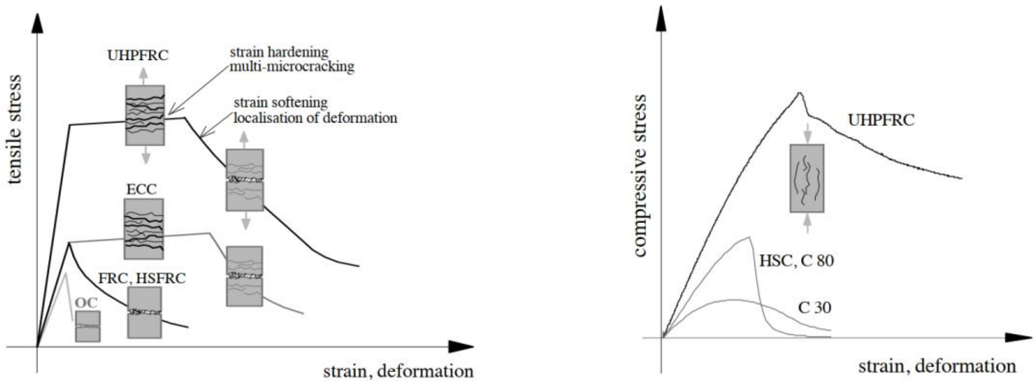

Figure 1. Response of UHPFRC in in uniaxial stress state in comparison to ordinary (OC) and fiber-reinforced concrete (FRC) [3].

The typical compositions of ordinary concrete, FRC, and UHPFRC are listed in Table 1. UHPFRC is distinguished as a fine-grained concrete, a high binder content, and a low water–cement ratio.

Table 1. Examples of composition of ordinary concrete (OC), fiber-reinforced concrete (FRC) and ultra-high-performance concrete (UHPFRC) .

	OC	FRC	UHPFRC
Components	[kg/m^3]	[kg/m^3]	[kg/m^3]
Portland cement	< 400	415-700	700 - 1000
Coarse aggregate	≈ 1000	920-1125	0 - 200
Fine aggregate, sand	≈ 700	575-750	1000 - 2000
Silica fume	-	0-50	200 - 300
Fibers	-	39-150	>150
Water	>200	125 - 150	110 - 200
Water-cement ratio	> 0.35	0.30-0.45	< 0.24
Density	2000 - 2800	2300 - 2500	> 2500
Mechanical properties	[MPa]	[MPa]	[MPa]
Compressive strength	< 60	30 - 80	> 150
Tensile strength	< 3	3-7	> 8
Modulus of elasticity	≈ 30	25-40	50 - 70

Adding fibers to the UHPC (Ultra-High-Performance Concrete) matrix produces a tensile behavior that can be illustrated schematically, as shown in Figure 2. The concept was first introduced in the 1960s by Romualdi, who demonstrated that cracking in concrete could be controlled through fibre bridging. [4].

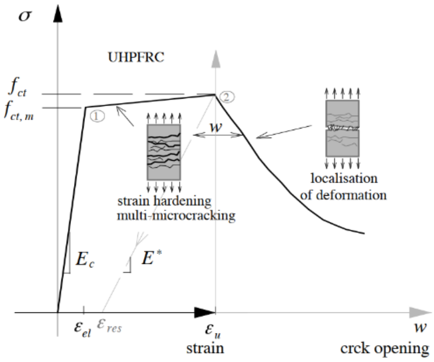

Figure 2. Uniaxial tensile response of UHPFRC element and notations for characteristic values [3].

The following types of behavior after uniaxial tensile test are identified:

- Linear-elastic manner up to limit stress $f_{ct,m}$, when matrix reaches its tensile strength
- The strain-hardening phase when the fibers continue to elongate while the matrix develops numerous discontinuities, leading to a reduction in the stiffness of the UHPFRC. This phase ends when its reached the ultimate tensile strength f_{ct} and corresponding strain ε_u.
- Strain softening behavior, as stress starts to decrease, the sections outside the weakest zone begin to unload, reducing their deformation, while the deformation localizes in the weakest section, forming what is known as a “macrocrack.”

Experimental results indicate that UHPFRC exhibits high tensile strength, on the order of 10 MPa, and, more notably, a very high tensile strain capacity (2–3 ‰), which is attained without any reduction in stress, as shown in Figure 3. The UHPFRC employed in this study, incorporating a 2.5 % steel fibre volume fraction, demonstrates a tensile strength of 9 MPa and a tension plateau extending to 2.5 ‰ [3].

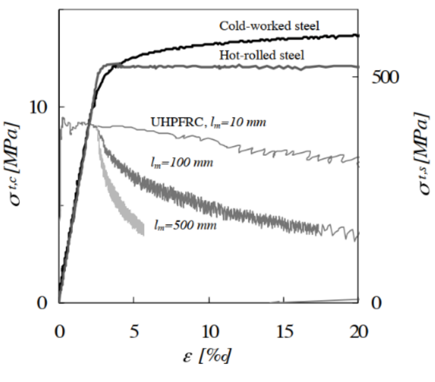

Figure 3. Comparison of tensile capacities of UHPFRC and reinforcing steel bars [3], [5].

Regarding durability, testing under strain-hardening behavior has shown that UHPFRC is practically impermeable to liquids-even under high tensile strains of up to 1.3 ‰. Under service-level stresses, UHPFRC remains practically crack-free. This behavior is due to the high volume of steel fibers, which limit the opening of microcracks. It should be kept in mind that the reinforcement follows the deformations of the UHPFRC, and the stresses observed in the reinforcement are twice as high as those in bars embedded in normal concrete under the same exposure conditions. In some cases, the use of reinforcing bars with a yield strength higher than 500 MPa is recommended [6].

3. SWITZERLAND PRACTICE

The concept of rehabilitating existing bridges through the use of UHPFRC emerged in Europe in the early 2000s. Thanks to the strong links between academia and the construction industry in Switzerland, the transfer of UHPFRC technology into practice was achieved rapidly [2]. Figure 2 presents a map of applications in Switzerland, since 2003. Within a 20-year time span, 316 applications were successfully implemented on various structures [7]. Among these, 250 applications involve the rehabilitation of federal and cantonal road bridges [1].

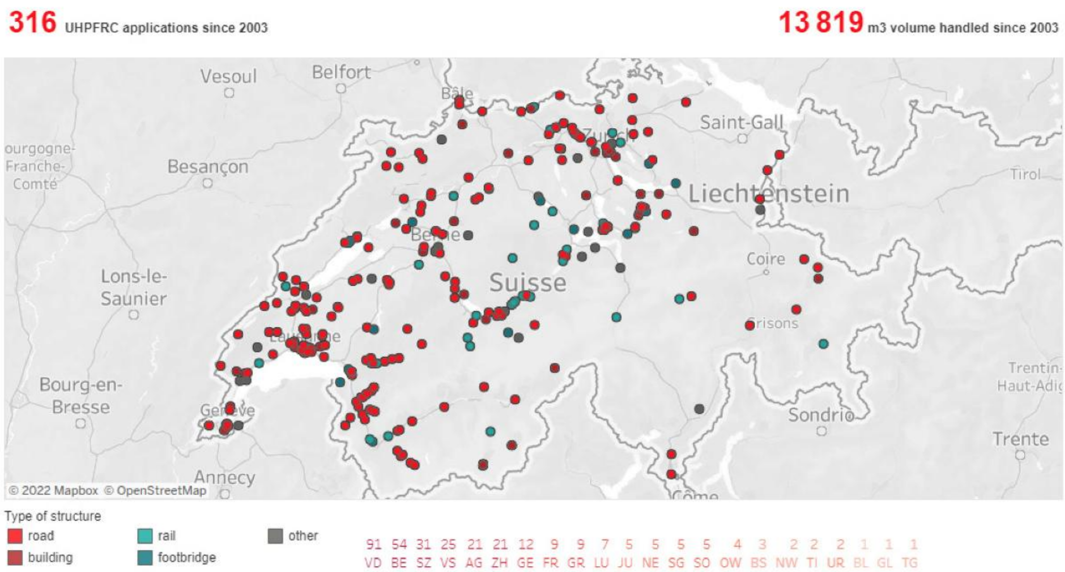

Figure 4. Figures and Applications of UHPFRC in Switzerland since 2003 (source: Structural Maintenance and Safety Laboratory-MCS, EPFL, January 2023) [7].

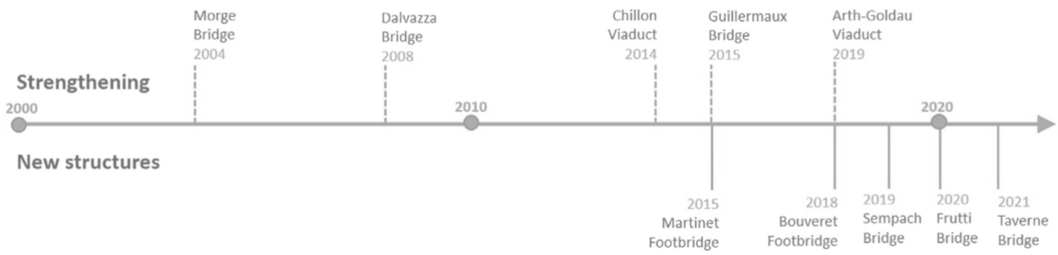

Figure 5. Timeline of strengthening and new structures using UHPFRC in Switzerland [2].

The first bridge application was the rehabilitation of the Morge Bridge in 2004, a reinforced concrete (RC) road bridge originally built in 1954. Since then, several historic bridges have also been rehabilitated, including the Dalvazza Bridge (built in 1925) and the Guillermaux Bridge (built in 1920), both of high cultural value. These interventions have allowed the preservation of the bridges original appearance while enhancing their load-bearing capacity to meet modern requirements [8]. In the meantime, the Swiss Society of Engineers and Architects (SIA) has introduced the SIA 269 [9] series to provide the basic principles and the procedure to be followed in the treatment of existing structures. Another type of UHPFRC application is the reinforcement of highway viaducts such as the Chillon Viaduct [10]. Figure 5 shows the sequence of interventions on existing bridges and the construction of new bridges using UHPFRC in Switzerland. Introduced in 2016, SIA 2052 [11] offered engineers research-based guidance on UHPFRC, including material properties, RC strengthening, and quality control.

As the most recent document, published in 2023, the ASTRA 82022 [12] guidelines compile the experience of past years and are intended for professional staff involved in the maintenance and construction of road infrastructure structures. The following section presents some examples from the aforementioned guidelines.

4. ASTRA GUIDELINES FOR UHFB

In German-speaking regions, Ultrahochleistungsfaserbeton (UHFB) is used, and this abbreviation will be used hereafter.

Some existing bridges were designed in accordance with earlier design codes and may therefore not fully meet current requirements with respect to bending and shear resistance. Nearly 50% of the turnover of the Swiss construction industry is devoted to conservation measures [13], highlighting the need for specific codes addressing existing structures. To address this practical need, the Swiss Society of Engineers and Architects (SIA) has been overseeing the project "SIA 269 – Fundamentals of the preservation of structures" since 2011 [9]. The design of existing structures with UHFB layers is carried out according to the principles of SIA 269 [9]. Actions are specified in SIA 269/1 [14]. Published in 2023, the ASTRA 82022 [12] guidelines incorporate the provisions of SIA 269 [9] as a fundamental part of the regulations for existing structures. The following section presents examples of strengthening in accordance with the ASTRA 82022 [12] guidelines.

Since UHFB remains watertight under service conditions, it is well suited for sealing deteriorated bridge decks, particularly when the upper zone of the concrete slab is damaged and requires replacement. The basic idea behind strengthening reinforced concrete elements with UHFB is to create a monolithic bond between a UHFB layer and the existing bridge deck. The resulting UHFB–concrete composite element consists of a reinforced concrete cross-section and a layer of UHFB or Stahl-UHFB, as shown in Fig. 6. The label "Stahl" refers to reinforcing or (R).

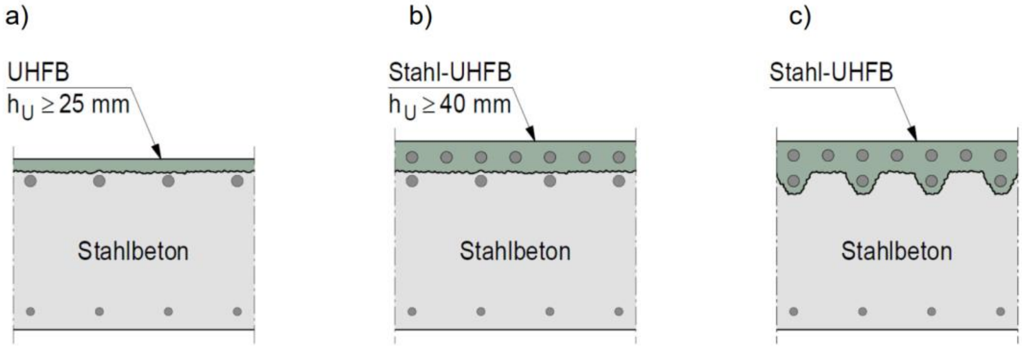

Figure 6. Typical configurations combining UHFB and reinforced concrete. A: UHFB as protective layer, B: Stahl-UHFB as reinforcing (Stahl-) and protective layer, C: Stahl-UHFB used for rehabilitation of corrosion damage of existing rebars and reinforcing layer [12].

A minimum UHFB layer thickness of 25 mm is required to ensure a protective function by preventing direct contact of the reinforced concrete with water and chloride ions (Figure 6a). The term "Stahl" used in Figures 6b and 6c refers to both an increase in the load-bearing capacity and the stiffness of the structural elements. Simultaneously, the UHFB layer also provides a protective function. This procedure often simplifies construction and reduces execution time, while the UHFB–concrete composite approach typically requires minimal intervention in the existing structure, as its self-weight is only marginally increased, helping to avoid the need to strengthen other structural elements or foundations.

In these guidelines, three fundamental project objectives are distinguished:

- Objective 1- Rehabilitation and protection of reinforced concrete elements
- Objective 2- Restoration or increase of the load-bearing capacity of bridge decks
- Objective 3- Increase of the load-bearing capacity of the entire structure

As far as durability is concerned, ASTRA 82022 [11] provides guidelines for structural details of bridges. The main objective is to achieve structures with the highest possible durability, requiring only planned maintenance and the replacement of wear parts such as pavement layers, drainage pipes, or safety barriers. This approach is consistent with the definition of "Dauerhaftigkeit" in SIA 260 [15].

4.1. REHABILITATION AND PROTECTION OF REINFORCED CONCRETE ELEMENTS

Figures 7 and 8 illustrate the concept of a UHFB layer used to rehabilitate and protect the reinforced concrete of bridge deck. The edge elements and parapets are also included. For practical and constructional reasons, the UHFB layer is typically 30 mm thick on horizontal surfaces and 40 mm thick on steeply inclined or vertical surfaces [12]. In German "Belag" means pavement or wearing course on a bridge deck.

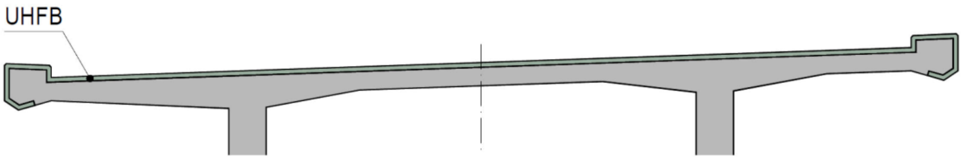

Figure 7. Principle for the rehabilitation and protection of bridge deck [12].

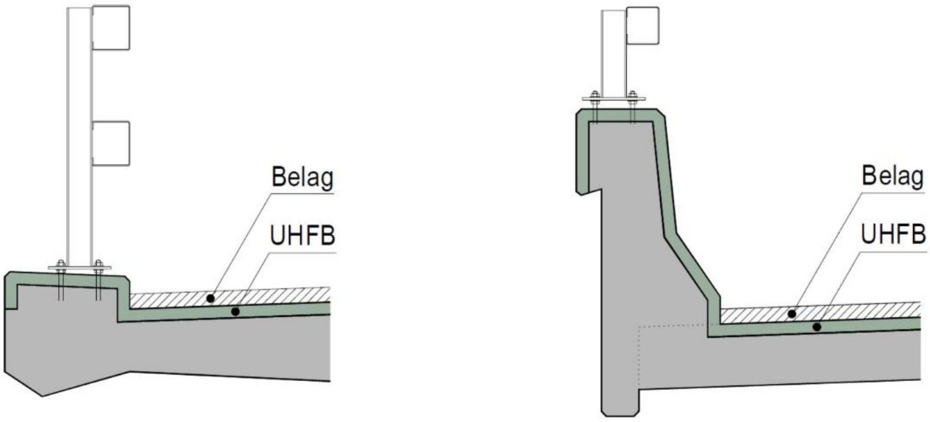

Figure 8. Rehabilitation and protection of bridge cornice and barrier [12].

Figure 9 show possible applications of self-compacting UHFB for wall-like elements with steeply inclined or vertical surfaces.

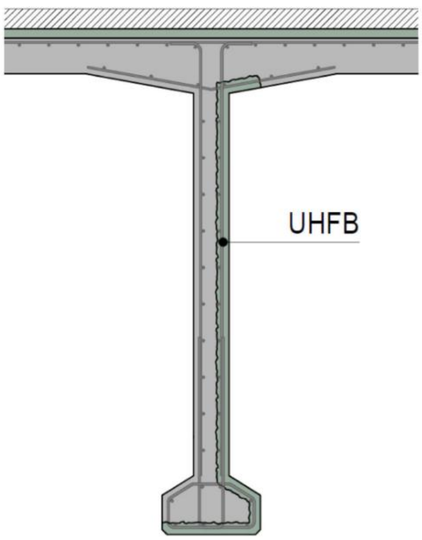

Figure 9. Principles for the rehabilitation and protection of wall-shaped reinforced concrete components in slender beam webs [12].

4.2. RESTORATION AND INCREASE OF THE LOAD-BEARING CAPACITY OF BRIDGE DECKS

Figure 10 illustrates the basic principle of strengthening deck slabs by applying a steel-reinforced UHFB layer onto the concrete surface, which has been pretreated using hydrodemolition. Before applying the new layer, it is important to moisten the previously prepared surface, while ensuring that no puddles are formed. This creates a monolithic bond between the Stahl-UHFB layer and the reinforced concrete slab. This procedure is intended for deck slabs that carry loads and forces in the transverse direction. In German "Stützbereich and Feldbereich" means support and span region, respectively.

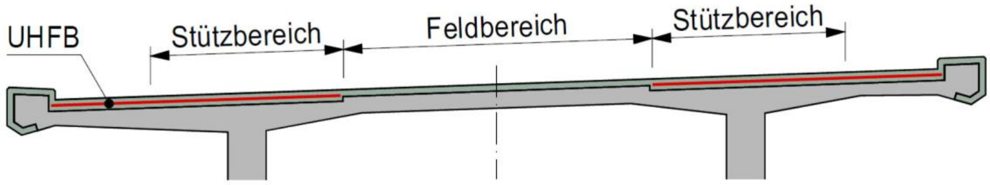

Figure 10. Principle of increasing the load-bearing capacity of reinforced concrete deck slabs using a Stahl-UHFB layer, forming a robust tensile band in the support region [12].

The concept significantly increases the bending resistance in the support region by forming a robust Stahl-UHFB tensile band, in order to redistribute the bending moments from the span to the supports. In addition to the bending capacity, the shear capacity has also been increased, eliminating the need for additional construction measures. The concrete removal of 30 mm is typically overcompensated by the UHFB layer, leading to a 20–40 mm increase in slab thickness and effective depth, while the additional self-weight is offset by reducing the asphalt pavement to 4 cm due to the watertight nature of UHFB.
Figure 11 demonstrates the principle of a deck widening symmetric to the girder axis using UHFB. The existing cantilever head is first removed and the connection reinforcement exposed or supplemented with post-installed anchors, after which the new cantilever slab with edge beam is cast in place using Stahl-UHFB.

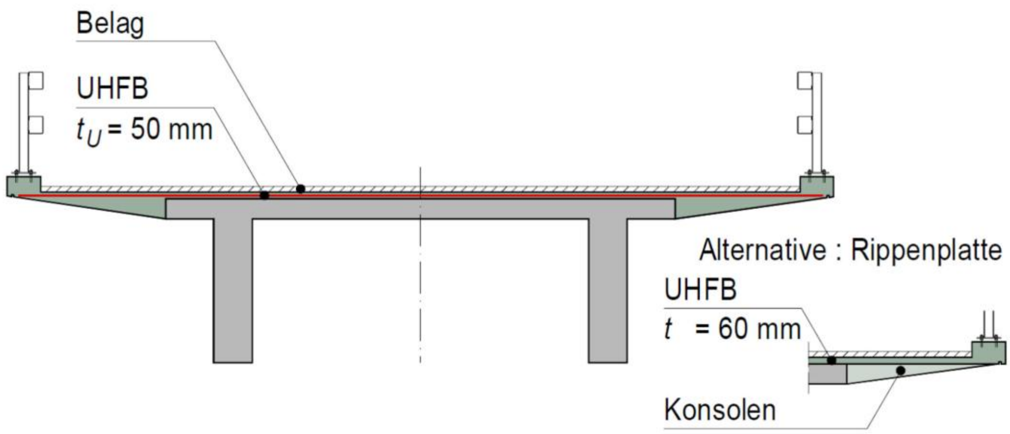

Figure 11. Principle of symmetric widening of the deck slab with two variants: a solid slab with thickness decreasing outward (top) and a ribbed slab (bottom right) [12].

Since typically one traffic lane must remain operational during construction, the Stahl-UHFB layer is cast in two stages with lapped longitudinal construction joint. The additional self-weight can be further reduced by using a ribbed slab (Rippenplatte) with ribs tapering outward. The slab thickness of the T-section is 60 mm, assuming a UHFB cover of 15 mm at both top and bottom, with transverse reinforcement bars of Ø16 mm and longitudinal bars of Ø12 mm.

4.3. INCREASE THE LOAD-BEARING CAPACITY OF THE STRUCTURE

The targeted use of Stahl-UHFB enables a significant increase in the load-bearing capacity of bridge girders in the main load-bearing direction without substantially increasing the permanent loads. This chapter demonstrates only two principles.

The basic principle illustrated in Figure 12 aims for an increase in the load-bearing capacity of the continuous beam by 15-30 %. In the transverse direction, the UHFB layer increases stiffness, promoting a more uniform distribution of concentrated live loads and reducing local peaks in bending moments and shear forces.

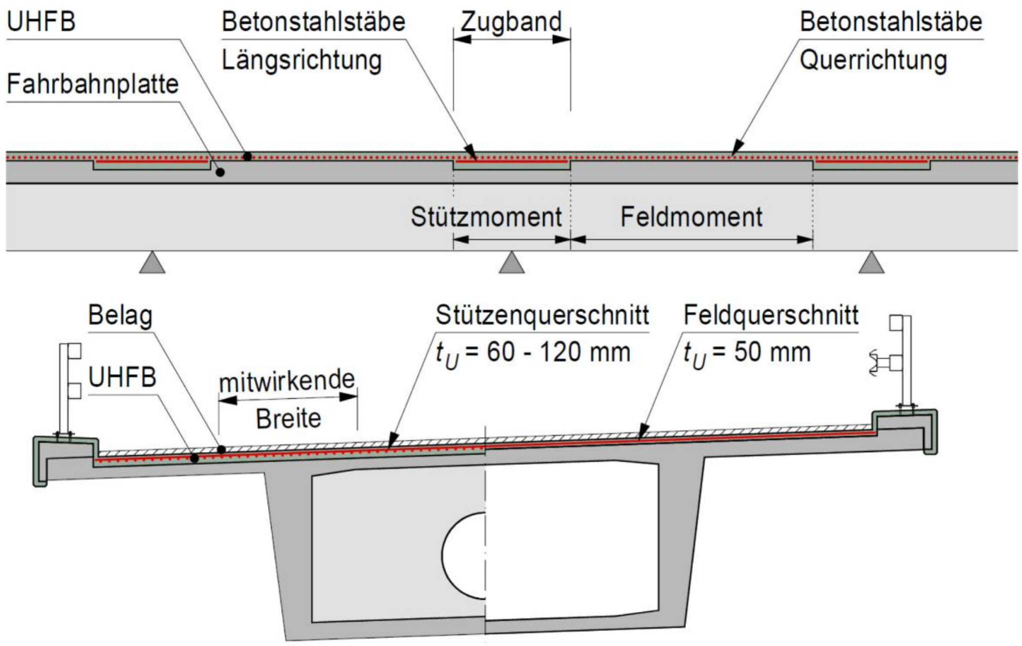

Figure 12. Principle of increasing the load-bearing capacity of reinforced concrete bridge girders through a Stahl-UHFB layer, incorporating a robust Stahl-UHFB tension tie in the support region [12].

In the span region, where the effect of the added layer on bending resistance is relatively small, the bending capacity can be further enhanced using CFRP laminates applied to the girder's underside. Figure 13 illustrates the basic principle of using bonded reinforcement.

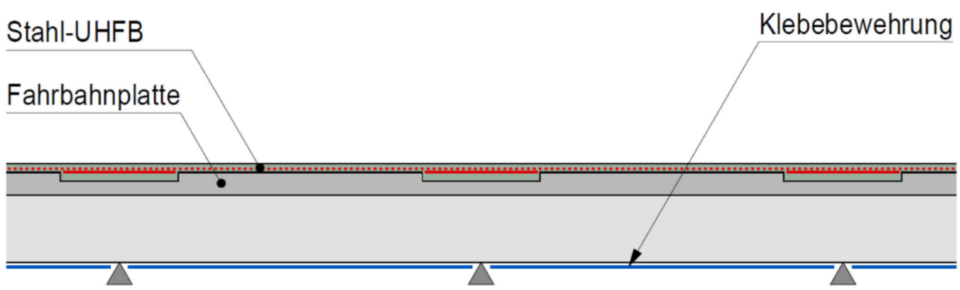

Figure 13. Using bonded reinforcement for the additional increase of bending resistance in the span [12].

The design and installation of bonded reinforcement is carried out in accordance with SIA 166 [16] . In contrast, installing external reinforcement on the underside of the girder is technically challenging and labor-intensive, and is therefore not recommended.

4.4. STRUCTURAL DETAILS FOR REPAIR AND INCREASE THE LOAD-BEARING CAPACITY OF THE STRUCTURE

This chapter demonstrates the formation of a monolithic (jointless) structure, eliminating both hinges and expansion joints. In addition to increasing the load-bearing capacity of the existing bridge through force-transmitting joint closure, this also significantly enhances its long-term durability.

4.4.1. Joint closure

Figure 14 illustrates the principle of the structural detail of a force-locked, bending-stiff joint closure of a Gerber hinge using UHFB.

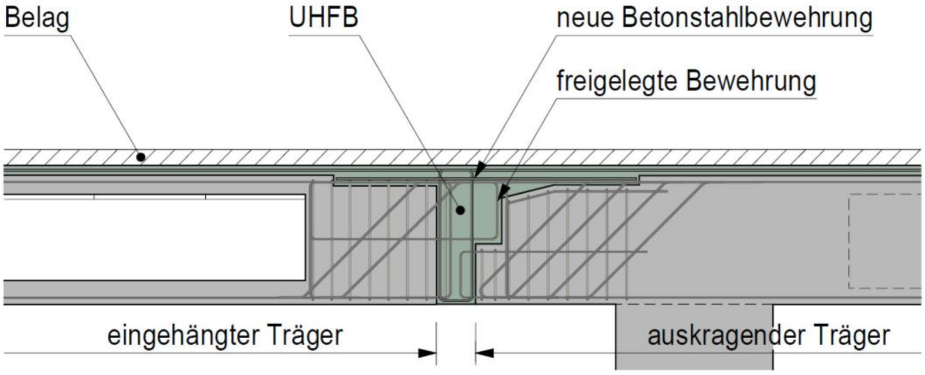

Figure 14. Joint closure of Gerber hinges using UHFB providing force transmission and flexural rigidity [12].

4.5. BRIDGE END AND APPROACH SLABS

Experience shows that expansion joints are vulnerable points in bridges, as leaking joints allow de-icing salts to penetrate and potentially cause serious damage, especially where prestressing cables are anchored at the bridge ends [17]. Damaged expansion joints also negatively affect driving comfort. Traditional repairs are labor-intensive and do not offer a significant improvement to these weak points. Due to their unsatisfactory long-term performance, there is a growing trend to replace expansion joints and bearings with monolithic connections in both new bridges and rehabilitation projects.

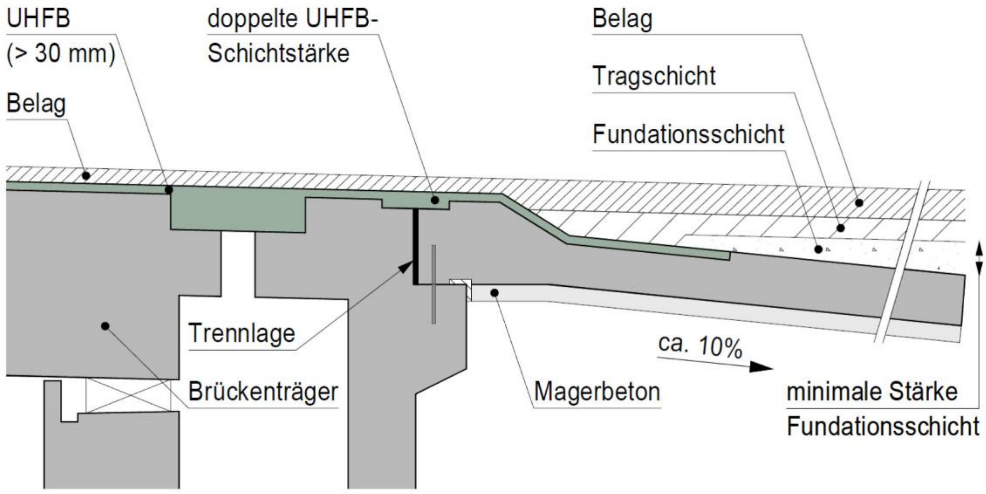

Figure 15. Monolithic connection of bridge girder, abutment, and approach slab(e.g., semi-integral bridge end with bearing, without expansion joint) [12].

Based on current knowledge in the field of integral bridge construction [18], expansion joints of existing bridges can be eliminated and closed without special verification for distances from the fixed point to the bridge end of up to 40 m for steel–concrete composite bridges and 50 m for reinforced concrete bridges. Figure 15 shows a monolithic structural detail of the intervention.

5. THE STRENGTHENING OF THE FERPÈCLE BRIDGE

5.1. BRIDGE EXISTING CONDITION

The Ferpècle Bridge is a prestressed reinforced concrete structure located near Sion in Swiss Alps. It was constructed in 1958 based on designs by the engineering firm B. Deléglise – P. Tremblet and represents one of the earliest post-tensioned bridges built in Switzerland. Structurally, the bridge consists of a simply supported beam with a span of 34.5 meters. The superstructure is formed by a prestressed concrete double-girder section. The width of useful bridge deck is 5.3 m. The beam has a structural depth of 1.75 meters and web width of 40 cm. At midspan, the slab thickness is 25 cm. The visual inspection showed that bridge was in condition rating 3 out of 5 [19].

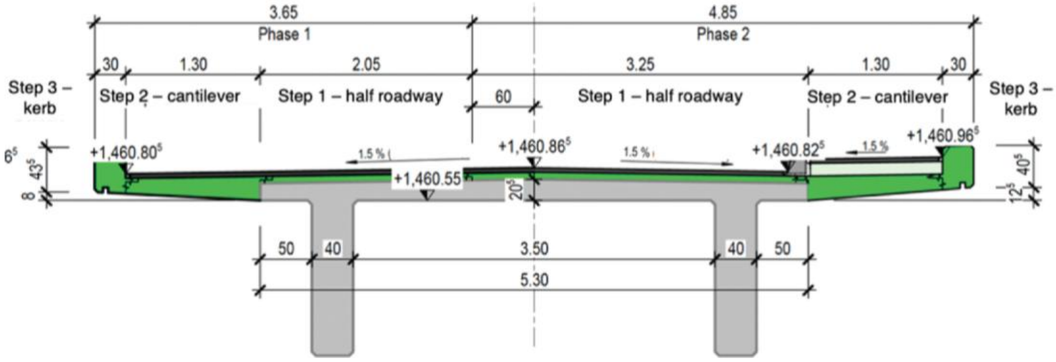

Figure 16. Characteristic cross section with UHFB intervention [20].

5.2. CONCEPTUAL DESIGN OF THE INTERVENTION

The owner requested the widening of the to accommodate increased traffic demands and to improve user safety. A width of 7.9 m was required. This will result in additional effects from permanent and live loads. The idea was to form a semi-integral concept with use of UHFB, creating a monolithic and hyperstatic structure. This will increase the load-bearing capacity and also enhance long-term performance by eliminating the expansion joints. In Figure 16, the subsequent intervention using UHFB is highlighted in green [20]. We observe a significant reduction in the edge beams compared to conventional concrete. The method of application in longitudinal section is illustrated in Figure 17 below. In the following, we will describe the sequence of interventions.

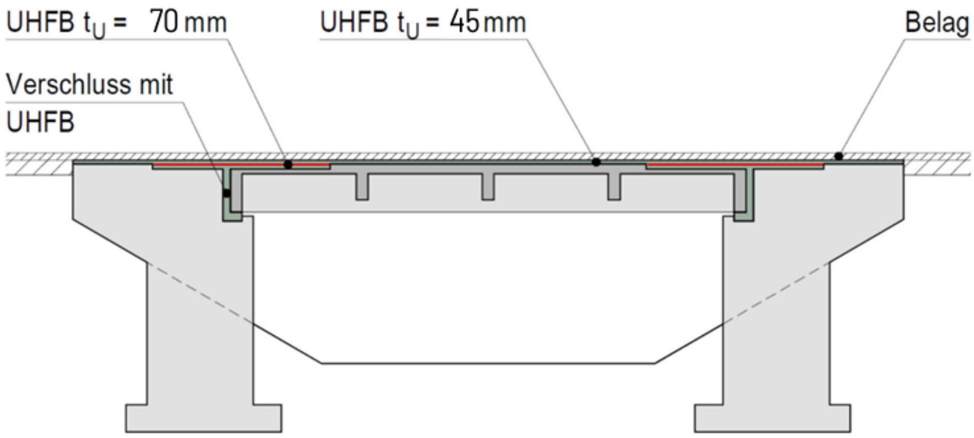

Figure 17. Conceptual design of the UHFB intervention, longitudinal section [21].

First, a 20 mm thick layer was removed in the span using hydrodemolition, after which a 45 mm thick UHFB layer was subsequently added. Transverse and longitudinal reinforcing bars Ø14 mm at 150 mm spacing have been included in the added layer. At the support region, a 70 mm thick layer of Stahl-UHFB is cast, with higher reinforcement consisting of Ø22 mm bars at 100 mm spacing due to the increased positive bending moment. The abutments are partially connected to the superstructure to achieve flexural rigidity at the supports [20]. As a result, the flexural load-bearing capacity increased by 44%.

Below are some of the photographs taken during the first phase of construction the bridge.

Figure 18. Phase 1 during construction period [21].

Figure 19. Existing girders in bright grey and UHFB cantilever slab in dark grey. Silver line represents an optical fiber for monitoring [21].

The intervention was validated through an innovative monitoring scheme involving strain, acceleration, and deflection data, with measurements collected during load tests. Two monitoring campaigns were conducted before and after the structural intervention to assess the changes resulting from strengthening with UHFB concrete. Each campaign included both static and dynamic excitations, which were combined for model updating [20]. The monitoring data show an increase in the first modal frequency and a reduction in deflections, indicating a significant increase in the structure's stiffness [20]. Deformations predicted by the numerical models before and after monitoring agreed well with those measured during the load tests [20]. The entire intervention, carried out in two phases, took 5 months and allowed alternating traffic flow to be maintained throughout the construction period. The unit price of 5 cm UHFB layer per deck area was €226 / m^2 [22] . The cost includes surface preparation, formwork, casting and curing of material. Figure 20 shows a beautiful view of the Ferpècle Bridge.

Figure 20. Completed bridge in 2023 [21].

6. CONCLUSIONS

This work draws attention to modern methods for the rehabilitation and strengthening of existing road bridges. In the coming period, the challenge of repairing and strengthening existing concrete bridges will confront our generation. Traditional intervention methods using ordinary concrete have certain limitations compared to the increasingly common use of UHPFRC in Europe. One of the countries leading in this practice is Switzerland. After many years of experience with this material, official guidelines for the maintenance and construction of structures using UHPFRC have been published. Some of the repair and strengthening methods from the ASTRA 82022 [12] guidelines are presented in this paper. One of the significant interventions on many jointed reinforced and prestressed concrete bridges is the creation of a monolithic (jointless) structure without expansion joints or hinges. In this way, in addition to increasing the load-bearing capacity of the existing bridge due to force-transmitting joint closure we significantly enhance its long-term durability. One such practical example of strengthening is the Ferpècle Bridge in Switzerland. After the intervention that involved widening the bridge deck from 5.3 to 7.9 m, the flexural capacity of the composite cross-section increased by 44%. Analysis of the monitoring data confirmed an increase in the first modal frequency and a reduction in deflections, indicating a significant enhancement of the structure's stiffness. This case study demonstrates that UHPFRC can effectively enhance existing structures through modifications to their static system.

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