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Edited by:
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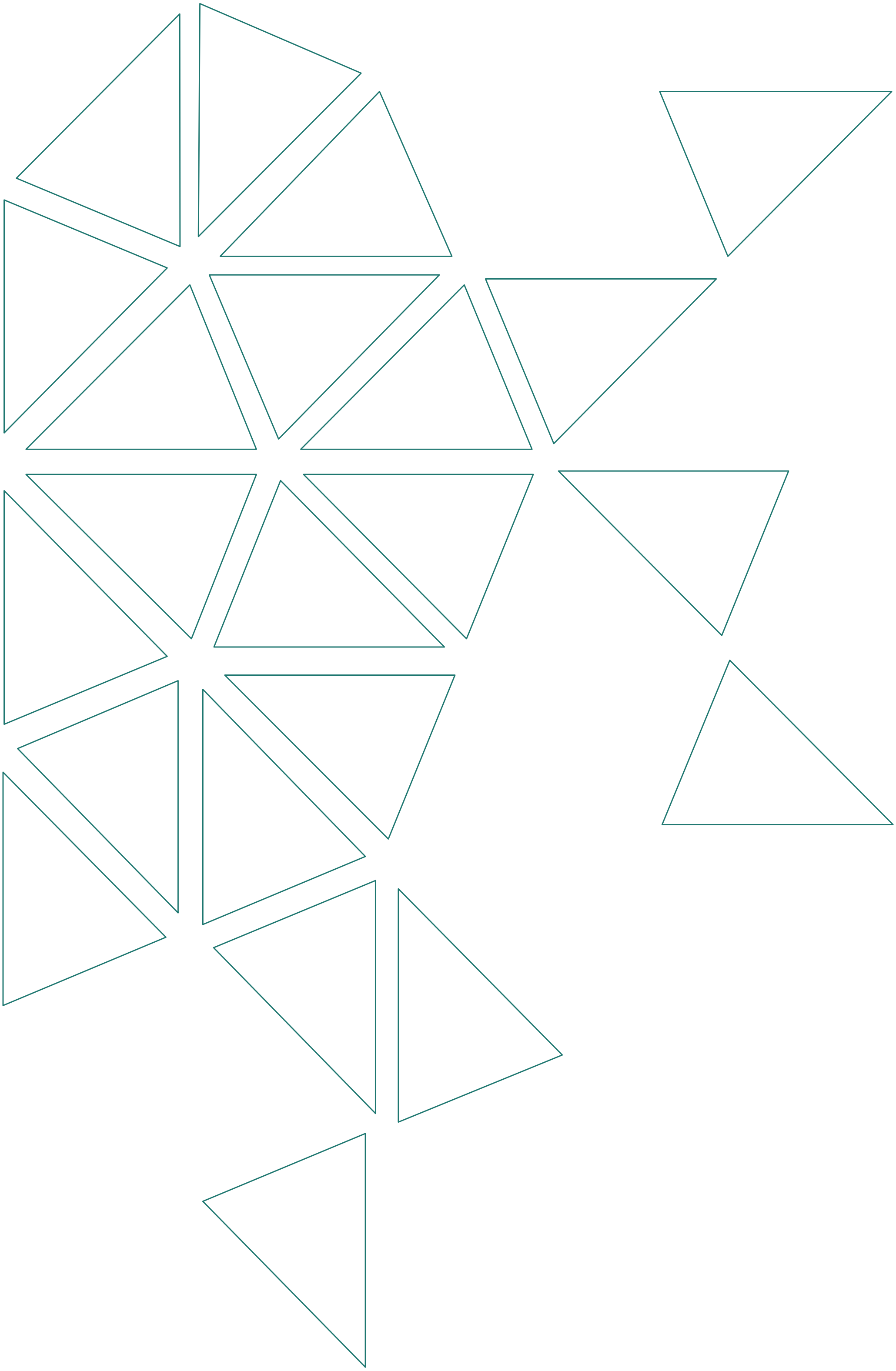

Circular economy

DESIGN OF NEW LOW-CARBON FLOOR SYSTEMS BY REUSING CUT CAST-IN-PLACE CONCRETE PIECES

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Abstract

As floors typically account for the largest share of a building embodied carbon footprint, new strategies to build low-carbon floors must be developed and implemented. Among these strategies, the reuse of existing components is a promising circular approach in which components are carefully extracted from buildings undergoing transformation or demolition and reused into new buildings. Recent research reviewed built examples that mostly reuse prefabricated reinforced-concrete (RC) components but also revealed a lack of design explorations for floor systems that reuse pieces extracted from cast-in-place (CIP) RC structures. This paper presents two new floor systems reclaiming pieces cut from typical CIP structures. In the first one, cut pieces are as long as the new span. In the second one, cut pieces are smaller and supported by girders as long as the new span. The environmental footprint of each new system is compared to conventional ones through a life-cycle assessment (LCA) and for multiple design parameters. In addition, a procedure is introduced to estimate the maximum cutting length that allows the reuse of pieces as simply-supported slabs. Results show that these lengths correspond to those of the donor slab if it spans up to 5.6 meters, depending on the slab thickness, construction period, and design uses. LCA shows radical carbon-footprint reductions that average 85 % for all simulations. Overall, results show that discarded concrete is a valuable material source for building innovative, efficient, low-carbon floor systems combining existing (de-)construction tools.

Keywords

circular economy, sustainable construction, reuse, reinforced concrete design, low-carbon slab, life-cycle analysis

INTRODUCTION

Figure 1 – Processes to reuse concrete: extraction (a, b), preparation and storage (c), installation (d).
Credits: (a) EPFL/SXL; (b) Ingeni SA, (c,d) FAZ Architectes.

The construction industry is a major contributor to alarming environmental deterioration, such as climate change, resource depletion, waste accumulation, and biodiversity loss. Alone, the construction sector emits 11% of global greenhouse gas emissions [1], calling for an urgent reduction of embodied carbon in new projects. Regarding buildings, most of the superstructure embodied carbon is in the floor systems. Indeed, floor structures account for up to 75 % of the embodied carbon emitted when constructing load-bearing systems, according to [2], or for more than 50 %, according to [3]. Strategies to reduce the environmental burden of new floors must thus be urgently implemented.

A prevalent design strategy to lower the embodied carbon in floors is the reduction of material consumption, mostly of concrete and steel. A complementary design strategy is the use of low environmental impact materials, including reused construction elements, i.e., components reclaimed from structures undergoing transformation or demolition and reused with no to slight alteration into new projects. Reusing structural components typically reduces the carbon footprint of new structures, prevents natural resource consumption, and reduces waste accumulation [4]. Research and practice have yet mainly focused on the reuse of steel or timber. However, concrete today is a significant construction waste stream in Europe, if not the largest as in Switzerland [5]. As demolitions are typically triggered by reasons independent of the state of the structure, demolished reinforced concrete (RC) structures are structurally sound, and their components could be used longer.

Different from recycling, the reuse of RC pieces in new projects is a little-known practice, where obsolete RC structures are not crushed into aggregates but carefully cut into pre-defined pieces, typically with diamond saws (Figure 1). A recent study has shed light on over 50 structures built with reused RC components between 1967 and 2022 in Europe and the United States [6]. Most of them reuse prefabricated RC elements, like wall or slab panels from mass-housing buildings, in buildings up to 7-storey high. In contrast, only a few projects have reused RC cut from cast-in-place (CIP) structures. The reason may reside in that defining where to cut pieces is CIP structures not trivial and that cutting implies a change in the static system unless new embedded connections are built.

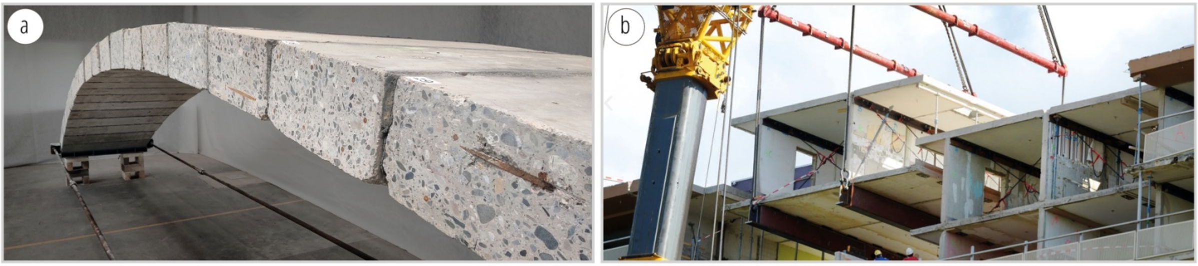

Figure 2 – Projects reusing small (a) or larger (b) pieces cut out of CIP RC structures.
Credits: (a) EPFL/SXL; (b) Superlocal.

Existing practice to reuse RC pieces cut from CIP structure is today bounded to two main approaches [6]. The first approach is to reuse parallelepiped pieces, i.e., blocks, to build structures that mostly work in compression. This approach has been used to build a 10-meter spanning arch [7] and parking pavements [8]. It globally allows adapting the length and width of the blocks to the new design but does not use the tensile strength provided by the reinforcing bars. The second approach is to reuse large structural frames that comprise both horizontal (slab) and vertical (wall or column) parts and preserve existing connections between plans. This approach has been used to build 2-storey high buildings [9]. It globally allows reusing most RC structural characteristics but highly constrains the new design layouts.

Between these two extremes, a third approach is yet to be studied. It takes advantage of all existing structural characteristics of both reclaimed concrete and steel reinforcement while allowing the design of space layouts distinct from the one of the donor building. Therefore, this study introduces new floor systems that reuse cut CIP RC pieces for spaces of various spans without strengthening, provides a procedure to estimate the cut piece maximum span, and assesses the environmental impacts of the new systems.

METHODOLOGY

Scope

The study focuses on the reuse of continuous CIP RC slabs, a widely used construction system in Switzerland. Donor slabs are parametrized according to common Swiss historic construction techniques. Swiss standards are used, and calculations refer to the pre-design stage. At this stage, hypotheses are formulated based on concrete construction history knowledge, architectural plans (i.e., the structure overall dimensions), construction year, use, and location. Structural hypotheses must be further verified on a case-by-case basis at a further project stage based on engineering drawings and monitoring campaigns (non-destructive tests, load testing).

Step 1: New system development

Before designing the new floor system, design objectives and constraints are defined. The new systems must reuse pieces cut from continuous unidirectional slabs spanning between 2 and 8 meters in housing or office buildings. The new systems are to be used for floors spanning between 2 and 8 meters in new housing and office buildings. No reinforcement or strengthening of the reused cut pieces is planned to ease and fasten the construction process. Thus, cut pieces must be reused as simply-supported slabs, and existing structural capacities must withstand all new efforts. In addition, deconstruction, preparation, and reassembly operations should require conventional tools, such as regular-size diamond saws, trucks, and lifting equipment. Consequently, the reclaimed piece width can be, at most, a regular truck width (i.e., 2.5 meters) and their length, at most, the donor-floor span. However, pieces are taken as long as possible within the donor-floor span to minimize costly operations on each reused cut piece.

Once the design brief is set, new systems are developed through an iterative design process. At least one solution must be available for each combination of donor slab and new floor span. Due to the change of static systems between the donor continuous CIP slab and the cut and simply-supported slab pieces, existing-structure knowledge and static considerations are combined to evaluate the maximum span of the RC reclaimed cut pieces L_c. Only maximal bending moment and resistance are considered as it is assumed to be the critical structural verification.

Step 2: Parametric life-cycle assessment

Life-cycle assessment (LCA) is a broadly used approach to compare the environmental impacts of design solutions. This study compares the detrimental environmental impacts of the newly developed reused-RC floor systems to those of a conventional flat RC slab, a widely used floor system in Switzerland through an LCA. Impacts are compared for floors spanning between 2 and 8 meters. In this study, the functional unit is the construction of a linear meter of a floor system for a housing or office building today in Switzerland. System boundaries start at the deconstruction or demolition of the obsolete structure, include the new, recycled, or reused material procurement and preparation, and end with the construction of the new floors. Boundaries exclude maintenance and end-of-life phases. The allocation method used is a cut-off approach [10].

The conventional flat slab has a thickness between 18 and 22 cm, depending on its span. Its reinforcement steel bar rate is 1.5%, as commonly used in this type of floor preliminary design. The impacts are calculated in terms of Global Warming Potential [kgCO2_e].

For the reused-RC floor systems, simulations are generated for all combinations of eight design parameters. The design parameters are: the donor-slab thickness, construction period, live load, the reused concrete and steel transportation distances, the new-system live load, and girder steel type.

To conduct the LCA, data are combined from different sources, notably the Swiss KBOB database [11] for conventional processes, the work of Devènes et al. [7] for processes related to concrete reuse, the work of Brütting et al. [12] for processes related to reused steel girders and construction companies for complementary information.

RESULTS

New floor systems

This section introduces the concept of new floor systems made of reused concrete. These new systems reuse pieces cut from donor CIP RC slabs as simply-supported slab pieces (Figure 5). The reused cut-piece span L_c must typically be cut shorter than the entire donor floor span L_0 so that the bending moment does not exceed the resistance despite the change of static systems. The method to estimate the maximum cut piece span L_c is described in the next section. Figure 3 introduces the two new CIP RC-reused systems, System A and System B.

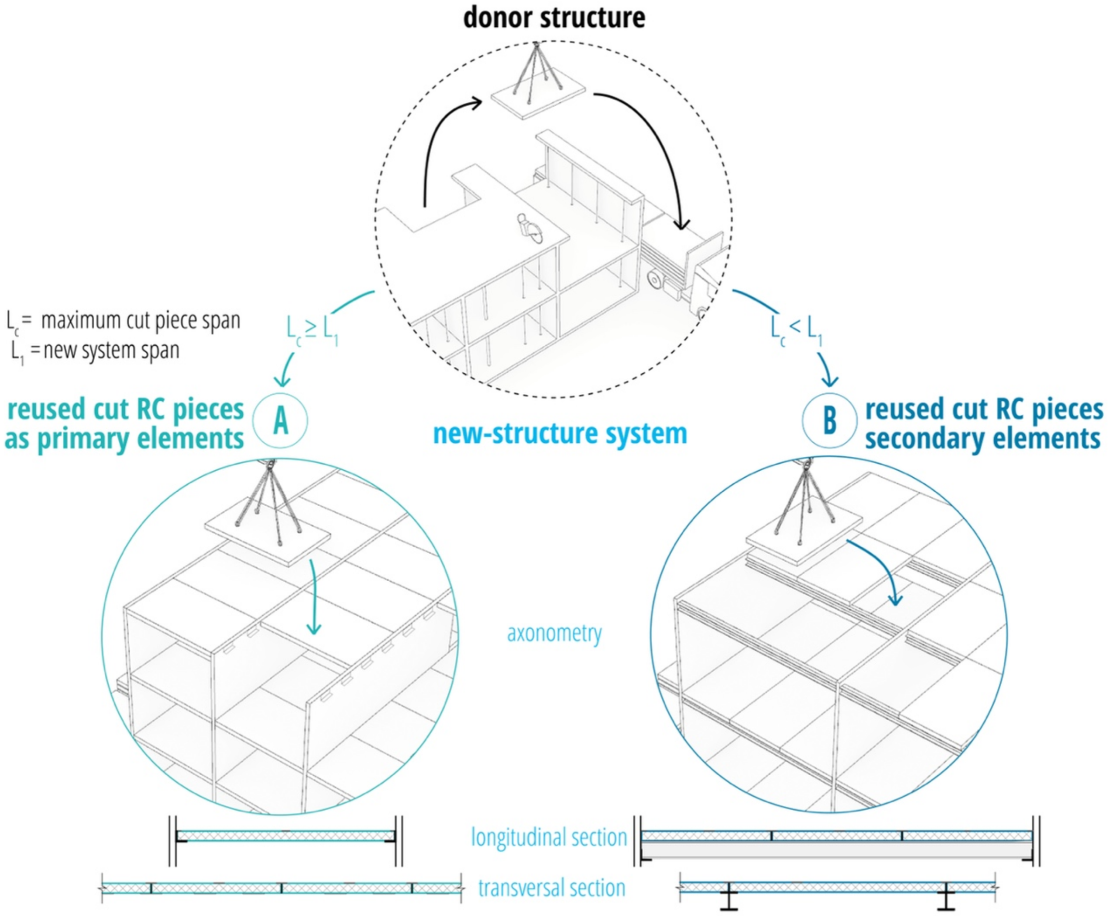

Figure 3 – Concept of the reused-RC floor systems: pieces are cut with saws from buildings undergoing transformation or demolition and reused over the longest span that static allows as primary (A) or secondary (B) elements in the new floors.

System A is used when the new floor span L_1 is equal to or shorter than the span of the cut pieces ($L_1 \leq L_c$). In System A, reclaimed cut pieces are reused as primary elements and span over the new floor span, and steel angles support the reclaimed cut pieces at the supports. System B is used when the new floor span is longer than the span of the cut pieces ($L_1 > L_c$). In System B, reclaimed cut pieces are reused as secondary elements and are supported by girders over the span. The design of the new girders can vary, but they are designed with standard H-shape steel profiles in this study. The profiles are either made of newly produced steel girders or reused. In both systems A and B, mortar fills the joints between the cut pieces, and steel plates ensure the lateral stability of the floor systems.

The new structural floor systems (Figure 4) provide an innovative and efficient way to reuse disposed CIP RC slabs. The reused-concrete floors support a high-quality reuse of discarded concrete, valuing their pre-existing structural capacities, including their bending resistance, and their sound- and fire-resistance. Both systems allow fast and dry construction, combining standard construction tools and techniques. The floors are designed to behave as well as regular floor systems, but they require no new materials besides the connectors and, if not reused, girders for system B. Systems are designed to be dismountable, and their components to be reused again into new floors with similar spans or rearranged in new floors with shorter spans (eventually trimming girders or cut pieces) or longer spans (using new girders).

Figure 4 – Low-angle views of systems A (a) and B (b).

Cut RC piece maximum span

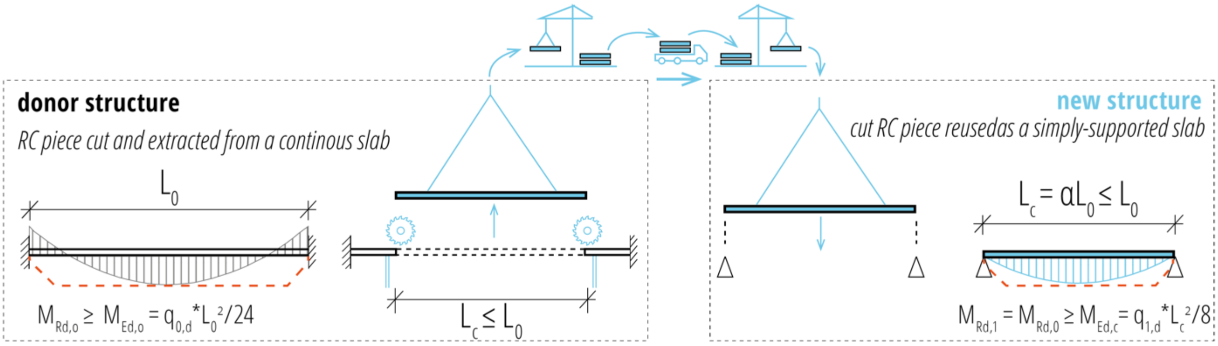

Figure 5. The new floor systems are made with simply-supported RC pieces cut from continuous slabs. Indices 0 refers to the donor structure, indices c to the cut RC pieces, and indices 1 to the new structure. Illustration of Situation I with determining tensile reinforcement.

In this section, the maximum span of reused cut RC pieces L_c is calculated using static considerations of both donor and receiver floor systems. Since the main difference between the donor and receiver floors is the modification of the static system, it is crucial to verify that the bending resistance of the slab $M_\mathrm{Rd,0}$ is sufficient for the new bending-moment levels in the cut pieces $M_\mathrm{Ed,c}$ ($M_\mathrm{Rd,0} \geq M_\mathrm{Ed,c}$). The initial donor-slab system is assumed to be continuous across its vertical supports, while the reused-RC floor system involves only simply-supported slabs (Figure 5). For similar spans and loads, the bending moment at mid-span for a given unidirectional slab triples when simply supported (Figure 6a, green line) compared to a continuous slab (Figure 6a, green line). Therefore, pieces must often be cut shorter than the entire donor floor span to reduce the bending moment ($L_c < L_0$).

Let's introduce $\alpha \in [\alpha_{min}, 1]$, the ratio between the maximum reusable span L_c that can be cut and reused as a simply-supported slab in the new system, and the continuous donor floor span L_0:

$$\alpha = \frac{L_c}{L_0} \tag{1}$$

For a given slab, α varies depending on L_0 and on whether the highest bending resistance is provided by tensile reinforcement $M_\mathrm{Rd,0,t}$ (Situation I) or minimum reinforcement defined in construction standards $M_\mathrm{Rd,0,m}$ (Situation II):

$$M_\mathrm{Rd,0} = \max(M_\mathrm{Rd,0,t}; M_\mathrm{Rd,0,m}) \tag{2}$$

The following two sub-sections describe how to define α and L_c for each case. Here is a short overview:

- In Situation I, the tensile reinforcement provides the highest bending resistance ($M_\mathrm{Rd,0} = M_\mathrm{Rd,0,t}$, blue zone in Figure 6a). The cut-piece span must be shorter than the donor slab so that the bending moment does not exceed the slab resistance. In this situation, a constant α ratio is used and is called α_{min}. Thus, in Situation I, $L_c = \alpha_{min} * L_0$.
- In Situation II, bending resistance is provided by the minimum reinforcement ($M_\mathrm{Rd,0} = M_\mathrm{Rd,0,m}$, grey zone in Figure 6a). In this situation, the maximum cut-piece span does not vary depending on

the donor slab span and thus is constant. This span corresponds to the lower bound of the maximum cut-piece span and is called $L_{\mathrm{c,min}}$.

Consequently, the maximum cut-piece span can be determined as follows:

$$L_{\mathrm{c}} = \max(\alpha_{min} * L_0; L_{c,min}) \tag{2}$$

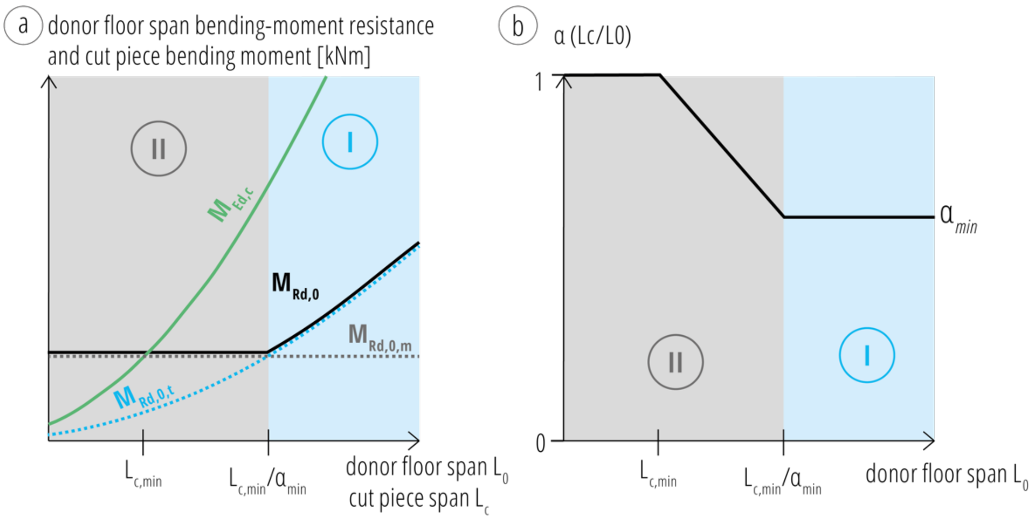

Figure 6. The bending moment in the new system compared to the bending moment of the donor floor span (a) and the ratio α between the donor floor span and the reusable cut-piece span (b).
The blue zones correspond to Situation I, where the highest bending resistance is provided by tensile reinforcement. The grey zones to Situation II, where the highest bending resistance is provided by minimum reinforcement.

Situation I: $L_c = \alpha_{min} * L_0$

This section explains how the maximum span of the cut pieces is defined when the resistance is determined by the tensile reinforcement ($M_{\mathrm{Rd,0}} = M_{\mathrm{Rd,0,t}}$, blue zone in Figure 6). The tensile reinforcement of the reused slab has been initially designed to resist the bending moment in the donor slab. The minimal value for the slab resistance $M_{Rd,0,t}$ is thus estimated as equal to the maximum bending moment at the midspan of the donor slab.

When defining the maximum span of the cut pieces in this situation, it must be considered that the bending moment at mid-span is tripled between a unidirectional continuous slab and a unidirectional simply-supported slab for similar spans and loads. Consequently, the cut-piece span L_{c} must be shorter than the donor floor span L_0, and the donor floor span L_0 must be cut at a constant ratio α_{min} so that the bending moment in the cut pieces $M_{Ed,c}$ does not exceed bending resistance. α_{min} can be estimated using:

$$\alpha_{min} = \sqrt{\frac{q_{0,d}}{3q_{1,d}}} \tag{3}$$

where $q_{0,d}$ and $q_{1,d}$ are the donor and receiver total load levels [kN/m], respectively. Consequently, if $q_{\mathrm{0,d}} \cong q_{\mathrm{\,1,d}}$, $\alpha_{min} \cong 0.58$.

Table 1 details α_{min} ratios for various donor and receiver uses, slab thicknesses, and typical live loads according to [13]. Overall, in Situation I pieces long up to 59 % of the donor floor span can be reused as simply supported slabs when donor and receiver live loads are similar. The ratio increases to 64 % if new-system live loads are lower and decreases to 59 % if receiver live loads are higher.

Table 1 - α_{min} ratio for several receiver and donor use and slab thickness combinations.

Donor design use	Receiver design use	Slab thickness [cm] 14	16	18	20	22	Average
Housing	Housing	0.59	0.59	0.60	0.60	0.60	0.59
Housing	Office	0.55	0.55	0.56	0.56	0.56	0.55
Office	Housing	0.64	0.64	0.64	0.64	0.64	0.64
Office	Office	0.59	0.59	0.59	0.60	0.60	0.59

Situation II: $L_c = L_{c,min}$

This section explains how the maximum span of the cut pieces is defined when the resistance is determined by the minimum reinforcement ($M_{\mathrm{Rd,0}} = M_{\mathrm{Rd,0,m}}$, grey zone in Figure 6). The minimum reinforcement is the minimum requirement of reinforcement quantities defined in construction standards. This minimum reinforcement provides a lower bound of the bending resistance $M_{Rd,0,m}$ that depends on the reused slab thickness, minimum reinforcement quantity, and steel resistance but is independent of slab span. Thus, for a given slab, $M_{Rd,0,m}$ is constant. Consequently, the lower bound span of the reused pieces $L_{\mathrm{c,min}}$ for a given load level in the new system $q_{1,\mathrm{d}}$ $[\frac{kN}{m}]$ is estimated as follows:

$$L_{\mathrm{c,min}} = \sqrt{8M_{Rd,0,m}/q_{1,\mathrm{d}}} + L_s \tag{5}$$

where L_s is the additional length required for the supports, which does not affect the bending moment. In this study, L_s is assumed to equal 15 cm.

To approximate $L_{\mathrm{c,min}}$ at the pre-design stage, current Swiss standards for existing structure (SIA 269) and past standards for new construction (SIA 262) are used. The minimum reinforcement quantity is set based on past construction norms, notably the Swiss concrete construction norm of 1956 [14], which requires a minimum reinforcement rate of 0.2 % of the slab volume. The steel resistance is taken in SIA 269 [15].

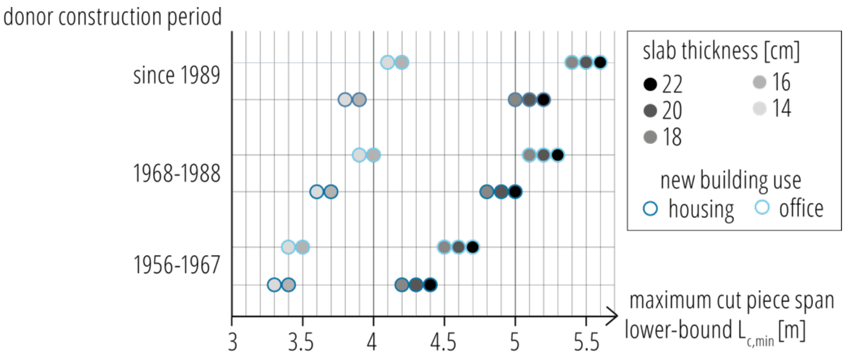

Figure 7 - $L_{c,min}$, the maximum span of cut pieces for reuse in Situations II

Figure 7 plots $L_{\mathrm{c,min}}$ for several donor slab thicknesses, construction periods, and new system uses. Overall, $L_{\mathrm{c,min}}$ ranges between 3.3 and 5.6 meters. $L_{\mathrm{c,min}}$ typically increases with thicker and more recent slabs. $L_{\mathrm{c,min}}$ is generally 0.1 to 0.3 meters longer when slabs are reused in housing buildings rather than office buildings, and it exceeds 4 meters for all slabs with a thickness of 18 cm or more.

Synthesis and illustrative donor floor example

Table 2 summarizes the L_c and the α ratio of the two Situations I and II and provides numerical values for one donor floor example at the pre-design stage. The donor floor example is an 18-cm thick slab cut in an office building built between 1968 and 1988 and reused for the floor of a new office building.

In the illustrative example, Situation II applies to pieces cut from donor floors that span between 2 and 7.9 meters. In this situation, the maximum cut-piece span L_c is constant and corresponds to the maximum cut-piece span lower bound $L_{c,m}$, which equals 4.7 meters in this example. Consequently, in this example, the α ratio for donor floor span not exceeding 4.7 meters ($L_0 \leq 4.7$ m) is equal to 1 and then linearly decreases until $\alpha = \alpha_{min}$, with α_{min} equals to 0.59. When $\alpha = \alpha_{min}$, Situation I applies and $L_c = \alpha_{min} * L_0$.

Table 2 – Span of cut pieces and ratio α for the two Situations I and II. Lower and upper bounds are taken for an illustrative example of a donor floor span floor: a slab of 18-cm thick from an office building.

Situ-ation	**donor floor span floor span L_0**	example [m]	**cut-piece span L_c**	example [m]	**reusable span ratio α**	example
I	$L_{c,min}/\alpha_{min} < L_0$	7.91 - 8.00	$\alpha_{min} * L_0$	4.7-4.8	α_{min}	0.59
II	$L_{c,min} < L_0 \leq L_{c,min}/\alpha_{min}$	4.71 - 7.90	$L_{c,min}$	4.7	$\alpha_{min} \leq \alpha < 1$	0.99-0.60
	$L_0 \leq L_{c,min}$	2.00 - 4.70	$L_{c,min}$	0-4.7	1	1

Environmental-impact reductions

The global-warming potential [kgCO2$_e$] of the reused-RC systems is compared to those of flat new/recycled-RC slabs. Results are first computed for two specific examples and then extended to a parametric study involving 480 simulations.

The two examples are a 4-meter and a 7-meter span new floor in an office building ($q_k = 3\ [\frac{kN}{m^2}]$), reusing the same donor floor span floor example as the previously introduced: an 18-cm thick slab cut from an office building built between 1968 and 1988. Figure 8 plots the distribution of the global-warming potential, considering a 100-km transportation distance for reused materials.

To build a 4-m long new floor, system A is used, with cut RC pieces reused as primary elements (Figure 8a). Environmental impacts are drastically reduced since they are cut by 83 %. Compared to a 1'000 m^2 new/recycled RC 20-cm thick slab, the production of 450 tons of concrete is avoided, 450 tons of RC are directly reused and diverted from the elimination route, and the emission of 71 tons of CO$_{2e}$ is avoided.

To build a 7-m long new floor, system B is used, with cut RC pieces reused as secondary elements supported by steel girders (Figure 8b). Two types of steel girders are studied: new and reused ones. The largest reductions, 91 %, are obtained when reused cut RC pieces are combined with reused-steel girders. Still, when new-steel girders support the reclaimed cut pieces, reductions reach 78 %. Compared to 1'000 m^2 of a flat new/recycled RC 22-cm thick slab, the production of 500 tons of concrete is avoided, 450 tons of reinforced concrete are directly reused and diverted from the elimination route, and the emission of 72 and 85 tons of CO$_{2e}$ is avoided, for systems with new and reused girders respectively.

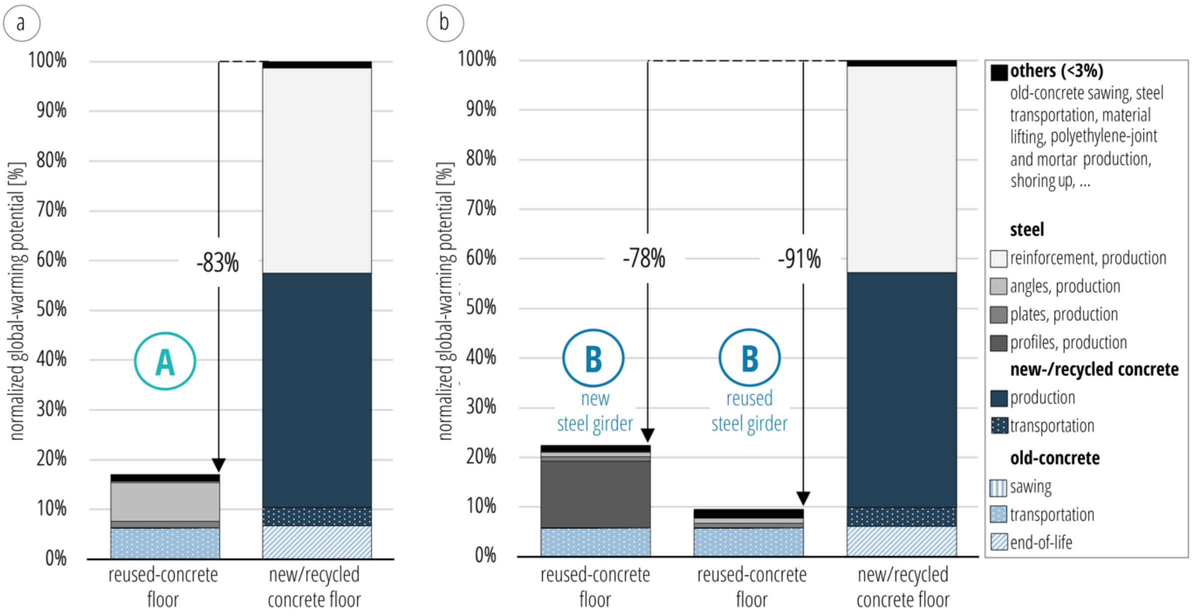

Figure 8 – Normalized global-warming potential of floors in a new office building reusing RC pieces cut from an 18-cm slab of an office building built between 1968 and 1988 compared to that of flat RC slabs.

The LCA is then extended through a parametric study involving 480 simulations. The simulations generated for all combinations of design parameters that are the donor floor span-slab thickness (between 14 to 22, with 2 cm steps), construction period (between 1956 and 1967, 1968 and 1987, or 1988 and later), live load (housing or office live load), the reused concrete and steel transportation distances (0 or 100 km), the new-system live load (housing or office live load), girder steel type (new or reused steel). In addition, in each simulation, impacts are calculated for all combinations of donor floor span and new floor spans ranging between 2 and 8 meters, with increments of 0.50 meters.

Results show that environmental impacts are considerably reduced when building floors with systems reusing RC components rather than with new/recycled RC flat slabs (Figure 9, right). Overall, reductions for all simulations average 85 %, with minimum gains of 64 % and maximum gains of 97 %.

Reductions reach an average of 88 % when cut RC pieces are reused on the same site and 82 % if transported over 100 km.

Maximum average reductions are 89 %, obtained for simulations run with reused-steel profiles as girders in System A. If recycled-steel profiles are used instead, reductions average 81 %. Reductions are not sensitive to the construction period. On the opposite, reductions increase when reused slab thickness decreases, with averages of 83 % for simulations with 22-cm thick slabs and 88 % for simulations with 14-cm thick slabs.

Average reductions vary between 76 and 88 % depending on the new floor span (Figure 9, a). Maximum reductions are for new floor spans of 4.5 or 5 meters. The lowest average reductions are for new floor spans between 2 to 3 meters because of a higher proportion of connectors and supports for which new steel must be produced.

To conclude, the study results corroborate that of concrete-reuse LCA available in the literature and collected by [6]. Moreover, results confirm that reusing concrete is a largely more efficient waste management strategy than recycling in terms of carbon footprint since recycled concrete mixes, though replacing a share of natural aggregates with recycled ones, still require as much cement as new concrete mixes and therefore have a similar carbon footprint as new ones [16]. On the opposite, reused concrete does not require new cement, besides an eventual small amount for connections.

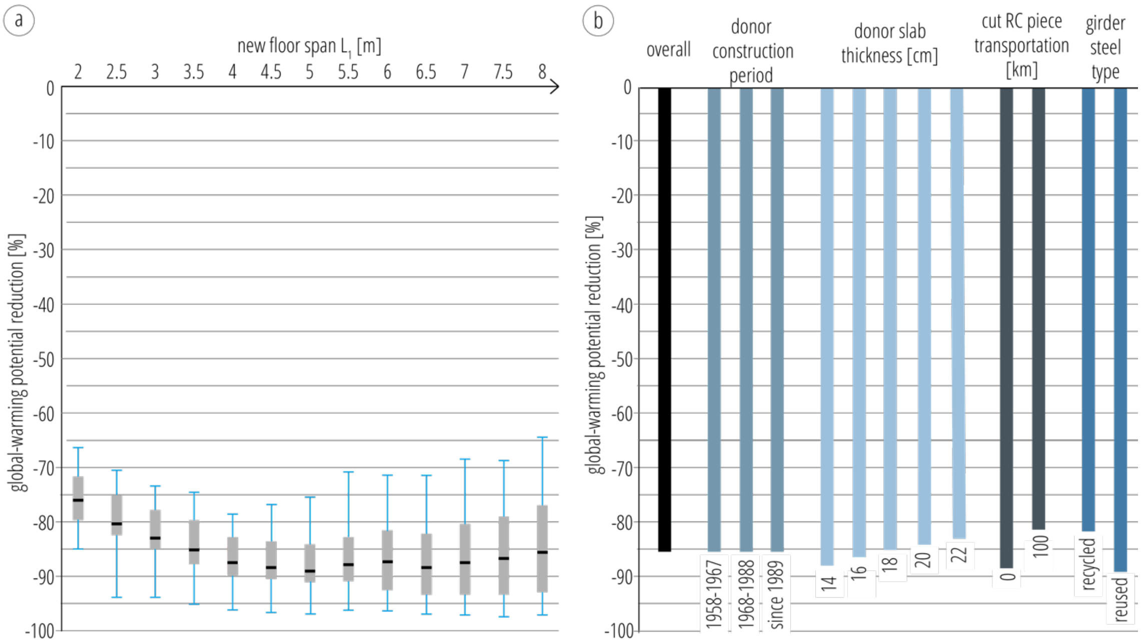

Figure 9 - Global-warming potential reduction of reused-concrete floors compared to flat RC slabs: box plot of all design-combination simulations (a) and mean for selected design parameters (b).

CONCLUSION

This paper focuses on the reuse potential of discarded CIP RC structures to design and build low-carbon floor systems. The paper first proposes two new conceptual floor systems that revalue discarded RC pieces. Then it provides a procedure to estimate the maximum span of the cut RC pieces for reuse as simply-supported slabs in pre-design and finally assesses the environmental impacts of the new systems for several combinations of design parameters. Results lead to the following conclusions:

- The new floor systems are innovative solutions to value one of the largest waste streams, RC, by reusing its existing structural characteristics. Systems are designed to be built combining standard tools, perform as well as conventional floors, and adapt to several new-structure spans.
- Cut pieces of continuous CIP RC slabs can be reused as simply supported slabs without strengthening or keying when they do not exceed a specific span. The maximum cut-piece span is as long as the donor floor span when the latter does not exceed 3.3 to 5.6 meters, depending on the donor floor age, thickness and design use, and new design use. For a longer donor floor span, the maximum cut-piece span corresponds to 100% to 54% of the donor-floor span.

- Radical carbon-footprint reductions are obtained with the new reuse systems compared to conventional new or recycled RC flat slabs. Estimated reductions average 85 % for all design-parameter combinations in the new reused-RC systems. They average 88 % when RC cut pieces are reused on the same site as the donor structure and 82 % when RC cut pieces are transported over 100 km.

Overall, discarded concrete is a valuable material source for designing low-carbon floors. The new reused CIP RC floor systems not only value existing structural capacities but also reduces new resource needs and waste generation. More importantly, the new systems provide a new benchmark for low-carbon floor design that supports the relevance of RC reuse for a more sustainable construction sector.

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