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Life-Cycle of Structures and Infrastructure Systems

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Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Building structures made of reused cut reinforced concrete slabs and walls: A case study

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ABSTRACT: Reuse of reinforced concrete (RC) components reduces construction's environmental impacts and waste. Rather than crushing the concrete of an obsolete structure, its components are saw cut and later reassembled in a new structure. The theoretical feasibility of this method is demonstrated through a case study: the design of a residential building structure that reclaims cast-in-place RC components from two 60-year-old office buildings scheduled for demolition. Parts of the source buildings are allocated to an optimal position in the target building using an algorithm that minimizes the need for strengthening. Construction details are developed for the slab-wall connections and the bracing system. An alternative conventional cast-in-place RC design is proposed for comparison, as well as a hybrid design balancing environmental and cost savings with technical readiness. The assessment of the designs confirms that reusing RC components allows saving up to 75% of greenhouse gas emissions for similar costs, as long as demolition and disposal of obsolete source material are considered.

1 INTRODUCTION

Concrete is the most commonly used building material and the related production of cement is responsible for at least 9% of global CO_2 emissions (Monteiro et al. 2017). Cement and concrete production also consume large quantities of raw materials such as gravel, sand and limestone, which, in combination with an increasing concrete demand, will most likely lead to a shortage of these natural resources in the near future (Habert et al. 2010).

Meanwhile, construction and demolition waste correspond to about one third of all waste in Europe (Zhang et al. 2022) of which about 30% is concrete rubble (Giorgi et al. 2018). Nowadays, the demolition of buildings is usually not due to structural deficiencies but to changes of requirements – e.g. new functions, use intensification, or improved energy efficiency. During demolition, concrete is most often crushed and used as backfilling material (Zhang et al. 2022) or as a substitution for natural aggregates in a new, so-called recycled concrete. However, because both need similar amounts of cement, CO_2 emissions for recycled concrete are comparable to those for a conventional mix, especially if the rubble has to be transported over long distances before use (Marinkovic et al. 2010, Knoeri et al. 2013).

To reduce the detrimental environmental impacts (DEI) of concrete construction, the service life of existing structural components should be extended as much as possible through maintenance, renovation and strengthening. When none of these options are feasible anymore, deconstruction and component reuse is preferable to demolition. Reuse involves carefully dismantling the structure into smaller elements that are then reassembled in a new structure. This strategy delays the waste production and significantly reduces the need for new materials and the related CO_2 emissions.

Since the 1980s, there have been several examples where prefabricated concrete components were deconstructed and reused in new structures, many of which demonstrate a major reduction in DEI (Küpfer et al. 2022). The reuse of components extracted from cast-in-place reinforced

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concrete (RC) structures is much less common. Recently, a pedestrian bridge named Re:Crete has been built from 25 reused blocks sawed out from concrete walls of a building undergoing renovation (Devènes et al. 2022). For this specific project, a 75% reduction in CO_{2eq} emissions was calculated when compared to a recycled concrete alternative.

Through a case study, this paper demonstrates the theoretical feasibility of constructing a residential *target* building with pre-existing cast-in-place RC components. The components are reclaimed from two *source* buildings that are expected to be demolished soon. The paper is organized as follows. Section 2 presents the design process specific to a RC-component-reuse project. The resulting design for the case study is given in section 3 including new construction details developed for connections. In addition to the reuse design, a conventional concrete construction alternative is developed, as well as a hybrid solution balancing environmental and cost savings with technical readiness. The alternatives are compared and assessed in terms of CO_{2eq} emissions and construction costs in section 4. Section 5 highlights the main conclusion of this work.

2 DESIGN METHODOLOGY

2.1 *Design process*

Figure 1 shows the 11 steps of the process for designing a load-bearing system from reclaimed cast-in-place RC components, including the required iterations. Step 1 consists in analyzing the source buildings to obtain the structural capacity of the different components available for reuse – e.g. bending-moment resistance for different slab parts and normal force resistance for walls and columns. In parallel, the floor plan of the target structure is defined and used to fix a preliminary load-bearing system – i.e. the layout of vertical load-bearing elements and the boundary conditions (step 2). The live loads are specified according to the space use while dead loads are set based on assumed structural thicknesses.

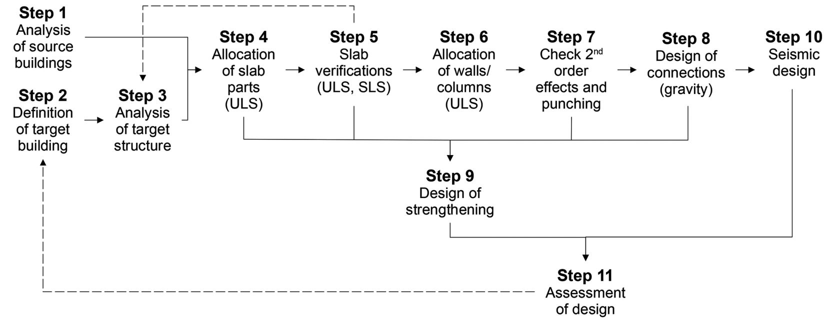


Figure 1. Selected design process.

In step 3, the target slab is divided into parts which are sought to be built in one piece – i.e. the position of joints in the target structure is defined. Different types of joints are considered, allowing or not the transmission of bending-moments or shear-forces (continuous, hinged, free, etc.). A Finite Element Model (FEM) of the target structure is created and joints are placed between the parts corresponding to their boundary condition. The action effects are calculated, which corresponds to the minimal resistance requirement of the target slab.

Subsequently, the dismantling and reassembly of floor slabs is planned. An algorithm is used in step 4 to allocate parts of the source slabs to the parts of the target slab defined in step 3. The allocation criterion is to minimize areas where structural strengthening is required to satisfy the bending-moment-resistance requirement at Ultimate Limit State (ULS). The shear-force-resistance requirement at ULS and deflections at the Serviceability Limit State (SLS) are subsequently checked in step 5. Deflections should not be larger than the limits fixed in in-force design codes. In case the shear-force resistance of the allocated slab is insufficient or deflection limits are not met, the slab is either strengthened or the load-bearing system is modified – e.g. by adding supports or changing the type of joints to remove hinges. The latter is a first iteration looping between step 5 and step 3. Changing the load-bearing system will modify action effects and the corresponding resistance requirements for the target slab. Therefore, the allocation of source parts (step 4) should be redone to find a satisfactory solution.

If walls and columns are also sought to be built from reclaimed components, a similar approach as for slab parts is followed. The list of available vertical load-bearing parts made in step 1 is updated in step 6 to take into account the results of step 4. On top of the walls available in the source structures, parts of the source slabs which were not used to reassemble the target slab are considered as available stock for wall elements. This available stock is then allocated to a position in the target building according to structural resistance. Then, columns are checked for second order effects and punching resistance of the reassembled slab is also verified (step 7).

After allocation of all structural components, connections and the required strengthening of the slab are designed in steps 8 and 9 to resist gravity-action effects. Connections should ensure the force transmission conditions chosen for the joints in the structural model. Finally, the lateral bracing system is designed to resist seismic loads in step 10.

Once the structural design of the target structure is completed, it is assessed in step 11 regarding different criteria – e.g. DEI and construction costs (cf. section 2.2). If performance is not satisfactory, the design is modified at different stages, particularly by modifying the desired target structure to make better use of the available stock of reclaimed components.

2.2 *Assessment*

2.2.1 *Functional unit and system boundaries*

Life-cycle and cost assessments are dependent on a predefined functional unit and limits of the analysis. For this paper, the functional unit is the load-bearing system of one story – i.e. the RC slab with its vertical supports (RC columns and walls) – in the new target structure. Non-structural elements are not taken into account.

For the purpose of comparison, different design alternatives are developed and assessed: conventional construction with new materials; construction with reused structural components; hybrid construction. For all alternatives, processes related to the construction of the new building and the production of new materials are considered in the system. The end-of-life of the source buildings is taken into account as well. This is especially relevant for projects where existing buildings are to be demolished prior to the construction of a new building – i.e. a replacement project. For the variants applying reuse, all processes related to the deconstruction of building parts to be reused are included as well as those related to the demolition and disposal of the remaining material. For the conventional variant, the demolition and disposal of the entire source buildings is accounted for. The operation, maintenance, and end-of-life stages of the new target structure are not considered in the system. Moreover, construction processes expected to be the same for all variants – e.g. cranes, site specific installations, foundations, etc. – are excluded from the comparative assessment.

2.2.2 *Life Cycle Assessment*

In order to evaluate the environmental impacts of reusing structural RC elements, a comparative Life Cycle Assessment (LCA) is conducted (International Organization for Standardization 2006). LCA has been previously applied to evaluate reductions of DEI when reusing structural elements (Yeung et al. 2017, Brütting et al. 2020a, b, Devènes et al. 2022).

As introduced in section 2.2.1, the analysis includes the product stage and the construction process stage of the project (construction stages A1-A5) as well as the end-of-life of the source buildings (construction stages C1-C4) according to the European standard for Life Cycle Assessments (CEN 2011). The impacts associated with recycling materials or reusing components are allocated to the final product resulting from the processes, i.e. following a cut-off approach (Schrijvers et al. 2016).

In this paper, the global warming potential (GWP) is chosen as the indicator for comparing the variants, expressed in kilograms of equivalent carbon dioxide ($kgCO_{2eq}$). Emission factors for the different processes are mainly taken from the Swiss LCA database (KBOB 2022).

2.2.3 *Construction costs*

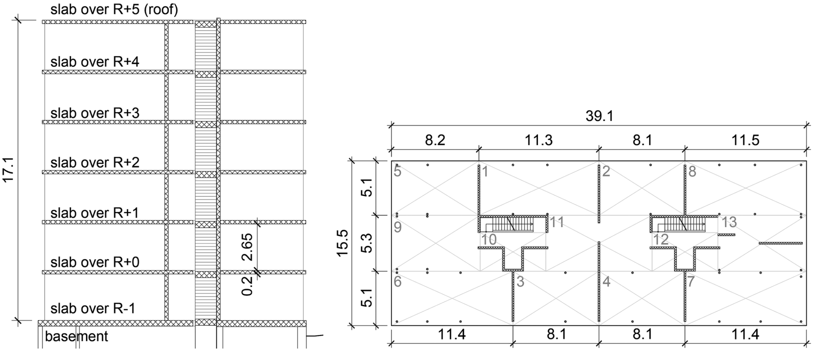
In order to evaluate the economical implications of reusing RC components, costs for dismantling the source structure and constructing the target structure are estimated for all variants. For this paper, unit prices for the reference year 2021 are used. They are mainly estimated from construction companies' bids, engineering office experience and average prices published in the Swiss Construction Price Index (FSO 2021).

3 CASE STUDY

3.1 *Source and target buildings*

The two source structures for the case study are cast-in-place RC slab-and-column systems of office buildings located on a former industrial site in the city of Basel, Switzerland, Figure 3. They were constructed in the late 1950's and are now destined to be dismantled following the urban re-qualification of the district.

The target building is shown in Figure 2. It is a 6-story residential building with an area of 606 m^2 per floor and a total height of 17.1 m above the ground. It is to be located on the same site as the source buildings.



(a) Section.

(b) Floor plan and division of slab.

Figure 2. Target building.

3.2 *Design alternatives*

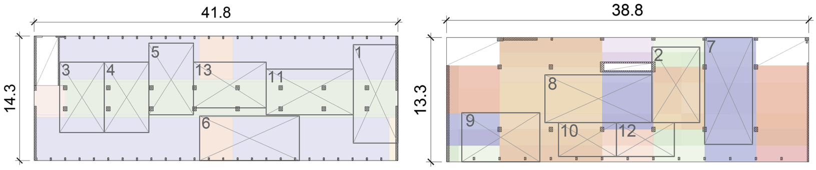
For the sake of comparison, three different design alternatives are developed. The first one, "Reuse", includes as many reclaimed RC components as possible. The details of this design are given in section 3.3. The second design alternative, "Conventional", instead uses only newly cast-in-place RC and is used as a reference for conventional construction methods. The third alternative, "Hybrid", is a combination of both variants that favors a simplified construction process for the bracing system: slabs and vertical supports are made of reclaimed components except for the bracing walls, i.e. the walls of the cores, that are made from new cast-in-place RC.

3.3 *Reuse-driven design*

3.3.1 *Slab design*

Figure 2b shows the division of the target floor slab into parts (step 3 of the design process, see Figure 1). For each part, a component of the source building must be allocated (step 4 of the design process, see Figure 1).

Figure 3 shows the floor plan of the considered source buildings. Color zones correspond to different bending-moment resistances which are used as an input for the allocation algorithm. Each zone is characterized by four values – i.e. positive and negative resisting bending-moment in x- and y-direction respectively. The final sawing position for every part allocated to the target slab, obtained after the design iterations, are also shown.



(a) Building A.

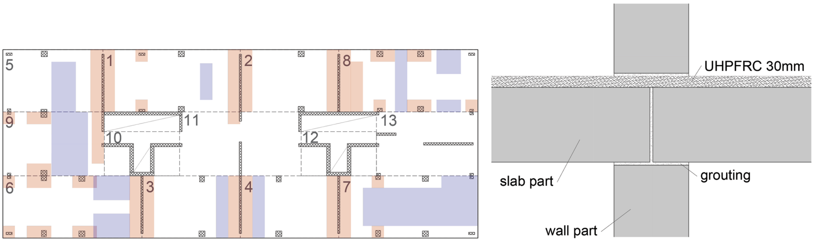
(b) Building B.

Figure 3. Distribution of bending-moment resistance across the source slabs and final sawing layout.

3.3.2 *Strengthening and connection details*

For the Reuse design variant of this case study, a layer of 20 to 35 mm of Ultra-High Performance Fiber Reinforced cementitious Composite (UHPFRC) is used to provide structural strengthening when necessary as well as continuity at the connections. The composite material is commonly used for rehabilitation of existing structures and allows bending as well as shear strengthening of the slab in all directions simultaneously (Habel et al. 2006, Bastien-Masse & Brühwiler 2016). The zones of the target building requiring a UHPFRC-layer are shown in Figure 4a. The blue zones illustrate bottom reinforcement, while the red zones are top reinforcement.

In the structural model of the target building, slabs are considered to be continuous over walls, meaning that there are negative bending moments over the supports. Therefore, as shown in Figure 4b., a layer of UHPFRC is applied on the upper surface of the slab in the joint region to transfer the tensile force from one slab element to the other.



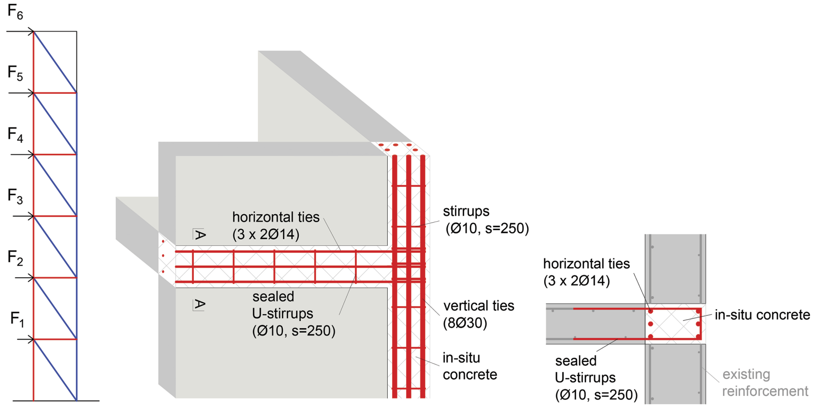
(a) Required slab strengthening (blue = bottom, red = top).

(b) Slab-wall connection using UHPFRC-layer.

Figure 4. Slab strengthening and slab-wall connection.

3.3.3 *Lateral bracing system*

The city of Basel, Switzerland, where the case study is located, has the second highest seismic risk in the country. Therefore, an adequate seismic design is required. For the Reuse design, bracing walls to resist seismic loads are sought to be built from reclaimed components as well. The analysis shows that the reclaimed components do not provide a sufficient cross-sectional resistance to resist lateral forces. Therefore, another bearing system is suggested, where each bracing wall is built as a truss system over the height of the whole building, as shown in Figure 5a. A compression strut forms in the reclaimed concrete walls, which is deviated by ties at each slab level. The connection between the walls is done as shown in Figures 5b, c, so that new reinforcement bars embedded inside cast-in-place concrete are introduced in between the reclaimed wall components as vertical and horizontal ties.



(a) Truss (red = tension, blue = compression).

(b) Core walls (1st floor) - Elevation.

(c) Section A-A.

Figure 5. Design of new bracing system with reclaimed concrete walls to resist lateral forces.

4 ASSESSMENT RESULTS

4.1 *Life Cycle Assessment*

Figure 6 shows the comparison of the GWP for the three design variants. It is assumed that the components to reuse are stored on the same site as the deconstruction of the source buildings and the construction of the target structure. Therefore, no transportation of reclaimed elements is considered for the Reuse and Hybrid design variants.

If the demolition of the source buildings is not considered, greenhouse gas emissions of the Reuse and Hybrid variants are respectively 77% and 73% lower than those of the Conventional variant. If the end-of-life is included in the LCA, ratios become 75% for the Reuse variant and 72% for the Hybrid variant. The Hybrid variant is slightly less favorable in terms of GWP than the Reuse variant due to the larger quantity of newly poured concrete. For both variants using reclaimed materials, the largest share of GWP is caused by the UHPFRC structural strengthening of the slab which amounts to about 60-70%.

4.2 *Construction costs*

Figure 7 shows the comparison of the estimated construction costs for the three variants, with a ±15% precision. The ratio of costs between variants differs significantly depending on whether the end-of-life of the source buildings is taken into account or not. If the costs of demolishing the source buildings are attributed to a different project than the construction of the target building, then the costs of the Reuse and Hybrid variants are respectively 54% and 56% higher than for the Conventional variant.

However, if the end-of-life of the source buildings is included in the analysis, demolition and material disposal drive up the costs of the Conventional variant to a level comparable to the variants applying reuse. Under these assumptions, the Reuse and Hybrid variants have costs within the ±15% precision range of those for the Conventional variant.

For the Reuse and Hybrid variants, the biggest share of costs is due to the deconstruction of the components to reuse, i.e. related to sawing (30-40%) and to lifting components with a crane (10-20%). New materials needed for the bracing system only amount to around 2-3% of total costs.

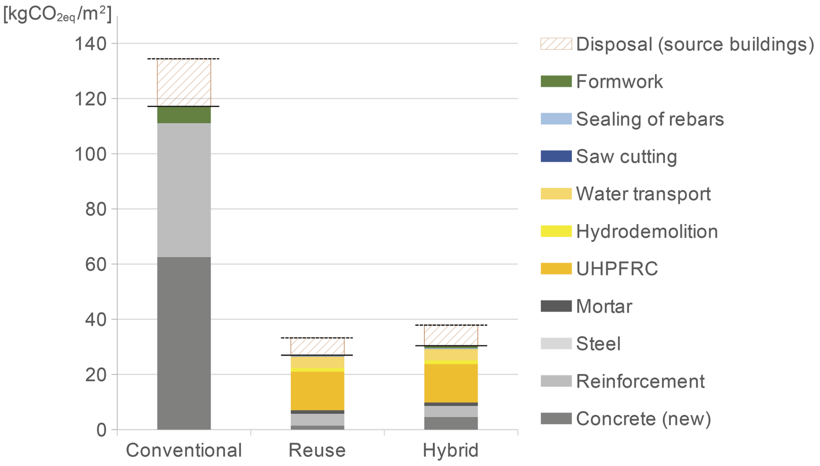


Figure 6. Comparison of global warming potential per floor area for different design alternatives.

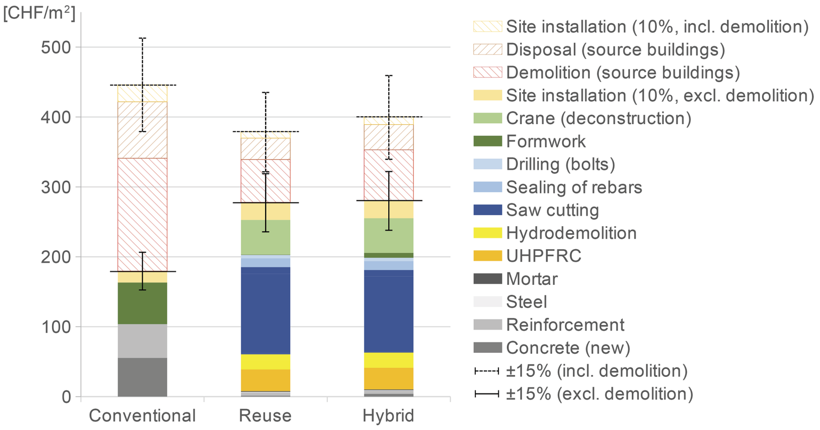


Figure 7. Comparison of construction costs per floor area for different design alternatives.

5 DISCUSSION AND CONCLUSION

The aim of this study is to investigate the technical feasibility as well as the benefits in terms of environmental impacts and costs of reusing RC components from obsolete structures in new constructions. To this end, the load-bearing structure of a residential building is designed with reclaimed cast-in-place RC components mined from two given source buildings. The final design is compared to an equivalent, conventionally built structure using new cast-in-place RC.

The study proves that technical solutions are available to design the structural system of a building floor from reclaimed cast-in-place RC elements. It is found that by reusing structural components greenhouse gas emissions are reduced by 75% compared to conventional construction techniques. Integrating a limited amount of newly cast-in-place RC in a structure mostly made from saw cut parts simplifies the construction process and at the same time achieves a similarly low level of global warming potential. In terms of construction costs, estimations show that reusing RC components competes with conventional construction methods only if the demolition and disposal of the source buildings are included in the analysis.

These are promising results, as they clearly show the potential of reuse to reduce the DEI of RC construction for a similar range of costs. Especially in times of supply bottlenecks and increasing material prices, when costs of conventional construction tend to increase, reuse becomes an interesting alternative that is beneficial not only from an ecological but also from a financial point of view. Yet, more studies like the present one are needed to support a widespread application of RC component reuse.

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