UHPFRC FOR THE PRESERVATION, STRENGTHENING, AND TRANSFORMATION OF EXISTING BUILDINGS

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Abstract

To meet current performance requirements and provide new architectural qualities, existing building structures are regularly demolished and replaced by new ones. This paper explores how ultra-high-performance fiber-reinforced cementitious composite (UHPFRC) offers new possibilities to transform, strengthen, and preserve existing buildings. This paper identifies and analyses over 50 case studies in Switzerland where UHPFRC is used in the context of existing buildings. These applications are first classified using the observed structural deficiencies. Then, the reasons why UHPFRC is chosen over demolition or another refurbishment technique are investigated. Results show that UHPFRC is often the most effective intervention for technical, economic, and project-management motivations. UHPFRC thus offers new possibilities to preserve and rehabilitate current building stocks that could contribute to sustainable construction practices by avoiding unnecessary replacement.

Résumé

Pour répondre aux exigences de performance actuelles et offrir de nouvelles qualités architecturales, trop de bâtiments existants sont encore démolis pour être remplacés. Cet article explore comment le composite cimentaire fibré ultra performant (CFUP) peut contribuer à préserver, renforcer et adapter des bâtiments existants. Plus de 50 études de cas de bâtiments existants en Suisse où du CFUP a été utilisé ont été identifiées. Ces applications sont d'abord classées en fonction des déficiences structurelles observées. Ensuite, les raisons pour lesquelles le CFUP est choisi sont analysées. Les résultats montrent que le CFUP est souvent l'intervention la plus efficace pour des raisons techniques, économiques et de gestion de projet. Le CFUP offre donc de nouvelles possibilités de préserver et de réhabiliter le parc immobilier actuel, contribuant aux pratiques de construction durable notamment en évitant les remplacements superflus.

1. INTRODUCTION

A key solution to make the construction sector more sustainable is to revalue existing structures to avoid the traditional demolition-reconstruction solution. Several motivations are usually cited for demolishing a building, such as the obsolescence of the current building, economic reasons (densification strategy), structural deficiencies, insufficient thermal or acoustic insulation performance, and durability issues [1]. The traditional demolition-reconstruction approach is so common practice that the average demolition age of buildings is decreasing and has been estimated to be 70 years in Zürich, Switzerland [2]. Nonetheless, preservation rather than replacement should always be the first conceptual solution, which motivates the development of new technical solutions to improve existing-structure performance [3].

High-performance materials offer new structural strengthening solutions [4]. For instance, Ultra-High Performance Fibre Reinforced Cementitious Composite (UHPFRC) has been extensively used to rehabilitate at least 300 existing bridges [5,6]. This cementitious fiber reinforced composite material is made of a mix of cement, silica fumes, fine hard particles (with a maximum grain size of 1 mm), water, admixtures, and a large amount of slender short steel fibres. UHPFRC materials should be differentiated from traditional concrete compositions and should be treated as unique materials with specific properties. It means that specific design codes and execution processes are needed, as introduced in Switzerland in 2016 and updated in 2024 [7].

The mechanical properties and structural performance of UHPFRC have been summarized by [8]. UHPFRC has significant tensile (up to 14 MPa) and compressive (up to 180 MPa) strengths. An important property of UHPFRC is the strain-hardening behavior in tension, meaning that UHPFRC elements remain crack-free and waterproof under service conditions. The UHPFRC elastic modulus in both tension and compression is between 45 and 50 GPa.

When strengthening an existing RC structure, UHPFRC is often added as an additional tension chord to improve the structural performance and durability of the existing structure. To simply improve the durability of an existing structure, a UHPFRC layer of 25 mm is sufficient. However, to improve structural performance, a UHPFRC layer of at least 40 mm, with a minimum cover of the steel reinforcement bars of 15 mm, is needed. These interventions result in structural systems with a monolithic behavior between the UHPFRC and RC elements.

Due to its high cement and steel-fibre content, the environmental impacts of the construction of UHPFRC elements have been investigated [9]. Studies have shown the importance of considering the entire intervention in the life-cycle analysis, as UHPFRC elements are usually more slender and thus up to 4 times lighter than concrete ones and require less maintenance [10]. When designs are optimized, and the use of UHPFRC is efficient, the environmental impact of structural designs is significantly reduced compared to conventional solutions, in particular because of the preservation of the existing structure [11].

UHPFRC applications to strengthen and transform buildings have been barely explored. This paper presents a collection and analysis of UHPFRC applications for the purpose of building rehabilitation and preservation. 53 UHPFRC applications have been realized and documented in Switzerland between 2007 and 2023. Two aspects are primarily investigated: the reasons why the building must be strengthened or transformed and the motivations for using UHPFRC over traditional intervention schemes. Several case studies are selected to illustrate the new possibilities offered by UHPFRC to enhance existing buildings and accommodate new user demands.

2 METHODOLOGY

A three-step methodology is used to evaluate the use of UHPFRC for intervention in structures of existing buildings. The first step is the data collection on the realized applications using (1) the online database of UHPFRC applications in Switzerland [12], (2) a survey of the literature, and (3) discussions with the main actors in the country. Applications on built infrastructure (bridges, retaining walls, tunnels, dams) are not included in the present analysis as they have already been extensively reviewed in the past [5,6].

The second step analyses the reasons why the UHPFRC interventions were made to preserve the existing buildings. Three reasons triggering a UHPFRC intervention in existing building structures have been identified:

1. **Structural strengthening**: The structural capacity of building elements needs to be increased to meet current safety requirements. The strengthening needs are subdivided into several specific types (bending, shear or punching-shear, structural rigidity, etc.).
2. **Durability**: Ongoing degradation processes (such as rebar corrosion or alkali-aggregate reaction) are identified or expected on the existing RC structure and could affect the structural performance.
3. **Architectural improvement**: The architectural quality of the building must be improved and these improvements would require modifying the structure. Two types of improvements are identified: building and structure extension (additional stories, balconies) and transformation (space enlarging, wall removal).

The third step analyzes why UHPFRC was chosen over other traditional methods of intervention. The analysis consists of (1) extracting recurrent motivations for UHPFRC use and (2) examining the implications of architectural and engineering projects based on economic, social, and technical dimensions. Case studies where the use of UHPFRC was the only solution to meet the needs of building structures to be preserved are also highlighted in the analysis.

Five main motivations have been identified: (1) technical advantages (i.e., mechanical properties of UHPFRC and principles of UHPFRC structural intervention), (2) economic benefits, (3) environmental gains, (4) project management ease (reduction of the intervention time, simplified intervention, etc.), (5) durability improvement. These themes cover the most important aspects of the complex design process with existing structures.

3. RESULTS

3.1 Overview of UHPFRC applications

53 UHPFRC applications for existing-building preservation realized between 2007 and 2023 throughout Switzerland have been identified (Figure 1a,c). UHPFRC has been used on several types of buildings (Figure 1b), and most applications occurred since 2013. The UHPFRC volume per application ranges from less than 1.0 to more than 400 cubic meters. These data show a wide range of applications of this material to enhance existing buildings.

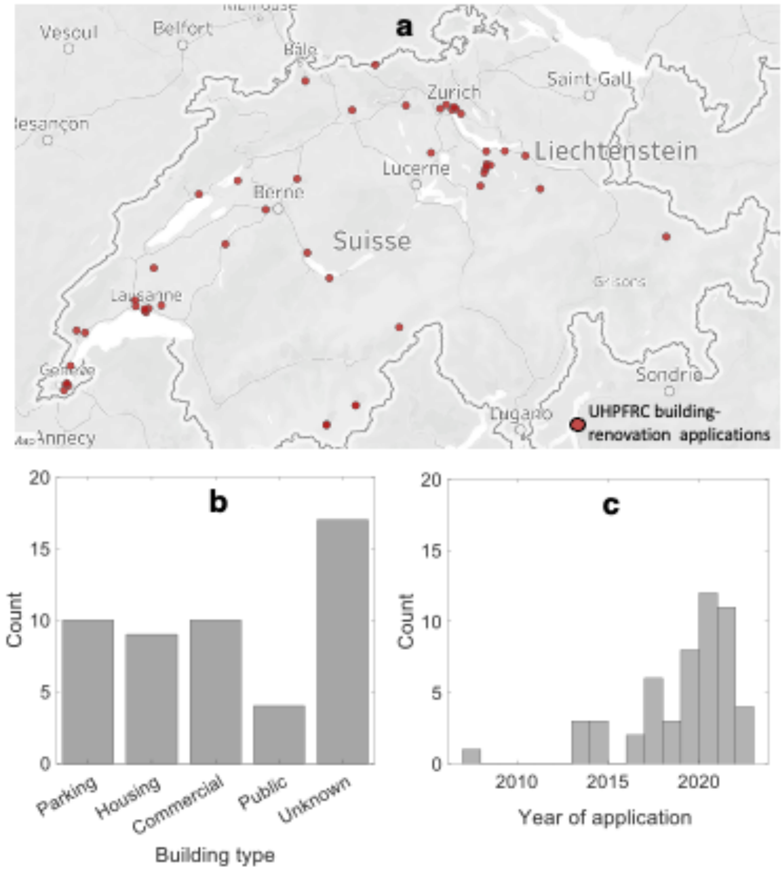

Figure 1. UHPFRC applications on existing Swiss buildings: building location (a), type of building (b), and year of UHPFRC intervention (c).

3.2 Reasons for preservation

This section analyzes the reasons for the preservation of existing buildings and the motivations for choosing UHPFRC. This analysis is based on the information available from reports, publications, and official documents made by the actors of these case studies. Reasons and motivations are the ones that have been explicitly cited in available project documents. Obviously, the actual decision process may have been more complex and considered other factors. The information available on some case studies was limited (especially for small applications with less than 10 m^3 of UHPFRC). In such cases, they are not considered in the motivation analyses and are labeled as “unknown”.

The distribution of the preservation reasons in the case-study corpus is shown in Figure 2a. Most applications involve the strengthening of the building’s structure, while durability issues are often invoked. The architectural extension of the building has also been cited in 7 case studies. 10 out of the 53 applications involve both durability and strengthening reasons.

The in-depth analysis of the strengthening interventions in Figure 2b shows that most applications involve enhancing either shear resistance, bending resistance, or serviceability (rigidity, vibration, …) behavior. 7 out of the 32 strengthening interventions involve both shear and bending strengthening. Increasing fire or seismic resistance is not often mentioned, although these schemes are common. It shows that UHPFRC may not always be the most cost-effective solution for these strengthening schemes.

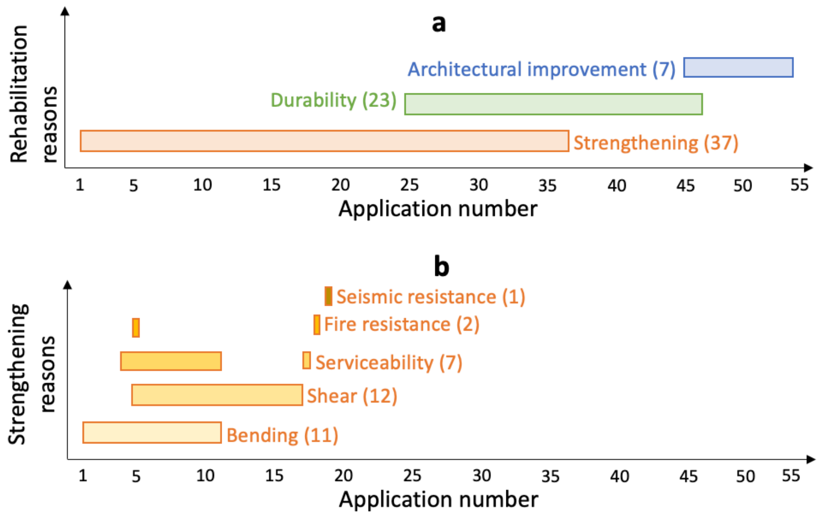

Figure 2. Reasons for preservation of existing structures (a) and details on strengthening interventions (b).

3.3 Motivation for UHPFRC use

Figure 3 shows the distribution of the evoked motivations for using UHPFRC over another solution in the case-study corpus. In all documented applications, technical motivations are cited. In these applications, UHPFRC has been selected because it has much higher mechanical properties (i.e., tensile strength and elastic modulus) than traditional reinforced concrete. Moreover, its high durability is also frequently mentioned. This motivation is particularly present in parking applications that are exposed to weather and de-icing salt and, therefore, often subject to reinforced concrete degradation issues such as rebar corrosion. The project management (i.e., UHPFRC often allows for significantly faster and/or simpler intervention) and thus economic motivations in terms of lower construction and user costs are often mentioned. The aesthetics motivation is only cited when the building is subject to an extension. Finally, the environmental motivation is rarely mentioned. It shows that there is still limited consideration of this aspect in the design process of the Swiss construction sector. It has been explicitly mentioned in 3 cases (but there are certainly more cases) that the building would have been demolished if the UHPFRC application was not available, making the environmental impacts of the interventions significantly lower than a demolition-reconstruction solution. Applications evoking these motivations are presented in the next Section.

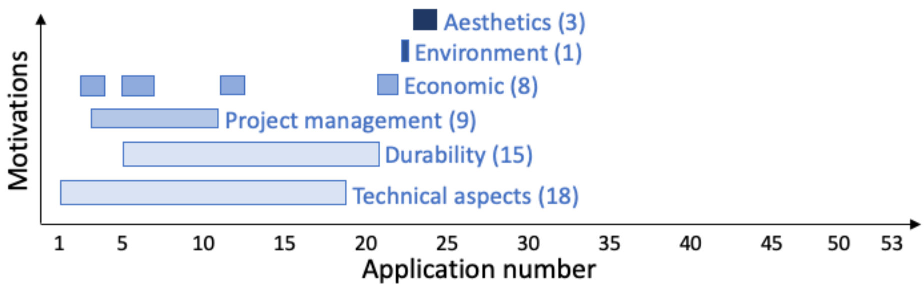

Figure 3 Motivations for the use of UHPFRC.

3.4 Application examples

Slab strengthening – The "Dupont" commercial building

The first type of UHPFRC application is to improve bending and shear resistance and deflection behavior by adding a layer of R-UHPFRC on existing slabs. This type of application has been realized on numerous existing bridge deck slabs in Switzerland.

Designed by the Swiss architects Haller & Schindler, the "Dupont" building in downtown Zürich, built in 1912-1913, is listed as a cultural heritage building because of its Art Deco façade and the innovative reinforced-concrete structure for its time (Figure 4a). The structure comprises slender unidirectional ribbed slabs over an area of 4,300 m^2. In 2017, studies were undertaken to transform the building from an office building to a hotel. The existing ribbed slabs showed insufficient bending and shear capacity, especially in the hogging zones (with negative bending moments and high shear forces). Adding a 40-mm UHPFRC layer (type UB, $f_{utu,k} = 10\ MPa$, C140) with closely-spaced steel rebars on the slabs [13] was the solution that allowed for strengthening the structure while preserving the aesthetic of the existing floor system and respecting existing geometrical constraints related to doors and windows. The intervention does not affect the structural expression of the protected floor system as it only involves applying a relatively thin material layer on the slab, meaning that this intervention is not visible from below and reduces only lightly the height to the ceiling. A conventional intervention in RC concrete would have required an additional layer of at least 80 mm, increasing the structural self-weight significantly, leading to an inefficient, invasive and costly intervention.

The durability of the strengthening layer is less critical inside a building than on infrastructure exposed to weathering. In the "Dupont" building, UHPFRC was thus used only in the area that needed strengthening. Elsewhere, fine-grained concrete ensures leveling of the overall slab surface and monolithic slab behavior to transmit loads to the strengthened zones. Experimental campaign has been performed to validate the intervention design, confirming that the structural capacity was increased by up to 200 % [14].

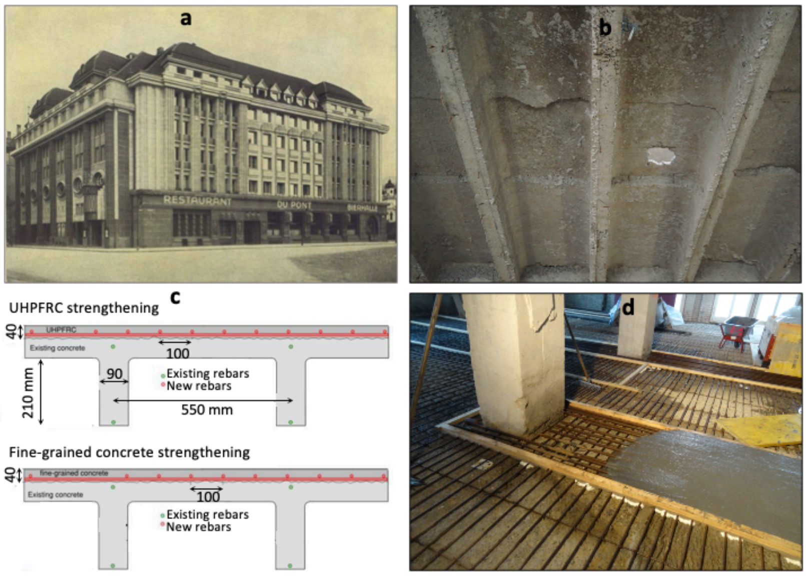

Figure 4 "Dupont" building: (a) Historic photograph of the building in 1914 (photo credit: J. Coulin); (b) existing ribbed slab before intervention; (c) intervention design, adapted from [13]; (d) casting of UHPFFRC.

Punching shear strengthening – The "Metropole 2000" commercial building

A second type of UHPFRC application is to improve the punching shear resistance of slabs near columns. This type of strengthening is particularly difficult using conventional techniques as it involves adding steel strengthening within the slab thickness. The UHPFRC technique has been used for example in the "Metropole 2000" commercial building (Lausanne, 1928) that needed to be strengthened due to an increase in live loads on the existing structure.

Realized in 2019, the UHPFFRC intervention required only strengthening on the upper surface of the slabs, where additional steel rebars were also added (diameters 20 and 12), making the construction work much simpler than conventional solutions (Figure 5). Again, the intervention was only performed near the column. The additional layer of UHPFRC (type UA, $f_{utu,k} = 7.7MPa$, C120) has the same thickness as the screed in the building, making the intervention invisible. Since the intervention was limited to the top surface of the slab, the floor below could remain in service for commercial activities, which had a significant beneficial economic effect.

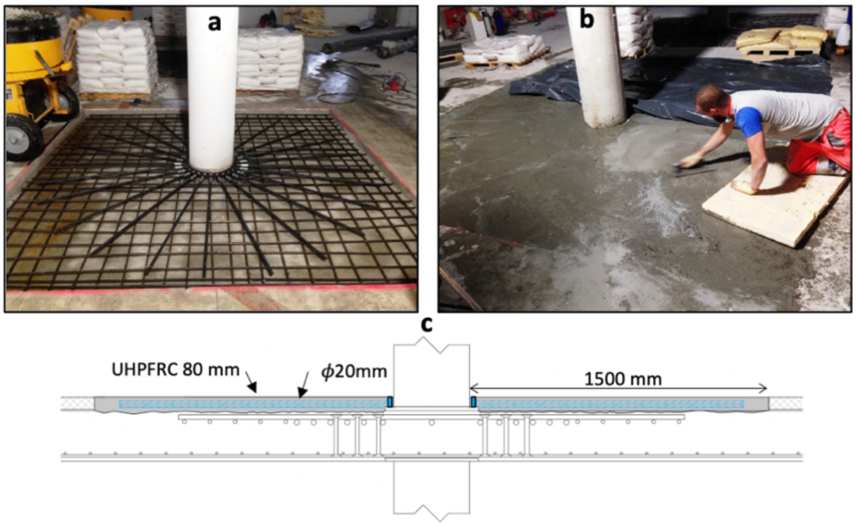

Figure 5 UHPFRC intervention on the "Metropole 2000" building for punching-shear strengthening: (a,b) photographs of the intervention; (c) scheme of the intervention.

Service condition and durability – IKEA parking building in Lyssach

A third type of application involves improving the structural conditions under serviceability and the durability of the building. This type of application builds on the waterproofing quality of UHPFRC and the possibilities to realize drivable surfaces, as well as its capacity to improve structural rigidity, allowing the avoidance of additional material such as asphalt pavement.

The two-story IKEA parking building in Lyssach was constructed in 2006. Asphalt was installed on the concrete slab of the top open deck. Because of the traffic-related vibrations, cracks quickly formed in both the asphalt and the concrete slab. The conventional solution of replacing the asphalt would have certainly led to the same issues in a few years.

The UHPFRC intervention was realized in 2021 in only four weeks to reduce the duration of the parking closure to a minimum. The asphalt was first removed, and the concrete surface was then hydrojetted. Next, 40 to 50 mm of UHPFRC (type UA) was cast on the entire parking surface (Figure 6). The durability of UHPFRC and its mechanical properties enable avoiding additional pavement layers and a waterproofing membrane, thus reducing construction time and cost. This application is also one with the largest volume of UHPFRC cast for a building application, as

430 m^3 have been poured on an area of 8400 m^2. Thanks to the low permeability and high mechanical properties of UHFPRC, this intervention provides significantly longer durability than a traditional solution.

Figure 6 UHPFRC Intervention of the Parking building to improve the durability and service condition of the parking (photo credit: Kibag.ch).

Rehabilitation of damaged structure – Holenstein textile factory

Another type of application is the rehabilitation of damaged structures. Thanks to the high mechanical properties of UHPFRC, heavily damaged concrete structures can be salvaged.

In 2020, a fire started in the textile factory in Holenstein for an unknown reason. The structure, especially the reinforced concrete beams supporting the façade, was significantly damaged. The structural safety was affected, and the first decision was to demolish it. Hopefully, a tailored rehabilitation intervention with UHPFRC has been suggested and accepted, allowing the conservation of the main load-carrying structure.

The damaged concrete was first removed from the beams. Then, UHPFRC (type UB) was poured as a jacket around the RC beams to reconstitute them. Fine polypropylene fibers were added to the UHPFRC mix to increase the fire resistance of the rehabilitated structure. This intervention also allowed the preservation of the building functionality and aesthetics. The intervention has also been faster than the conventional demolition-reconstruction solution, enabling the quick restart of the factory operation after the event, which implied significant economic benefits. Overall, construction costs and environmental impacts were very low compared to the initially intended demolition-reconstruction project.

Figure 7 Intervention in Holenstein textile factory after the fire damage to rehabilitate the structure (photo credit: E. Kälin).

Extension of existing buildings – Lausanne Olympic Museum

The last application involves the architectural transformation of an existing building. UHPFRC (type UA approximatively) is used as the main structural material for the vertical extension (additional story) of the structure, where the new roof is made of a UHPFRC beam grid.

The Olympic Museum in Lausanne was built in 1993. It was then renovated and extended in 2013. An additional top floor was needed for a new restaurant. Slender pre-stressed UHPFRC beams (length of 18 to 21 meters, depth of 1 meter, width of 8 to 10 cm) have been chosen as structural elements of the new roof structure (Figure 8). This beam grid is supported by RC walls and steel columns in traditional construction.

The high mechanical properties of UHPFRC enable long cantilevers, minimizing the need for support. The thin elements allow for significant natural light in the restaurant. The low weight of the UHPFRC elements eased the construction works thanks to prefabrication and reduced additional loads on foundations as the self-weight of UHPFRC structures typically is 3 to 4 times lighter compared to an RC structure fulfilling the same function. Moreover, the UHPFRC color and its mineral texture integrate well with the existing marble facade.

Figure 8 Extension with a new pergola in UHPFRC at the Lausanne Olympic Museum (photo credit: Brauen Wälchli Architectes, Marc Schellenberg).

4. CONCLUSIONS

This paper reviews the use of UHPFRC to strengthen and modify existing buildings to preserve them. The review is based on the collection and analysis of 53 UHPFRC applications on buildings realized between 2007 and 2023 in Switzerland. The study shows that UHPFRC has been used to strengthen, improve the durability, and extend multiple buildings. Thanks to its high mechanical performance, UHPFRC intervention enables fast, economical, and minimally invasive strengthening of existing structures, thereby reducing construction cost and time of unavailability of the building for use. UHPFRC high durability minimizes the number of materials (and material types) for interventions on the exposed building parts. For some of these applications, the building could be saved only thanks to UHPFRC properties. This material thus offers new possibilities for the preservation and modification of existing buildings. The environmental impacts of UHPFRC intervention on these elements will be investigated in more detail in future work as they have not often been considered in the decision processes of these interventions. Yet, the environmental impact of UHPFRC preservation projects is obviously significantly better than demolition-reconstruction projects.

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