Nature Communications

https://doi.org/10.1038/s41467-026-69103-x

Article in Press

Environmental and economic benefits of UHPFRC intervention in bridge management for the Swiss network

Received: 5 May 2025

Accepted: 22 January 2026

Cite this article as: Bertola, N., Küpfer, C., Brühwiler, E. Environmental and economic benefits of UHPFRC intervention in bridge management for the Swiss network. *Nat Commun* (2026). https://doi.org/10.1038/s41467-026-69103-x

Numa Bertola, Célia Küpfer & Eugen Brühwiler

Environmental and economic benefits of UHPFRC intervention in bridge management for the Swiss Network

Numa Bertola[1,*]

Célia Küpfer[2,3]

Eugen Brühwiler[4]

[1] Department of Engineering, Faculty of Science, Technology and Medicine (FSTM), University of Luxembourg, Esch-sur-Alzette, Luxembourg. Corresponding author: numa.bertola@uni.lu. ORCID: 0000-0002-4151-3123
[*]Corresponding author
[2] Peter Guo-hua Fu School of Architecture, Faculty of Engineering, McGill University, Montreal, Canada. ORCID: 0009-0005-1718-4840
[3] Structural Xploration Lab, Institute of Architecture, School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Fribourg, Switzerland.
[4] Institute of Civil Engineering, School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland. ORCID: 0000-0003-2321-010X

Abstract

Current infrastructure management frameworks typically involve replacing bridges at the end of their intended service duration or when significant structural deficiencies arise, resulting in high costs and environmental impacts. Novel structural-strengthening methods using ultra-high-performance fiber-reinforced cementitious composite (UHPFRC) have allowed the preservation of hundreds of bridges in several countries. Their service duration has been extended, and their performance has been improved to match that of a new structure. Examining the Swiss federal network (3,903 bridges), it is found that interventions using the UHPFRC method are feasible on more than 99.7 % of structures, demonstrating that the structural intervention can be technically applied to most bridges in this network. On the given case study, systematically applying the UHPFRC method would lead to savings of up to 7.7 $MtCO_{2eq}$, and 18.5 billion CHF over the next 80 years compared to current engineering practice. This study highlights the significant potential of systematically implementing the UHPFRC method for sustainable and cost-effective infrastructure management.

1 Introduction

Bridges are critical elements within civil transportation infrastructure networks, often lacking viable alternatives if they become unavailable[1]. Increasing traffic loads and exposure to environmental factors accelerate their deterioration[2]. Therefore, it is essential to prioritize bridge management for sustainable and resilient infrastructure systems[3]. Most bridges in developed countries were built in the second half of the 20th century, and they are approaching the end of their intended service duration[4]. Decisions regarding their replacement are becoming increasingly urgent, with significant implications for safety as well as environmental and economic impacts.

The right timing for intervention must be determined to avoid unnecessary replacements, implying large economic and environmental impacts[5], and ensure structural safety to prevent tragic collapses[6]. Despite its well-known subjectivity, most decisions on bridge maintenance are based only on visual inspection[7]. Decisions on replacement are often made based on defects visually observed, conventional methods developed for new designs, and the belief that only a demolition-reconstruction solution is possible[8]. More informed strategies are needed to preserve existing structures without compromising user safety[9].

UHPFRC, which stands for ultra-high-performance fiber-reinforced cementitious composite, is a structural material with unique properties that has been developed for more than 40 years[10–12]. It is made of cement (700-1000 kg/m^3), fine hard particles (maximum grain size of 1mm) – mostly sand and silica fume, water (water-binder ratio between 0.15 and 0.20), admixture, and a large amount of short and slender steel fibers (more than 3 vol.-%)[13–15]. The mechanical properties, both in tension and compression, are 4 to 5 times higher than those of conventional concrete[16,17], with a significant deformation capacity. It offers very long durability as elements remain waterproof under service load levels[18–20].

UHPFRC uniquely combines high mechanical properties and long-term durability, allowing for the development of new regenerative strengthening methods to preserve existing structures[21,22]. For these reasons, the number of UHPFRC-method applications has significantly increased in the last decade, especially in Switzerland[23–26]. Numerous cases have demonstrated that the UHPFRC method is among the most suitable solutions for preserving existing bridges[22,24,27]. Other retrofitting solutions exist[28–30] (i.e., additional prestressing or fiber-reinforced polymer composite lamellas), but they do not simultaneously increase structural capacity and durability.

The typical UHPFRC method generally consists of applying a layer of this material with steel reinforcement on top of bridge decks[22] (Fig. 1). The thickness usually varies between 30 mm – which only increases durability – and 50 to 100 mm, where steel reinforcement bars are also included to increase structural resistance. Altogether, the UHPFRC intervention allows for increasing structural capacities (bending, shear, fatigue, stiffness,…) by up to 50 %[21]. The existing concrete surface is first prepared through hydro-jetting to achieve sufficient roughness to create a composite behavior between UHPFRC and concrete by adherence[31,32]. When UHPFRC is poured, the roughened concrete substrate must also be wet to ensure the bonding through hydration at the interface[33,34]. The structural strengthening is continuous throughout the entire bridge length and extends across the entire deck to ensure UHPFRC waterproofing continuity[24].

If needed, it can also be applied to bridge girder webs or within box girders as detailed in the Supplementary Method. Moreover, curbs are often either replaced by UHPFRC ones of smaller size or jacketed with UHPFRC to minimize future maintenance. When possible, dilatation or half joints are force-locked with UHPFRC to stop degradation in these critical locations[35] and increase structural stiffness and safety. If local deterioration is observed (concrete spalling, rebar corrosion), the intervention involves replacing the contaminated and damaged concrete with UHPFRC, and corroded rebars are supplemented or replaced with new ones[22]. The UHPFRC intervention enables strengthening both longitudinal and transversal structural capacities of the bridge and improves the durability of the exposed deck as well as underneath girders.

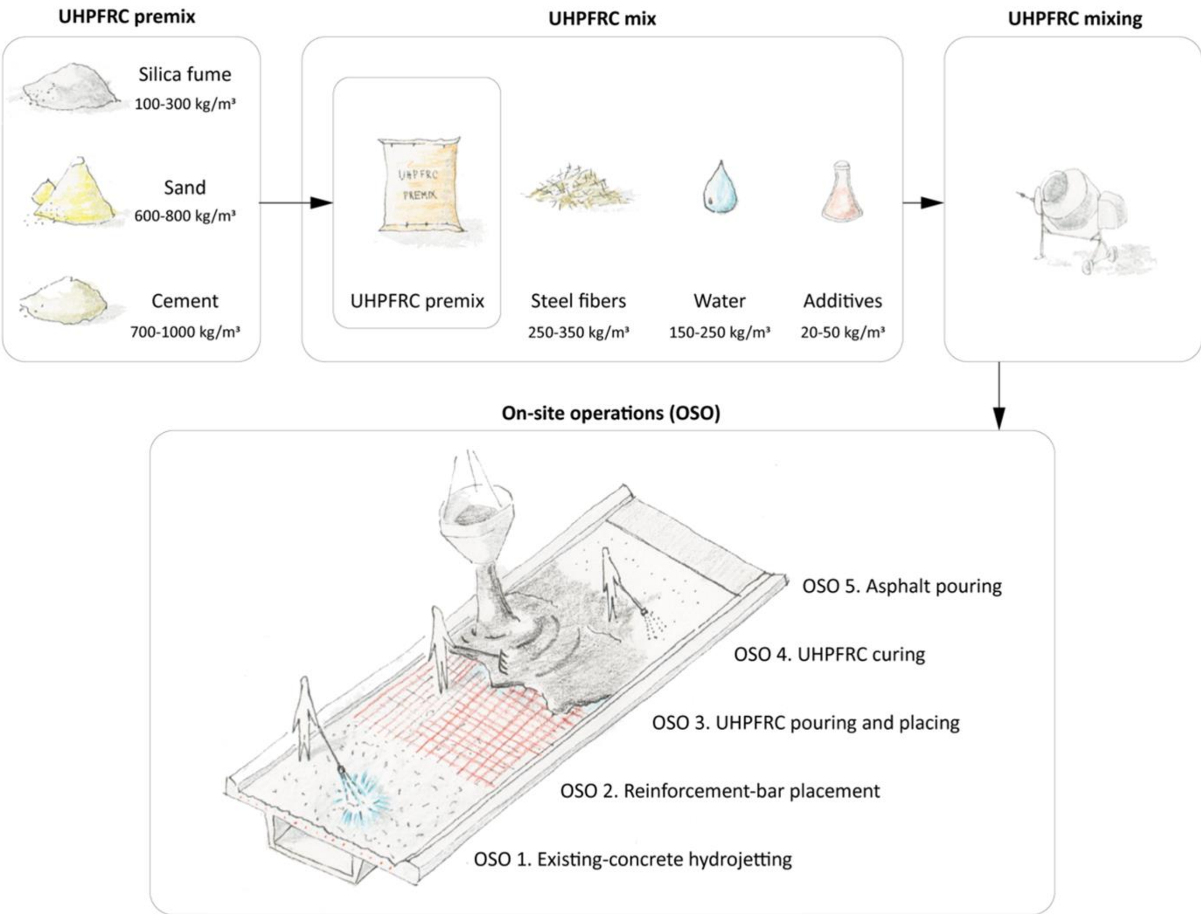

Fig. 1 UHPFRC-method intervention on bridges. Drawing made by the authors; several graphics of the first line were largely redrawn from [36].

UHPFRC was employed to strengthen and rehabilitate more than 300 bridges throughout Switzerland between 2011 and 2024[24] (Fig. 2). Among them, 120 involved structural strengthening, which is referred to as the UHPFRC method (as described in Fig. 1), while the remaining involved only a durability intervention (i.e., no structural strengthening).

Some of these realized structural-strengthening applications are shown in Fig. 2. The size of the strengthened bridges ranges from small 20-m^2-deck bridges to major viaducts, with decks exceeding 20,000 m^2, with lengths from a few meters to more than 2000 meters. The number of spans of the strengthened bridges also varies from long single-span bridges to multi-span bridges. The initial construction year of the strengthened bridges spans from 1785 to the 1990s. The UHPFRC method was also applied to bridges with overall condition grades according to the Swiss condition rating[7], ranging from 1 (bridge in good condition – best grade) to 5 (bridge in an alarming state – worst grade). The interventions were applied to all common structural types, including box girders[37,38], multiple-beam bridges[21,24], two-girder bridges[39], arch bridges[40], slab bridges[41], and composite steel-RC sections[35]. Longitudinal systems of strengthened bridges involvs long viaducts (>1000 meters) to single-span bridges (< 40 meters), as well as arch structures, and multi-span bridges. Moreover, the UHPFRC method was applied to reinforced concrete (RC), prestressed concrete (PC), masonry, steel, and steel-concrete composite bridges.

In most projects, the requirements from bridge owners were that the existing bridge strengthened with the UHPFRC method should have the same guarantees in terms of structural performance (code requirements) and durability as a new structural design (i.e., 80 years). In all case studies, the structural intervention allows for extending the structure service duration by several decades (typically 80 years), avoiding the need for replacement in the foreseeable future. In most of these case studies, the alternative solution involved the replacement of the bridge, suggesting that the UHPFRC method was the only alternative available[21,24].

The environmental impacts of interventions using the UHPFRC method have been quantified through life-cycle assessment (LCA) from material production[42–45] to the evaluation of the resulting UHPFRC structural elements[40,46,47]. Studies have demonstrated the potential of this novel material and its related construction method for sustainable development at the structural scale[40,47,48]. Several studies exist on the life-cycle costs (LCC) of UHPFRC-method interventions compared to a traditional replacement[49–51]. Nonetheless, all these studies focus only on case-by-case comparisons, and a larger-scale analysis is missing to evaluate the economic and environmental potential of the UHPFRC method.

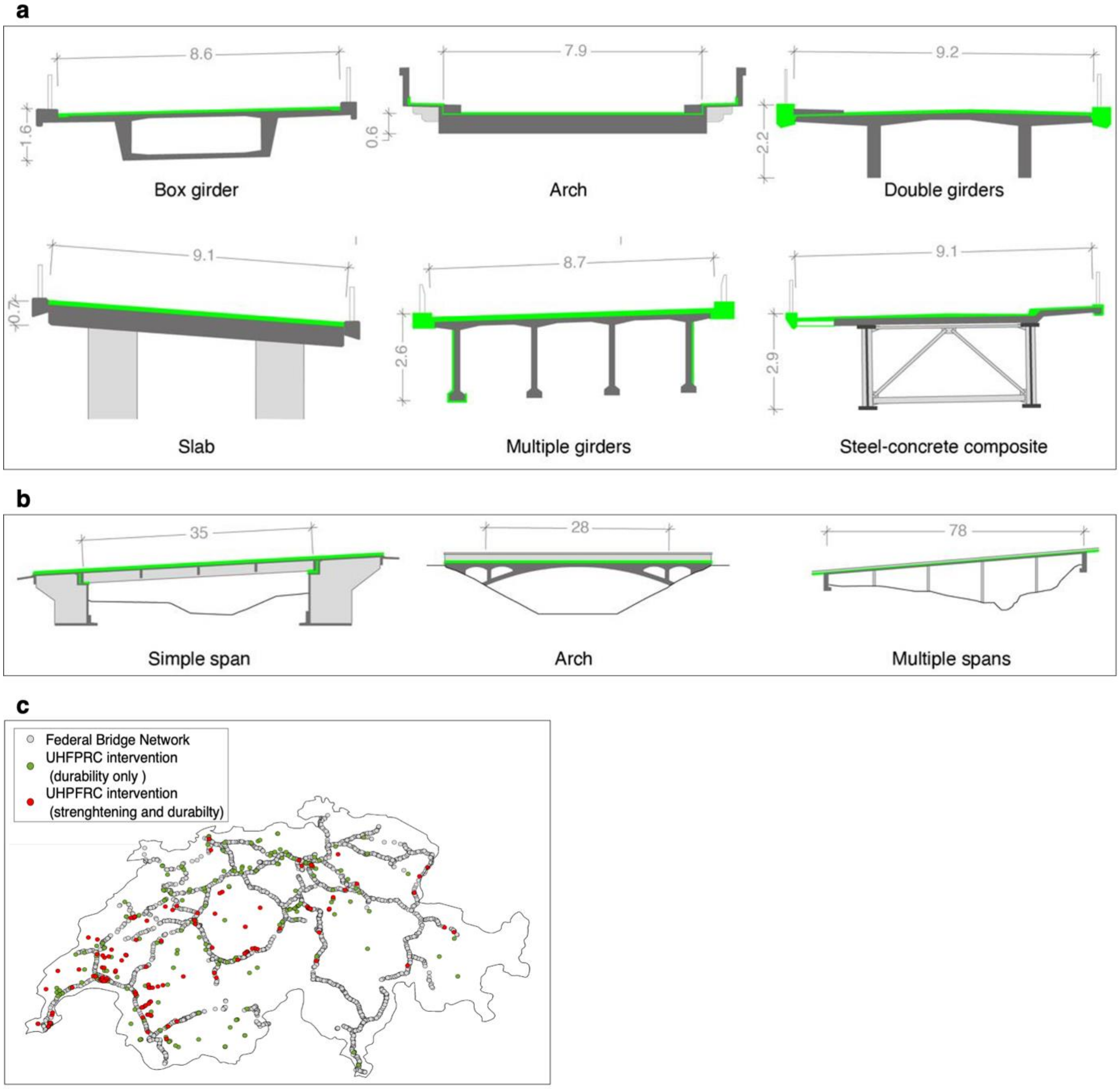

Fig. 2 Typical structural interventions made with the UHPFRC method. a) Cross-section; b) longitudinal profile. c) Map of the UHPFRC-method intervention and the Swiss Federal Road Network used as a case study.

This study presents a network-scale assessment of UHPFRC-method interventions. By combining bridge-stock characteristics with LCC and LCA comparisons, the study quantifies for the first time the large-scale potential of systematically applying UHPFRC across an entire bridge stock.This paper quantifies the potential savings of systematically applying the UHPFRC method at the network scale (the "UHPFRC strategy") rather than demolishing and replacing bridges (the "demolition-reconstruction strategy"). The study integrates insights from realized UHPFRC-method projects and bridge-network characteristics to determine UHPFRC-method applicability on the bridge-network elements. Then, a methodology is proposed to quantify cost and carbon savings based on bridge-replacement scenarios. The Swiss federal bridge stock (3,903 bridges) of the Swiss motorway network is used as a case study.

2 Results

UHPFRC-method technical applicability

The properties of the bridges already strengthened with the UHPFRC method in Switzerland (presented in Section **Error! Reference source not found.**) are compared with those of the Swiss federal network, which comprises 3,903 bridges. This comparison aims to evaluate whether the UHPFRC method is applicable to the entire bridge network or only to a subset of bridges. Information on the bridge-network key attributes was provided by the Swiss Federal Road Office[52]. Six key attributes are compared (Fig. 3), and the following ratios are obtained (Equation 2):

1. Material ratio r_m: the UHPFRC method has been mainly applied to RC decks, a feature present in 99.75 % of the bridge deck area of the network. A few bridges in the network involve non-conventional materials such as aluminum or ground earth, for which a specific analysis would be needed to determine whether an intervention with the UHPFRC method is feasible. Therefore, the material ratio lies between: $r_m \in [0.9975 - 1.0]$.
2. Structural type ratio r_t: most bridges in the network involve continuous girders, simply-supported beams, or frames as structural systems. The UHPFRC method has been applied to strengthen all these bridge types (Fig. 2). Less than 2 % of the bridge-network surface involves cable-stayed, suspended, or truss systems. By examining these 38 bridges in detail, they are all partially or fully made of reinforced concrete (i.e., concrete deck). It is thus assumed that the UHPFRC intervention is technically applicable to these bridges. The range of UHPFRC intervention on bridge type is thus $r_t = 1.0$.
3. Surface ratio r_{su} (expressed in deck surface in m^2): bridge-network deck surface ranges from 10 to 70,000 m^2. Past UHPFRC-method applications cover similar ranges. Therefore, the applicability surface ratio is $r_{su} = 1.0$.
4. Span ratio r_{sp}: the number of spans ranges from 1 to 300 in the bridge network. UHPFRC-method interventions have been applied to single- to multi-span structures, thus $r_{sp} = 1.0$.

5. Condition ratio r_g: based on recent visual inspections, most bridges are in good or acceptable condition. Less than 2% are in poor condition (grade 4), and 0% are in an alarming state (grade 5), indicating the overall very good condition of the bridges in this network. The UHPFRC-method interventions have been implemented even on bridges in grades 4[37,53] and 5[38], thus $r_g = 1.0$.
6. Construction year ratio r_y: all bridges in the network were built between 1800 and 2024, and 99.7 % of them after 1920. The UHPFRC method was applied to bridges built between the 1800s and the 1990s. The UHPFRC-method application is also technically feasible on more recent bridges. Therefore, the construction-year ratio is taken equal to $r_y = 1.0$.

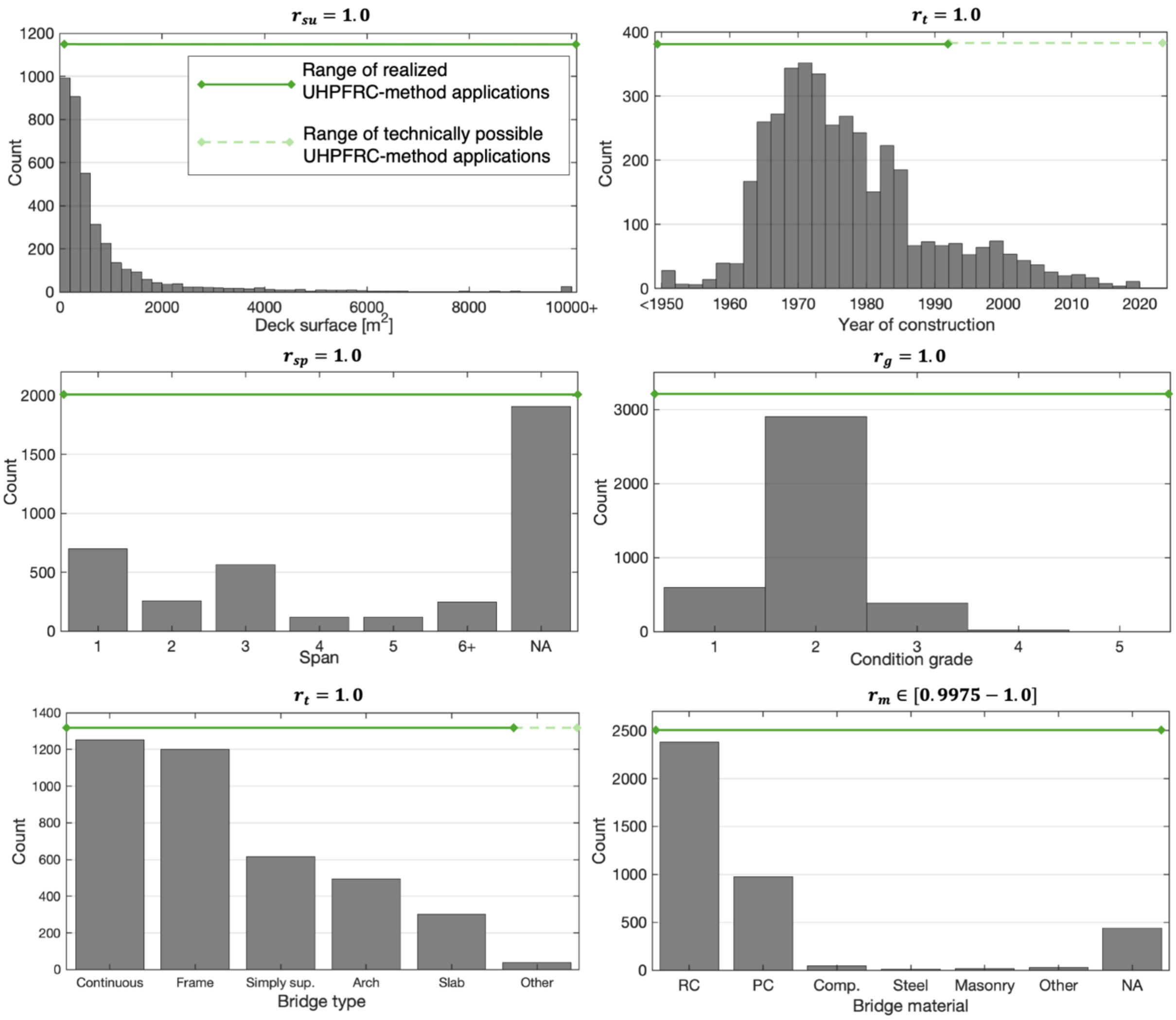

Fig. 3 Distribution of key attributes of bridges in the network and comparison with UHPFRC-method intervention applicability.

Bridge-scale analysis

After the applicability study, a detailed comparison of construction costs and environmental impacts is first conducted at the bridge scale. The comparison between a UHPFRC-method intervention and a replacement project is made on the most common bridge type in the network, i.e., the highway overpass (which represents 26 % of bridges in the network). Two similar realized case studies are selected: one is a UHPFRC-method intervention on an existing bridge, and the other is a bridge replacement. Both bridges have similar lengths, widths, and functions. The UHPFRC-method intervention dates to 2020 on a structure built in 1967, while the replacement project is from 2024. The structural designs of the interventions and replacement projects are shown in Fig. 4a,b. The material quantities needed for LCA have been quantified using construction drawings and information provided by the bridge owners. The environmental impacts of the new bridge are equal to 1085 $kgCO_{2eq}/m^2$, where 62 % comes from the impacts of the superstructure and the remaining 38 % from the substructure. The UHPFRC-method intervention has an environmental impact of 179.8 $kgCO_{2eq}/m^2$, where the production of UHPFRC and steel reinforcement accounts for 74.1 % and 10.4 %, respectively. The comparison between the new bridge and the UHPFRC-method intervention (Fig. 4c) shows a significant carbon reduction of 83%.

To extend the set of case studies and allow comparison at the network scale, an LCA is conducted on 17 realized case studies of structural intervention with the UHPFRC method (Fig. 4d, details are given in Supplementary Method). Based on these case studies, the UHPFRC-method interventions have a mean environmental impact of 165 $kgCO_{2eq}/m^2$ (mean value in the last column of Supplementary Table 1). The environmental impact variations (minimum value of 120 $kgCO_{2eq}/m^2$; maximum value of 226 $kgCO_{2eq}/m^2$; standard deviation 28.2 $kgCO_{2eq}/m^2$) can be explained by several factors, such as the condition and structural capacity of the bridge (if the damage magnitude is important, more UHPFRC is needed for strengthening; hence higher $kgCO_{2eq}/m^2$), the optimization of material uses in the intervention project, and whether the curbs need to be replaced.

To evaluate the carbon savings of the UHPFRC-method interventions, the above results are compared to the environmental impacts of bridge replacement. Unfortunately, no database exists on Swiss bridge designs. The environmental data of the new bridges are taken from the international literature[54–56]. These databases have collected information on several hundred bridges since 2000 mostly in the United Kingdom. It is assumed that these values can be taken as benchmarks for Switzerland due to similarities in construction practices, design standards, and material production environmental impacts[57,58]. Bridge-realized projects cover various structural systems, main construction materials, and sizes (lengths from less than 10 meters to more than 1000 meters). In these databases, LCA boundaries include modules A1 to A5.

All of these studies report an average value for new bridges between 2250 and 2760 $kgCO_{2eq}/m^2$. It is essential to emphasize the large variability in these databases (bridge-design global-warming potential (GWP) values between 1000 and 5000 $kgCO_{2eq}/m^2$). This variation is mainly explained by the environmental-impact variability of the substructure construction, but other parameters (span, structural design, bridge type) can also significantly impact the total bridge GWP. Due to this large variability, two values are considered for the environmental impact of new bridges: a "mean" value of 2250 $kgCO_{2eq}/m^2$ (the lowest mean value of the above-mentioned studies) and "best practice" of 1000 $kgCO_{2eq}/m^2$ (the lower bound of these studies).

Given its mean GWP of 165 $kgCO_{2eq}/m^2$, the UHPFRC-method intervention leads to a drastic reduction between 92.9 % and 84.0 % compared to the mean and best-practice GWP of the new bridge designs, respectively (Fig. 4e). The GWP of the UHPFRC-method intervention remains constant with respect to the bridge deck area. This means that the environmental impact is similar for small bridges (length of less than 30 meters) and large viaducts (length of more than 1000 meters). For all structure sizes, the quantity of UHPFRC used approximately corresponds to an average 55 mm-thick layer over the bridge deck area. These case studies demonstrate the large environmental benefits at the structural scale of avoiding bridge replacement thanks to a UHPFRC-method intervention.

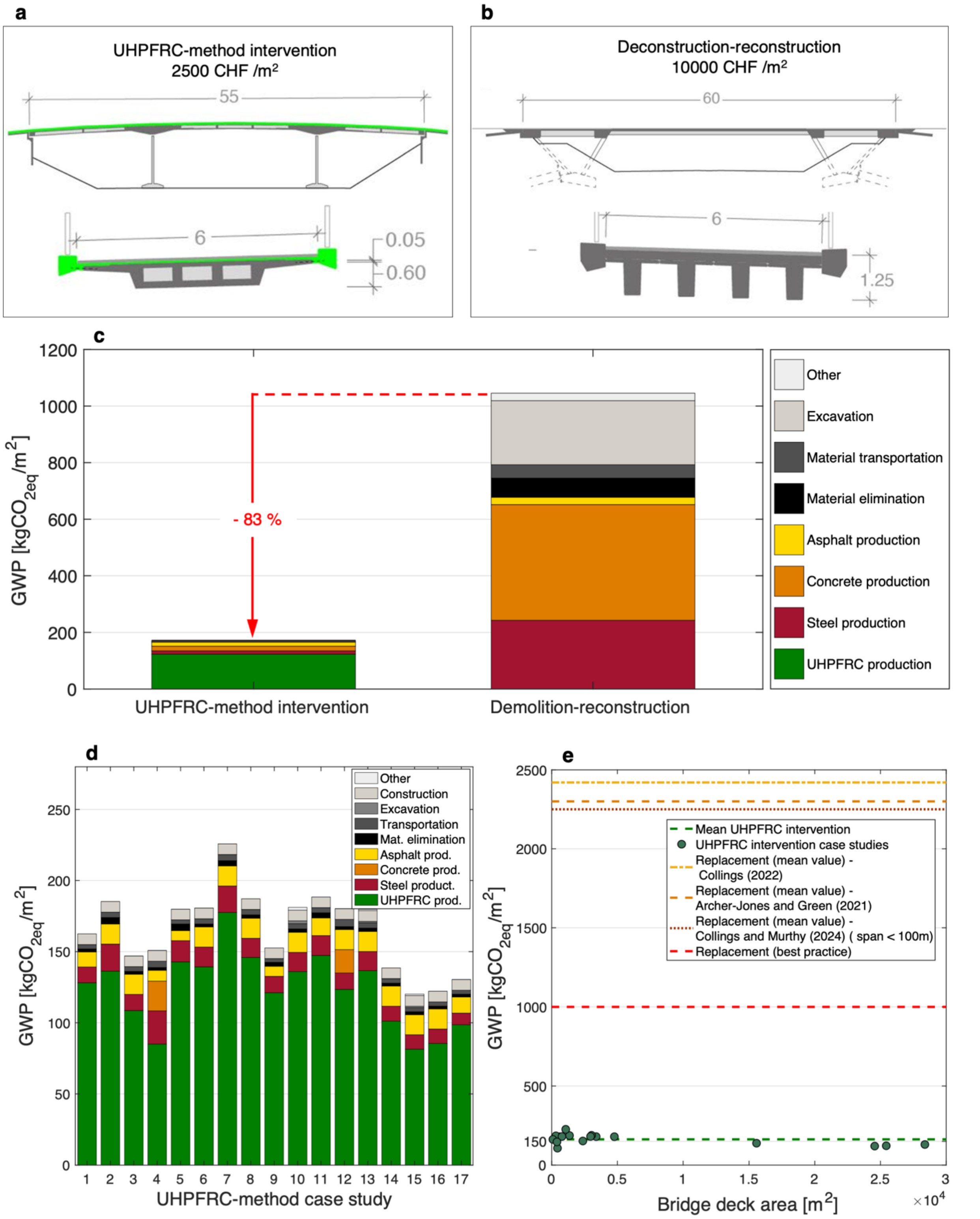

Fig. 4 Bridge scale UHPFRC-method intervention global warming potential (GWP) in comparison with demolition-reconstruction solution. a) UHPFRC-method intervention on a case study of a PC box girder overpass; b) demolition-reconstruction of a PC overpass; c) life-cycle analysis (LCA) comparison of the bridge with UHPFRC-method intervention (a) with the bridge demolition-reconstruction solution (b); d) UHPFRC-method intervention LCAs for 17 case studies; e) comparison of the GWP of bridge new designs (from literature [54–56]) and UHPFRC-method intervention (this study) with respect to bridge deck area.

Next, the LCC is performed. Construction-cost datasets outside Switzerland are of limited interest due to cost discrepancies between countries and their local construction markets. Based on the procurement platform of the Swiss Confederation (SIMAP), discussions with bridge owners, and information not publicly available on the case studies, the replacement project costs are estimated to be about 10,000 CHF/m^2, while the UHPFRC method costs about 2,500 CHF/m^2, showing the significant cost savings of the UHPFRC method (cost ratio of 1:4). These cost estimations are made at the pre-design stage, and a variability of ±15 % is expected, given Swiss standards[59]. It is worth noting that the UHPFRC material and its casting have a cost between 200 and 300 CHF/m^2 for large bridges and between 300 and 400 CHF/m^2 for small bridges. Therefore, the material costs account for only 10 to 20% of the total construction costs for the UHPFRC method. The majority of intervention costs are due to the renewal of bridge equipment (bearing, vehicle retention and dilation joint devices, etc.), new bituminous pavement, as well as construction site facilities (scaffolding, installation areas) and temporary structures, e.g., to keep the bridge in operation.

Network-scale analysis

This section presents the potential carbon and cost savings that could be achieved by systematically applying the UHPFRC method rather than traditional bridge replacement at the network scale. To evaluate these savings potentials on the Swiss Federal Road bridge network, the number of future bridge replacements is first estimated through scenarios (Section Network management scenarios). Cost and carbon savings have been calculated with the Supplementary Code 1.

In Scenario 1 (design-based scenario), where bridge replacement is linked to bridge construction year, most bridge replacements will occur between 2045 and 2065 (Fig. 5a). In Scenario 2 (degradation-based scenario), where bridge replacement estimate is based on bridge-degradation extrapolations, the number of replacements will increase until 2085 and then slightly decrease. In Scenario 3 (budget-based scenario), a constant number of replacements is considered, and it is aligned with the current average number of replacements: 10 bridges per year. Over the 80-year time horizon, the total number of bridge replacements is equal to 3903 (100 %), 3028 (77.5 %), and 800 (20.5 %), for Scenarios 1, 2, and 3, respectively. The discrepancies between scenarios 1, 2, and 3 highlight the uncertainty in predicting future replacement numbers and underscore the need for further research on this topic.

Fig. 5b shows the carbon savings of the UHPFRC strategy, including mean (2250 $kgCO_{2eq}/m^2$) and best-practice values (1000 $kgCO_{2eq}/m^2$) for the demolition-reconstruction strategy. The carbon savings are significant across all scenarios and demolition-reconstruction environmental benchmarks. Compared to the mean-impact benchmark, the carbon savings for Scenario 1 reach 7.7 MT CO_{2eq} over 80 years. For Scenario 2, the carbon savings are 6.4 MT CO_{2eq}, while for Scenario 3, they are 1.7 MT CO_{2eq}. The large discrepancy in carbon savings between the scenarios is explained by the significant difference in the number of bridge replacements per scenario.

Cost savings are calculated by including potential construction-cost variability for both the UHPFRC-method intervention and replacement solution (Fig. 5c). The cost savings are also significant for each scenario. The mean cost savings could reach 14.9 BCHF, 9.1 BCHF, and 3.0 BCHF for Scenarios 1, 2, and 3, respectively. These results demonstrate that a bridge-network management based on the UHPFRC strategy can lead to tremendous carbon and cost savings simultaneously.

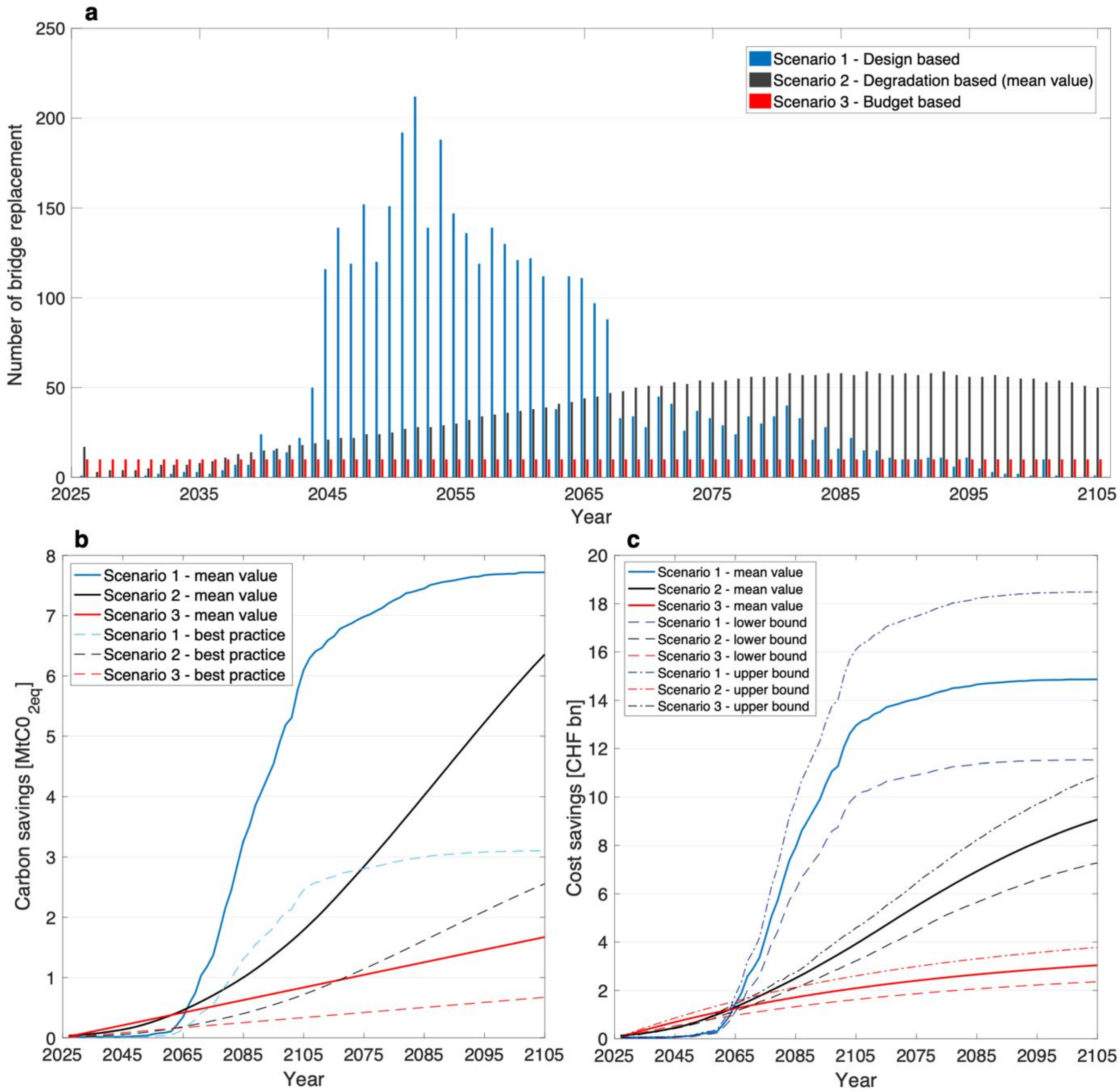

Fig. 5 Network-scale cost and carbon savings thank to the UHPFRC strategy. a) Number of bridge replacements per year for each scenario; b) cumulative carbon savings with the UHPFRC strategy relative to either the mean value (2250 $kgCO_{2eq}/m^2$) or the best-practice value (1000 $kgCO_{2eq}/m^2$) of demolition-reconstruction strategy environmental impacts; c) cumulative cost savings with the UHPFRC strategy relative to the demolition-reconstruction strategy.

Fig. 6a shows the bridge management gap (BMG) per year. It evaluates the sufficiency of the current replacement budget of the asset manager (100 MCHF/year, covering about 10 replacements per year) compared with the needed bridge replacements of Scenario 2. For the demolition-reconstruction strategy, a backlog is observed starting in 2036. With the UHPFRC strategy, the bridge replacement backlog is not expected to begin until 2063.

The cumulative BMG (Fig. 6b) shows that the demolition-reconstruction strategy will result in a total bridge replacement backlog of 2228 bridges (57.1 % of the network) in 2105 (80 years after

2025). With the UHPFRC strategy implemented today, a bridge replacement surplus of 178 (4.6 % of the network) will be achieved. Thus, if the UHPFRC method is systematically adopted at a network scale, the current budget is sufficient, and preventive interventions can be implemented before bridges reach an alarming state.

The systematic implementation of the UHPFRC strategy should be initiated by 2031 at the latest to avoid a bridge replacement backlog by 2105, showing the importance of rapidly implementing the UHPFRC strategy. To avoid the bridge replacement backlog with the demolition-reconstruction strategy by 2105, the budget would need to be multiplied by 3.8. This means adding 280 million CHF/year from 2025 onward, which would be unnecessary with the UHPFRC strategy. The UHPFRC strategy could thus avoid a significant budget increase if implemented rapidly and systematically.

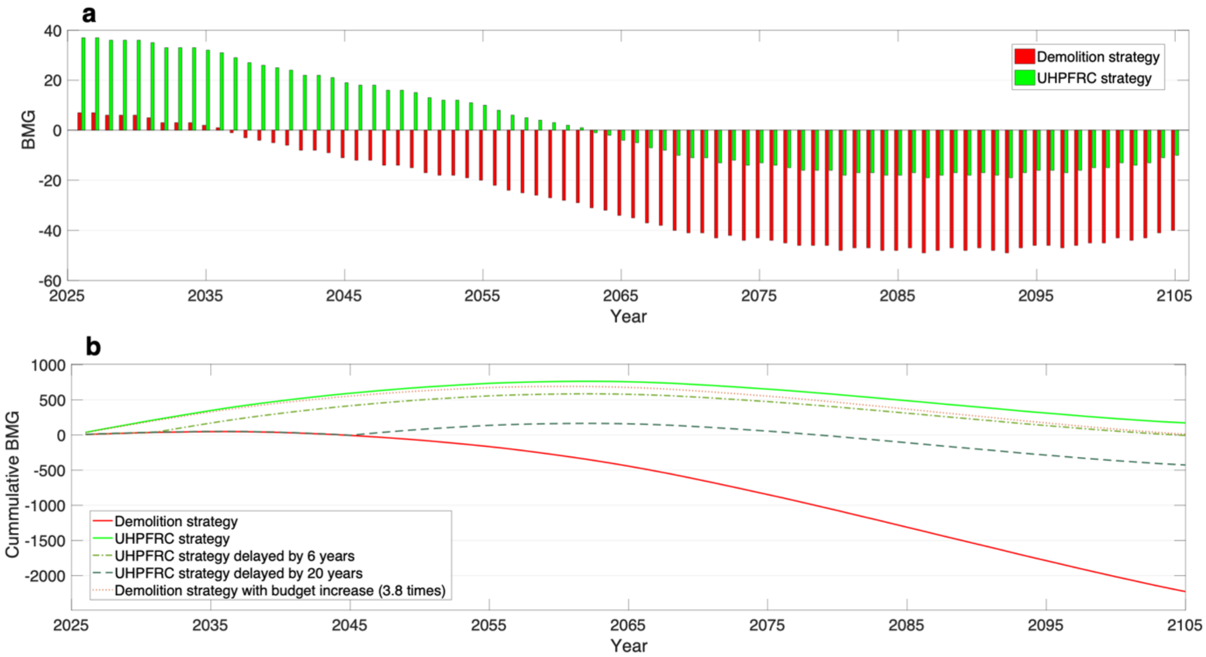

Fig. 6 Bridge management gap (BMG) compared to bridge-replacement needs of Scenario 2. a) yearly BMG; b) cumulative BMG.

Sensitivity analyses on cost and carbon savings

Following the initial network analyses, one-way deterministic sensitivity analyses are performed, varying key economic and environmental parameters individually within plausible ranges (i.e., 2 standard deviations from the mean or reasonable variation assumptions) to evaluate their impact on total carbon and cost savings at the network level (Fig. 7). These analyses use Scenario 2 and the average GWP value of bridge replacement (i.e., GWP equals 2250 $kgCO_{2eq}/m^2$) as a baseline scenario (blue lines). Results are presented as cumulative values until 2105. Carbon-saving sensitivities are analyzed according to the applicability ratio (Fig. 7a), the GWP per m^2 for the UHPFRC method (Fig. 7b), and for a bridge replacement (Fig. 7c). Cost-savings sensitivities are analyzed according to the applicability ratio (Fig. 7d), the cost ratio between the UHPFRC method and the bridge replacement (Fig. 7e), and the discount rate hypothesis (Fig. 7f).

Regarding carbon savings, decreasing the applicability ratio of the UHPFRC method from 1.0 to 0.8 reduces total carbon savings proportionally, indicating that the overall conclusion remains strong even if the UHPFRC method is deemed infeasible on many bridges. Variations in the GWP of UHPFRC interventions between 100 and 200 $kgCO_{2eq}/m^2$ (about 2 standard deviations from the mean) have only a small impact compared to the total network-scale savings, as these values are minor relative to the GWP of bridge replacements. Conversely, assumptions about the carbon footprint of new bridge construction (1500–3000 $kgCO_{2eq}/m^2$; ±33.3% of the mean value) can affect the carbon savings between 4.0 and 8.5 $MTCO_{2eq}$. This demonstrates that UHPFRC-method interventions still reliably deliver reductions of several megatons of carbon.

Regarding cost savings, variations in the applicability ratios between 1.0 and 0.8 consistently reduce the savings from 9.0 to 7.2 billion CHF, with proportional reductions. The cost ratio adjustment confirms that even under conservative assumptions where the ratio would be 1:3 instead of 1:4 (baseline scenario), cost savings would exceed 8.0 billion CHF by the end of the period. Fig. 7f underscores the strong influence of the discount rate: compared to the baseline scenario, where a 2 % discount rate is applied, a lower rate (0 %) would increase total cost savings to 22.8 billion CHF. A higher discount rate (4 %) would reduce the total cost savings to 4.3 billion CHF. The discount rate is thus the most significant parameter; however, it does not alter the conclusion that the UHPFRC strategy leads to significant cost reductions in infrastructure management.

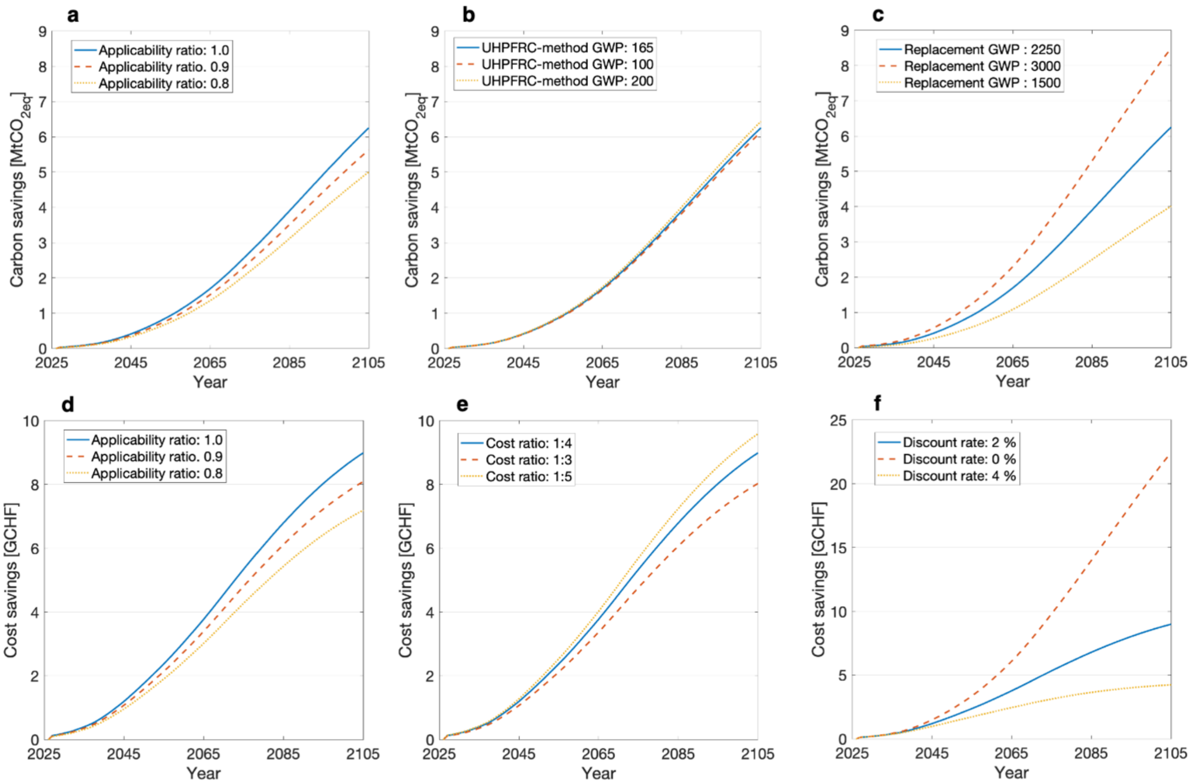

Fig. 7 Sensitivity analysis with blue lines as the baselines. a) Carbon savings with respect to the applicability ratio; b) carbon savings with respect to the UHPFRC-method global warming potential (GWP); c) carbon savings with respect to the bridge-replacement GWP; d) cost savings with respect to the applicability ratio; e) cost savings with respect to the cost ratio between UHPFRC strategy and demolition-reconstruction strategy; f) cost savings with respect to the discount rate.

3 Discussion

Previous works have focused mainly on individual case studies or component-level analyses of UHPFRC applications[40,46,60], but no prior research has addressed systematic implementation across an entire national bridge stock. The absence of comparable network-scale studies underlines the novelty of our contribution, while also highlighting the need for further work to validate and extend the methodology in other contexts.

This study demonstrates the economic and environmental potential of the UHPFRC method to avoid replacing bridges on the Swiss Federal Road network for all bridge-replacement scenarios. At the network scale, the analyses show that the UHPFRC-method intervention offers significant benefits in terms of sustainability and cost-effectiveness compared to the conventional demolition-reconstruction solution.

The study reveals that both cost and GWP indicators are not conflicting but are positively correlated. However, the correlation is not perfect due to the inclusion of the discount rate (2%) in the LCC. This indicates that UHPFRC-method interventions are robustly aligned with both economic and environmental objectives, but the magnitude of cost savings is more sensitive to financial assumptions. The proposed intervention scheme thus supports stakeholders in more sustainable infrastructure management.

Despite the significant environmental benefits of the proposed UHPFRC method, its environmental impacts could be reduced further in the future. Multiple research studies aim to reduce the carbon footprint of UHPFRC by replacing steel fibres with polyethylene fibres and/or reducing the clinker content of cement[40,61], with a potential reduction of the carbon footprint by 50 % without compromising significantly on the material properties. Moreover, in many applications, the quantity of UHPFRC could have been optimized based on today's experience. It is thus envisioned that the environmental impacts of UHPFRC intervention could be smaller than 100 $kgCO_{2eq}/m^2$ in the future[40].

The UHPFRC method prevents direct exposure to water and de-icing salts on concrete bridge superstructures. Reducing water exposure prevents and stops alkali-silicate reactions on concrete structures, as demonstrated for the Chillon Viaduc[62]. Due to its temperate and dry climate, Switzerland has a limited risk of carbonation-induced corrosion. For more aggressive climates (i.e., tropical), the UHPFRC-method intervention could be combined with a hydrophobic treatment on bridge-girder webs to ensure durability, which has not been accounted for in the present study. The present study did not consider indirect costs and related environmental impacts, but they may be significant, sometimes larger than the direct impacts[63,64]. Structural interventions with the UHPFRC method have often enabled a reduction of up to 50 % in the duration of construction works, while maintaining the bridge open throughout construction [24]. Conversely, replacement projects often require rerouting traffic through temporary structures or alternative paths. The indirect impacts of both solutions are highly case-study dependent, and their quantification is beyond the scope of the current study. Future work aims to quantify indirect costs and carbon savings.

The infrastructure-management scenarios involve only a binary decision regarding bridge replacement. Nonetheless, bridge management involves more potential decisions, such as preventive maintenance, to reduce the need for bridge replacement. A smaller UHPFRC intervention (of 30 mm thickness without reinforcement bars) could also be used as a waterproof protection layer to prevent concrete degradation[65,66]. Future work will include other maintenance interventions in the analysis.

Beyond Switzerland, UHPFRC has shown significant interest worldwide[23]. For example, 200,000 m³ were used in China alone in 2024[67]. Resources for producing UHPFRC are widely available worldwide, enabling a large number of UHPFRC interventions. A limiting factor could be the regional availability of UHPFRC mix and the training of structural engineers, bridge owners, and contractors. These limiting factors would only require additional time for unlocking a large number of applications, as demonstrated in Switzerland. Additionally, specific construction standards and design guidelines, such as the Swiss standard for UHPFRC CT 2052[68], must be developed to trigger more UHPFRC applications worldwide. The specificities of the local bridge network, material impact, and construction cost and practices may affect quantitative cost and carbon savings, but should not change the conclusion that the UHPFRC method is a more cost-effective and sustainable solution for existing bridge management.

Replacing an ‘old’ or ‘deficient’ bridge is often a management choice rather than a technical necessity. In many cases, the UHPFRC method is a relevant alternative that must be investigated, as it may offer significant cost and environmental benefits compared to replacement. Given both economic and environmental savings, the UHPFRC method should become the default option when dealing with bridges approaching their intended “end of use” in bridge stocks similar to the Swiss Federal Road network.

4 Methods

Framework overview

This section provides an overview of the methodological flowchart used to evaluate the network-scale potential of UHPFRC-method interventions (Fig. 8). The framework combines analyses at structural and network scales. In this framework, when a bridge approaches its intended service duration or reaches a critical condition state where the structural integrity is not guaranteed, the bridge owner’s decision is limited to two options:

1. Demolishing and rebuilding the structure – called the demolition-reconstruction strategy.
2. Extending its service duration through a UHPFRC-method intervention (details of the intervention in Supplementary Method) – called the UHPFRC strategy.

First, for each strategy, environmental impacts and construction costs are quantified based on experience from performed applications and databases (see Section Cost and carbon savings). The next step is to evaluate the applicability of the UHPFRC method on the bridge network, combining structural and network-scale data. This assessment (detailed in Section UHPFRC-method technical applicability) estimates the percentage of bridges in the network where the UHPFRC-method intervention is technically feasible. Next, the number of bridges in the network that will theoretically require replacement in the following years is estimated (see Section Network management scenarios). Finally, combining the cost and carbon savings, the technical applicability of the UHPFRC-method intervention and the bridge-network evolution scenarios, the UHPFRC-strategy potential is quantified over the investigated period (Section UHPFRC strategy potential).

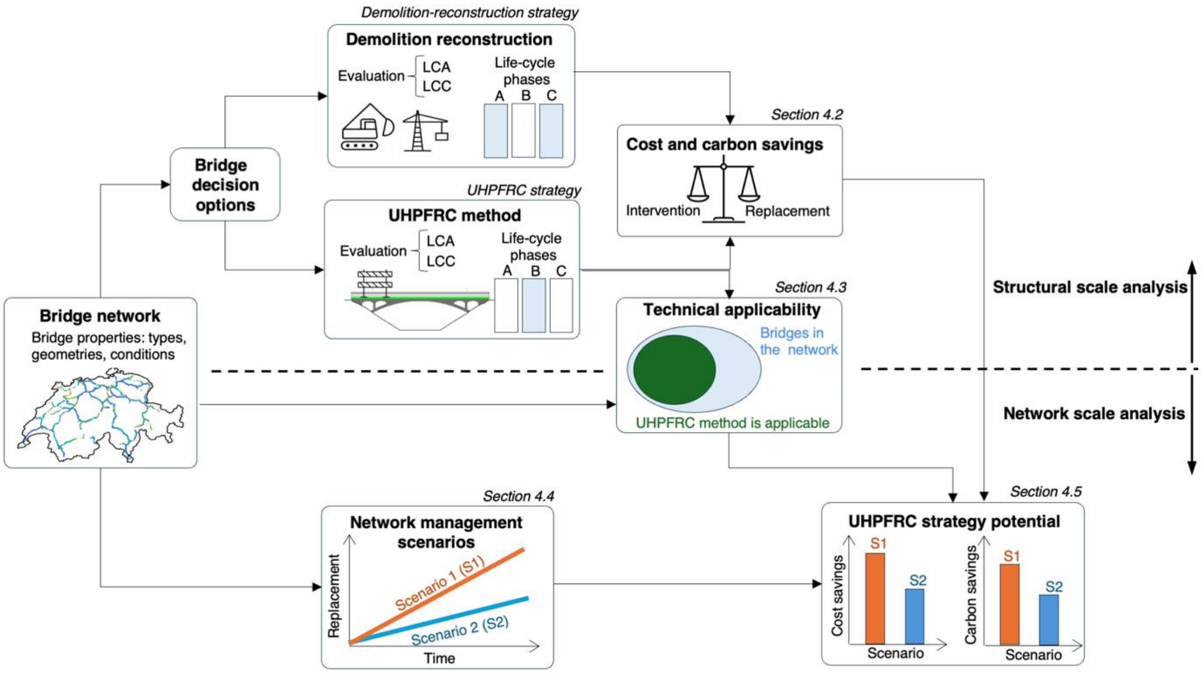

Fig. 8 Flowchart of the proposed framework to quantify the benefits of the UHPFRC strategy vs the traditional demolition-reconstruction strategy

Cost and carbon savings

This section introduces the methodology used for comparing the life-cycle costs (LCC) and life-cycle assessment (LCA) of the UHPFRC intervention with those of the traditional demolition-reconstruction solution. The LCA (ISO 14040 and 14044[69]) and LCC (ISO 15686[70]) frameworks have been adapted for UHPFRC-method interventions. Hypotheses for LCA and LCC are presented below.

The functional unit is the extension of the bridge service duration for an additional 80 years, either through its demolition and reconstruction (traditional intervention) or through a UHPFRC intervention. Given the difference between the two solutions, the following system boundaries are considered, following the LCA stages (information modules)[71]. For the demolition-reconstruction solution, the system includes the "end-of-life" stage of the structures to be demolished (modules C1-C4) and the production, transportation to the bridge site, and construction processes of the components needed for the new structure (modules A1-A5). For the UHPFRC intervention, the system includes the rehabilitation and strengthening of the bridge ("refurbishment" LCA module B5) as it aims for a major intervention to extend service life. The UHPFRC-method intervention includes the removal of damaged concrete and asphalt pavement, concrete curbs (if replaced) (modules C1-C4), and the production and transportation of the materials needed for the intervention (modules A1-A5).

The bridge maintenance prior to and after UHPFRC-method intervention (module B2), which would involve replacing expansion joints, bearing devices, asphalt pavement, and vehicle retention devices, is not included in the analyses as it is assumed to be similar in each strategy. The elimination of the bridge components (module C) in the replacement strategy is neglected in this study due to limited available information on existing bridge designs and the low influence of elimination on the overall environmental impacts (2 to 4 %) according to the literature[57,72]. This simplification leads to a slight underestimation of the environmental impacts of the replacement strategy.

For the LCA, the global warming potential (GWP) metric[73], expressed in $kgCO_{2eq,}$ is the sole environmental indicator. The life-cycle inventories for material processes, material transportation, and waste elimination are sourced from the KBOB database for Switzerland (version 6.2, 06.12.2024 update)[74], which is based on the Ecoinvent 3 database[58]. The GWP impact of UHPFRC production is unfortunately not included in the database. They are taken from the literature on commercial UHPFRC products available in Switzerland[40,47], which have also been evaluated using Ecoinvent data. For all projects, an average distance of 50 km is considered for all material transportation with 16-to-32-ton trucks for module A4. Details of environmental impact factors are presented in Supplementary Table 2.

Concerning the LCC, costs are quantified in Swiss Francs (CHF) and include all direct project costs, namely materials, labor, and equipment. At the time of writing in September 2025, 1 CHF

= 1.25 USD. Cost estimations are based on information provided by bridge owners and documented case studies[60,75,76]. LCC analyses use a constant 2 % discount rate per year, which is a typical value considered by Swiss bridge owners, reflecting the value of money over time.

To facilitate the comparison across case studies, LCC and LCA results (in CHF and $kgCO_{2eq}$, respectively) are reported per unit of functional bridge deck area (m^2). The functional bridge deck area spans from curb to curb.

The following limitations of the LCA and LCC methods are recognized. Constant impact factors are used (i.e., the material production GWP is independent of the volume produced), which may underestimate impacts for large-scale productions and overestimate impacts for small-scale ones. The analysis also does not consider the potential future evolution of industrial processes and environmental impact factors.

UHPFRC-method technical applicability

This section introduces the method used to determine the subset of bridges in the network that can be strengthened using the UHPFRC method. This assessment involves comparing bridge key attributes – structural system, construction materials, geometry, construction year, and condition state – to those of successful UHPFRC intervention based on Swiss documented case studies (Section **Error! Reference source not found.**).

An applicability ratio r_a is introduced to represent the global share of the overall bridge deck area within the bridge network suitable for a structural intervention with the UHPFRC method. As multiple factors must be accounted for, the applicability ratio is evaluated as the union of a set of ratios depending on bridge key attributes. It accounts for the combination of all bridge subsets that meet all the applicability criteria of the UHPFRC method:

$$r_a = \cup_i r_i \quad (1)$$

Each ratio r_i represents the fraction of the total deck surface in the network where UHPFRC application is technically feasible:

$$r_i = \frac{total\ bridge\ deck\ area\ suitable\ for\ UHPFRC\ method}{total\ bridge\ deck\ area\ in\ the\ network} \in [0,1] \quad (2)$$

The considered ratios r_i are the following:

1. Material ratio r_m: assesses the feasibility of the UHPFRC method with respect to bridge construction materials (e.g., concrete, steel, masonry).

2. Structural type ratio r_t: assesses the feasibility of UHPFRC-method interventions with respect to bridge structural configurations (e.g., continuous beams, frames, single beams).
3. Surface ratio r_{su}: assesses the feasibility of UHPFRC-method interventions with respect to bridge deck surface area.
4. Span ratio r_{sp}: assesses the feasibility of UHPFRC-method interventions with respect to different span numbers in the network (from 1 to multiple spans).
5. Condition ratio r_c : assesses the feasibility of UHPFRC-method interventions according to current bridge condition grades (from grade 1 – good condition – to grade 5 – alarming state) as applied in Switzerland[7].
6. Construction year ratio r_y: assesses the feasibility of UHPFRC-method interventions based on the bridge's construction year (from the early 1800s to 2020s). The construction year is relevant as it reflects the ability to apply UHPFRC on evolving construction practices.

Network management scenarios

This section presents the bridge-replacement evaluation method at the network scale. Predicting the number of future bridge replacements is challenging; therefore, three scenarios are considered. For each scenario, bridges due for replacement are estimated annually until 2105 (80-year horizon). The considered scenarios are the following:

1. Design-based scenario (Scenario 1): This scenario assumes that all bridges will be replaced at the end of their intended service duration. In this scenario, bridges are maintained conventionally until they reach 80 years and are thus either replaced or rehabilitated/strengthened using the UHPFRC method. This scenario aims to provide an upper bound for the number of replacements, as it is likely that bridges at the end of the intended service duration will not be replaced if they are still in acceptable or good condition.
2. Degradation-based scenario (Scenario 2): This scenario utilises predictions of the condition degradation of the bridges in the network to define when bridges will be replaced. In this scenario, it is conservatively assumed that bridges are replaced when they reach an alarming state, i.e., the worst grade (5/5) according to the Swiss bridge-condition rating system[7]. Grade 5 means the structural integrity is compromised, and urgent safety measures, such as decommissioning, must be taken on the bridge.

Such bridge-condition evolution predictions can be made using Markov-Chain simulations of the bridge-element condition evolution with degradation models from the latest bridge inspection[77]. The Swiss Federal Road Office implemented this method, and the results were detailed in a report for the studied bridge network[78]. These prediction datasets are used to determine the number of replacements per year in Scenario 2.

3. **Budget-based scenario (Scenario 3):** This scenario is based on the current bridge-replacement budget, which allows an average of 10 bridges to be replaced per year. This scenario assumes a constant replacement number per year, meaning that the same inflation-adjusted budget is projected over the next 80 years, independently of the bridge condition in the network. The bridge owner of the present network case study is currently following this strategy. This scenario represents a lower bound for the number of bridge replacements as it does not account for the expected increase in replacement needs due to ongoing bridge condition degradation.

UHPFRC strategy potential

The benefits of performing a UHPFRC-method intervention rather than the traditional demolition-reconstruction solution at the network scale are quantified by combining information from the cost and environmental savings at the structural scale, the applicability rate of the UHPFRC-method intervention on the network, and the bridge replacement scenarios. For each year and scenario, the suitable bridge deck surface to be replaced or strengthened is calculated based on the network total bridge deck surface multiplied by the applicability ratio (Equation 1). Then, this number is multiplied by the normalized environmental and cost savings per year. The savings are summed over the 80 years considered, and the scenario results are compared.

The current bridge-replacement budget is then evaluated by calculating the bridge management gap. The bridge management gap (BMG [# bridges]) compares the number of bridges that should be replaced each year (based on a given replacement scenario) with the current number of bridges being replaced, given the asset managers' budget, as used in Scenario 3. A positive value indicates a budget surplus, allowing one or more bridges to be replaced/maintained proactively (i.e., before reaching an alarming state), whereas a negative value indicates a budget shortfall and the budget should be increased or traffic restrictions on the network implemented.

In each year i, the bridge management replacement gap BMG is calculated by comparing the number of bridge replacements under Scenario j $N_{r,j}$ with the number of bridges feasibly addressed by the proposed strategy N_s, assuming a constant budget (Equation 3). For the demolition-reconstruction strategy, the current asset manager's budget allows for 10 replacements per year ($N_s = 10$). For the UHPFRC strategy, the number of interventions will be higher (assumed as $N_s = 40$), as the UHPFRC intervention is estimated to be four times cheaper (2,500 rather than 10,000 CHF/m^2) than a bridge replacement (Section Bridge-scale analysis).

$$BMG(i)\ [\#\ \text{bridges}] = N_{r,j}(i) - N_s(i)\ \forall i \in [2025; 2105] \quad (3)$$

Data availability statement

The input datasets (i.e., bridge condition data) used in this study are not publicly available due to confidentiality agreements with bridge owners. However, datasets generated and analysed during the study (i.e., bridge replacement scenarios, cost and carbon savings, and case study results) are available from the corresponding author upon request. Source data are provided with this paper.

Code availability statement

Carbon and cost-saving potential algorithms are available as Supplementary Code 1.

References

1. Sánchez-Silva, M., Frangopol, D. M., Padgett, J. & Soliman, M. Maintenance and Operation of Infrastructure Systems: Review. *J. Struct. Eng.* **142**, F4016004 (2016).

2. Yanweerasak, T., Pansuk, W., Akiyama, M. & Frangopol, D. M. Life-cycle reliability assessment of reinforced concrete bridges under multiple hazards. *Struct. Infrastruct. Eng.* **14**, 1011–1024 (2018).

3. Bocchini, P., Frangopol, D., Ummenhofer, T. & Zinke, T. Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach. *J. Infrastruct. Syst.* **20**, 04014004 (2014).

4. Biondini, F. & Frangopol, D. M. Life-Cycle Performance of Deteriorating Structural Systems under Uncertainty: Review. *J. Struct. Eng.* **142**, F4016001 (2016).

5. Barone, G., Frangopol, D. M. & Soliman, M. Optimization of Life-Cycle Maintenance of Deteriorating Bridges with Respect to Expected Annual System Failure Rate and Expected Cumulative Cost. *J. Struct. Eng.* **140**, 04013043 (2014).

6. Zhang, G., Liu, Y., Liu, J., Lan, S. & Yang, J. Causes and statistical characteristics of bridge failures: A review. *J. Traffic Transp. Eng. Engl. Ed.* **9**, 388–406 (2022).

7. Bertola, N. & Brühwiler, E. Risk-based methodology to assess bridge condition based on visual inspection. *Struct. Infrastruct. Eng.* **0**, 1–14 (2021).

8. Ye, C., Kuok, S.-C., Butler, L. J. & Middleton, C. R. Implementing bridge model updating for operation and maintenance purposes: examination based on UK practitioners' views. *Struct. Infrastruct. Eng.* **18**, 1638–1657 (2022).

9. Brühwiler, E. Framework to engineer existing bridges for sustainability, validated by applications. *Struct. Infrastruct. Eng.* 1–15 (2025) doi:10.1080/15732479.2025.2453485.

10. Habel, K., Viviani, M., Denarié, E. & Brühwiler, E. Development of the mechanical properties of an Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). *Cem. Concr. Res.* **36**, 1362–1370 (2006).

11. Du, J. *et al.* New development of ultra-high-performance concrete (UHPC). *Compos. Part B Eng.* **224**, 109220 (2021).

12. Graybeal, B. A. *Material Property Characterization of Ultra-High Performance Concrete*. https://rosap.ntl.bts.gov/view/dot/38714/ (2006).

13. Yu, R., Spiesz, P. & Brouwers, H. J. H. Mix design and properties assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). *Cem. Concr. Res.* **56**, 29–39 (2014).

14. Shi, C. *et al.* A review on ultra high performance concrete: Part I. Raw materials and mixture design. *Constr. Build. Mater.* **101**, 741–751 (2015).

15. Wang, D. *et al.* A review on ultra high performance concrete: Part II. Hydration, microstructure and properties. *Constr. Build. Mater.* **96**, 368–377 (2015).

16. Yoo, D.-Y. & Banthia, N. Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review. *Cem. Concr. Compos.* **73**, 267–280 (2016).

17. Hung, C.-C., El-Tawil, S. & Chao, S.-H. A Review of Developments and Challenges for UHPC in Structural Engineering: Behavior, Analysis, and Design. *J. Struct. Eng.* **147**, 03121001 (2021).

18. Charron, J.-P., Denarié, E. & Brühwiler, E. Permeability of ultra high performance fiber reinforced concretes (UHPFRC) under high stresses. *Mater. Struct.* **40**, 269–277 (2007).

19. Toutlemonde, F. *et al.* Long-term material performance checked on world's oldest UHPFRC road bridges at Bourg-Lès-Valence. in 265–274 (Marseille, France, 2013).

20. Li, J., Wu, Z., Shi, C., Yuan, Q. & Zhang, Z. Durability of ultra-high performance concrete – A review. *Constr. Build. Mater.* **255**, 119296 (2020).

21. Brühwiler, E. UHPFRC technology to enhance the performance of existing concrete bridges. *Struct. Infrastruct. Eng.* **16**, 94–105 (2020).

22. Brühwiler, E. & Denarié, E. Rehabilitation and Strengthening of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete. *Struct. Eng. Int.* **23**, 450–457 (2013).

23. Graybeal, B. *et al.* International Perspective on UHPC in Bridge Engineering. *J. Bridge Eng.* **25**, 04020094 (2020).

24. Bertola, N., Schiltz, P., Denarié, E. & Brühwiler, E. A Review of the Use of UHPFRC in Bridge Rehabilitation and New Construction in Switzerland. *Front. Built Environ.* **7**, 155 (2021).

25. Xue, J. *et al.* Review of ultra-high performance concrete and its application in bridge engineering. *Constr. Build. Mater.* **260**, 119844 (2020).

26. Zhou, M., Lu, W., Song, J. & Lee, G. C. Application of Ultra-High Performance Concrete in bridge engineering. *Constr. Build. Mater.* **186**, 1256–1267 (2018).

27. Brühwiler, E. About the process of technology transfer from research to engineering practice. *Struct. Infrastruct. Eng.* in print (2025).

28. Schranz, B. *et al.* Strengthening and prestressing of bridge decks with ribbed iron-based shape memory alloy bars. *Eng. Struct.* **241**, 112467 (2021).

29. Madaj, A. & Mossor, K. Evaluation of External Prestressing as a Strengthening Method for Existing Concrete Bridges. *Struct. Eng. Int.* **29**, 412–416 (2019).

30. Zou, X., Lin, H., Feng, P., Bao, Y. & Wang, J. A review on FRP-concrete hybrid sections for bridge applications. *Compos. Struct.* **262**, 113336 (2021).

31. Feng, S., Xiao, H., Liu, R. & Liu, M. The bond properties between ultra-high-performance concrete and normal strength concrete substrate: Bond macro-performance and overlay transition zone microstructure. *Cem. Concr. Compos.* **128**, 104436 (2022).

32. Huang, Y., Grünewald, S., Schlangen, E. & Luković, M. Strengthening of concrete structures with ultra high performance fiber reinforced concrete (UHPFRC): A critical review. *Constr. Build. Mater.* **336**, 127398 (2022).

33. Bentz, D. P. *et al.* Influence of substrate moisture state and roughness on interface microstructure and bond strength: Slant shear vs. pull-off testing. *Cem. Concr. Compos.* **87**, 63–72 (2018).

34. Beushausen, H., Höhlig, B. & Talotti, M. The influence of substrate moisture preparation on bond strength of concrete overlays and the microstructure of the OTZ. *Cem. Concr. Res.* **92**, 84–91 (2017).

35. Brühwiler, E. UHPFRC technology for the extension of the service duration of bridges. in *Bridge Maintenance, Safety, Management, Digitalization and Sustainability* 158–166 (CRC Press, 2024).

36. Habert, G. *et al.* Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **1**, 559–573 (2020).

37. Brühwiler, E. & Bastien Masse, M. Strengthening the Chillon viaducts deck slabs with reinforced UHPFRC. in *IABSE Conference Geneva 2015 'Structural Engineering: Providing Solutions to Global Challenges'* 1171 (IABSE, Geneva, Switzerland, 2015).

38. El Jisr, H., Moreillon, L. & Menétrey, P. Strengthening of the Riddes Viaduct Through UHPFRC-Based Rehabilitation. *Struct. Eng. Int.* **0**, 1–9 (2023).

39. Bertola, N. J., Brühwiler, E. & Favre, J.-F. Renforcement et élargissement du Pont de Ferpècle via un clavage des culées en CFUP armé. in (2023).

40. Hajiesmaeili, A., Pittau, F., Denarié, E. & Habert, G. Life Cycle Analysis of Strengthening Existing RC Structures with R-PE-UHPFRC. *Sustainability* **11**, 6923 (2019).

41. Brochellaz, L., Laurencet, P. & Brühwiler, E. Renforcement au CFUP du pont de Bramois sur le Torrent de Verbier. in *3ème Journée Suisse du BFUP* 25–36 (2019).

42. Sameer, H. *et al.* Environmental assessment of ultra-high-performance concrete using carbon, material, and water footprint. *Materials* **12**, 851 (2019).

43. Randl, N., Steiner, T., Ofner, S., Baumgartner, E. & Mészöly, T. Development of UHPC mixtures from an ecological point of view. *Constr. Build. Mater.* **67**, 373–378 (2014).

44. Lande, I. & Terje Thorstensen, R. Comprehensive sustainability strategy for the emerging ultra-high-performance concrete (UHPC) industry. *Clean. Mater.* 100183 (2023) doi:10.1016/j.clema.2023.100183.

45. Habert, G., Denarié, E., Šajna, A. & Rossi, P. Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cem. Concr. Compos.* **38**, 1–11 (2013).

46. Fan, J., Huang, W., Wang, H., Adams, M. P. & Bandelt, M. J. Multi-physics simulation–driven assessment of environmental and cost performance in ultra-high performance concrete (UHPC) bridge deck under local climate effects. *Eng. Struct.* **343**, 121029 (2025).

47. Bertola, N., Küpfer, C., Kälin, E. & Brühwiler, E. Assessment of the Environmental Impacts of Bridge Designs Involving UHPFRC. *Sustainability* **13**, 12399 (2021).

48. Shao, Y., Parks, A. & Ostertag, C. P. Carbon Footprint between Steel-Reinforced Concrete and UHPC Beams. *J. Struct. Eng.* **149**, 06023001 (2023).

49. di Summa, D., Parpanesi, M., Ferrara, L. & De Belie, N. A holistic life cycle design approach to enhance the sustainability of concrete structures. *Struct. Concr.* **24**, 7684–7704 (2023).

50. Dong, Y. Performance assessment and design of ultra-high performance concrete (UHPC) structures incorporating life-cycle cost and environmental impacts. *Constr. Build. Mater.* **167**, 414–425 (2018).

51. Bertola, N., Kälin, E. & Brühwiler, E. Environmental and Life-Cycle Cost Evaluation of a Composite Timber-UHPFRC Bridge. in vol. 3 (Iowa State University Digital Press, 2023).

52. Federal Roads Office (FEDRO). https://www.astra.admin.ch/astra/en/home.html.

53. Federal Road Office (FEDRO). *RAPPORT SUR L'ÉTAT DU RÉSEAU DES ROUTES NATIONALES 2023*. 56 https://www.astra.admin.ch/astra/fr/home/themes/routes-nationales/reseau/rapport-d-etat-des-routes-nationales.html (2024).

54. Collings, D. The Carbon Footprint of Bridges. *Struct. Eng. Int.* **32**, 501–506 (2022).

55. Collings, D. & Murthy, S. An update on bridge carbon footprint data. *Proc. Inst. Civ. Eng. - Bridge Eng.* 1–21 (2024) doi:10.1680/jbren.23.00032.

56. Archer-Jones, C. & Green, D. Carbon targets for bridges: a proposed SCORS-style rating scheme. *Struct. Eng.* **99**, (2021).

57. Orr, J., Gibbons, O. & Arnold, W. A brief guide to calculating embodied carbon. *Struct Eng* **98**, 22–27 (2020).

58. KBOB, K. der B. L. der öffentlichen B. Ökobilanzdaten im Baubereich. https://www.kbob.admin.ch/kbob/de/home/themen-leistungen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html (2024).

59. Swiss Society of Engineers and Architects. Règlement concernant les prestations et honoraires des ingénieurs civils - SIA 103. (2020).

60. Bertola, N. & Brühwiler, E. Transforming The Static System of Prestressed Concrete Bridges Using UHPFRC. *J. Bridge Eng.* under review (2025).

61. Yu, R. *et al.* Sustainable development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): Towards to an optimized concrete matrix and efficient fibre application. *J. Clean. Prod.* **162**, 220–233 (2017).

62. Brühwiler, E. *et al.* Strengthening the Chillon viaducts deck slabs with reinforced UHPFRC. in *IABSE Symposium Report* vol. 105 1–8 (International Association for Bridge and Structural Engineering, 2015).

63. Adey, B., Hajdin, R. & Brühwiler, E. Effect of Common Cause Failures on Indirect Costs. *J. Bridge Eng.* **9**, 200–208 (2004).

64. Tran, H., Robert, D., Gunarathna, P. & Setunge, S. Estimating Cost of Bridge Closure for Bridge Network Rehabilitation Priorities. *J. Constr. Eng. Manag.* **150**, 04024071 (2024).

65. Haber, Z. B., McDonagh, M., Foden, A. & Sadasivam, S. *Ultra-High Performance Concrete (UHPC) Overlays: An Example of Lifecycle Cost Analysis [Tech Note]*. (2022).

66. Yuan, Y., Wu, C. & Jiang, X. Experimental study on the fatigue behavior of the orthotropic steel deck rehabilitated by UHPC overlay. *J. Constr. Steel Res.* **157**, 1–9 (2019).

67. Jun, Z. 2024 Highlights of UHPC Developments in China. *White Hub* https://www.white-hub.com/innovation-sustainability/2024-highlights-uhpc-developments-china (2025).

68. Technical Leaflet on UHPFRC: Materials, Design and Application. 48 (2016).

69. Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K. & Klüppel, H.-J. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **11**, 80–85 (2006).

70. Sjöström, C. *et al.* Implementation of the European Construction Products Directive via the ISO 15686 standards. in *9th Conference of Durability of Building Materials and Components, Brisbane 2002* (2002).

71. European Standards. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (includes Corrigendum :2021). (2022) doi:10.31030/3294005.

72. Jalaei, F., Zhang, J., Ayuk, N. M.- & McLeod, C. Environmental life cycle assessment (LCA) for design of climate-resilient bridges – a comprehensive review and a case study. *Int. J. Constr. Manag.* https://www.tandfonline.com/doi/abs/10.1080/15623599.2024.2304479 (2025).

73. DIN EN ISO 14044. (2021) doi:10.31030/3179656.

74. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).

75. Brühwiler, E., Oesterlee, C. & Redaelli, D. *Béton Fibré Ultra Performant: Concevoir, Dimensionner, Construire. 3ème Journée d'étude, 24 Octobre 2019*. 196 https://www.heia-fr.ch/media/vmvibli0/gesamt-tagungsband-uhfb-2019.pdf (2019).

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

77. Cesare, M. A., Santamarina, C., Turkstra, C. & Vanmarcke, E. H. Modeling Bridge Deterioration with Markov Chains. *J. Transp. Eng.* **118**, 820–833 (1992).

78. Marsili, F. *et al. Abschätzung Der Restnutzungsdauer von Brückenbauwerken Durch Entwicklung Und Erprobung Hybrider Modelle - ENDURE*. 264 (2024).

Acknowledgments

The authors are thankful for the data and input provided by Dr. Dimitrios Papastergiou and Charles-Henry Demory (Federal Roads Office FEDRO) and Dr. Marian Ralbovsky (Austrian Institute of Technology).

Author contribution statement

NB, CK and EB contributed to the conceptualization of the study. NB and CK performed the analyses. NB developed the code and drafted the manuscript. All authors reviewed and approved the final version.

Competing Interests Statement

The authors declare no competing interests.

Figure legends

Editorial Summary:
The study evaluates using ultra-high-performance fiber-reinforced cementitious composite (UHPFRC) for bridge maintenance in Switzerland, finding it feasible for 99.7% of bridges, potentially saving 7.7 million tons of CO2 equivalent and 18.5 billion Swiss francs over 80 years compared to traditional methods.

Peer review information: *Nature Communications* thanks Pamela Haverkamp, Gabriel Sas and Helder Sousa for their contribution to the peer review of this work. A peer review file is available.