Methods to assess the Carbon Footprint of Structures involving UHPFRC Elements

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The development of Ultra-High Performance Fibre-Reinforced Cementitious Composite (UHPFRC) has enabled the design of lightweight constructions. Although the greenhouse gas emissions of UHPFRC per volume are higher than that of conventional concrete, its use reduces the required amount of material in structures. As UHPFRC is waterproof under service conditions, this material also enhances the durability of structures, significantly decreasing the need for maintenance throughout the service duration. Hence, a cradle-to-grave analysis at the project level is crucial to assess the environmental impact of structural designs. This study proposes a method to evaluate the ecological footprint of structural designs made of UHPFRC using three different time horizons: construction, maintenance, and elimination. The environmental impacts of design alternatives in UHPFRC and conventional concrete are compared using two case studies. The findings indicate that UHPFRC structures lead to a significant decrease in the environmental impacts over the service duration, offering promising results for sustainable construction.

Keywords: Ultra-High Performance Fibre-Reinforced Cementitious Composite (UHPFRC); Structural UHPFRC; Life-Cycle Assessment (LCA); Lightweight Structures

1 Introduction

Ultra-High Performance Fibre-Reinforced Cementitious Composite (UHPFRC) has been extensively used to design lightweight structures [1,2]. UHPFRC is made of a mix of cement, fine or coarse particles, water, superplasticizer, and a large quantity of short slender steel fibres (minimum of 3-volume %) [3]. The structural performance and mechanical properties of UHPFRC have been summarized in [4]. Thanks to the strain-hardening behavior of the material, structural elements made in UHPFRC remain crack-free under service conditions [5], meaning they are waterproof. Significantly less maintenance on these elements is thus expected over the service duration compared to conventional reinforced-concrete designs [6].

Environmental impacts of structural designs are becoming an important concern as it is crucial to decrease the greenhouse-gas emissions of the construction sector. Due to its high cement and steel fibre content, the environmental impacts of the construction of UHPFRC elements have been reviewed [7]. Studies on bridge rehabilitation with UHPFRC [8] and new structural designs [9] have shown that UHPFRC solutions may have significantly lowered environmental impacts compared to conventional solutions. These studies usually do not account for the carbon footprint of the maintenance and elimination schemes. Moreover, the impacts of the solutions on other aspects of the project (i.e., the design of subsequent elements) are often neglected.

This study presents two case studies involving UHPFRC where the environmental impacts are assessed in a comprehensive way over the structural service duration and the project boundary. Both case studies (a timber-UHPFRC bridge and a fixed railway track) show that structural designs involving UHPFRC have significantly lower environmental impact when considering the appropriate system boundary and time horizon.

2 Methodology to assess environmental impacts of UHPFRC structures

In this section, the methodology to assess the environmental impacts of UHPFRC structures is presented. This methodology is based on life-cycle assessment (LCA) framework defined in DIN EN ISO 14044 [10] and has been tailored for the case of UHPFRC construction (Figure 1), where standard steps are written in italic. This analysis includes the comparison of UHPFRC structures and conventional designs (such as reinforced-concrete elements).

After generating various bridge design options (Step 1), it is crucial to define the system boundary for conducting an LCA (Step 2). The system boundaries establish the processes that are included in the comparison. For instance, cradle-to-grave evaluations of structural designs during specific service life are considered. The system boundary should include all project aspects that may be influenced by the alternatives but processes that are common to all bridge design alternatives (i.e., equipment component) are excluded as they do not influence the comparison. The functional unit quantifies the service provided by the studied system (Step 3). In the case of new structural design, the functional unit typically is the use and maintenance of the structure during a defined service duration and its elimination afterward.

Once the system boundary and functional unit are defined, the environmental impacts of each design can be evaluated (Step 4). Typical phases of DIN EN 15804 are included in italic [11]. All exchanges between the environment and the product system are included in the evaluations. In this study, environmental impacts of material processes, freight transportation, and waste treatments are taken from the 2023 update of the KBOB database for Switzerland [12]. Cradle-to-grave analyses are calculated using the global warming potential (GWP), expressed in kg CO2 equivalent. These calculations are performed for three time-horizons. Maintenance and elimination processes must be considered as they represent a significant part of the environmental impacts of a structure over its service duration. These evaluations have much larger uncertainties associated as it is not certain how these processes will be performed in several decades. Therefore, the three-time-horizon comparison allows a comprehensive evaluation of the environmental impacts of structural designs.

The last step (Step 5) consists in comparing environmental-impact results between design alternatives. The design alternative with the lowest value should be preferred. To include a more comprehensive comparison, a multi-criteria decision analysis could be used to include additional criteria such as the construction costs and the duration of the construction [13].

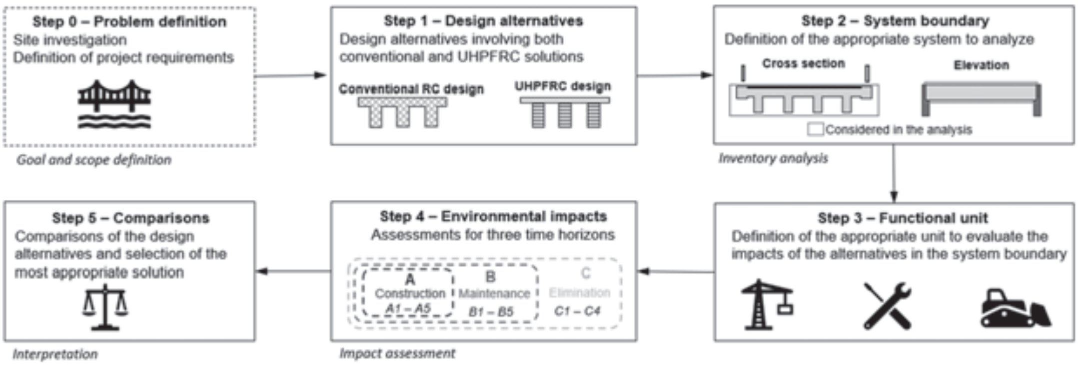

Figure 1: Methodology to assess the environmental impacts of structural designs made of UHPFRC.

3 Case studies

Fruttli Bridge

The first case study involves the design of a short-span bridge in central Switzerland. This new bridge replaces a previous superstructure but uses existing abutments. The structure has a single span of 10 m, and the deck must have a width of 3.5 m. Two engineering offices have designed alternatives: a timber-UHPFRC bridge and a conventional reinforced-concrete slab. The timber-UHPFRC solution has been selected by the bridge owners, driven by the lower construction costs.

The timber-UHPFRC solution involves four glued-laminated timber girders (depth of 530 mm in depth and width of 260 mm) (Figure 2). These girders are connected to a slender UHPFRC cast-on-site slab (thickness between 85 and 140 mm) through steel connectors. Due to the waterproofing quality of the UHPFRC deck, timber girders are expected to remain dry over the service duration, minimizing the expected maintenance. The conventional reinforced-concrete bridge is a 60-cm thick slab. As the abutments are conserved, the boundary condition involves the production, maintenance, and elimination of the bridge superstructure. The equipment involved in both alternatives (such as railings) is excluded. The functional unit in this case study is the construction, the use over its service duration, and its disposal of the superstructure. The timber-UHPFRC solution has environmental impacts 39 % smaller than the concrete one. Importantly, both solutions have almost the same environmental burdens for the construction of the structures, showing that most of the benefits arise from the maintenance and elimination processes. It is thus crucial to account for these aspects in the LCA of structural designs.

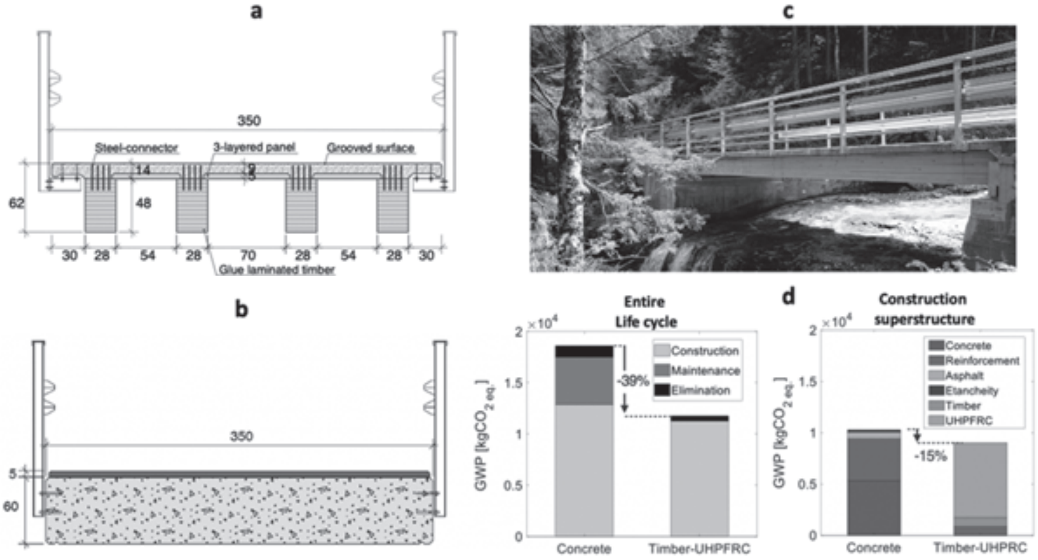

Figure 2: Fruttli Bridge, a) Design alternative in timber-UHPFRC bridge; b) Conventional reinforced-concrete solution; c) Photograph of the timber-UHPFRC bridge; d) environmental impacts of both solutions.

Railway track at Zurich airport

The second case study involves the renewal of the fixed railway track at the underground station of Zurich Airport (Switzerland). The four existing railway tracks (each 640 m long) were built in 1980 in conventional concrete. The prefabricated monoblocks of reinforced concrete were fixed on the top of the reinforced concrete track using grouting. After 30 years of use, significant damage in the monoblocks was observed, and the fixed railway track should be rehabilitated. Moreover, the platform heights at the station did not meet the current requirements of disability equality. In this case, the best solution was lowering the rail level in relation to the platform level.

Two solutions have been proposed (Figure 3): 1:1 replacement of monoblocks with the rebuilding of the existing railway tracks and a UHPFRC solution that provides the replacement of the existing concrete monoblocks by the cast-in-place thin UHPFRC pedestals and avoids the rebuilding of the existing railway tracks. The second solution has been implemented as it was significantly cheaper (30 %), and less maintenance was expected. The environmental impacts of both alternatives are compared in Figure 3D. The UHPFRC solution has a significantly lower environmental impact (85 %), mostly due to the avoidance of adjusting the railway tracks and lower maintenance over the service duration. Nonetheless, the construction of the monoblocs has a slightly smaller impact (8 %) using the conventional solution. This case study highlights the importance of the definition of the system boundary for LCA. When considering only a subsystem (i.e., the monobloc construction), wrong conclusions can be drawn. In this case study, the

UHPFRC solution is significantly better because it avoids the need to adapt the existing railway tracks, leading to a significantly smaller intervention.

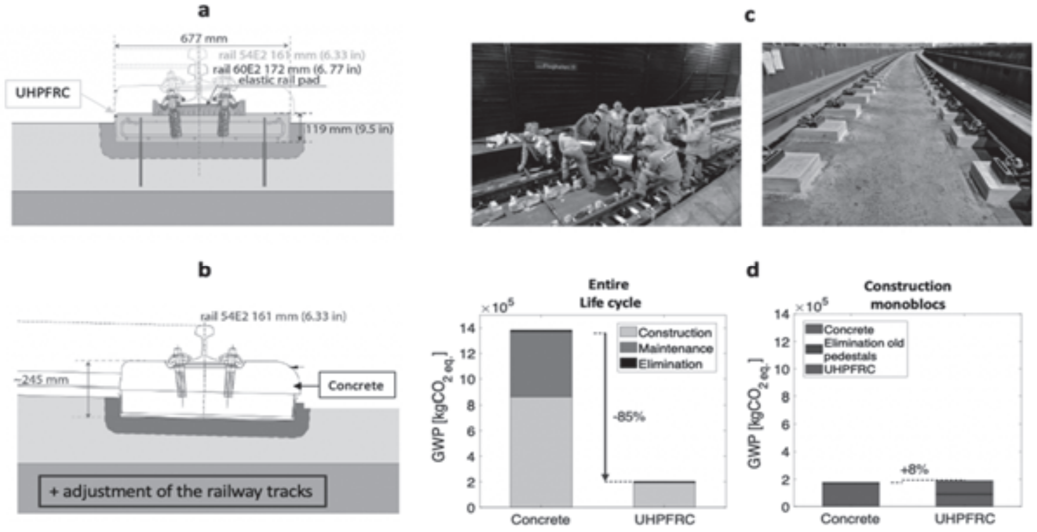

Figure 3: a) Design of the pedestal in UHPFRC; b) Conventional reinforced-concrete solution; c) Photographs of the construction of the UHPFRC solution ; d) environmental impacts of both solutions.

4 Conclusions

This paper proposes a methodology to assess the environmental impacts of UHPFRC structures. Based on LCA, this methodology involves a comprehensive life-cycle analysis on the system boundary through multiple time horizons. The methodology was applied to two UHPFRC case studies (Fruttli Bridge, Zurich Airport train station). In both cases, the UHPFRC designs have a significant reduction in the carbon footprint compared to traditional solutions in concrete, by 39 % and 85 % respectively. These results highlight the potential of UHPFRC to reduce the environmental impacts of structural designs, leading to a more sustainable construction sector.

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