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FLO:RE – A new floor system made of reused reinforced concrete and steel elements

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Abstract

Carefully extracting reinforced concrete (RC) elements from soon-to-be demolished structures and reusing them as load-bearing components is an emerging circular low-carbon alternative to building new structures. As floor construction typically accounts for the most upfront carbon footprint of buildings, this paper presents the design, structural verifications and construction process of FLO:RE, a new floor system built with reused saw-cut RC slab elements and steel beams. To value all pre-existing properties, the new system reuses the RC elements in bending, taking advantage of the existing steel reinforcement. The life-cycle assessment (LCA) shows that the upfront carbon footprint of the reused system can be as low as 5 $kgCO_{2,eq}/m^2$, reducing by up to 94 % compared to conventional RC flat slabs. The construction and monitoring of a 30-m^2 mock-up demonstrate the new-system construction ease and structural performance. This study proves the technical feasibility of reusing old RC slab elements in new floor systems.

Keywords: structural design, component reuse, reinforced concrete floor, life-cycle assessment, embodied carbon, circular economy, concrete reuse

1 Introduction

Concrete is not only the most used construction material worldwide, with an estimated yearly consumption approaching 30 billion tons (1): it is also the most discarded construction material, e.g., accounting for about 35 % of Swiss demolition waste (2). Today, even if in good condition, discarded concrete is crushed and, at best, downcycled as aggregates in new concrete mixes, where it partly replaces natural stone aggregates. Still, this process does not reduce upfront carbon emissions as the same or even higher cement quantity is needed for these mixes (3), and cement is responsible for the main part of carbon emissions during concrete production.

Figure 1. FLO:RE mock-up, made of reused reinforced-concrete and reused steel elements.

Well-known strategies exist to reduce both the demand for new concrete and the generation of concrete waste. The first one consists in maintaining the existing built environment in use as long as possible, avoiding new constructions. However, land pressure in densely populated areas usually leads to the premature replacement of existing buildings by larger ones. Many buildings today are demolished even if they are still in a structurally sound state (4,5).

Another end-of-life strategy for obsolete concrete structures consists of reusing portions of it in new assemblies. Compared to material recycling, component reuse aims to maintain the geometry and mechanical properties of the structural elements and recombine them in new structures after only minor alterations. Reuse is less energy- and carbon-intensive than the conventional deconstruction–recycling–reconstruction process (6). It also avoids the extraction and processing of raw materials and delays the generation of concrete waste. Despite its numerous benefits for greater sustainability, reuse is still barely explored in practice, especially for concrete, due to the challenge linked to the deconstruction and lack of guidelines to design with reclaimed elements.

Recent research documented over 50 structures built with reclaimed concrete elements between 1967 and 2022 in the United States and Europe (7). This study showed environmental gains in all documented projects and positive economic benefits in some of them. Most of these projects concern reused precast elements rather than elements saw-cut from cast-in-place structures. While the reuse of precast elements builds on pre-existing connections between components, reusing cast-in-place concrete elements requires defining the appropriate cutting locations and modifying the structural system of the elements (8).

As cast-in-place concrete structures are the dominant construction type in some countries, including Switzerland, developing reuse solutions that reclaim cut elements from cast-in-place concrete structures is a necessary step for greater circularity in the construction sector. A few recent applications reused saw-cut cast-in-place concrete elements. Among them, the *Re:Crete footbridge* (9) was built from 25 concrete blocks to form a 10-m-span arch stabilised by two prestressing cables. The *RebuiLT pavilion* reused six large modules made of a "mushroom" column and its top and bottom slabs (10). A wall prototype was also built, piling up flat debris from conventional demolition (11).

As floor construction accounts for most embodied carbon in buildings (12), it is crucial to find sustainable solutions for floor systems, too. This paper presents the first application of reusing saw-cut cast-in-place reinforced concrete (RC) slab elements into floor systems.

The concept of FLO:RE, a new floor system reusing saw-cut RC elements in bending, is introduced in section 2, together with the necessary structural verification guidelines. Section 3 presents the construction process of a 30-m^2 mock-up, while section 4 assesses its structural performances and its upfront global warming potential. The study conclusions are summarised in Section 5.

2 Reusing cast-in-place concrete

2.1 FLO:RE concept

This section presents the concept and construction process of new structural floor systems built from cast-in-place RC elements saw-cut from soon-to-be-demolished building slabs (Figure 2) and called FLO:RE.

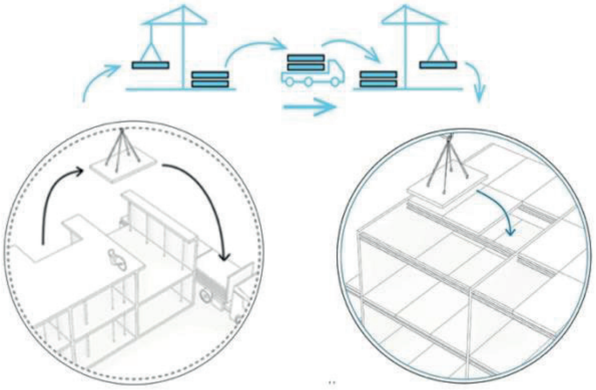

Figure 2 Process of reusing cast-in-place concrete in FLO:RE systems, adapted from (13).

To build the new floor systems, RC elements are first cut using diamond saw blades from existing slabs that have been previously shored up. To optimise costs, the RC-element dimensions are as large as possible given the structural resistance of the existing slab (13), on-site lifting capacity and transportation constraints, i.e., truck size and payload.

Once holes have been drilled for future connections (see section 2.2.4), elements are directly assembled in the new floor system. If the elements span as long as the new structure, they are used as primary elements spanning the entire distance between two walls. Otherwise, they are used as secondary elements over primary girders, for instance, in steel. Reused-RC elements are similar to precast elements except for the following differences:

- elements capacity and geometry are predefined by the donor building;
- shrinkage has already happened;
- the section may be cracked due to the previous loading history;
- anchorage length of reinforcement steel bars is not ensured at the element end as they are cut during extraction.

The fact that the reinforcement bar layout and the material properties of the reclaimed elements are partly unknown can be compensated by structural analysis of the existing donor slabs and knowledge of old construction practices and standards. This is the principle showcased in the structural-verification guidelines described below.

2.2 Structural verifications

2.2.1 Overview

In this section, the structural verifications required to reuse elements saw-cut from cast-in-place RC continuous slabs are presented. These verifications are based on Swiss standards for new construction and existing buildings (14,15).

When planning the reuse of RC elements reclaimed from an existing structure, it is often the case that some information is missing, such as the reinforcement bar layout and the material properties. Hypotheses can be made based on common construction practices at the period when the donor building was erected. A minimal reinforcement area A_s can be estimated using the recommandations of former codes: either from the minimal reinforcement ratio or from the bending actions due to the design loads. Hypotheses can also be made on material properties according to these former standards.

These estimations can later be validated through non-destructive or destructive testing on the donor building site as well as direct measurements of properties once RC elements are extracted.

2.2.2 Bending resistance

The bending resistance of the reused element is calculated similarly to a conventional new RC slab: it depends on the reinforcement properties (area of reinforcement A_s, yield strength f_{sd}), and the beam depth h. The main difference is that the anchorage length l_{bd} of the reinforcement bars is not ensured near the saw-cut edge of the reused element. In this location, the reinforcement-bar capacity as well as the bending resistance is therefore reduced.

It can be conservatively taken that, for full anchorage, $l_{bd,min} \geq 40\phi$, with ϕ the reinforcement-bar diameter. The bending resistance loss is assumed to be linearly proportional to the anchorage length (Eqn 1). Nonetheless, it is unlikely that the bending capacity at the element midspan will be affected.

$$M_{Rd}(x) = \begin{cases} 0.81 \cdot h \cdot A_s \cdot f_{sd} \cdot \frac{x}{40\phi}, & x < 40\phi \\ 0.81 \cdot h \cdot A_s \cdot f_{sd}, & 40\phi \leq x \leq l - 40\phi \\ 0.81 \cdot h \cdot A_s \cdot \frac{l-x}{40\phi}, & x > l - 40\phi \end{cases} \tag{1}$$

2.2.3 Shear resistance

The shear resistance v_{Rd} of the reclaimed slab elements (without shear reinforcement) is calculated using Eqn (2). It depends on the effective depth d_v and on the concrete shear resistance τ_{cd}. In a first approximation, it is considered that, at the supports, there is no stress in the existing reinforcement bars due to bending and the coefficient for shear-resistance of slabs k_d can be taken equal to 1.

$$v_{Rd} = k_d \tau_{cd} d_v \tag{2}$$

This shear resistance can only develop if the longitudinal reinforcement bars can carry the resulting tensile force T_d. At a support of width b, this tensile force (Eqn 3) is in equilibrium with the resultant of the fanning compression towards the support (inclined at an angle α) and shear force V_d (16).

$$T_d = V_d \frac{\cot\alpha + b/z}{2} \tag{3}$$

For reused-RC elements that have cut reinforcement bars at their end, the shear resistance is thus limited by the resistance T_{Rd} of the tie (Eqn 4) which again depends on the anchorage length.

$$T_{Rd} = \frac{l_{bd}}{l_{bd,net}} A_s f_{sd} = \frac{b}{l_{bd,net}} A_s f_{sd} \tag{4}$$

The anchorage is null at the extremity of the reused slab element, and it only develops over the support width. The effective anchorage length l_{bd} is thus equal to the support length b. The full anchorage length of reinforcement bars $l_{bd,net}$, usually taken as 40 times the rebar diameter, can also be reduced by 30% in the support zone (14). Comprehensive shear resistance models will be developed for reused-concrete elements in future work.

2.2.4 Steel-concrete connections

The connection between the reused concrete elements and the primary steel girders must be carefully designed. In this study, a demountable bolted connection is chosen (Figure 6). It is conservatively assumed that this connection only transfers the horizontal loads (wind and seismic) to the steel girders and that no composite action is created.

The connection is designed to resist to the horizontal loads through friction (Eqn 5). The preloading force $F_{pr,d}$ in the bolts is chosen to ensure sufficient resistance while considering a minimum reduction of 40% for the creep effects. The friction coefficient μ_k is assumed to be equal to 0.20 (15).

$$V_{Rd} = \mu_k F_{pr,d} \tag{5}$$

2.2.5 Deflection

The serviceability limit state is ensured by limiting the deflection of a structural element, which depends on its rigidity, its span, and the load levels. The long-term deflection is obtained with the creep coefficient φ and is interpolated between the uncracked and the cracked value. The creep coefficient φ is calculated using the simplified model of Eurocode 1992-1-1 (17), assuming a loading age equal to the age of the reused element. Construction of the FLO:RE mock-up

3 Construction of the FLO:RE mock-up

3.1 Overview

In this section, a mock-up of the FLO:RE reused RC floor system is presented (Figure 1), built in 2023 at EPFL, Switzerland. Four saw-cut RC slab elements of 2.5 by 3.0 meters and three 5-m long steel girders (two HEA 200 and one HEA 240) were reclaimed for the mock-up, creating a total area of 30 m^2.

3.2 Donor buildings

RC elements and steel profiles were reclaimed from two donor buildings in Switzerland (Figure 3). The RC elements were saw-cut from the flat roof of an industrial building from the 1960s. It was demolished in 2023 to be replaced by a denser, mixed residential and office building. The steel profiles were reclaimed from the structure of an industrial hall. Erected in the 1970s, the hall was demolished in 2023 as part of a site densification and industry-to-office urban project.

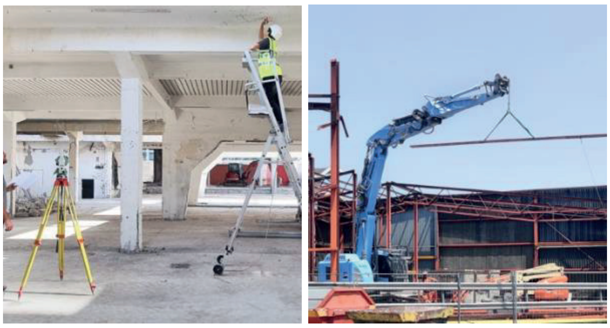

Figure 3. RC (left) and steel (right) donor buildings.

3.3 (De-)construction process

The RC-element donor structure was first shored up to ensure structural safety during and after element extraction. Once a land surveyor marked sawing lines, the RC elements were cut out using circular saws, lifted using the articulated arm of an excavator, and transported to the assembly site on a regular truck (Figure 4). There, holes were drilled in every RC-element corner for the lateral stability connection with the steel girders.

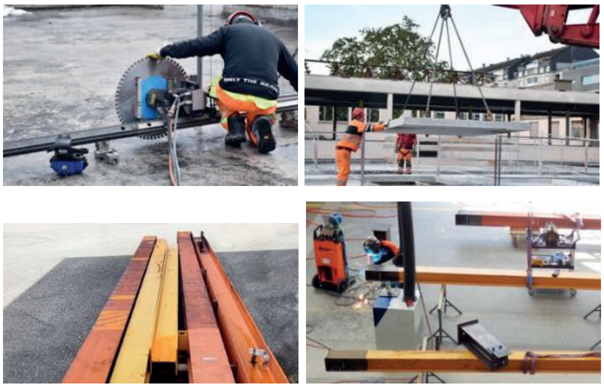

Figure 4. Material supply and preparation: RC element sawing (top left) and lifting (top right), steel profile storage (bottom left), and reconditioning (bottom right).

Once salvaged, the reused steel profiles were cut to the required 5-m length, and the surplus was used to build the mock-up's vertical supports. Stiffeners were also welded at supports.

Finally, the RC elements were installed on the reused steel profiles, previously topped with layered recycled rubber (Figure 5), to ensure even support. The connection between steel and concrete elements was insured with bolted preloaded threaded rods.

4 Assessment of the FLO:RE mock-up

4.1 Material properties

Material properties were first estimated based on the Swiss standards for existing structures (Table 1). The concrete grade is assumed to correspond to a current C12/15, and the elastic modulus E_c is then reduced to reflect pre-existing cracks in the reclaimed RC elements in deflection calculation. The rebar yield stress f_{sk} is assumed to be equal to 345 MPa, and the girder steel grade is fixed at S235.

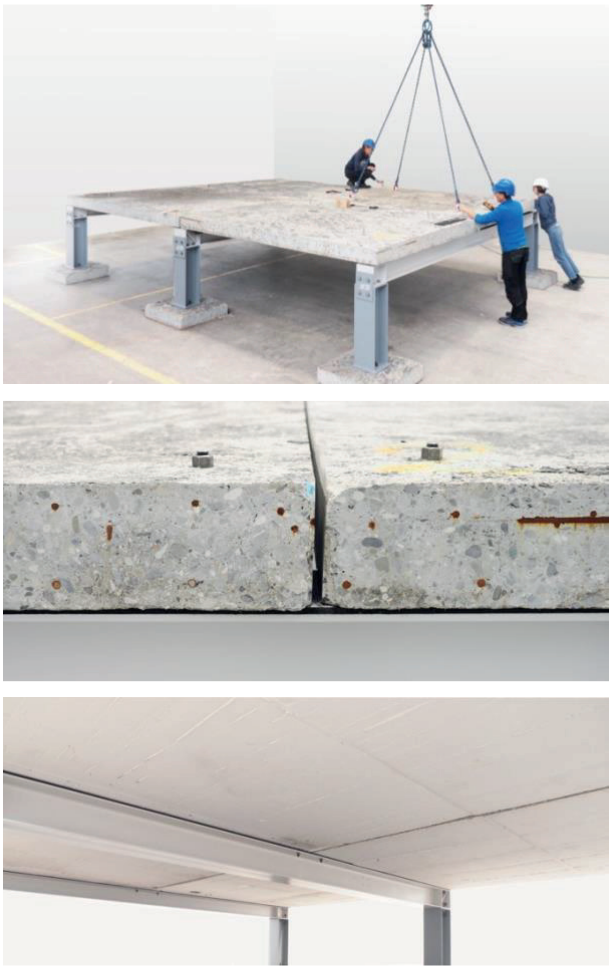

Figure 5. Assembly (top), connection bolting (middle) and final result (bottom).

Once elements have been reclaimed, material testing was performed to validate the assumed properties (Table 1). Concrete grade has been verified with compressive tests on samples. Tensile tests were performed on reinforcement steel bars samples taken on the donor building slab. These tests allowed updating the material properties and showed that they were conservatively estimated beforehand.

4.2 Assumed loads

The mock-up is designed as if it was part of an office building. Over the RC slab elements, a permanent load of 2 kN/m^2 for the screed and flooring and a live load of 3 kN/m^2 are considered.

To evaluate the horizontal loads (wind and seismic), the floor system is assumed to be part of a small 4-level building located in Lausanne, Switzerland. The supposed area of each floor is 150 m^2.

The maximum allowable deflection for an office building floor is 1/300 of the span.

Table 1. Material properties

Element	Unit	Initial estimation	Material testing results
Concrete f_{ck}	MPa	13	33
Concrete elastic modulus E_c	GPa	27'000	36'500
Rebar f_{sk}	MPa	345	499
Steel girder f_{yk}	MPa	235	--

4.3 Structural verifications

Structural safety is verified using the ratio n of the capacity over the action effects of the loads (Eqn 6), a metric called degree of compliance (18).

$$n = Capacity/Demand = \frac{R_d}{E_d} \geq 1.0 \qquad (6)$$

Degrees of compliance for the mock-up structural elements are shown in Table 2. Spans of the reused RC elements were maximised based on the initial assessment of their bending and shear capacities, as reflected by the low value of n. Concrete slab capacities were estimated based on the slab depth directly measured at 150 mm on the donor building site and an assumed reinforcement layout of ϕ8mm, spaced at 150 mm. This reinforcement area corresponds to the minimal reinforcement ratio prescribed by the standards at the time when the donor-building was constructed (see section 2.2.1).

The steel girder design is governed by the serviceability limit states, where the long-term deflection includes both the reused RC elements deflection and the steel girder deflection.

Using the updated material properties, Table 2 shows that the floor system has a significant reserve of capacity. This result highlights the conservative approach used during the design phase and it emphasises the importance of correctly evaluating the material properties of the reclaimed elements early in the design process to avoid over-designing.

Table 2. Degree of compliance, n

Element	Initial assessment	After material-property identification
RC slab – bending	1.05	1.61
RC slab – shear	1.15	1.74
Steel girders – bending	1.43	1.51
Steel girders – shear	3.65	3.83
SLS – long term deflection	1.13	1.68

Using Eqn (5) and the calculated horizontal loads, results in a connection made of 16-mm diameter high-strength threaded rods preloaded at 50 kN (Figure 6). Connections are placed in the corner of each reclaimed RC element.

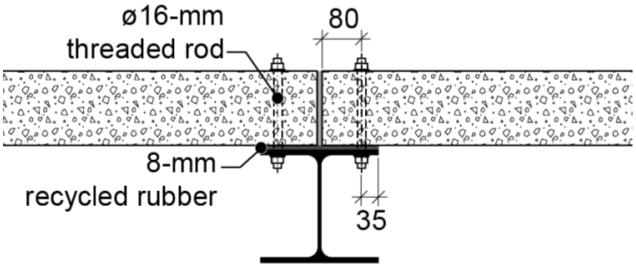

Figure 6. Steel-concrete connection.

4.4 Load test results

After its construction, the mock-up has been load-tested. An extra saw-cut RC slab element of 2,7 tons and of the same dimension was placed consecutively on each slab of the mock-up – i.e. in each corner of the mock-up. It created an equivalent load of 3,7 kN/m^2 (Figure 7), which is just above the permanent serviceability state. Eight LVDT sensors were used to measure the deflections at supports, at midspan of the steel girders and midspan of the reused-RC elements.

Load-test results (Figure 8) show predominantly elastic deformations of all slab elements. The maximum deflection is 1,63 mm, which is significantly less than the most severe acceptable deflection in the Swiss standards of 5,4 mm (span/500). A partial composite action was probably created with the bolted connections between the steel beams and the RC slab elements, resulting in stiffer behaviour.

Figure 7. Photograph of the load test.

Small irreversible deformations were observed (on average 0,2 mm). Many reasons could explain these irreversible deformations, such as pre-existing concrete cracking, settlements of the supports, plastic deformation of the rubber, plastic deformation of the steel profile, or a combination of the reasons mentioned above. Nevertheless, the load tests confirmed the good behaviour of the floor system made of reclaimed elements.

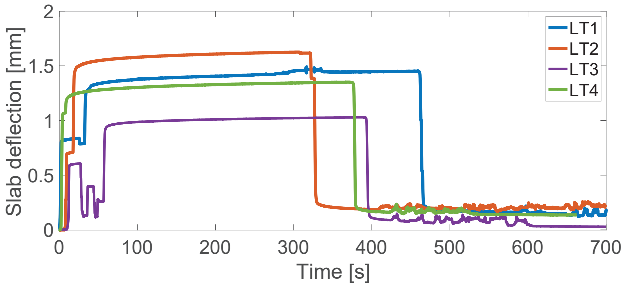

Figure 8. Midspan slab deflection measured during the four load tests (loading in each corner).

4.5 Life-cycle analysis

A life-cycle analysis is performed to quantify the upfront global-warming potential of the new FLO:RE floor system. The functional unit is the construction of one square meter of load-bearing slab in an office building in 2023. The analysis uses a cut-off approach. System boundaries start at the demolition of the donor building (C1-C4) and stop after the assembly of the floor system (A1-A5). Results of the FLO:RE mock-up are compared to that of a conventional flat RC slab designed based on Swiss standards. This slab is 22-cm thick.

Results show that the FLO:RE mock-up has an ultra-low global warming potential (Figure 9), with a footprint as low as 14 $kgCO_{2,eq}/m^2$ when built 140 km from the donor buildings, 6 $kgCO_{2,eq}/m^2$ if built within a radius of 20 km around the donors and 5 $kgCO_{2,eq}/m^2$ if built on the same site as the donors (no transportation). This corresponds to an 82 %, 92 %, and 94 % global-warming potential reduction compared to a new flat RC slab. It confirms that the FLO:RE system is an ultra-low carbon solution for the construction of floors.

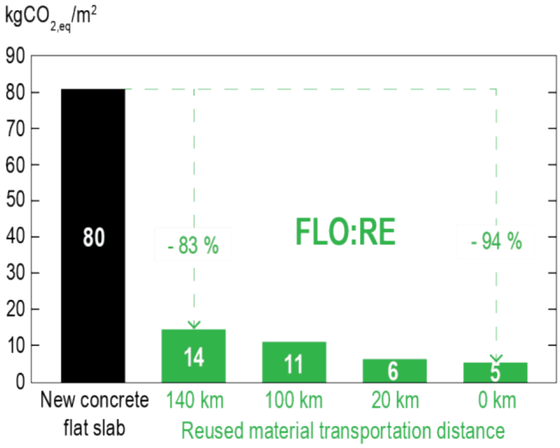

Figure 9. Global warming potential of the FLO:RE mock-up and conventional design.

5 Conclusions

The construction of the FLO:RE mock-up demonstrates the technical feasibility of building floor systems designed with reused RC elements. Steel girders and RC slab elements were reclaimed from decommissioned buildings in Switzerland and re-assembled in a novel floor system with a shallow carbon footprint. Material testing and load-test results enable the validation of several design hypotheses, showing the ability to conservatively predict the structural behaviour of reused RC elements as well as steel girders. Compared to concrete recycling, reusing concrete elements drastically reduces the need for new cement production and material excavation. Because it also delays the landfilling of obsolete concrete, RC reuse is an alternative of choice to increase the sustainability and circularity of new structural systems.

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