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Adding value to bridges by monitoring and UHPFRC technology

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ABSTRACT: Structures have more than one design life. Nowadays, modern structural engineers are advised to implement novel methods and technologies to provide a second service life for existing structures. Structural and fatigue safety of bridges shall be verified using data from in-situ long term structural monitoring to update traffic action effects. More realistic and precise data on structural behavior allow for extending significantly the service life of fatigue prone bridges. If strengthening interventions are necessary, their objective must be to effectively improve the bridge structure. A novel technology is presented to improve bridges using Ultra-High Performance Fibre Reinforced Cement-based composite materials (UHPFRC). This technology is applied in Switzerland for more than 10 years because it is cost-effective while it significantly extends the service life and reduces maintenance of the improved bridges.

1 INTRODUCTION

1.1 Editorial remarks

Current structural engineering often results in invasive intervention on existing bridges including even replacement of bridges. This unsatisfactory situation leading to heavy socio-economic burden, is not due to missing know-how in the domain of structural engineering. There are too many standards and codes, reluctance because of liability issues and a general thinking still driven by new construction. These factors explain why most structural engineers are over-conservative and lack of motivation and curiosity for innovation and progress in engineering of existing structures.

Obviously, this situation has to be challenged and changed radically as public expenditure for infrastructure (including civil structures like bridges) should be invested into improvement and extension of existing infrastructure creating real added value. This change needs to rely on scientific research. The purpose of research in engineering domains is not only to produce peer-reviewed papers but also to implement new knowledge into practice. Application is the best peer-review of research.

1.2 General Approach

With respect to civil structures like bridges, the basic idea behind our research and application activities is to (1) accurately determine in-situ structural behaviour in order to be able to perform more precise and realistic verification of structural and fatigue safety, and (2) the targeted use of advanced materials for the improvement of structural behaviour and resistance. The ultimate goal is to limit construction intervention to a strict minimum while providing a future long service life for structures. We call this approach examination engineering (short: Examineering). “Examineering” thus also means to leave the traditional “assessment and retrofit”.

1.3 Objective of this keynote lecture

The objective of this keynote lecture is to highlight two novel structural engineering approaches with the goal to significantly extend the service duration of existing bridges:

(1) A novel approach is suggested for structural and fatigue safety verification using directly data from in-situ long term structural monitoring to determine updated traffic action effects.

(2) If interventions are necessary, their objective must be to effectively improve the structure (not only to repair or retrofit it). A new technology is presented to improve concrete bridges using Ultra-High Performance Fibre Reinforced Cement-based composite materials (UHPFRC).

Concerned because structural engineering could and should make progress at higher speed than over the last decades, general aspects of maintenance and management of bridges are also presented explicitly and “between the lines” as “food for thoughts”.

2 DESIGN LIFE VERSUS SERVICE LIFE OR “HOW LONG CAN A STRUCTURE BE IN SERVICE ?”

Databases of bridge stocks show that actually the average age of bridges increases every year. It is easy to anticipate that in the future the average age of bridges will increase. Is this supposed to be a problem ? No, because the age of a bridge (calculated as duration (in years) since its year of construction until today) is not essential. Decisive is the condition of the bridge and its performance with respect to the requirements of use. Therefore, it is advisable to speak about an “equivalent age” of the bridge that results directly from the current bridge condition and performance (Fig. 1).

Figure 1. The railway bridge over the Rhine River between Koblenz (Switzerland) and Waldshut (Germany) is in service since 1859. Its performance in terms of fatigue and structural capacity is sufficient to fulfill the requirements of future rail traffic of higher demand (Brühwiler 2012). After the execution of low-cost maintenance interventions, the bridge now has a low “equivalent age”.

In Europe, most structural engineers implicitly consider a lifetime of a bridge of 70 to 100 years as “design life”, referring to codes of “Basis of design” where such numbers are given as indicative values. However, often it is not understood that these indicative year numbers (1) apply to bridges to be built, (2) mean that the new bridge shall serve for several generations, and (3) are not valid for existing bridges. A design life of 70 to 100 years is arbitrary. The misunderstanding is that many structural engineers implicitly think that the lifespan of a bridge is the same as the one of a human being. The same structural engineers thus often consider a bridge older than 50 years as being “old”. Consequently, it is implicitly assumed that an “old” bridge will soon be demolished, and “repair” or “retrofit” to survive the “remaining service life” (of maybe 20 years) is enough. Obviously, this is not rational and makes no sense !

For economic and technical reasons, it is neither justified nor possible to replace existing bridges simply because they reach what might be considered their “design life” (of 70 to 100 years). Instead, when dealing with existing bridges in terms of future service duration, it should be distinguished between the *short term* (from today up to 20 to 25 years), *medium term* (anticipated use from 25 to 50 years from now) and *long term* (anticipated use beyond 50 years). Since it is likely that in 50 years from trucks and trains will still be using the transportation infrastructure, examination of existing bridges and resulting interventions always should target the long term. The vision is thus always to provide a second service duration for an existing bridge irrespective of its year of construction.

In addition, many bridges are monuments and cultural heritage. Because of their cultural and aesthetic values, they simply cannot be just replaced. The Golden Gate Bridge, the Brooklyn Bridge or other monument bridges (like the one in Fig. 1) cannot be replaced simply because they are at the “end of their design life” ! Therefore, the ambitious task and challenge of modern structural engineering of existing bridges is to devise cost-effective ways to keep (in particular) these bridges in service forever while implementing the requirements of modern use.

The agreed future use of a bridge in terms of live loads and service duration shall depend on functional and economic considerations as well as on the owner’s strategy. When conducting an examination of an existing bridge, the maximum possible structural performance shall always be determined. The mere knowledge of the real performance of an existing bridge is very important for the owner, because the adaptability of the bridge regarding future requirements of use may be more easily established as a potential. Whether the owner decides to exploit this performance or not depends on his infrastructure management strategy.

3 IN-SITU LONG TERM STRUCTURAL MONITORING TO UPDATE TRAFFIC ACTION EFFECTS

3.1 Context

In many countries, bridges have been in service already for several generations. As part of the transportation infrastructure, bridges add value to the public economy. Therefore, there is high interest in economic performance while providing unrestricted use (e.g. without limitation of traffic loads) and responding to increasing traffic demands. Obviously, there is a need to extend the service life of bridges significantly beyond 70 to 100 years (which often is the arbitrarily presumed service duration of bridges). The contemporary approach to examine the structural performance of existing bridges, is based on an inherent methodology that essentially includes collecting detailed in-situ information, for example, by long term monitoring of structural behavior.

Regarding existing bridges, a greater source of uncertainty lies on the traffic loading, i.e., the action effects arriving in the structural elements. In recent years, increasingly sophisticated approaches have emerged for load effect estimation using traffic simulations incorporating Weigh-in-Motion (WIM) data which form the basis of load models in design and "assessment" codes. While vital for the design of new bridges, these codes are based on generic heavy vehicle data from a range of locations and therefore may not represent the site conditions at the existing bridge under investigation. In addition, codes include provisions for illegally overloaded vehicles that could be reduced substantially through adequate policing (on roads and on railways).

An important feature of existing bridge safety verification is that an existing structure can be monitored to determine the real 'action effects' experienced. The advent of cheap and high storage capacity hardware in recent years means that direct measurement of elemental action effects via structural monitoring is now a viable option. Monitoring can overcome limitations of accurately modelling in-service behaviour at an elemental level. For example, material properties may change over time and secondary elements may reduce the stress levels in the structural parts which can provide uncertainty in modelling, but these effects are inherent in the measured data.

This Section highlights the approach to verify and predict the future service duration as well as the structural safety of existing bridges, in particular the fatigue safety, using data from monitoring. The approach is illustrated by means of application cases in Switzerland. The objective is to show that extending the service life by following the proposed approach will allow continuous use of existing bridges rather than their costly replacement or invasive strengthening.

3.2 Basic approach using data from monitoring

3.2.1 Introduction

Examination (casually called "assessment") of an existing structure may be performed following the principles such as the ones defined in the Swiss Standards for existing structures enforced by the Swiss Society of Engineers and Architects (SIA) (Brühwiler et al. 2012, SIA 269 2011). In Switzerland, these standards provide the regulative basis the structural engineer can rely on, to deal professionally with existing bridges. These principles lead to a methodology inherent to existing structures which has already been successfully applied over the last 25 years. Yet, many structural engineers nowadays still apply the codes valid for the design of new structures to assess existing structures. This is fundamentally wrong and often leads to unnecessary and costly interventions. A change of paradigm is needed aiming the structural engineering community to clearly distinguish between codes for new structures and codes for existing structures.

The contemporary approach to existing bridges is based on updating, which means collecting and exploiting detailed in-situ information from the existing structure while reducing uncertainties in structural parameters. The controlling parameters are determined as precisely as needed following a stepwise procedure with increasing focus on details. The general examination comprises the whole structure with the objective to identify aspects that need to be examined in more detail. One or more detailed examinations follow with the focus on the identified aspects.

3.2.2 Structural safety verification format

The structural safety verifications are performed using updated values, called examination values, with the objective to verify for the existing structure that the relevant limit states are not exceeded. In general, deterministic verification will be conducted. The notion of degree of compliance n is introduced in the deterministic verification of the structural safety:

$$n = \frac{R_{d,updated}}{E_{d,updated}} \tag{1}$$

where $R_{d,updated}$ and $E_{d,updated}$ are the examination values of resistance and action effect, respectively. The degree of compliance is a numerical statement showing the extent to which an existing structure fulfils the structural safety requirements. This formulation not only gives the information whether the structural safety is fulfilled. It also indicates by how much the verification is fulfilled (or not). The latter is necessary to evaluate the plausibility of results and in view of the planning of interventions. In this context, monitoring of structural behavior has thereby the general objective to determine more accurately effective action effects in terms of measured strains (stresses), displacements or accelerations, arriving in structural bridge elements.

3.2.3 Determination of updated action effect

In a first step of verification on Level 1 (general examination), the examination value of action effect $E_{d,updated}$ is determined using updated load models (for permanent and live loads) which are applied to a structural model to obtain sectional forces, stresses and strains, i.e. action effects, through structural analysis (Fig. 2). This approach is analogous to the one generally applied for the design of new structures. While this simple approach can lead in many cases to suitable results (i.e. showing that structural safety is fulfilled), it only takes partly advantage of the fact that the existing structure exists and thereby information may be gained.

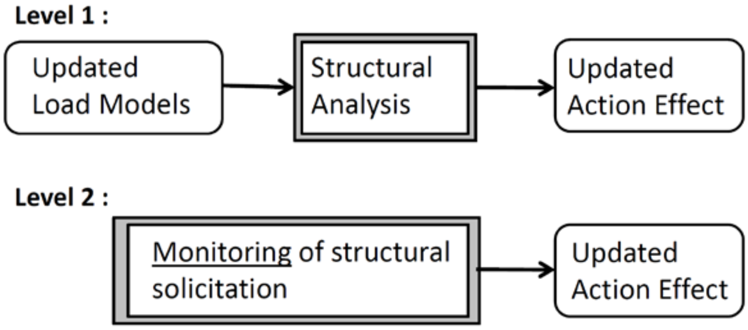


Figure 2. Determination of updated action effect.

If the safety verification is not conclusive on Level 1, further updating is performed on Level 2 as detailed examination, by performing monitoring of action effects due to live loads (Fig. 2). In this way, traffic action effects are directly measured by monitoring while reducing thus sources of uncertainty. However, it may not be possible to obtain monitored data directly in cross sections determinant for the structural safety verification. Also, action effect due to permanent load (self-weight of the bridge) is not recorded by monitoring. Structural analysis using refined numerical models is thus needed to “translate” monitored data to sections determinant for the structural safety verification (Fig. 3) and to determine the solicitation of the existing bridge due to permanent loads.

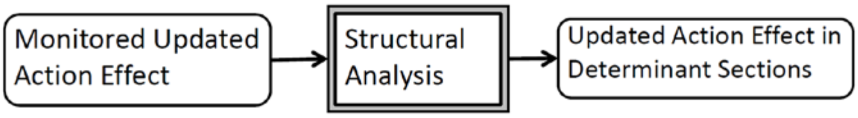


Figure 3. Translation of monitored data to sections determinant for structural safety.

Consequently, the use of structural models changes its significance when compared to structural analyses for the design of new structures. Also, monitored data are used to calibrate the structural model with the objective to obtain sectional forces as accurate as possible reducing thereby uncertainty usually implied in structural models. Such a calibrated structural model may then be used to determine, for example, fatigue action effects of future traffic scenarios. It is noteworthy that following the approach on Level 2, no more traffic load model is needed since solicitation of structural elements is directly recorded which obviously is the most reliable information to verify structural bridge safety.

3.2.4 Safety requirements

The structural safety requirements imposed on an existing structure need to be clearly defined as they may have a major influence on the extent of interventions. Monitoring of action effects on structural elements reduces uncertainties. Yet, some safety margin needs to be respected, either by considering a partial safety factor or, in the case of fatigue safety verification, by some criterion of target level of acceptable fatigue damage.

3.3 Examples of long term structural monitoring and application

3.3.1 Introduction

In the following, some examples of long term monitoring of bridges are briefly outlined. “Long term” means one year and longer. The practical examples all also had the character of research projects aiming at scientific benefit in the framework of doctoral theses. The goal of these research and development activities is to provide finally a rational and ready-to-use structural monitoring tool of reasonable cost that shall be used in the near future on a routinely basis by the structural engineers commissioned to perform an examination of an existing structure. (Structural monitoring shall become as self-evident for the structural engineer like f.ex. software of Finite Element models which nowadays are used on a routinely basis. Modern structural engineers shall be equipped with a “pocket-monitoring” kit.)

3.3.2 Railway Bridge over the Rhine at Eglisau

Long term monitoring over one year of structural elements of a riveted railway bridge structure of high value as cultural heritage and in service since 1897 (Fig. 4) has been conducted in 2012 (Brühwiler et al., 2013). Monitored values were exploited by Rainflow analysis and served as the basis for the fatigue safety verification. As the locations of measurements are not always identical with the cross sections of verification, measured strains were translated to the relevant verification cross section by means of detailed structural analyses.

Figure 4. Railway bridge across the River Rhine at Eglisau, Switzerland.

Using these values, all fatigue relevant structural details were first verified with respect to a fatigue endurance limit of riveted joints of 51 or 58MPa. Then, damage accumulation calculation according to the Palmgren-Miner Rule was performed for one elements for which the fatigue endurance limit check was not fulfilled. Sufficient fatigue safety could finally be verified for the entire riveted structure and additional service duration of more than 50 years for this riveted structure was validated. Actually, the examination showed that there is no notable fatigue damage in the riveted structure. Consequently, the riveted bridge structure also accommodates for higher future traffic loading.

Remark: Riveted steel bridges were built in the 19th Century and up to the 1950ies. In the past, riveted bridges were systematically replaced. Nowadays, they are still generally considered by structural engineers to be "old", "brittle" and vulnerable to fatigue which is often demonstrated "scientifically" by some code-based "recalculation" using over-conservative load models. The author currently is involved in riveted steel railway bridges in three countries in Europe (outside Switzerland). While in one country the bridge engineers of the responsible authority welcome the approach presented here, in the two other country, the positions are dogmatic and even the economic benefit of preservation and further use of the riveted bridge is denied. This shows how much a change in paradigm is needed.

3.3.3 Deck slab of a highway bridge at Morges

A novel approach was investigated for determining if a monitoring regime is sufficiently long to obtain a reliable extreme value estimate of the action effect. A case study of the highway bridge at Morges in Switzerland (Fig. 5) in service since 1964 was used, with one year of continuous high-frequency measurements (Treacy et al. 2013). The focus was on direct measurement of the traffic action effects in the bridge's deck slab reinforcement. One year of element-level continuous measurements was performed, providing a detailed insight into the structural behaviour of the monitored deck slab.

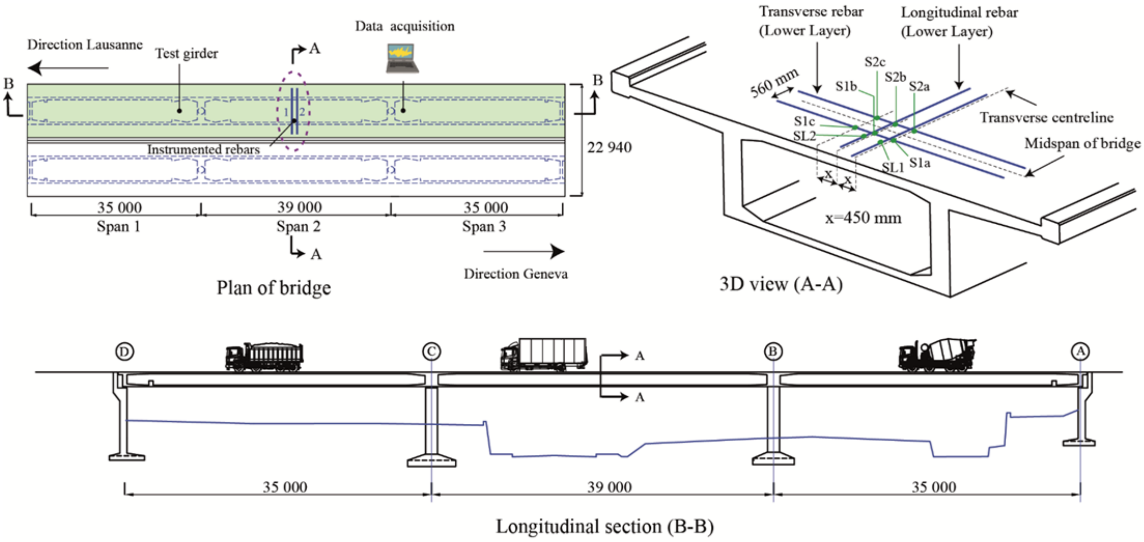


Figure 5. Top: Highway bridge at Morges; Bottom: Schematic of bridge geometry and monitoring system with strain measurement of rebars in the slab (dimensions in mm), taken from (Treacy et al. 2013).

It was found that direct measurement of strain in steel rebars has considerable potential as a means of determining the local behaviour of extreme traffic action effects in RC bridge deck slabs which are often the critical element of existing bridges. A comprehensive statistical procedure for the determination of site-specific, element-specific extreme traffic action effects for normal traffic conditions was proposed. The results showed that the predicted extreme values are strongly influenced by the record accumulation behaviour for daily maximum measured strains. Single extreme events significantly higher than the average daily maxima have a strong effect on extreme value predictions. Consequently, relatively long measurement periods (of at least 180 days) are needed to obtain stability of extreme predictions. The presented application on an existing highway bridge in Switzerland has also shown the rebar strain and hence stress predictions are far too low to provide any concerns in terms of structural and fatigue safety.

3.3.4 Construction joint of a posttensioned highway bridge in Berne

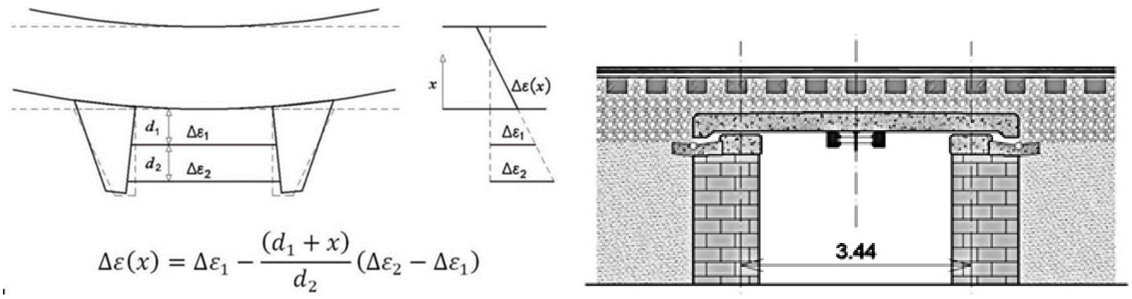
Fatigue issues in medium-span reinforced or posttensioned concrete road bridges are rare or limited to deck slabs, primarily because of the high ratio of the dead load to live load in such structures. Where fatigue problems have arisen, they have generally been due to poor detailing issues, sometimes combined with durability problems. One such example is the construction joints of certain post-tensioned concrete road bridges built in Europe during the 1960s and 1970s, which have been found to be fatigue vulnerable.

In the case of the construction joint details of a highway bridge in Berne, detailed modelling combined with traditional fatigue load models were found to be insufficient in explaining the real structural behaviour and to verify sufficient fatigue safety. Subsequently, a long-term monitoring campaign was performed over three years to accurately determine the real action effects in the reinforcement elements due to thermal and traffic effects (Treacy & Brühwiler, 2015). This information was subsequently injected into fatigue damage calculation models. The field monitoring provided precise information on the complex structural behaviour of the posttensioned construction joint detail. While a low number of fatigue damaging stresses were found in the rebars examined, there are very high reserves in terms of future fatigue life.

The monitoring campaign also revealed that seasonal temperature effects have a significant impact on the crack openings at construction joints and also on the size of the crack width changes. Consequently, the monitoring campaign should last at least 1 year to include all seasonal temperature effects. As a result, the need for expensive strengthening measures could be alleviated. By using the latest measurement techniques, accurate results could be achieved relatively easily and inexpensively in comparison with intervention costs on such structures.

3.3.5 Short span railway bridge at Chillon Castle

Monitoring data was obtained from measurements on a short span slab bridge in reinforced concrete using an original deformation measuring device (Fig. 6) (Grigoriou & Brühwiler 2016). The railway traffic action effect was represented by the distribution of its maxima per train passage. The tail of the distribution of train maxima followed excellently a shifted exponential distribution.



$$\Delta\varepsilon(x) = \Delta\varepsilon_1 - \frac{(d_1 + x)}{d_2}(\Delta\varepsilon_2 - \Delta\varepsilon_1)$$

Figure 6. Top: Measurement principle of deformation monitoring device; Bottom: longitudinal section of the slab bridge with the installed device, taken from (Grigoriou & Brühwiler 2016).

The examination value was calculated (without resorting to load models and structural analysis) by extreme value theory. In addition, the duration of the monitoring period, in terms of the number of recorded freight train incidents, was taken into account in the determination of the examination value of the action effect by means of a confidence upper bound.

It was found that for the presented monitoring campaign of six months the uncertainty from the limited duration of monitoring leads to an increase of the examination value by 18%; this increase could possibly be reduced to 10% for a monitoring period of one year and to 6% for a period of two years. A monitoring based safety verification procedure was developed and failure probabilities per freight train incident (and not per unit of time) were calculated. It was also found that measured maximal deformation (and thus stress) of the bridge due to railway traffic was several times smaller than predicted by conventional structural analysis using load models from codes.

3.4 Concluding remarks

The briefly described examples allow to state that more precise data is obtained from monitoring campaigns compared to traditional structural analysis using load models. The suggested approach to determine updated traffic action effects allows for explicit consideration of data from long term monitoring. Monitored data allow for accurate determination of fatigue relevant stresses in fatigue prone structural elements. Hence, uncertainties in the determination of updated action effects are reduced. Assessment of existing bridges based on so-called "re-calculations" are found to be unrealistic, leading to over-conservative results and should therefore be abandoned (Brühwiler 2018).

The present approach is economic as the cost for the long term monitoring and accompanying studies is only a small fraction of the cost of hypothetical major bridge strengthening or replacement. The present approach also allows for a respectful treatment of existing bridges in terms of resources (material, energy) as well as of cultural and aesthetic values.

4 IMPROVING EXISTING BRIDGES USING UHPFRC

4.1 Introduction

Reinforced concrete (RC) structures generally show satisfactory performance in terms of structural behaviour and durability, except for the zones that are exposed to severe environmental influences and high mechanical loading such as RC slabs of bridges, parkings or industrial buildings. Rehabilitation of deteriorated RC structures is a heavy burden from the socio-economic viewpoint since it leads also to significant user costs. Therefore, novel concepts and technologies for the rehabilitation and strengthening of RC structures need to be developed. If such interventions are necessary, their objective must be to effectively improve the structure (not just to "repair" or "retrofit" it). We should talk of "improvement" of structures by (strengthening or rehabilitation) intervention.

In the following, a new technology is presented to improve RC structures such as bridges using Ultra-High Performance Fibre Reinforced Cementitious composite materials (UHPFRC). This technology is applied because it is cost-effective while it can be expected that the service life is significantly extended and maintenance of the improved bridges is reduced (Brühwiler & Denarié 2013, Brühwiler 2019).

4.2 Basic concept of the UHPFRC strengthening technology

UHPFRC have excellent mechanical properties in terms of strength and durability. This led to the basic conceptual idea (developed in 1999) to use UHPFRC only in the zones of the RC structure where the outstanding UHPFRC properties are fully exploited. UHPFRC is used to strengthen the structure where it is exposed to severe environmental conditions (e.g. de-icing salts, marine environment, chemical attack) and high mechanical loading (e.g. concentrated forces, wear, fatigue, impact). Parts of the structure that are subjected to relatively moderate exposure remain in conventional structural concrete. This concept is applicable both to rehabilitate and strengthen existing structures and to build new structures.

Slabs and beams are strengthened by adding a layer of UHPFRC to the top of the slab, thus creating a monolithic composite section (Fig. 9).

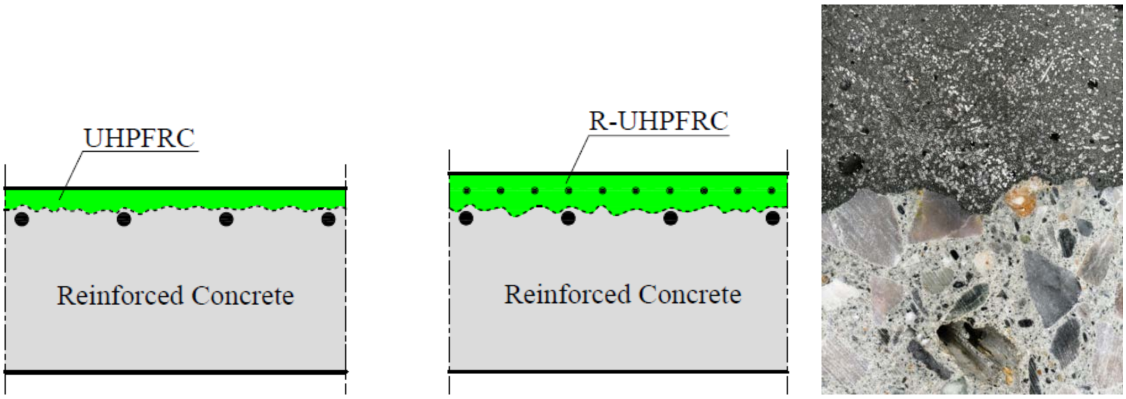
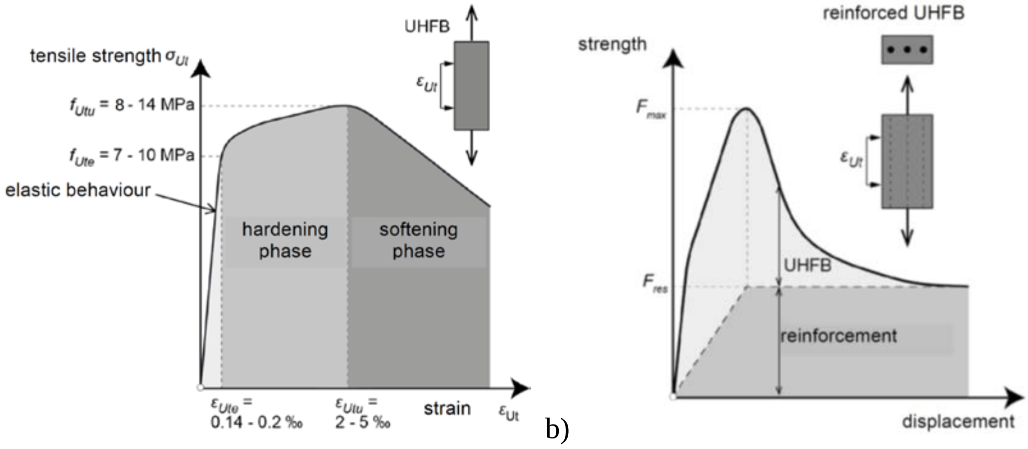


Figure 9. Basic configuration of composite structural elements combining R-UHPFRC and conventional RC: Top, left: UHPFRC layer (thickness 25 to 40mm) has a protective function only; Top, right: R-UHPFRC layer (thickness of 40 to 80mm or more) has both structural resistance and protective functions; Bottom: UHPFRC – concrete core showing the perfect bond between the two materials. UHPFRC obviously is not a concrete !

The combination of the UHPFRC protective and mechanical properties with the steel reinforcing bars (reinforced UHPFRC or R-UHPFRC) (Fig. 9) provides a simple and efficient way of increasing the stiffness and structural resistance capacity while keeping compact cross sections: (1) The relatively thin UHPFRC layer on the existing RC elements forms a monolithic composite element. UHPFRC acts as an external reinforcement, increasing thus the bending and shear resistance. (2) An additional benefit is that UHPFRC has extremely low permeability and thus serves as waterproofing layer protecting the slab from environ-mental influences.

Depending on the structural and material properties of the composite system, more or less pronounced built-in tensile stresses in the range of 3 to 6 MPa (or about 30 to 60% of the elastic limit stress) are induced in the UHPFRC layer due to restrained deformations at early age. These built-in stresses are resisted (without crack formation) thanks to the relatively high tensile strength and the strain hardening behaviour of UHPFRC (Fig. 10a). Consequently, the tensile behaviour of UHPFRC is of first importance to realize composite structural elements without crack formation. Sufficiently pronounced strain hardening behaviour of UHPFRC is only obtained for steel fibre contents of more than 3% in volume and using short steel fibres (which show a relatively high modulus of elasticity) with a slenderness higher than 65.



a) b)

Figure 10. a) Tensile behaviour of UHPFRC in three phases: 1 elastic up to the elastic limit stress, 2 strain hardening characterized by fibre activation, up to the strain corresponding to the tensile strength, 3 post-peak domain showing pronounced strain softening. b) Tensile behaviour of R-UHPFRC (UHPFRC with incorporated steel reinforcing bar): superposition of the steel rebar and the UHPFRC tensile behaviour.

The main reasons to complement UHPFRC by steel reinforcing bars (to be placed in the main stress direction only) are a significant improvement of the tensile behaviour of plain UHPFRC and a reduction of unfavourable effects of anisotropic fibre orientation (Fig. 10b). Small diameter steel reinforcing bars (arranged with relatively small spacing) provide in-plane continuity to the UHPFRC layer and ensure its monolithic action with the RC element in flexural members. The rebars increase not only the resistance but also improve the deformation capacity and strain hardening behaviour of UHPFRC. Thus, the reinforcing bars enhance the apparent UHPFRC tensile behaviour.

4.3 Some applications using UHPFRC

In the following, four applications, all realized in Switzerland, out of more than 50 applications performed over the last 11 years, are briefly described to show the versatility of UHPFRC technology to improve RC bridges to provide a second service life. In all application cases, strain hardening UHPFRC was cast. To ensure perfect bond between UHPFRC layer and concrete substrate, the surface of the concrete substrate was always roughened by high pressure water jetting and water saturated before UHPFRC casting.

4.3.1 Strengthening of Montbovon Bridge

In autumn 2013, the 100-year-old RC girder bridge with a total length of 50m was rehabilitated and strengthened for modern traffic needs (including higher loads exceptionally heavy transportation) in view of a second long service duration (Fig. 11) (Métry & Brühwiler 2015). The strengthening concept consisted in increasing the structural resistance of the Π–girder by the combination of external post-tensioning (providing compressive stress in the cross section) and a R-UHPFRC layer of varying thickness from 30 to 60 mm on top of the slab. This strengthening concept turned out to be very effective leading to a significant increase in structural resistance. The bridge while respecting structural safety requirements will carry any future traffic loads. The UHPFRC layer also serves as waterproofing of the slab.

The construction works could be optimized such that full closure for traffic of the bridge was limited to five days. The improved bridge structure now possesses the same performance like a new bridge. However, the intervention costs were only about half of the estimated cost for a replacement bridge.

Figure 11. Montbovon Bridge after strengthening and rehabilitation, and UHPFRC casting.

4.3.2 Strengthening and rehabilitation of a highway overpass in Berne

The static system of this bridge used for combined road and tramway traffic was modified from a system of massive post-tensioned hollow core slabs including a single span Gerber beam to a monolithic frame structure (Feller & Hartenbach 2015). Using R-UHPFRC to strengthen locally the top and bottom flanges, the two Gerber joints were blocked and bending capacity of the hollow core slabs was increased. In addition, the R-UHPFRC also serves as waterproofing layer. The strengthening and rehabilitation works were performed in 2014. Filling of the Gerber joints was realized with flowable UHPFRC mix while the UHPFRC layer on the slab was cast with the mix allowing for slope stability of 3 %. Subsequently, rolled asphalt was placed on the UHPFRC layer.

4.3.3 Guillermaux Road Bridge

The Guillermaux Bridge built in 1921 crosses the Broye River in the small town of Payerne in Switzerland (Fig. 12). This bridge is classified by the cultural heritage authorities for its aesthetic qualities including elements of decoration and parapets with sculptural figurines as well as for the expression of the audacious flat arch. Also, it is one of the first concrete bridges in Switzerland. The bridge carries a 6.5m wide bi-directional roadway and sidewalks. The structure is in early reinforced concrete. Initially the massive arch had three hinges: at the arch crown and the two abutments. The arch span is 27.60m for a rise of 2.80m (rise to span ratio of 1:10) leading to a remarkably flat arch of 0.65m thickness and 8.2m width.

Examination and reason of intervention: As the slab surface of the bridge never was equipped with waterproofing, the concrete of the bridge structure showed signs of water infiltration and leachates that have been reported already several decades ago. Rebar corrosion was relatively limited except for the intrados of the arch showing significant corrosion. This condition was as the result of lacking maintenance. Elements like the parapets were in relatively good condition. The restoration of the bridge was motivated by (1) the partially defective condition of the reinforced concrete and (2) the requalification of the road crossing the bridge. The requirement of utilization after restoration was an unrestricted modern road traffic including specially authorized exceptional heavy vehicles.

Remark: Town officials never raised the issue of replacing this almost 100 years old bridge “in bad shape” (that would have been “assessed” by most structural engineers as a structure “at the end of its design life”, thus dedicated for replacement). They highlighted the cultural and aesthetic values of this bridge as a witness of the past and in the urban context of their town. They wanted to keep this bridge as the main element of an entire road that was to be modernized and requalified.

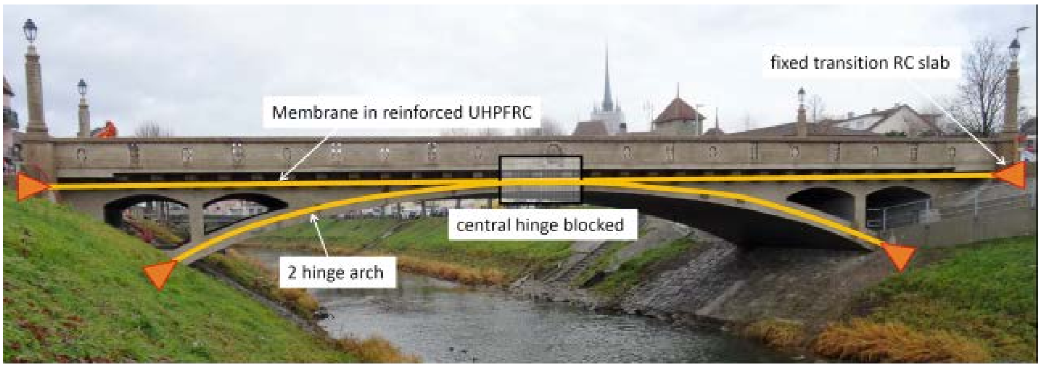


Figure 12. Guillermaux Road Bridge: Intervention concept with change in static system leading to significant increase in structural resistance.

Intervention concept and construction works: In order to improve the bridge structure in view of the next service duration, new technology using UHPFRC was applied as follows (Fig. 12). (1) A 50mm thick layer of UHPFRC reinforced with steel rebars aligned in the longitudinal main stress carrying direction was cast over the entire length of the bridge's top surface providing a tensile chord. (2) This R-UHPFRC tensile chord was fixed at both extremities in the new transition slabs that were anchored in the ground. (3) The hinge at the arch crown was locked using R-UHPFRC such as to allow for bending resistance. (4) In addition to its structural function, the UHPFRC layer on the deck provides a waterproof top surface to improve and guarantee durability of the bridge by preventing water ingress.

The change in static system allowed for a significant increase of the stiffness of the bridge structure and consequently a reduction of sectional forces (moments) in the main arch and the deck slab. The increase in structural resistance was thus significant (almost 60%). Consequently, the verifications of the structural safety of the bridge structure showed that all traffic load requirements are largely fulfilled.

The construction works were conducted during 2015 and presented no particular difficulties (Fig. 13). The UHPFRC strengthening intervention on the structure is not visible, and the decorative elements of the parapets were restored according to the rules applied to monuments. Consequently, requirements regarding preserving cultural values were met. Also, intervention costs were significantly lower than the costs for a (hypothetical) bridge replacement.

Figure 13. Casting of the UHPFRC on the deck slab; the UHPFRC layer incorporates steel rebars. Restored decorative elements of the parapets.

4.3.4 Chillon Highway Viaducts

The Chillon Viaducts are two parallel highway structures opened to traffic in 1969 and located on the shores of Lake Geneva near Montreux in Switzerland (Fig. 14). The structure with a total length of 2’120m consists of a variable height box girder built by posttensioned segmental construction with epoxy-glued joints and spans between 92 m and 104 m. The construction method including precast elements was innovative at that time, also because of the variable geometry of the structure both in plan view and elevation as the viaducts follow a curved hill.

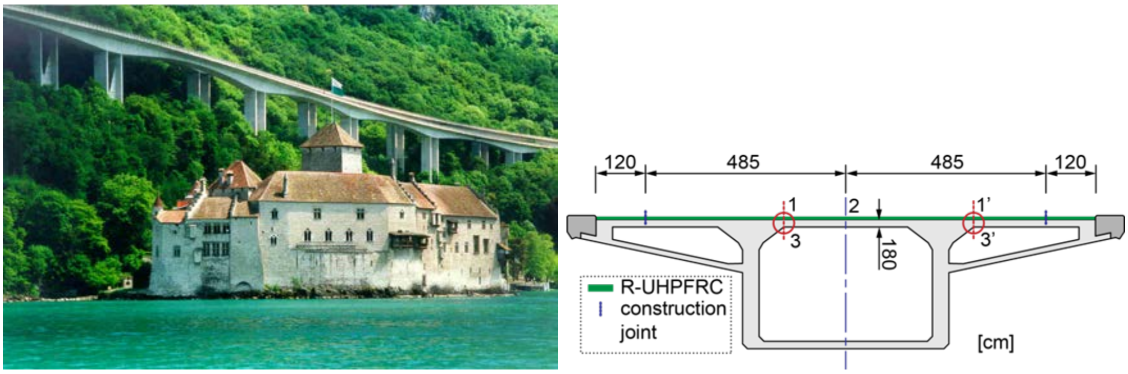


Figure 14. Chillon Highway Viaducts and Chillon Castle at the shores of Lake Geneva. Concept of strengthening using R-UHPFRC.

The Chillon viaducts have a high cultural value and are considered today as an outstanding art structure from the main era of highway construction in Switzerland. The viaducts have an economic importance for the region as they are the main road link between the shores of Lake Geneva and the mountainous Canton of Wallis, carrying approximately 50’000 vehicles per day.

Examination and reason for intervention: In 2012, during rehabilitation works on the viaducts, early signs of the alkali-aggregate reaction (AAR) were discovered in the concrete. It was anticipated that in later stages, this reaction could lead to the deterioration of the concrete material properties. This would mean an insufficient structural safety at Ultimate Limit State as well as unacceptable performance under service loading. It was thus necessary to develop a concept for rehabilitation and strengthening, an intervention that had to be cost-effective in terms of direct construction costs and user costs (Brühwiler et al. 2015).

Intervention concept and construction works: The application of a layer of R-UHPFRC was quickly found to be the most effective technique to respond to the requirements. With its outstanding properties, a layer of strain-hardening UHPFRC combines waterproofing and reinforcement of the slab. The objective of the intervention was thus to reduce the rate of the reaction and anticipate the loss in strength of the concrete.

By casting one layer of R-UHPFRC on the deck slab of the viaducts the following beneficial effects were achieved (Fig. 14): (1) Increase in the deck slab’s ultimate resistance in the transverse direction in bending and shear, (2) increase in the deck slab’s stiffness to enhance the serviceability of the slab and the fatigue safety of the existing RC elements in view of future higher traffic demands in number of vehicles and axle loads, (3) increase in the hogging bending moment resistance and the stiffness in the longitudinal direction of the box girder, (4) provide waterproofing to protect the existing concrete of the slab from water ingress and thus limit further development of the AAR, (5) limit duration and cost of the intervention by realizing all above listed requirements and structural functions by the casting of just one layer of R-UHPFRC.

The two viaducts were strengthened using R-UHPFRC respectively during the summers of 2014 and 2015. The UHPFRC layer was cast over one 2’120 m long viaduct in less than 30 working days. This very fast execution was made possible by the use of a casting machine specially developed by the contractor for the placement of fresh UHPFRC (Fig. 15).

Figure 15. Casting of the UHPFRC using a machine.

The cost of intervention was an order of magnitude smaller than the estimated cost of conventional methods (using reinforced concrete) which turned out to be invasive as these methods would have called for a significant increase in dead weight triggering major strengthening of the bridge girder, piers and foundation. Facing this fact sheet, the owner actually decided without hesitation to apply on this major structure a new technology (that nonetheless made already its proof on many smaller bridges over the last 10 years). Professional collaboration between the owner and his mandated consulting engineers, experts and contractor was a key element for the successful UHPFRC application which can be considered being unique worldwide.

4.4 Conclusive remarks

The UHPFRC technology combines effectively the protection and resistance properties of UHPFRC. It thus really improves the structure by significantly increased structural resistance and durability. The selection of briefly described applications demonstrates the effectiveness of the UHPFRC strengthening technology in terms of technical solution, duration of works as well as intervention costs and economy. The UHPFRC technology is used to strengthen the bridge structure and to accommodate for future traffic loading and extend significantly its service duration. Also early concrete bridges are enhanced economically to become sufficiently performant for future use. Obviously, this original concept should also be applied for the construction of durable new reinforced concrete structures.

5 CONCLUSIONS

Structures like bridges have more than one “design life”. There are no “old” bridges; there are only bridges that provide adequate performance (or not). Novel structural engineering methods and technologies are nowadays available to provide a next service duration for existing bridges.

Structural and fatigue safety of bridges shall be verified using data from in-situ long term structural monitoring to update traffic action effects. More realistic and precise data on structural behaviour allow for extending significantly the service life of fatigue prone structures.

If strengthening interventions are necessary, their objective must be to effectively improve the structure. The UHPFRC technology allows to improve structures like bridges. This technology is applied in Switzerland for more than 10 years because it is cost-effective while it significantly extends the service duration.

Remarks: The “philosophy” proposed in this paper is in agreement with the principles of sustainable development in terms of cost effectiveness (economy), economical use of resources and compatible social impact of bridges as important part of transportation infrastructure. Enhancing existing bridges and extending their service duration also means giving value to bridges as well as appreciating the art of structural engineering and identity of structural engineers.

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