Environmental and Life-Cycle Cost Evaluation of a Composite Timber-UHPFRC Bridge

Numa Bertola, Ph.D. (corresponding author) – Postdoctoral Researcher, Laboratory for Maintenance and Safety of Structures, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, Email: numa.bertola@epfl.ch

Edgar Kälin – Structural Engineer, Ingenieurbüro Edgar Kälin AG, Werner-Kälin-Strasse 7, 8840 Einsiedeln, Switzerland.

Eugen Brühwiler, Ph.D. – Full Professor, Laboratory for Maintenance and Safety of Structures, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland.

Abstract

Ultra-High-Performance Fibre Reinforced Cementitious Composite (UHPFRC) has recently been used to design lightweight structures and strengthen existing ones, with more than 300 applications in Switzerland. Several composite timber-UHPFRC bridges have been built in Switzerland, also to reduce the environmental impact of the construction. Girders are typically made of timber girders, while the deck slab is in UHPFRC. This high-performance material reduces, typically by 3, the deck weight compared to traditional reinforced-concrete slabs. Using UHPFRC also improves the durability of the timber elements as the UHPFRC deck slab remains crack-free under service conditions, meaning that the timber, located underneath the deck, remains dry and protected from direct water contact. This paper proposes a methodology to compare UHPFRC structures with traditional reinforced-concrete designs by evaluating the environmental impact and life-cycle costs over the expected bridge service duration. The first timber-UHPFRC bridge built in Switzerland is used as an example. Results show that composite structures can significantly reduce the environmental impact and costs of short-span bridge design. Timber-UHPFRC composite structures are thus promising to enhance sustainability of the construction sector, especially in the infrastructure domain. Moreover, the methodology supports bridge owners in assessing the life-cycle costs and environmental impacts of structural designs involving UHPFRC with their associated maintenance scheme, leading to better decision-making.

Keywords: Structural UHPFRC, Ultra-High-Performance Fibre-Reinforced Cementitious Composite. Life-Cycle Analysis, Life-Cycle Costs, Timber-UHPFRC, Lightweight Bridges.

1. Introduction

Ultra-High-Performance Fibre Reinforced Cementitious Composite (UHPFRC) is most promising as it has been used worldwide to design lightweight structures for 20 years (Bertola, Schiltz, et al.; Graybeal et al.). UHPFRC is made of a mix of cement, fine hard particles (with a maximum grain size of 1 mm), water, admixtures and additives, and a large amount of short slender steel fibers with a minimal requirement of 3-volume % (Brühwiler and Denarié). UHPFRC differs from concrete thanks to its compact matrix, the exclusion of aggregate, and a large quantity of steel fibers.

The structural performance and mechanical properties of UHPFRC have been summarized by (Brühwiler). UHPFRC has significant resistance in compression (up to 150 MPa) but also in tension (up to 16 MPa), while elastic modulus is equal to 45 to 50 GPa. Importantly, the material has a strain-hardening domain in tension until a strain of 2-4 ‰. The inclusion of reinforcement bars (R-UHPFRC) in the material significantly improves tensile strength, similarly to RC structures. Thanks to the strain-hardening behavior of the material, UHPFRC elements remain crack-free under service conditions. UHPFRC elements are thus waterproof.

The design of new civil infrastructure, such as bridges should be carefully made due to the costs and environmental impacts of the decision. This choice should account for the environmental impacts and costs of design alternatives over the entire service duration (Coenen et al.). Life-cycle costs (LCC) over the bridge service duration have been frequently assessed. A general formulation to evaluate LCC has been proposed (Frangopol et al.).

The impact of UHPFRC production has been reviewed (Pushkar and Ribakov) for new UHPFRC elements but without accounting for the influence of this high-performance material on maintenance. Studies on bridge rehabilitation with UHPFRC (Hajiesmaeili et al.; Sameer et al.) have shown interventions made with UHPFRC have significantly lowered detrimental environmental impacts compared to a traditional deconstruction-reconstruction solution. A recent study has compared new bridge designs made of UHPFRC and shows lower environmental impacts compared to conventional reinforced concrete (Bertola, Küpfer, et al.).

As lightweight structures are designed in UHPFRC (Bertola, Schiltz, et al.), the combination with timber is promising for bridge designs. Using timber for bridge girders ensures low environmental impacts on the structure, while UHPFRC for the deck provides the stiffness to support live loads with a limited increase of the deadweight compared to a reinforced-concrete deck. Additionally, the durability properties of UHPFRC provide good protection to timber elements against water and chemical ingress. Several pioneer bridges have been built in composite timber-UHPFRC in Switzerland since 2018 (Berchtold et al.; Kälin and Roggenmoser).

2. Evaluation of timber-UHPFRC structures

Bridge design can involve various structural alternatives made of different materials. The selection of the structural system affects the design and the maintenance scheme of the bridge and, thus, their life-cycle environmental impacts and costs. The comparison methodology includes several steps (Figure 1) that are detailed below. Once the main constraints of the problems are set, such as bridge dimensions and execution requirements, several structural designs are generated (Step 1), such as a timber-UHPFRC design or a conventional RC structure.

Once bridge design alternatives are generated, the system boundaries and the functional unit must be defined for comparison (Step 2). The functional unit and the system boundaries explicitly define processes included in the comparison, such as the cradle-to-grave comparison of bridge designs over a given service duration.

Then, bridge designs are evaluated in terms of life-cycle environmental impacts (LCA) and life-cycle costs (LCC) in respectively Step 2 and Step 3. The LCA aims to quantify the environmental impacts of considered systems; here, the bridge solutions. Following (Frangopol et al.) The LCC involves evaluating the sum of the construction costs C_{cons}, the routine inspection costs C_{insp}, the maintenance costs C_{maint}, the elimination costs C_{elim} and the failure costs C_f (Equation 1).

$$C_{tot} = C_{cons} + C_{insp} + C_{maint} + C_{elim} + C_f \quad (1)$$

These evaluations must account for three main phases of the bridge use duration: the construction of the structure, its maintenance during the use, and its elimination at the end of the service duration. These phases are associated with different levels of uncertainties that require hypotheses, such as future maintenance schemes or the elimination of UHPFRC, with little evidence in the literature (Sameer et al.).

Another strong hypothesis is the definition of the service duration of the bridge. Although decision-makers today typically set a minimum use duration before the bridge construction, bridges do not need to be replaced at the end of the theoretical service duration (Brühwiler et al.). As maintenance schemes usually involve recurring interventions, LCA and LCCA of a bridge design are significantly influenced by the initial definition of the bridge service duration. The final step involves selecting the best alternative based on performance criteria. When only the environmental impacts and life-cycle costs are involved, benefit-cost analysis can be performed.

When large uncertainties are associated with maintenance and elimination processes, a comparison of the three time horizons (construction, maintenance, elimination) should be performed. As each time horizon involves different uncertainties on environmental impacts and costs of maintenance scheme and service duration, this stepwise procedure helps select optimal solutions considering uncertainties over the bridge service duration.

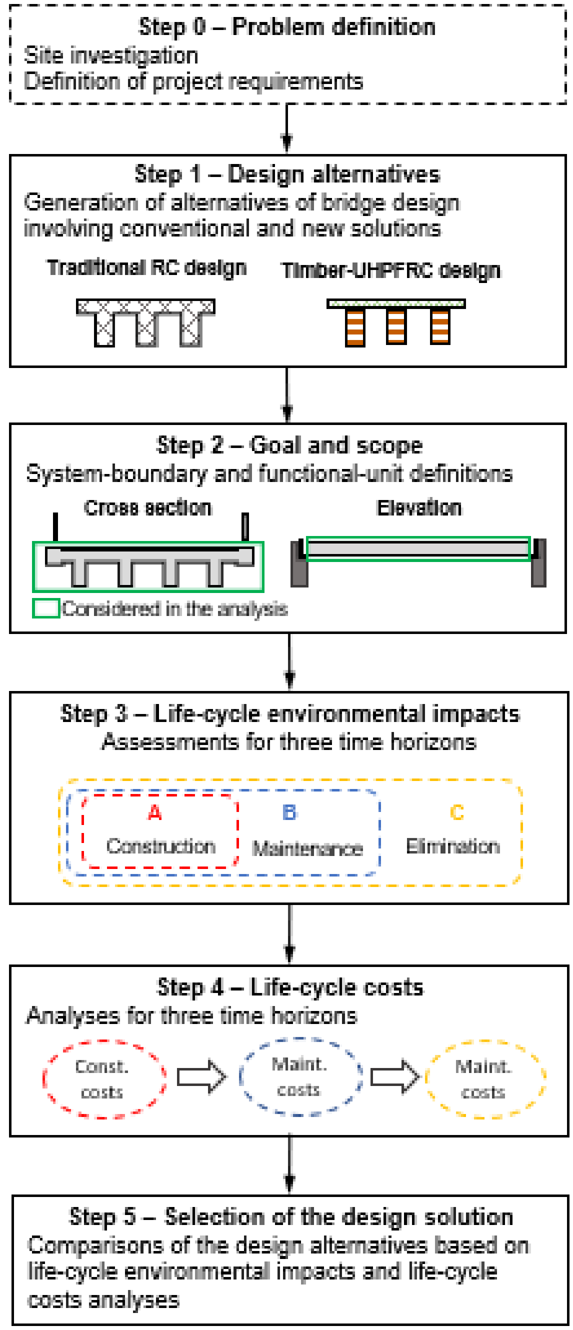

Figure 1. Overview of the methodology to compare bridge solutions.

3. Case study – Fruttli Bridge

3.1. Introduction

In this section, a timber-UHPFRC bridge is compared to a conventional reinforced-concrete structural alternative. These two alternatives were proposed by design offices, and bridge owners have selected the first solution. This decision was mostly based on construction costs. The timber-UHPFRC bridge was built in 2020 in central Switzerland. The bridge is located on a secondary road and is mostly used by agricultural traffic.

First, the site characteristics are detailed. The new structure must connect the banks of a small river. This structure must replace an old RC bridge in bad condition. The structure has a single span of about 10 m for a width of 3.5 m. This novel superstructure is built upon the existing abutment and must not reduce the current hydraulic clearance.

As both alternatives will reuse the existing abutments, these elements are thus not included in this comparison. Similarly, the equipment components used in both alternatives, such as railings and expansion joints, are not included in this comparison as they are not affecting the results. All structural elements necessary for their construction, maintenance, and elimination are included in the comparison.

Figure 2 Presentation of the Fruttli Bridge and casting of the UHPFRC deck slab.

3.2. Design Alternatives

In this section, both bridge designs are presented. Due to the small span of the bridge and the constraints of the hydraulic clearance, the timber-UHPFRC is built following a girder-slab solution. Following a material optimization process, four main girders (depth of 530 mm; width of 260 mm), made of glued-laminated timber (GL28c) from Swiss wood (Figure 3a), are connected to the UHPFRC slab with a thickness between 85 and 140 mm. The full connection between the UHPFRC slab and the timber girders is made through steel connectors. The UHPFRC slab is also reinforced using 24 rebars with a diameter of 14 mm in the transverse direction. This slab is cast directly on wooden panels. Due to the properties of UHPFRC, this element also works as a protective layer for timber elements, avoiding a waterproofing membrane. Thanks to this protection, timber girders are expected to remain in good condition over the bridge use duration, and thus few maintenance interventions are expected (Bertola, Küpfer, et al.). The UHPFRC top surface is grooved, enabling vehicles to pass directly on the slab, and thus the inclusion of an asphalt-pavement layer is not required in this bridge alternative. This alternative requires a new substructure involving an abutment made of concrete (C30/37), and an HEB 180 to support the timber girders. The total weight of the superstructure is equal to 21 tons.

The second bridge design is a conventional reinforced-concrete structure. This structure is made of a cast-on-site slab (Figure 3b). The required volume of concrete volume is estimated at 25 m^3, which leads to a weight of the superstructure of 63 tons. The steel reinforcement is estimated at 120 kg/m^3, representing 2670 kg of steel. A conventional waterproof layer (5-mm thick) and an asphalt pavement layer (80-mm thick) are included in the design alternative. A conventional concrete C30/37 is considered for the analyses.

One major constraint of this alternative is that the poured-concrete structure requires 28 days of setting. A temporary bridge must be built during the construction of the new structure. This temporary structure requires bringing and removing 300 m^3 of gravel to the construction site. The environmental impacts and construction costs of the temporary bridge are linked to the transportation of the gravel and the temporary bridge of 20 tons.

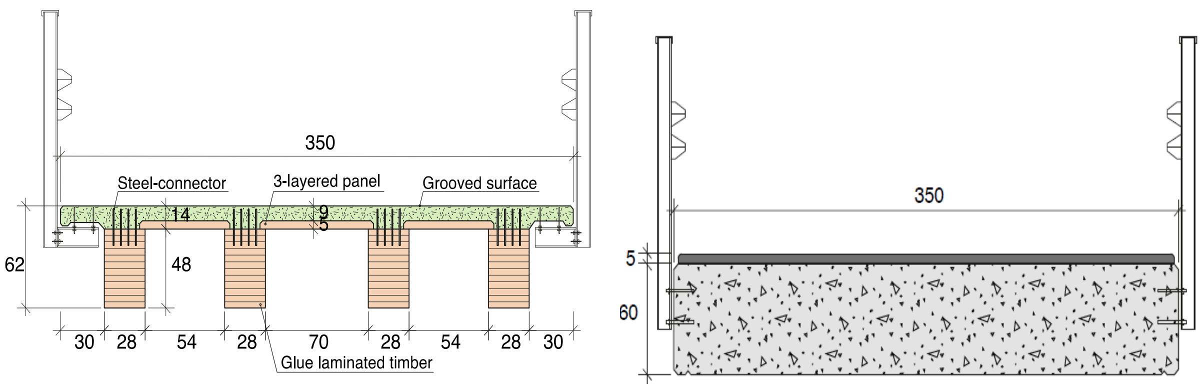

Figure 3 Alternatives: A) timber-UHPRC; B) Reinforced-concrete bridge.

3.3. Life-Cycle Environmental impacts

In this section, the LCA of both bridge alternatives is evaluated. This comparison involved a cradle-to-grave analysis, following the system boundary. The environmental impacts are quantified using the 2022 update of the KBOB database (Wernet et al.) and using the global warming potential (GWP), expressed in kg CO2 equivalent.

Figure 9 presents the comparison of the bridge environmental impacts over the total use duration. The conventional concrete structure has a larger environmental footprint (38.7 %) than the timber-UHPFRC bridge. For the concrete bridge, maintenance represents approximately 30% of the environmental impact, while maintenance processes have negligible influence on the environmental impacts of the timber-UHPFRC bridge. For conventional RC structures, maintenance represents a significant part of the total environmental impact over the bridge service duration, and this part is avoided with the proposed timber-UHPFRC structure thanks to the durability properties of UHPFRC and the avoidance of asphalt pavement.

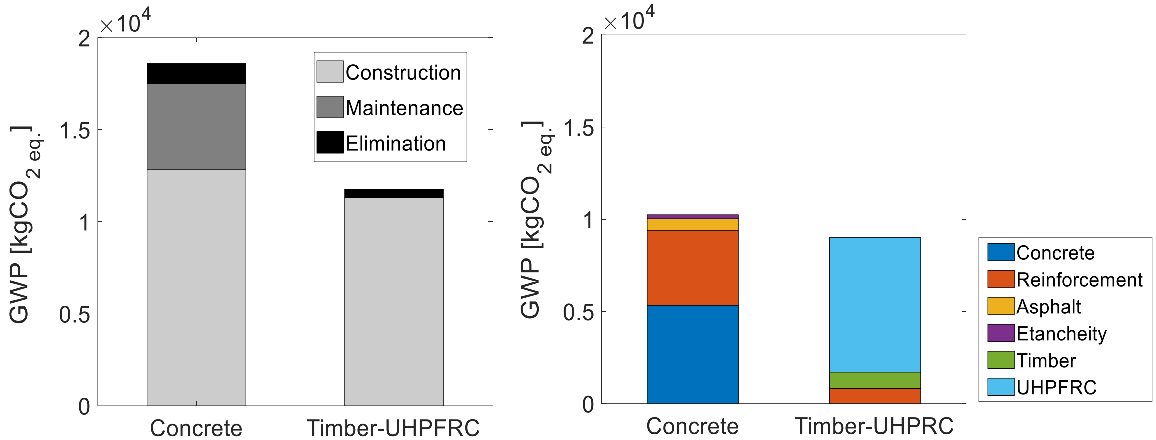

Figure 4 Environmental impact of bridge designs. A) Total impacts over the bridge service duration. B) impacts of the construction of the bridge superstructure.

3.4. Life-Cycle Costs

The LCC of both alternatives are evaluated based on Equation (1). The failure costs C_f and routine inspection costs C_{insp} are assumed to be equal for both bridge designs and are thus not included in the comparison. Construction costs are evaluated based on Swiss database for material costs (Federal Statistical Office), and discussions with engineers and contractors.

Discounting in economic evaluation implies that maintenance costs occurring at different timing are valued differently. A typical monetary discount rate of 2 % per year has been included in cost evaluations of the maintenance C_{maint} and elimination C_{elim} processes (Frangopol and Liu). For the RC alternative, the maintenance involves the replacement of the asphalt and waterproofing layers as well as a curb replacement and deck concrete rehabilitation after 40 years.

The total costs of both bridge designs are evaluated in Figure 5. Life-cycle costs of the RC structure are 43 % higher than the timber-UHPFRC bridge. This difference is due to a more important construction cost (20 %) and significant maintenance costs throughout the service duration. Material costs are higher for the timber-UHPFRC structure (Figure 5B) than for the conventional RC bridge. However, as smaller quantities of materials are required for the composite bridge, transport costs and installation costs are smaller. Additionally, the RC bridge requires building a temporary structure that has a high cost.

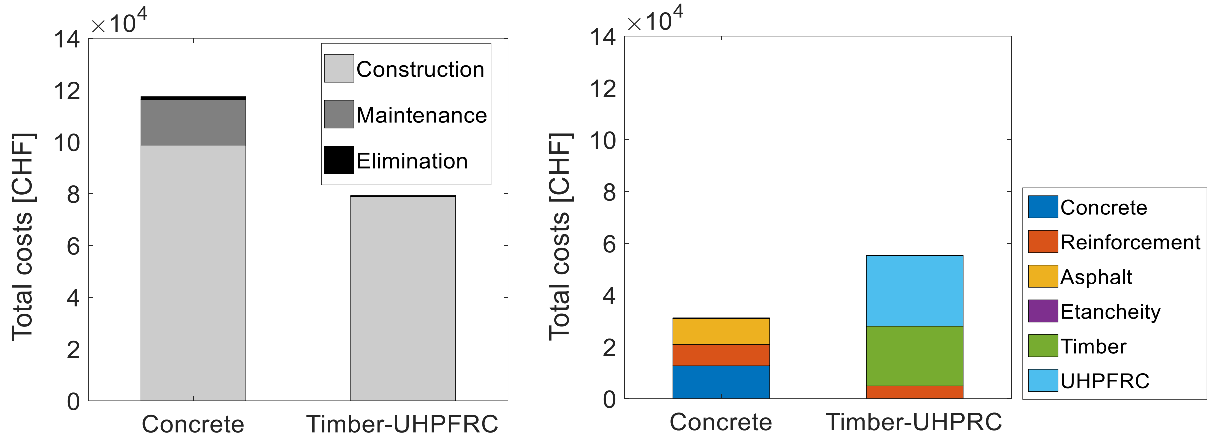

Figure 5 Life-cycle costs of bridge designs. A) Total costs over the bridge service duration; B) Construction costs of the bridge superstructure.

3.5. Comparison of Design Alternative

The last step involves a comparison of the two design alternatives. Table 1 summarizes the results of both environmental impacts and life-cycle cost evaluations. The timber-UHPFRC bridge is expected to reduce the environmental impacts by 38 % compared to the traditional reinforced-concrete solution. The life-cycle costs of the composite bridge are also reduced by 30 %, showing that more sustainable solutions are not necessarily more expensive.

Composite structures involving timber and UHPFRC involve lightweight design, significantly reducing the required construction material. Thanks to UHPFRC properties, these structures are durable, limiting the required maintenance to its minimum. Therefore, these innovative designs are in line with the principles of sustainable construction.

Table 1 Comparison of bridge-design solutions.

Alternative	Superstructure weight [kg]	Environmental impacts [kgCO$_{2\ eq}$]	Total costs [CHF]
Reinforced Concrete	63,422	18,608	119,958
Timber UHPFRC	20,890	11’401	83,762

4. Conclusions

In this paper, the design of composite structures made of UHPFRC and timber is investigated. A methodology to accurately assess these designs in comparison to conventional structures, following both life-cycle costs and environmental impacts. This method has been applied to the first application of a timber-UHPFRC bridge. Compared to the alternative solution made of a conventional RC structure, the composite bridge is both cheaper and has smaller environmental impact. Timber (environmentally friendly, light) and UHPFRC (light, protective) have complementary properties. Timber-UHPFRC composite structures offer innovative solutions for bridge design in agreement with the sustainability-development principles. The composite timber-

UHPFRC bridge significantly reduces the environmental impacts and life-cycle costs compared to conventional reinforced-concrete structures, leading to more sustainable bridge construction.

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