Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Making bridges sustainable

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ABSTRACT: Lack of incentives mainly explains why the implementation of novel methods and technologies in bridge engineering practice is generally postponed by the engineering community despite the urgent need to advance also bridge engineering to meet the objectives of sustainability. Novel engineering methods and technologies are presented in this paper to extend the service duration of existing bridges while meeting the requirements of modern use. Accurate determination of bridge behavior using data from in-situ measurements and long-term monitoring of traffic action effects allow to verify realistically the structural and fatigue safety of bridges. If interventions are necessary, a targeted use of advanced high-performance materials such as UHPFRC allows to rehabilitate and strengthen effectively reinforced concrete bridges. This approach follows the principle of sustainability to preserve material resources and their grey energy that are already in use, thereby limiting greenhouse gas emissions to a minimum when requalifying and adapting existing bridges to future use.

1 INTRODUCTION

1.1 *Sustainability and existing bridges*

Civil engineers will be called upon to find solutions to mitigate the unpredictable effects of the climate change on people. Currently, civil engineers are still primarily trained to build new structures without learning how to consider *concretely* the principles of sustainability of constructions. A turning point in the education of engineers and practicing engineers is urgently needed. To soften the effects of the climate change on people, greenhouse gas emissions must be radically reduced. It is obvious that rehabilitation, adaptation and modification of existing structures and bridges must be given first priority. We must value the existing and avoid the still commonly practiced “demolition-replacement” approach including high material consumption and high greenhouse gas emissions, and also loss of cultural values.

Civil Engineers are trained to build new structures. These “new builders” are only partially or not at all competent to engineer existing structures. That’s why, methods of new construction are applied to existing bridges under the title “re-calculation” and interventions are designed using code provisions for new structures. But an existing bridge exists ! A stress in a rebar can be measured directly. It does not have to be “re-calculated”, which, due to significant model uncertainties, leads to unrealistic though over-conservative results.

In addition, “new builders” describe a bridge that is f.ex. 60 years in use, as an “old” bridge that - like humans - has a “lifespan” of 80 to 100 years. But bridges are not living beings and have thus no “lifespan” and no “remaining life”. Bridges are useful objects, bind enormous amounts of resources and heavily burden the environment. In outstanding cases, bridges are also built culture. For economic reasons alone and out of respect for the environment, bridges should in principle be preserved for as long as people use trains and road vehicles. Bridges (and other structures) are not consumer goods to be thrown away and, at best, recycled. The profession has yet to be “converted” to the engineering of existing structures!

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1.2 *Engineering of existing structures*

"Engineering of existing structures" requires an own approach as it implies to precisely determine the capacity and structural resistance of an existing structure with respect to its intended use and exposure. This process is called "updating". The basic methodology is to collect systematically and specifically detailed information on the existing structure, by non-destructive testing methods and measurements (monitoring). In this way, the determinant variables related to the loading action effects and the resistance of structural elements are determined as realistically as possible. This procedure is not new and in principle already permitted by standards. However, it is rarely used because practicing engineers are not trained or competent to do so.

"Engineering of existing structures" has the goal to show that existing structures can be subjected to higher loads by exploring and exploiting often available load-bearing reserves while meeting the safety requirements. Only when all possibilities for updating the bridge have been exhausted and the requirements for structural safety and usability can still not be met, interventions to strengthen structural elements are necessary. The extent of the intervention and the consumption of resources should thereby be as limited as possible. New technologies and high-performance building materials are often effective means to achieve this goal.

"Engineering of existing structures" also implies "Baukultur" (building culture) and knowledge of the history of structural engineering. But most engineers have yet to develop their sensitivity for questions of cultural values of structures and the preservation of monuments of various degrees of importance. Accordingly, the subject of building culture should be part of the basic competences of structural engineers.

"Engineering of existing structures" is needed to avoid cost-intensive or even unnecessary interventions, which are often the result of incomplete know-how of structural engineers and lack of sufficient information about the existing structure.

1.3 *Standards for engineering of existing structures*

When dealing with existing structures, the "new builders" among structural engineers apply standards valid for the design of new structures. This is a problematic approach as standards for new structures are obviously not applicable to existing structures. Only some provisions may be analogously applied to existing structures.

Over the last 30 years, a methodology inherent to existing structures has evolved, presented at numerous scientific and professional conferences, and successfully applied in many existing bridge cases. However, it has not yet been fully adopted in practice by the majority of structural engineers. This is explained by the fact that there are no standards available which practicing engineers can rely on.

For this reason, the Swiss Society of Engineers and Architects (SIA) elaborated a series of standards exclusively devoted to the engineering of existing structures, published in January 2011 as SIA269 Standards (Brühwiler et al. 2012). This pioneering initiative may still be considered as unique worldwide. Switzerland is a country with well-developed built infrastructure, and the enforcing of these standards led to a marked improvement of engineering projects related to existing structures, implying significant socio-economic benefits and reducing the environmental impact of structures.

In Europe, CEN-TC 250-SC 10 is elaborating a standard, entitled "Basis of structural and geotechnical assessment of existing structures" (CEN-TC 250-SC10, 2022), which relies on contents of the Swiss SIA269 Standard. This initiative can be interpreted as a "memorandum of understanding" that standards for existing structures are needed. However, this European standard is currently limited to basic principles and still requires time and discussions to achieve agreement among all member countries.

Worldwide, in many countries there seem to be no concerns about existing bridges being exposed f.ex. to higher traffic loading or deteriorating bridge condition. Commonly, in these countries, engineering of existing structures is limited to condition assessment, and invasive methods often implement "demolition-replacement" projects, implying high construction costs and high environmental impacts. As a consequence, the need to introduce standards for the engineering of existing structures is not prevailing in these countries.

Overall, the situation related to the engineering of existing structures is unsatisfactory and still rather unprofessional, which is also the result of the traditional conservatism of structural engineers that, as "new builders", underestimate the significance of engineering of existing structures.

1.4 *Outline*

After this review of the current situation of the engineering of existing structures based on the authors rich practical experience in Switzerland and worldwide, this paper contains two main parts:

- Chapter 2 presents recent research findings by the author and his research team in the domain of *monitoring-based verification* of existing structures. Rational ready-to-use engineering methods are deduced to investigate as precisely as possible *action effects* (f.ex. due to traffic loading) on bridge structures, while current structural engineering is more at ease in the determination of ultimate resistance of structural elements.
- Chapter 3 is a brief overview of the current state-of-knowledge of the *UHPFRC Technology* to rehabilitate and strengthen existing bridges, as mostly developed and implemented in practice by the author and his research team.

Both domains follow the goal to radically *preserve existing bridges* and to follow the principle of sustainability of continued use of material resources and their grey energy, thereby limiting greenhouse gas emissions to a minimum when adapting bridges to future use.

2 MEASUREMENT AND MONITORING BASED VERIFICATION OF FATIGUE AND STRUCTURAL SAFETY

2.1 *Methodology*

2.1.1 *Basic approach*

The modern approach to existing structures is based on "updating", which means collecting and exploiting detailed in-situ information from the existing structure while reducing uncertainties in structural parameters (Brühwiler et al. 2012). The controlling parameters are determined as precisely as needed following a stepwise procedure with increasing focus on details.

The structural safety verification is finally performed using updated values, called examination (or assessment) values. 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 for the evaluation of results and in view of the planning of interventions.

2.1.2 *Non-destructive evaluation*

In a first step, examination (often called: assessment) of existing structures is typically conducted using construction drawings (if available), information on materials and visual inspection. While a broad range of sensing and monitoring technologies have been developed over the last decades, *non-destructive evaluation (NDE)* is still rarely used for the condition survey and safety verification of existing bridges. NDE techniques include both *non-destructive testing (NDT)* and *structural performance (or: "health") monitoring (SPM)* (Bertola et al. 2022) (Figure 1):

– In NDT, instruments and sensors are deployed temporarily to measure the response due to a known stimulus, to determine structural (e.g., location of reinforcing bars, element thickness, etc.) and material properties (e.g., modulus of elasticity and strength) as well as characteristics of structural behavior (e.g., rigidity, deformation, deflections). Techniques include ground penetrating radar (GPR), ultrasonic testing (UST), acoustic emission (AE), rebound hammer testing or load testing.

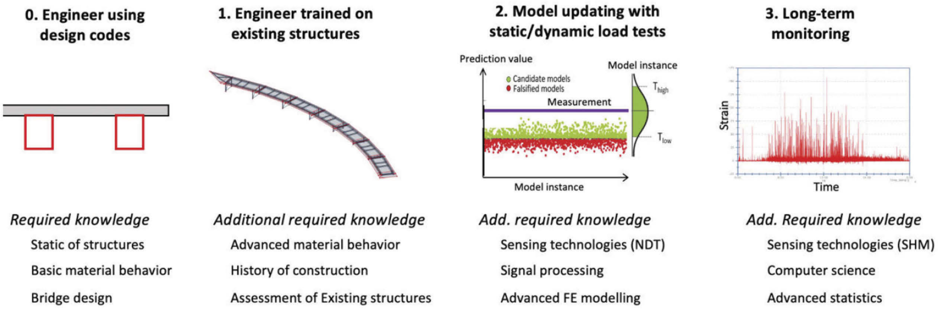

Figure 1. Stepwise procedure with increasing refinement, from Step 0 to 3, for the examination of existing structures with the associated training required, taken from (Bertola et al. 2022).

– In SPM, sensors are mounted in targeted locations of the bridge structure to collect strain and temperature data over rather long time using periodically sampled response measurements. SPM data are useful to describe condition changes and monitor degradation processes. Stress histograms due to traffic loading, temperature induced stress and changes of material and geometric properties are monitored. This data is then analyzed to support the fatigue and structural safety verifications of existing bridges.

Most sensor data such as deformations, strains and accelerations are indirect measures of material and structural properties and behavior. Therefore, data interpretation is indispensable, and in-situ measurements often must be complemented by advanced structural analysis. Calibrated finite-element (FE) models are needed to provide accurate data on structural behavior and capacity.

Although NDE information may lead to more sustainable and cost-effective management of existing infrastructure, it requires additional training for structural engineers that are usually not included in current curricula (Figure 1).

2.1.3 *Practicability of NDE, in-situ measurements and monitoring*

The verification of structural safety must thus be based on in-situ measurements of actual structural behavior, rather than theoretical design-based engineering values. Several ways to measure, monitor, and analyze structural behavior are possible and should be carefully selected based on the objectives of monitoring, case study, sensor availability and training of engineers.

The advent of cheap and high storage capacity hardware in recent years means that direct measurement of action effects in structural elements via structural monitoring is now a viable option. On purpose tailored compact monitoring equipment is a rational and ready-to-use tool of reasonable cost that can be used on a routinely basis by bridge engineers commissioned to perform an examination of an existing bridge. In this way, structural monitoring becomes as self-evident for engineers as f.ex. the routinely use of software tools implementing Finite Element models.

Obviously, current practitioners' perception of monitoring as being complex, costly and not always providing useful results needs to be challenged and altered. Researchers have a responsibility to support practice.

2.2 *Risk-based bridge inspection*

The visual inspection of existing bridges is a critical step in bridge safety verification, as the detection and quantification of damage must be accurate, reliable and useful to conduct realistic examination of existing bridges. Often, a condition value ranging from 1 to 5 is given to each bridge. As only element-based degradations are currently considered in bridge-condition evaluations, inaccurate assessments of global structural safety are also provided by bridge inspectors.

A risk-based methodology provides a more objective and reliable examination of the bridge condition based on visual-inspection data. Degradation states of bridge elements are coupled with element-failure consequences on the global structural safety in risk analysis. Risk-based methodologies have been proposed in the past and are even in use. However, it is crucial to validate them in the field in order to have them accepted by practice.

A recent case study of a strategic road involving sixty bridges was conducted to assess bridge conditions applying a novel risk-based methodology based on visual inspections (Bertola & Brühwiler 2023). The study revealed that including element-failure consequences in bridge-condition assessments supports more accurate evaluations of the impacts of damage on the global structural safety, leading to more objective decisions on management actions and interventions. Analyses of four damaged bridges showed that traditional inspection methods often lead to over-pessimistic assessments in terms of structural damage, and this can lead to unnecessary or excessive rehabilitation interventions.

2.3 *Updating traffic action effects by structural monitoring*

In recent years, monitoring has offered a significant complement or even alternative to traditional analytical safety verification approaches. However, there still remains a lack of guidance for the use of monitored data in structural safety verification. Often, relatively short time frames of monitoring are used. Additionally, temperature effects often have a significant influence on the structural response which requires adequate consideration.

2.3.1 *Duration of monitoring*

The duration of monitoring has an important influence on predicted characteristic action effects and is thus of first importance regarding reliability of data. In order to determine if a monitoring campaign is sufficiently long to obtain a reliable extreme value estimate of the action effect, a case study of a highway bridge in Switzerland, with one year of continuous high-frequency measurements, was analyzed by means of several approaches (Treacy et al. 2014). The focus was on direct measurement of the traffic action effects in the bridge's deck slab steel reinforcement bars. A comprehensive statistical approach for determination of site- and element-specific extreme traffic action effects was conducted.

The study showed that the time required to capture stable record behavior in the deck slab rebars is highly dependent on element location and orientation, as well as the local traffic composition. The behavior of the predicted extreme values was strongly influenced by the record accumulation behavior for daily maximum measured strains. Single extreme events significantly higher than the average daily maxima had a strong effect on the extreme value predictions.

2.3.2 *Fatigue and temperature effects*

The results of 28-month-long monitoring of a slab portion of a highway viaduct using strain gauges and thermocouples were investigated (Sawicki & Brühwiler 2020). The post-tensioned reinforced concrete structure was strengthened with a layer of UHPFRC (see Chapter 3). Strain gauges were used to measure stress values in the bottom layer of reinforcement bars in the slab, while thermocouples recorded the global behavior of the structure due to ambient temperature variation (Figure 2).

The study revealed that the stress variation due to the thermal action can be as large as the response due to traffic action, even in a massive structure. Monitoring data was analyzed for fatigue and structural safety verification and compared with traditional re-calculation on Level 1, showing that assessment by re-calculation is highly conservative, leading to significant overestimation of structural action effects.

The fatigue safety of existing bridges may be assessed using data from monitoring. This data is then used to assess fatigue due to the past traffic and to extrapolate to the future service duration using traffic scenarios as given by the bridge owner. Due to the randomness of

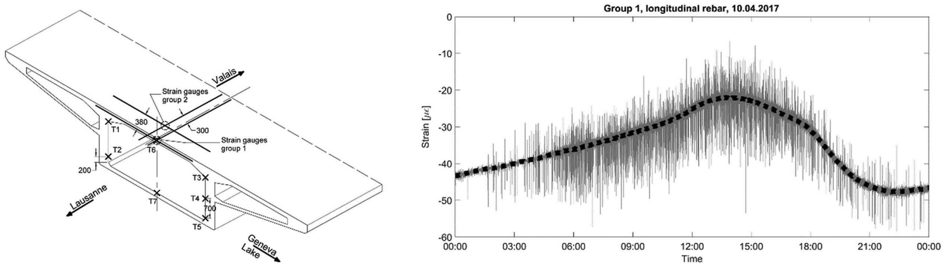

Figure 2. Left: Scheme of monitoring with strain gauges on rebars and thermocouples (T1–T7) (dimensions in mm); right: Strain recorded during 1 day on group 1 longitudinal rebar; filtered-out "thermal wave" is shown with dotted line, taken from (Sawicki & Brühwiler 2020).

traffic loading, there exists a likelihood of over- and under-estimation of potential fatigue damage in the case of short-term monitoring campaigns. As a consequence, the influence of monitoring duration on the obtained results must be known.

To investigate this research question, datasets collected during long-term (>3 years) monitoring campaigns of two bridges were analyzed (Sawicki & Brühwiler 2022). The two road bridges had different nature of traffic: a two-lane highway viaduct with heavy traffic, and a bridge with a bi-directional regional traffic. The deck slabs of both bridges were monitored using strain gauges installed on reinforcement bars. The daily, seasonal and year-to-year measured traffic action effects were analyzed, and a theoretical equivalent fatigue damage was calculated.

The resampling method was used for the simulation of possible short-term monitoring campaigns during the period considered, with different order of heavy vehicles arriving. The Extreme Value Theory served to answer what is the required monitoring duration for reliable results. Methods to consider the monitoring duration in fatigue damage calculations were proposed and validated.

In order to verify the efficiency of the UHPFRC strengthening (see Chapter 3) and to further evaluate its long-term performance, a structural monitoring campaign was implemented, relying on low-cost, yet easily deployable, sensors, including a suite of accelerometers, strain gauges, temperature and humidity sensors (Martin-Sanz et al. 2020). The monitoring data was first processed by means of standard modal analysis methods as well as non-stationary time-series analysis tools. In a second step, a Finite Element model of the system was built and updated, and subsequently exploited to deliver a comparison between the original and strengthened structure using reliability analysis, confirming the efficiency of the UHPFRC strengthening.

2.3.3 *NDT of bridge deck condition*

RC bridge deck condition was monitored during one year by means of AE (acoustic emission) permanent measurements (Bayane & Brühwiler 2020). The study has shown that the structural response and characteristics of the slab under operational and environmental loading can be investigated within reasonable postprocessing work and statistical analyses. AE measurements allowed to identify the nature of cracking activity in the concrete slab as a function of traffic loading and ambient temperature variation. The method was validated on combining the AE and strain gauge measurements, performed on a bridge deck slab in service for 60 years, providing finally useful information for structural and fatigue safety evaluation.

2.3.4 *Monitoring-based examination value*

The examination value of the railway traffic action effect was calculated from long-term monitoring data without resorting to load models and structural analysis (Grigoriou & Brühwiler 2016). Monitoring data was obtained from measurements on a short span RC slab bridge. The action effect is represented by the distribution of its maxima per train passage. The end tail of the distribution was modelled by a shifted exponential distribution, and the examination value was calculated by extreme value theory, using additionally a confidence upper bound in order to consider the monitoring duration.

The monitoring-based safety verification procedure was developed through probabilistic modelling and reliability calculations, based on failure probabilities per freight train incident (and not per unit of time). The duration of the monitoring period, in terms of the number of recorded freight train incidents, was considered in the examination value of the action effect by means of a confidence upper bound.

On the other hand, the annual variation of temperature had a significant indirect effect on the traffic action effect and, unless monitoring was preformed over several years, the uncertainty related to this effect can only be considered by empirical factors.

The relatively simple semi-probabilistic method gave results close to the more complex FORM. For the six-month monitoring campaign, the uncertainty from the limited duration of monitoring resulted in an increase of the examination value by 18%. This increase could possibly be reduced to 10% for a one-year monitoring period and to 6% for two years.

2.3.5 *Dynamic action effects*

All previously described and other bridge measurement campaigns confirmed that there is no notable dynamic amplification of road and rail traffic effects on structural bridge elements like slabs or rail track system, if stress and strain are directly measured on relevant rebar and concrete as well as steel element locations. The plausibility of this significant finding can be explained by simple dynamic models (Ludescher & Brühwiler 2009).

Consequently, no dynamic amplification factor needs to be considered on Level 1 verifications by re-calculation using traffic load models, while on advanced level monitoring-based examinations eventual dynamic effects are implicitly included in the measurement results.

2.4 *Updating permanent actions*

In the case of massive bridge structures like the ones in reinforced concrete, often more than 60% of the total action effect on structural elements is due to permanent actions (consisting of the self-weight of the structure and equipment (f.ex. pavement)). In extreme cases, permanent actions represent 80% of the total examination value of action effect.

As a consequence, NDT is required to provide precise data of structural dimensions, in particular thickness of structural elements and pavement, and the volumetric load of materials, to update the characteristic value of permanent actions.

Updating by means of NDT reduces uncertainties which in turn provides the basis to update also the load factor for permanent action, in the framework of the basic deterministic safety verification. Application of the well-known semi-probabilistic method has shown to be an effective mean to update permanent actions effects, while adequately respecting safety requirements.

2.5 *Structural identification and value of information*

The monitoring of existing bridges has the potential to improve bridge management. Monitoring data help identify unknown model-parameter values. Then, this information is used to accurately evaluate bridge condition and behavior, such as to predict reserve capacity and fatigue resistance, avoiding invasive interventions or replacement. This model-updating method is called structural identification.

The benefits of structural identification depend on the selected monitoring system, including sensor types, number of sensors and device locations. As these choices are usually made using engineering judgment and qualitative metrics, the selected measurement systems may be sub-optimal, leading to a low cost-benefit ratio of bridge load testing and monitoring.

Methodologies now exist to design optimized measurement systems based on their cost-benefit ratio. Such a methodology has been suggested and validated by means of a composite steel-concrete bridge in Switzerland (Bertola et al. 2022, Bertola & al. 2023). It was found that a rational methodology to design measurement systems helps to reduce the number of sensors without compromising the information gain, thus significantly improving the cost-benefit of bridge load testing and monitoring.

Monitoring data from several sources can be used to develop accurate physics-based models and Error-domain model falsification (EDMF) (Goulet & Smith 2013) to analyze measurements, enabling accurate identification of structural parameters necessary f.ex. to verify fatigue safety of existing bridges (Bayane et al. 2021).

2.6 *Training in engineering of existing structures*

Structural engineers today are still educated mainly to design new structures. Engineers are thus often ill-equipped to deal with maintenance and preservation of existing structures.

Consequently, educational programs should be modernized and developed to the engineering of existing structures. Such programs would still include certain basic structural engineering courses (like structural mechanics) but also elaborate on structural behavior and material properties, and how these can be determined by means of NDT and SPM, in sum referred to as non-destructive evaluation NDE. Because these tools are traditionally not included in the structural engineering curriculum, a new set of basic interdisciplinary skills from the domains of mechanical and electrical engineering, as well as computer science (data analysis, signal processing, etc.), need to be acquired by the students.

Measurement-informed approaches for structural analysis require training beyond traditional structural engineering backgrounds. Engineers must understand the potential of sensor devices in terms of data collection and signal processing. Moreover, model updating requires building refined FE models to accurately predict structural behavior under in-situ conditions. When long-term monitoring measurements are collected, very large data sets need to be analyzed and interpreted, which requires special training. Statistical and data science tools, such as machine learning, could be appropriately used to f.ex. differentiate signal from noise.

3 REHABILITATION AND STRENGTHENING USING UHPFRC

3.1 *Introduction*

Construction of reinforced concrete bridges is very successful because it is cheap. However, the problems of insufficient durability are known for several decades. Rehabilitation of bridges in reinforced concrete using traditional methods implies high intervention and user costs which represent a heavy burden for national economies and the environment. Nevertheless, there is no end of RC bridge construction in view… ! Many bridge engineers and the profession do not seem to care about this problem and are not motivated to make progress !

UHPFRC stands for Ultra-High-Performance Fiber Reinforced Cementitious Composite materials. UHPFRC is composed of cement and other reactive powders, additions, hard fine particles, low amount of water, admixtures and very high amount of relatively short and slender steel fibers. The composition of UHPFRC is optimized with respect to compaction of particles leading to a waterproof material up to a tensile strain of about 0,1 %. The tensile strength of UHPFRC typically is about 12 MPa and the material shows significant strain-hardening behavior in tension. UHPFRC has compressive strength higher than 140 MPa. UHP(FR)C is nowadays used in many countries, mostly in the domain of new construction (Graybeal et al. 2021).

The author and his team have developed the UHPFRC rehabilitation and strengthening technology over the last 25 years by means of scientific research and applications (Bertola et al. 2021, Brühwiler 2019). In Switzerland (8,7 million inhabitants, area of 41′000 km^2) there are currently more than 350 reinforced concrete structures, mainly bridges, that have been improved using the UHPFRC Technology, since 2004. This is the by far highest UHPFRC application rate in the world with respect to the size of the country.

The main reason for this successful implementation of a new technology in practice is that compared to traditional methods using concrete, mortar and epoxy coatings, the UHPFRC Technology is economic in terms of costs and material use, allows for an accelerated construction process and provides durable structures for further use reducing or eliminating maintenance costs.

By applying a UHPFRC reinforcement and waterproofing layer, the use of an existing RC bridge can continue. In this way, new requirements of use are accommodated in an economical, environmentally friendly and socially responsible manner. The UHPFRC Technology is also particularly suitable for bridges of high cultural values, since interventions are usually not visible.

3.2 *Principles of UHPFRC-concrete composite elements*

UHPFRC is used as a high-performance building material to improve existing bridges in traditional reinforced concrete with the aim of remedying, through a targeted supplement with UHPFRC, the known deficiencies of reinforced concrete.

3.2.1 *Concept*

The basic idea of reinforcing structural RC bridge elements with UHPFRC is to monolithically connect a 25 to 80 mm thick UHPFRC layer with the RC cross-section. The resulting UHPFRC-concrete composite element consists of a RC cross-section and a layer of UHPFRC or R-UHPFRC (incorporating steel reinforcement bars) according to Figure 3. The term “strengthening” used here includes the increase in resistance and rigidity of structural bridge elements. At the same time, the UHPFRC layer also provides the protection function by a watertight barrier to shield reinforced concrete from direct contact with water and chloride ions.

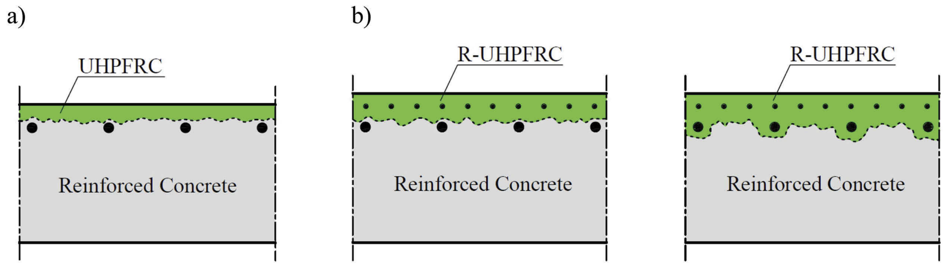

Figure 3. Basic configurations of the UHPFRC-concrete composite construction: a) protective function and increase in rigidity under service conditions, b) protective function and increase in element rigidity and ultimate resistance (rebars in the RC may be integrated or not in the R-UHPFRC layer).

The essentials of UHPFRC-concrete composite behavior can be summarized as follows:

3.2.2 *Behaviour in bending*

When in tension, the R-UHPFRC layer principally acts as an added flexural reinforcement chord for the RC member. Both the steel rebars and the UHPFRC contribute to the structural resistance. RC beams strengthened with a R-UHPFRC layer show significant increase in elastic stiffness and ultimate resistance when compared to the initial RC member.

The bond between UHPFRC and concrete is obtained by preparing the concrete substrate surface by high pressure water jetting or sand blasting. The concrete substrate has to be wetted and needs to be moist when the layer of UHPFRC is cast. This surface preparation provides a full bond between the UHPFRC and the concrete substrate with monolithic behaviour.

The plastic post-peak rotation capacity of strengthened RC beams is maintained with an appropriate design of the rebars in the UHPFRC layer. The structural behaviour in terms of moment – curvature relation and the ultimate bending resistance are calculated using the conventional sectional model, extended to account for the R-UHPFRC layer in the monolithic section (Figure 4).

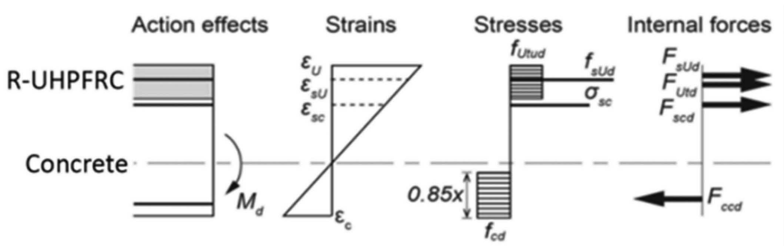

Figure 4. Plane section analysis for ultimate bending resistance.

When subjected to compressive stresses, the R-UHPFRC layer acts as a compression flange but the high UHPFRC compressive strength can usually not be fully exploited. This is because the compressive strength of the adjacent concrete below the UHPFRC layer often is three to six times lower, and thus concrete would crush prior to the UHFPRC reaching its compressive strength.

3.2.3 *Behaviour in combined bending and shear*
Testing of R-UHPFRC – RC composite beams revealed that the addition of a layer of R-UHPFRC delays the formation of the inclined shear crack in the concrete section. For many geometric configurations, the R-UHPFRC layer modifies the failure mode from well-known RC shear failure with little deformation to a ductile flexural failure mode.

A shear failure is observed in a composite section only for specific geometric and material configurations. Due to the experimentally observed failure mechanism, the ultimate shear resistance is composed of the contributions due to concrete web crushing, vertical steel reinforcement yielding and a two hinge-bending mechanism of the R-UHPFRC layer. Accordingly, analytical expressions have been deduced to calculate the ultimate shear strength of RC slabs and beams strengthened by a R-UHPFRC layer.

3.2.4 *Fatigue behaviour*
Bending fatigue tests on R-UHPFRC – RC composite elements revealed the existence of a fatigue limit at 10 million cycles at a fatigue stress level of about 50 % of the ultimate static resistance of the R-UHPFRC – RC beams. Consequently, fatigue design rules for R-UHPFRC – RC members under bending fatigue need to account for steel rebar and UHPFRC fatigue resistances. Fatigue stresses are calculated using an elastic sectional model similar to the one shown in Figure 4.

3.2.5 *Design provisions*
Rational design provisions for the application and implementation of R-UHPFRC in structural engineering are given in the Swiss Standard SIA 2052 (SIA2052 2016) which is still the only UHPFRC Standard explicitly treating the application of UHPFRC for the enhancement of existing concrete structures. Is the experts basic education as “new builders” the reason why other code committees don’t integrate the engineering of existing structures in their UHP(FR)C codes ?

3.3 *Design concepts to improve bridges*

Obviously, UHPFRC should generally be used as a material to rehabilitate and restore damaged reinforced concrete elements, thereby replacing the use of inferior materials like repair mortars or epoxy coatings. In the following, concepts are presented to increase structural resistance of R-UHPFRC improved RC bridges:

3.3.1 *Project objective 1: Restoring and increasing the resistance of bridge deck slabs*
Bridge deck slabs made of reinforced concrete are subject to particularly high loading due to environmental influences and traffic loads. Accordingly, there is a high demand for intervention to restore and increase the structural resistance of deck slabs.

Figure 5 shows the basic strengthening concept of bridge deck slabs by applying a R-UHPFRC layer to the existing concrete slab. Bridge deck slabs carry loads and forces mainly in the transverse direction. Correspondingly, a distinction is made between the sagging moment zone (positive bending moments) and the hogging moment zone (negative bending moments) above the webs of beams or box girders.

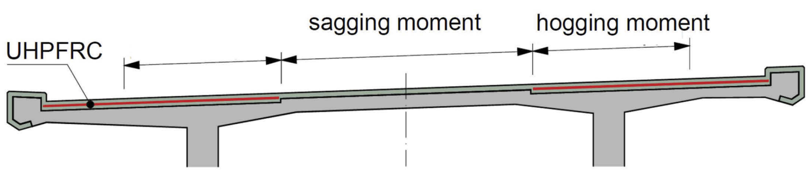

Figure 5. Concept of increasing the resistance of the original RC deck slab by means of the R-UHPFRC layer forming a strong R-UHPFRC tension chord in the hogging moment zone.

The concept is to significantly increase the flexural resistance in the hogging moment zone by forming a strong R-UHPFRC tension chord allowing for moment redistribution from the sagging to the hogging moment zone at ULS (ultimate limit state) according to the plasticity theory, given that the UHPFRC layer under compression in the sagging moment zone only leads to a comparatively small increase in the flexural resistance.

The R-UHPFRC tension chord must be compensated by a correspondingly strong compression zone. In order to ensure the balance of the tensile and compressive forces resulting in the bending cross-section, the effective concrete compressive strength is exploited, which has usually increased considerably (i.e. by 20 to 50 % compared to the 28-day compressive strength) during the bridge's service duration usually of several decades. This well-known time-dependent increase in strength is estimated using analytical expressions given in scientific literature and standards, and verified by means of non-destructive testing on the structure. In this way, strengthening of the compression zone can often be avoided.

By creating a R-UHPFRC tension chord, the ultimate shear resistance is also greatly increased in the hogging moment zone, such that the shear force check is usually fulfilled easily. By the R-UHPFRC reinforcement, the slab rigidity is significantly increased, which greatly reduces fatigue stresses in the steel reinforcement bars and in the concrete. The fatigue safety check is therefore usually fulfilled with margins.

3.3.2 *Project objective 2: Increasing the resistance of bridge girders*

The targeted use of R-UHPFRC, in particular as a R-UHPFRC tension chord, enables a significant increase in the load-bearing capacity of bridge girders in the longitudinal direction without significantly increasing permanent actions (by the additional R-UHPFRC layer) and without the intervention becoming visible. For this purpose, a modification of the static system is usually appropriate. Two basic principles are described as follows.

Principle 1: Reinforcement of continuous beams by means of a R-UHPFRC layer

In statically indeterminate systems such as continuous beams, the bending resistance in the hogging moment zone is greatly increased by the formation of a strong R-UHPFRC tension chord in order to be able to carry out a plastic moment redistribution from the sagging to the hogging moment zones at ULS, similar to the concept related to deck slabs (Figure 6). However, this moment redistribution is only possible if the bending cross-sections are sufficiently ductile, which must be verified. For this purpose, a non-linear finite element analysis is often useful if the empirical rules of standards are not satisfactory.

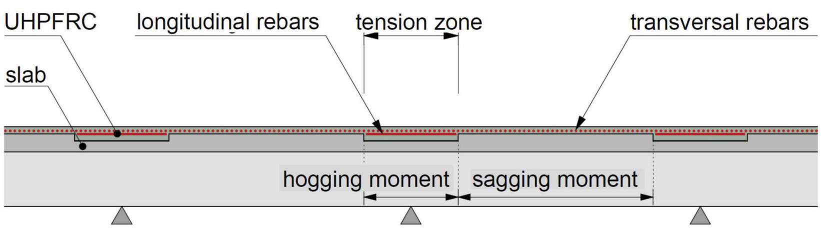

Figure 6. Principle of increasing the ultimate resistance of reinforced concrete bridge girders using a R-UHPFRC layer with the formation of a strong R-UHPFRC tension band in the support area.

This principle is efficient in that an increase in the load-bearing capacity (ultimate resistance) of 15 to 30% (and in extreme cases up to 50%) can be obtained. In this way, for example, severe damage such as failure of prestressing cables due to corrosion can be compensated without having to install costly additional tendons.

As in the sagging moment zone of a bridge girder, the R-UHPFRC layer only leads to a small increase of the flexural resistance, a need for additional reinforcement of the tension zone at the bottom of simple and continuous beams can be accommodated for by CFRP (carbon fiber reinforced plastics) lamellas on the underside of the bottom flange or by additional external posttensioning tendons.

Principle 2: Creation of hyperstatic systems by force-locked closure of dilation joints

For existing short and medium span RC bridges with lengths up to 80m, all dilatation joints can be eliminated using UHPFRC. Force-fit joint closure leads to hyperstatic systems. Particularly, the structural behavior of the modified abutments needs to be investigated applying recent knowledge in the area of integral RC bridge structures. In the case of existing bridges, the dilatation movement to be considered is limited to that due to changes in temperature alone, since girder deformation due to final shrinkage and creep of the existing concrete is negligible.

Bridges consisting of a series of simple beams that are force-fitted monolithically in the support zone by R-UHPFRC, are converted into a continuous beam and are thus analyzed like continuous beams according to Principle 1.

Figure 7a shows the concept of joint closure in the abutment area of a single span beam. In the case of pier-like abutments with large dimensions, a frame structure can be created. By modifying the end zones of the beam to frame corners, the bending stress is redistributed from the sagging zone to the frame corners and thus relieved. By installing the R-UHPFRC tension chord in the abutment zones and a UHPFRC layer over the entire deck, the dilatation joints are eliminated and the reinforced concrete is protected from chlorides and water.

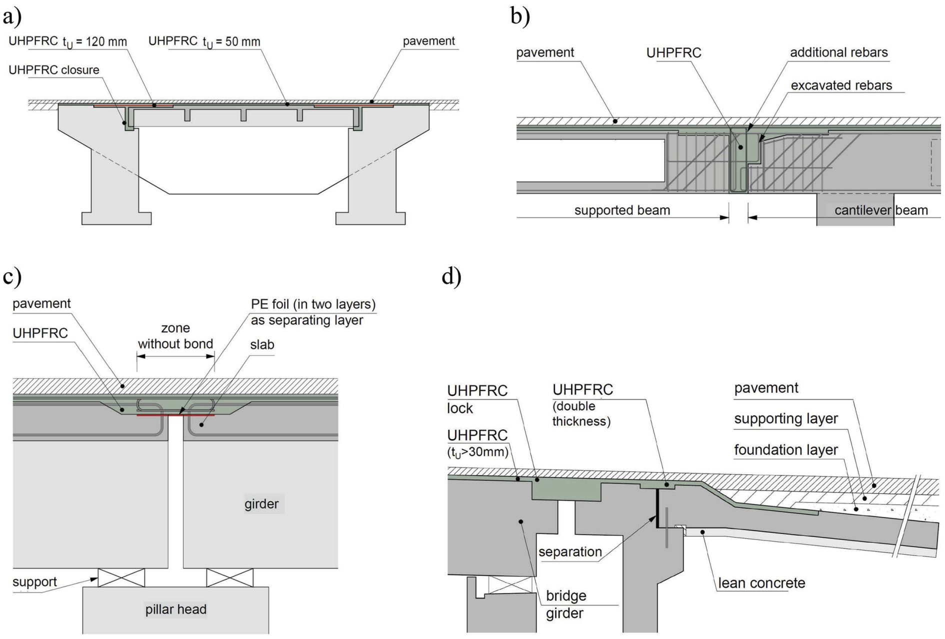

Figure 7. Principle of UHPFRC joint closure: a) in the abutment zones of a single span bridge to create a half-frame, b) force-locked Gerber joint, c) partial joint closure for beam chains, also called “link slab”, and d) creation of a semi-integral bridge end.

Figure 7b shows the constructional detail of a force-locked Gerber joint, which is bending- and shear resistant. The UHPFRC lock is anchored into the existing RC bridge structure with rebar inserts on both sides.

In the case of single span girders in series, the partial joint closure at the level of the deck slab shown in Figure 7c can be suitable. A relatively massive unbonded slab in R-UHPFRC, called “link slab”, is anchored in the adjacent RC deck slabs to connect two adjacent bridge girders by a continuous deck slab. The length of the connecting UHPFRC slab is designed such that temperature related deformations are absorbed by deformation of the “link slab”. The static functioning of the original simple beams is not modified by this intervention. This “link slab” principle can also be implemented in the transition from the bridge to the road for dilations up to ±10 mm.

Figure 7d shows the design of a semi-integral abutment by means of a R-UHPFRC lock connecting the bridge deck slab to the transition (or approach) slab, thereby waterproofing the bridge end zone and eliminating the dilation joint above the bridge bearing and thus a major bridge damage situation.

By forming force-locked UHPFRC connections, the structure is stiffened, which usually increases structural resistance. Obviously, the entire strengthened structure and in particular the UHPFRC-locked zone must be analyzed accordingly and the force flow in the modified structure must be carefully verified.

3.4 *Three selected recent applications*

Among numerous UHPFRC application projects with involvement of the author in conceptual design, dimensioning, project proof and quality control, three recent projects are selected and briefly described in the following:

3.4.1 *Riddes Viaduct*

The 1.2 km long road viaduct (Figure 8a) consisting of a twin continuous box girder in post-tensioned concrete built in 1976 is a major overpass over a railway line, highway and a river.

a) b)

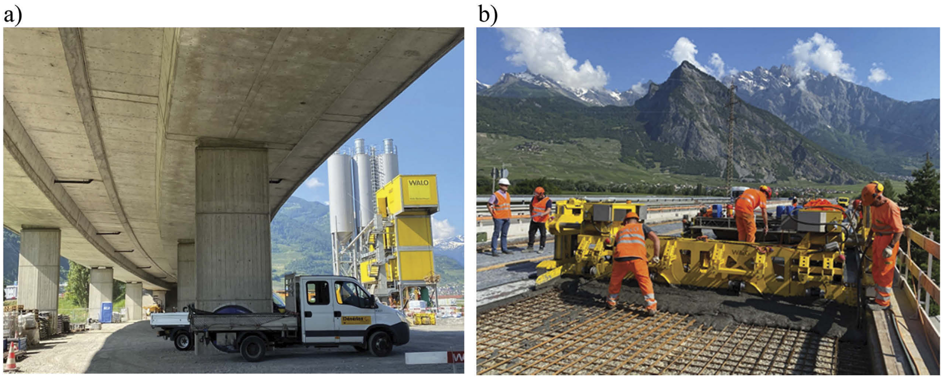

Figure 8. a) UHPFRC ready mix plant next to the Riddes Viaduct, b) UHPFRC casting on the deck slab.

RC damage including corrosion of prestressing tendons and steel rebars as well as alcali-aggregate reaction lead to a significant deficit in structural resistance. Strengthening intervention was urgently needed. The objective of the intervention was to over-strengthen the girder for flexural resistance to accommodate for (1) potential loss of 1/3 of post-tensioning, (2) 30% AAR-related forecasted concrete strength reduction and (3) local damage of the deck slab.

The R-UHPFRC intervention method was found to be most cost-effective and rapid to rescue the viaduct's post-tensioned concrete structure. The concept and design of strengthening was following the principle shown in Figure 6 and the design provisions of the Swiss UHPFRC standard (SIA 2052, 2016) including detailed non-linear FE analyses. The UHPFRC layer was cast in 2021 on the deck slab of the viaduct using a casting machine (Figure 8b).

3.4.2 *Aare Bridge Schinznach*

This 120 m long three span road bridge for bi-directional road traffic and with a pedestrian walkway was built in 1954. This bridge belongs to the first generation of steel-concrete composite bridges and has significant cultural values.

The cross section consists of two main steel girders and the RC deck slab. The RC slab showed ordinary steel rebar corrosion damage, and the pedestrian walkway had to be widened to accommodate for future user demand. In addition, examination of the composite structure and the deck slab revealed deficits in structural capacity and thus structural strengthening was required.

a) b)

Figure 9. a) View of the steel-concrete composite bridge after R-UHPFRC strengthening, b) casting of UHPFRC with immediate application of curing compound.

The strengthening consisted in adding a 60mm thick layer of UHPFRC incorporating steel reinforcement bars in orthogonal directions to waterproof and protect the RC slab as well as to increase the resistance of the slab in the transverse direction and the hogging moment capacity over the piers in the longitudinal direction. The UHPFRC casting works were realized in two days in Summer 2022 (Figure 9b).

The R-UHPFRC strengthening was optimized such that strengthening of the two steel girders could be avoided, reducing the intervention on the main structure in steel to the renewal of the corrosion protection coating only.

3.4.3 *Viaducts Pont d'Ouche*

Built as part of a vast motorway program in the 1960s, the 504 m long Pont d'Ouche twin viaducts are one of the major elements of the A6 motorway in France (Figure 10a). At the time of their construction, they were unique by its geometric characteristics, since built entirely in curves and in slope, and by the structure being made up of prestressed prefabricated isostatic beams with spans of 36m with cast-in-place connecting slabs. This rational structural system for RC viaducts, which was very often realized in France and worldwide, allowed realization in a record time of 20 months and the inauguration of the viaducts in October 1970.

a) b)

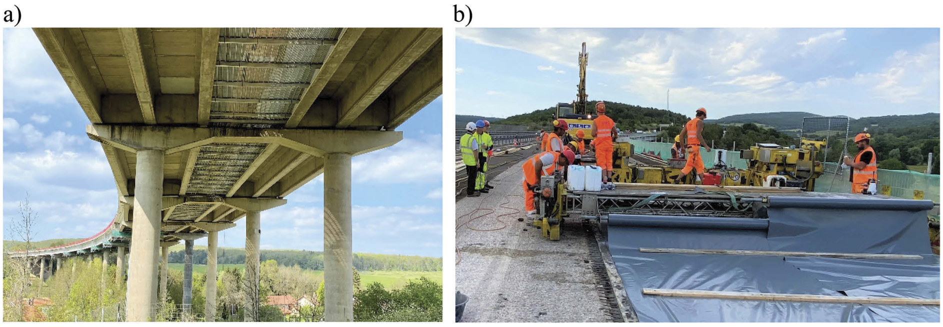

Figure 10. a) View of the twin viaduct structure with triple PC-girder cross section, b) casting of UHPFRC and curing with a plastic foil.

Installation of a robust water proofing layer in UHPFRC, repair of rebar corrosion damage and structural strengthening of the slab zone near the curbs to resist possible vehicle impact forces on the new vehicle retaining system, were the main reasons for realizing the UHPFRC project. The UHPFRC layer on the deck slab of the first viaduct was cast in 2022 using a casting machine (sure 10b). The same UHPFRC intervention will be realized in 2023 on the adjacent viaduct.

3.5 *UHPFRC Technology and sustainability*

The two most efficient materials in the building industry, steel and cement, are currently criticized as being particularly harmful to the environment. This ignores the fact that it depends on how these building materials are used. UHPFRC contains relatively high quantities of cement and steel, so that the energy input and greenhouse gas emissions per kg of UHPFRC are high compared to most other building materials.

Nevertheless, the principles of sustainability can be well respected through the targeted use of UHPFRC. This is because UHPFRC is a high-performance building material with which the required technical performance of structures is achieved with small material quantities. In addition, "eco"-UHPFRC mixtures have already been developed (Hajiesmaeili et al. 2021), allowing for a reduction of the environmental impact of the UHPFRC material alone. Also, UHPFRC can be decomposed and recycled.

When dealing with existing structures, the use of UHPFRC leads to: *"Improve instead of replace!"* UHFB technology is able to rehabilitate and strengthen, actually to salvage, existing RC structures. In this way, material resources and grey energy already in use are further utilized, thanks to a relatively small amount of UHPFRC. The existing structure is valorized and upgraded in an economic manner.

4 CONCLUSION

Engineering of existing bridges comprises accurate determination of structural behavior and targeted use of advanced materials for improvement of structural performance with the ultimate goal of limiting construction intervention to a strict minimum while extending the service duration and thus limiting "life cycle costs".

Two basic novel engineering methods and technologies were described to preserve existing bridges and to improve them to accommodate to the requirements of future utilization:

- NDE (non-destructive evaluation) is ready to be used in engineering practice to determine accurately traffic action effects with the goal to achieve realistic structural and fatigue safety verifications of existing bridges.
- If interventions are necessary, the UHPFRC Technology provides effective solutions to rehabilitate and strengthen existing bridges with little use of materials to upgrade them for future utilization.

These methods and technologies have already been successfully applied in practice, demonstrating their effectiveness. Recently, the Swiss Federal Roads Office has published a documentation to facilitate the use of the UHPFRC Technology for the preservation existing and the construction of new engineering structures of the road infrastructure (FEDRO 2023).

The presented approach follows the principle of sustainability to preserve material resources and their grey energy that are already in use, thereby limiting greenhouse gas emissions to a minimum and thus *making bridges sustainable*.

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