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Low-tech methods for the reuse of reinforced concrete structural elements

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Low-tech methods for the reuse of reinforced concrete structural elements

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Abstract. Most of existing buildings are made of concrete, new buildings are being built with it and others are demolished when still in good structural condition. This drives increased demands for raw materials, greenhouse gas emissions, and an accumulation of demolition waste. When in-situ rehabilitation or transformation is deemed unfeasible, a promising circular economy strategy to reduce these impacts is to reuse reinforced concrete (RC) load-bearing elements from obsolete donor structures into new receiving structures. Consequently, there is a need to adapt methods and processes to the specificities of RC element reuse by integrating knowledge on existing structures, deconstruction and construction techniques and structural optimization. To facilitate the supply chain of reclaimed RC components, the planning and execution of the deconstruction of an obsolete donor structure must be linked to the planning and execution of the construction of a new receiving structure. Using three recent case studies in Switzerland, this paper highlights how low-tech methods and procedures can be used to plan RC element reuse. A complete set of tools is introduced to evaluate an existing donor structure, plan its optimal deconstruction, and design the new receiving building. They include a reusability assessment method, a reuse-driven design process, and a data validation procedure. The case studies confirm that, depending on transport distances, reusing RC elements in a new structure can save up to 75% of CO2-eq emissions compared to standard RC construction techniques.

1. Introduction

Since the second half of the 20th century, concrete is the world's most widely used construction material. Reinforced concrete (RC) constitutes a large part of the load-bearing structures of existing and new buildings. However, even if still in good condition, RC buildings are often demolished prematurely to make place for new real estate operations, disregarding their potential for renovation or transformation. Consequently, concrete waste alone accounts for 30% of total construction and demolition waste [1]. Moreover, the environment is negatively impacted by the extraction of raw materials and the cement production required for new concrete. Approximately 9% of global greenhouse gas emissions are attributed to the production of cement alone [2].

When building replacement cannot be avoided, reusing structural RC elements is a promising circular approach to reduce waste and the detrimental environmental impacts of concrete construction. It consists in carefully extracting structural elements in good condition from an obsolete building – the donor building – to reuse them within a new building – the receiving building. A recent review identified 54 structures built with reclaimed concrete elements since the 1980s and highlighted the various opportunities and barriers of the technique [3]. The main barriers concern the lack of technical guidance

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and feedback on project management risks. The recent experience by the authors also emphasize the need for adapting conventional design phases to the specificities of structural element reuse.

On this basis, a new workflow is proposed in this paper to facilitate the reuse of structural RC elements, as detailed in Figure 1. In addition, the paper reviews the phases specific to reuse through three case studies, highlighting how low-tech methods are readily available and can be easily adapted for reuse.

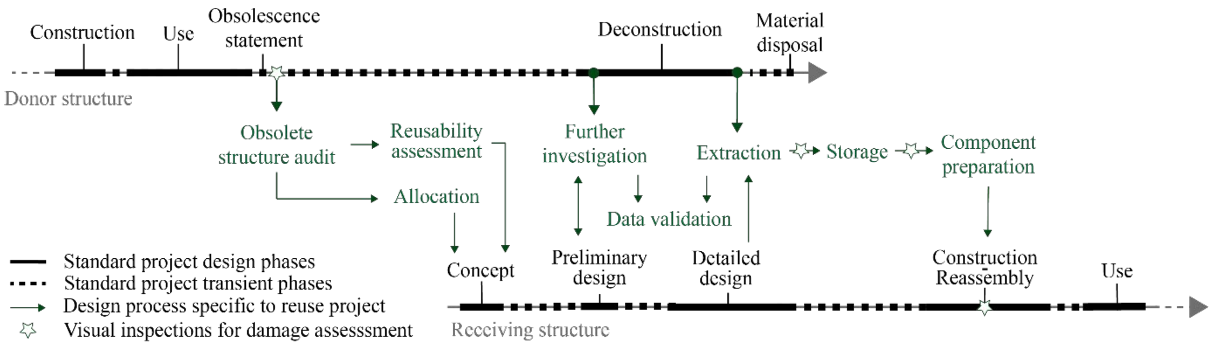

Figure 1. Design process sequences for the donor and receiving structures of reuse projects.

The paper is organized following the reuse design phases introduced in Figure 1. Section 2 presents a procedure for the obsolete building audit using two case studies. This first step in the process is realized after the building obsolescence statement and before any other design phase. Then, a reusability assessment verifies if a structural RC element is suitable for reuse based on durability and structural capacity, as introduced in section 3. Durability of the structural RC elements is evaluated by assessing any pre-existing damage and determining their impact on the intended use of the element in the receiving building. Developed around the third case study, an allocation method based on the structural capacity of the donor building and the structural demand of the receiving building is proposed in section 4. In section 5, a data validation process suggests continuous monitoring of the elements through visual inspection from deconstruction to reassembly. Lastly, section 6 discusses the environmental benefits of reusing structural RC elements in new buildings before concluding the paper in section 7.

2. Obsolete building audit

Based on existing procedures [4] adapted for the specificities of structural RC, the obsolete building audit aims to acquire all relevant and useful information on the donor building's RC elements to design the new receiving structure with them. It follows the obsolescence statement and precedes the deconstruction of the donor building, as expressed in Figure 1.

The first case study, used to develop the audit procedure and illustrated in Figure 2a, concerns three 15-story buildings in Zürich, formally used to house the nearby hospital staff. The deconstruction of these buildings is one of the options that the owners consider, which would make available a large amount of RC elements.

The obsolete building audit is straightforward and starts with an inventory of the elements in the structural RC system of the donor building. It includes their classification, census, and the collection of their properties – i.e., geometry, reinforcement layout, mechanical characteristics, etc. Figure 2b-d presents some available methods and tools – e.g., review of existing data, visual inspections, material investigations, etc. The inventory is completed by a damage assessment considering the specificities of RC – i.e., concrete cracking and spalling, steel corrosion, etc. Inspired by existing structure damage assessments [5], element conditions are classified on five levels, from good (grade A) to failure (grade E). It is mainly based on visual inspection but can also be corrected by results from in-depth material investigations. Figure 2e shows the damage assessment outputs for the first case study. All information from the obsolete structure audit is finally synthesized on factsheets by element type. The audit steps of the obsolete building are detailed in Devènes et al. [6].

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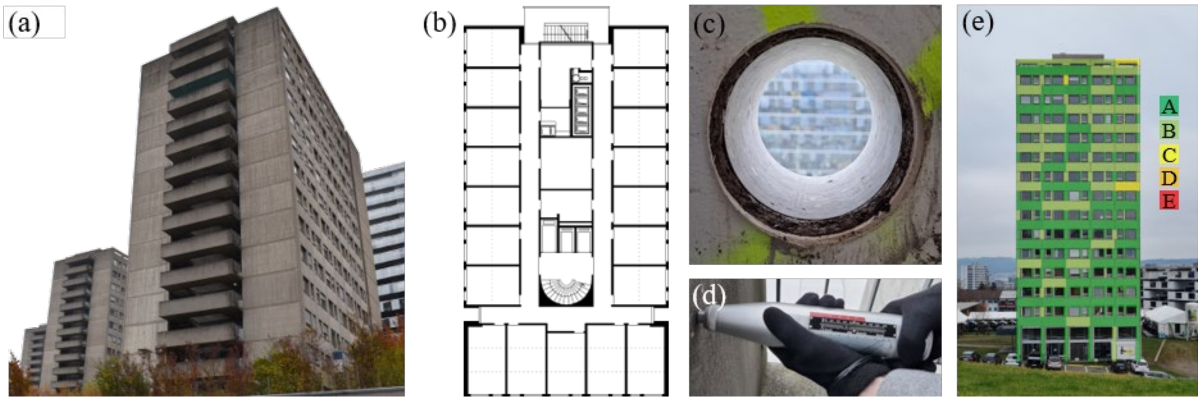

Figure 2. Obsolete structure audit for the first case study (a) – Procedure steps: (b) review of existing data, (c) destructive and (d) non-destructive investigations, (e) damage assessment based on five levels (from A to E).

For this first case study, all concrete formwork and reinforcement drawings from the construction period are available, thus facilitating the classification of the elements and data collection. This is not the case for the donor building of the second case study, an office building in Basel where only architectural drawings are available for the audit. The reinforcement layout and the resulting bending resistance are thus estimated using a combination of analytical methods, destructive openings in the concrete cover, and non-destructive scans with Ground Penetrative Radar (GPR). A lower bound bending resistance of the slabs is computed from the minimal reinforcement ratio requirements obtained from the in-force codes at the time of construction. The static system of the slab is then analyzed, and the minimal requirements for bending resistances are further refined using again the design methods of former codes. Finally, the localized destructive investigations (Figure 3a), in combination with the GPR scans of whole slabs (Figure 3b), allow validation of a reinforcement layout with enough certainty to plan its reuse and integrate this information in the element factsheet. Figure 3c shows the floor plan of the building in which the bending resistances, resulting from the analysis, are represented in light and dark green.

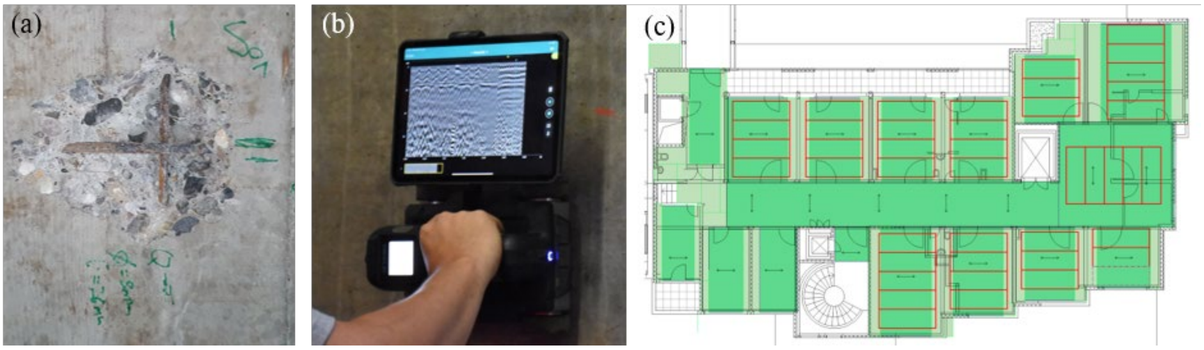

Figure 3. Obsolete structure audit for the second case study: (a) destructive openings in the concrete cover, (b) GPR investigation, and (c) floor plan with varying bending resistances (light and dark green) and sawing layout (red)

3. Reusability assessment

Once the information on the structural RC elements is collected through the obsolete structure audit, it is used as input to assess the elements' reusability. The reuse potential of RC elements depends on both the durability and the structural capacity.

Vulnerable to weather conditions, the durability of structural RC elements is an essential factor that may limit their reuse potential. Thus, a decision-making tool is proposed regarding durability conditions to help find the best solution to reuse the structural RC element while reducing subjectivity and downcycling as much as possible. This tool is based on three criteria: (1) the pre-existing damages defined during the damage assessment of the obsolete building audit; (2) the intended use, defined by the stability criterion and water exposition of the elements in the new receiving structure; (3) the planned interventions that can modify the elements condition. Combining these three criteria leads to a reusability grading from *reusable* to *not reusable* [6].

Along with durability, structural capacity is the other key factor in assessing the reuse potential of structural RC elements. The resistance is dictated by concrete compressive strength and steel rebars strength and layout. As identified in section 2, these properties are investigated during the obsolete building audit. In combination with allocation methods, introduced in section 4, it must then be verified if the resistance available in the reclaimed RC elements is sufficient, with or without further post-installed reinforcement, for the requirements of the receiving building.

The reusability assessment does not lead to a unique solution. An iterative design process varying the stability, water exposition, and intervention levels leads to an optimal reuse solution. Nevertheless, it should always remain proportionate regarding either economic or environmental points of view.

4. Allocation process

Defining the sawing pattern of a donor building depends on the allocation of the resulting elements to the receiving structure in a way that ensures the required resistance. In the second case study presented in section 2, the donor building slab elements are used for the construction of the floor slabs of a new receiving office building, also in Basel. The simple bending moment resistance layout of the donor slab and the unique requirement for bending resistance and geometry of the receiving slab leads to a straightforward definition of the sawing pattern, shown in red in Figure 3c, mainly based on geometrical consideration.

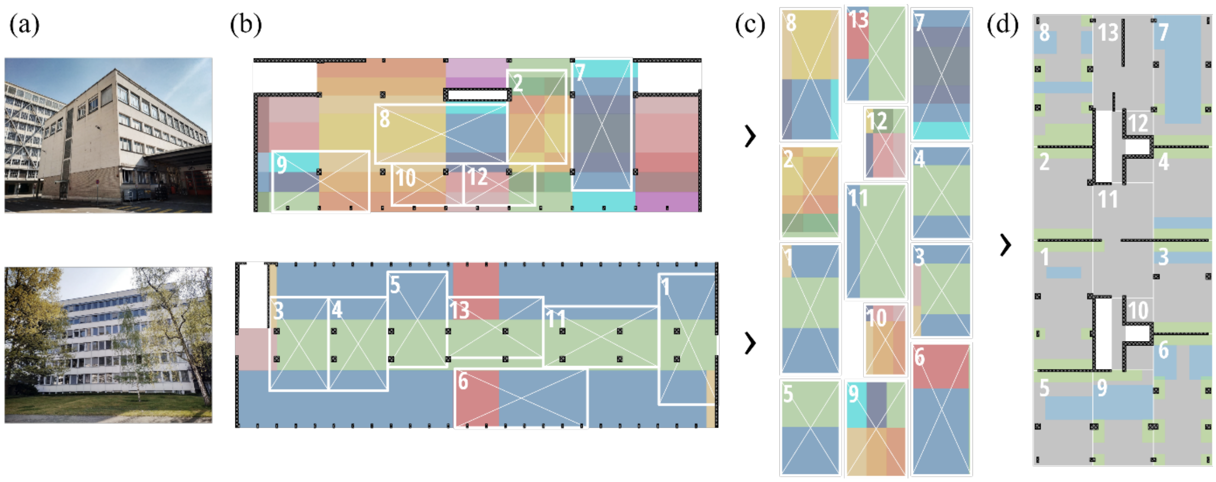

Figure 4. Allocation process for the third case study: (a) donor buildings, (b) bending moment capacity and sawing scheme of their slab, (c) reassembly layout of the receiving slab, and (d) strengthening needs

The third case study leads to a more complex design process. A new residential building is to be built in Basel with reclaimed structural RC elements from two donor buildings soon to be deconstructed and located on the same site. An algorithm is developed in [7] to allocate parts of the donor buildings to an optimal position in the receiving building, as shown in Figure 4. It aims at reducing the required structural strengthening of the reclaimed elements while meeting the bending resistance requirements of the receiving building. It results in the definition of an optimal sawing pattern implying that this study must be carried out before the donor building deconstruction, as illustrated in Figure 1.

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5. Data validation

When the concept of the new building and the related sawing pattern of the donor building are fixed, additional investigations and visual inspection are required to clear any remaining uncertainties and validate the good quality of the reclaimed RC elements. These extra steps should integrate with the planning of the deconstruction of the donor building and construction of the receiving building, see Figure 1.

During deconstruction, the reclaimed elements should be verified one last time using GPR scanning to validate their suitability for the receiving building, especially if original reinforcement drawings are missing. After deconstruction and before evacuation of the donor site, the dimensions of the elements (width, length, and thickness) and layout of the sawed rebars on the cut face (diameter and spacing) should be controlled. Surveillance through visual inspection is recommended between the deconstruction and reassembly stages, expressed by the green stars in the project sequence illustrated in Figure 1. The possible damages are shown in Figure 5.

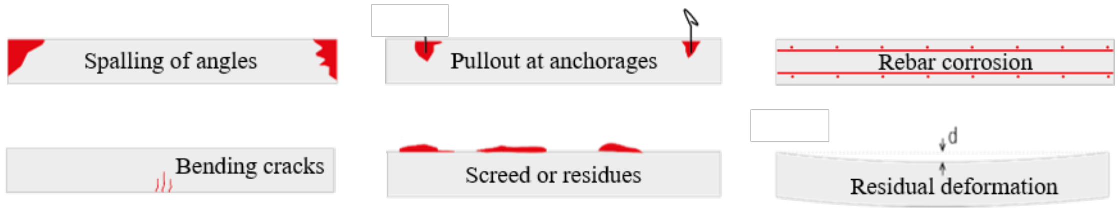

Figure 5. Visual inspection to check potential damage occurrences after deconstruction and transport.

6. Potential environmental savings

As stated previously, reusing structural RC elements is a circular strategy with a high potential to reduce the environmental impacts of concrete construction. The environmental impact of a construction project is here computed with a Life Cycle Assessment (LCA). Results usually compare the global warming potential for different alternatives, expressed in kilograms of CO_2-equivalent, and estimated for each fabrication and construction step of each alternative.

When the reuse of RC elements is made possible through the realization of an obsolete building audit and a reusability assessment, the disposal and the production of substantial quantities of material are avoided. For instance, if the deconstruction of the buildings of the first case study (Figure 2) were to be decided, the reuse of all their RC elements in a reusable condition would save more than 5’500 tons of concrete from landfilling. It would also avoid 1’705 $tCO_{2\text{-eq}}$ of emission to produce new RC elements.

For the third case study (Figure 4), the global warming potential of designing a new project with reused RC elements is compared to the design of an identical building made of new cast-in-place RC. The LCA is detailed in [7] and the main results state that 75% of $kgCO_{2\text{-eq}}$ can be saved when the elements are reused on the same site – i.e., the donor and receiving buildings are on the same site location, and there is no transportation of elements. In other cases, transport can cause a significant share of the global warming potential of the reuse project. However, other projects have shown that the reclaimed elements can be transported over several kilometers before reaching the impact levels of conventional new RC solutions [8]. Therefore, transport distances should be minimized as much as possible between each stage – i.e., from deconstruction to storage to reassembly sites. For instance, each kilometer of transport of all elements reused in the second case study (Figure 3) – i.e., 350 tons of RC elements – increases the global warming potential of the project by 64 $kgCO_2$-eq.

7. Conclusion

This paper reviews the design phases required to plan the reuse of RC structural elements, linking a deconstruction donor project to a new construction receiving project. It starts with auditing the obsolete donor building, which feeds the reusability assessment and allocation process. The reusability assessment verifies if the elements from the donor building are adequate to build the receiving one, regarding their durability and structural capacity. The allocation process computes a sawing plan of the donor building, considering the geometrical and resistance requirements of the receiving building. In all those processes, the needed tools and methods are already industry-standard for existing structure evaluations or new construction designs. They are well known to engineers and require only minor adaption to the specificities of reuse. The different case studies used to illustrate the different phases also show that reusing RC elements significantly reduces demolition waste while lowering the global warming potential of new constructions.

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Credit author statement
J Devènes: Section 2, 3, and 5 formal analysis, Writing – Original draft, Visualization. **M Bastien-Masse:** Conceptualization, Support to formal analysis, Writing – Reviewing & Editing, Supervision, Project administration, Founding acquisition. **N Widmer:** Section 4 and 6 formal analysis, Writing – Reviewing, Visualization. **C Fivet**: Conceptualization, Writing – Reviewing, Supervision, Founding acquisition.

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