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Re:Crete – reuse of concrete elements in new structures: A footbridge prototype

J. Brütting, J. Devènes, C. Küpfer, M. Bastien-Masse & C. Fivet
Structural Xploration Lab, Swiss Federal Institute of Technology in Lausanne (EPFL), Fribourg, Switzerland

ABSTRACT: Concrete accounts for the largest share of worldwide building material use and waste generation, with cement production being responsible for approximately 9% of global anthropogenic CO_2 emissions. A currently untapped strategy to significantly reduce these environmental impacts consists in reusing reinforced concrete (RC) elements in new load-bearing applications. This paper presents a new design-and-build concept to reuse cast-in-place RC wall and slab elements sourced from obsolete buildings. The applicability of the proposed paradigm is demonstrated through a prototype: a 10-m spanning post-tensioned segmental arch made of 25 reclaimed concrete blocks. The paper illustrates the complete workflow, including the sourcing of the blocks through sawing and the prototype assembly. A comparative Life Cycle Assessment shows that the prototype structure has a significantly lower environmental impact than equivalent designs made of new material.

1 INTRODUCTION

Concrete has many qualities such as availability, moldability, incombustibility, durability, and resistance, making it the most widely used construction material today. However, the cement production needed for new concrete manufacturing is highly energy- and resource-intensive. The global cement industry is responsible for approximately 9% of all process-related CO_2 emissions (Monteiro et al. 2017). Due to limited extraction capacities and increasing concrete demand for new construction, a shortage of raw materials – e.g. sand, aggregates – is expected to occur in some regions in the near future (Habert et al. 2010). Furthermore, urban densification often makes the demolition of existing structures a prerequisite for new constructions, resulting in large amounts of waste. In Europe, concrete rubble represents the largest share of demolition waste (Zhang et al. 2022). Hence, there is a need to develop new means of building with concrete, that maintain its qualities, delay the generation of demolition waste, and avoid new cement production.

One such means consists in extending the service life of reinforced concrete (RC) structures already existing in the building stock. To do so, repair, strengthening, and adaptation of load-bearing systems are the favored options according to circular economy principles, yet they are not always feasible. Constantly evolving spatial needs of building users, urban densifications, logics of a fast return on investment in the real estate market, and energy retrofit campaigns often lead to the premature obsolescence of buildings and their subsequent demolition. The demolition happens even though the load-bearing systems are still in good condition and could have been used over a longer service life (Salama 2017). In such scenarios where demolition is inevitable, crushing down concrete and recycling it as aggregates for foundation layers or new concrete production is the favored strategy today. However, producing recycled aggregate concrete still generates as much CO_2 as new concrete production (Knoeri et al. 2013; Marinković et al. 2010) and it implies the loss of the inherent, still useful mechanical properties of the obsolete RC structures. For these reasons, the direct reuse of RC elements in new load-bearing applications is seen as a necessary strategy that can delay the crushing of obsolete RC structures and reduce the environmental impacts of new constructions by avoiding raw material and energy use, CO_2 emissions, and waste.

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To date, only a few examples of concrete reuse in new load-bearing applications exist. Prefabricated RC elements have been dismantled from existing buildings and reused in new constructions in the Netherlands (Coenen et al. 1990), Sweden, Germany (Mettke et al. 2008), and Finland (Huuhka et al. 2015a) For prefabricated RC elements, dis- and reassembly may follow the inverse of the construction system logic. Instead, dismantling and reusing cast-in-place RC elements, which represent the larger material share in load-bearing structures, is less straightforward.

This paper demonstrates the feasibility and potential of reusing cast-in-place RC elements through the realization of the "Re:Crete" footbridge prototype, a 10-m spanning segmental arch (Figure 1). The arch consists of 25 RC blocks obtained from a building renovation site, cut to appropriate size on site, assembled, and stabilized via two post-tensioning cables. Section 2 presents the structural design process, material sourcing, and assembly of the prototype. In section 3, a comparative Life Cycle Assessment (LCA) shows the significant CO_2 reductions achieved through RC element reuse compared to new construction. Section 4 discusses the obtained results and concludes the contributions of this work.

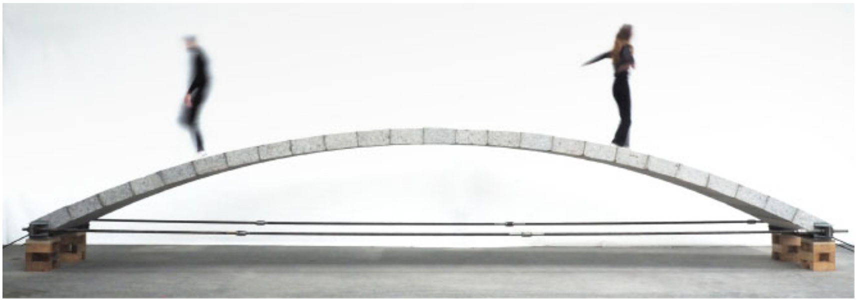

Figure 1. The Re:Crete footbridge prototype.

2 FOOTBRIDGE PROTOTYPE

2.1 *Concept*

Masonry arch structures have long been used for bridges as the applied loads are transferred to the supports through compression. Equivalently, this prototype features an arch shape to make optimal use of the intrinsic concrete material qualities: its high compressive strength. Reclaimed RC elements are employed as voussoirs of a segmental arch – a circular arch with an opening angle of less than 180˚ – and further stabilized via internal post-tensioning cables. The structural system relates to existing examples of post-tensioned stone constructions such as the *Punt da Suransuns* and the *Wasserfallbrücke* in Switzerland (Conzett 2000), the granite beams by Hennecke & Kusser (2014), or the *Padre Pio Church* in Italy (Milan & Simonelli 2001).

Typically, arches without backfill are vulnerable to asymmetric external loads. Such loads lead to bending moments, considered as normal stress with an eccentricity to the centroidal axis of the arch cross-section. When the eccentricity is so large that the thrust line lies outside the cross-section, the arch is unstable (Heyman 1966).

Figure 2(a) shows the system geometry of the arch with a span of 10 m and a rise of 1.20 m. The force diagram on the right expresses the forces in the thrust line (pink) when the arch is subjected to self-weight (grey) and asymmetric live loads (orange). Due to the arch slenderness and the flat geometry, the thrust line lies outside the cross-section (Figure 2(a), pink area). Post-tensioning the arch via centric cables creates an artificial normal force and radial load, which over-compresses the RC blocks so that the thrust line is brought back inside the cross-section, as shown in Figure 2(b) (Todisco et al. 2018). Via the post-tensioning, the slender segmental arch becomes stable also for asymmetric loading and without any backfill, while experiencing stresses far below the compressive strength of regular building construction concrete.

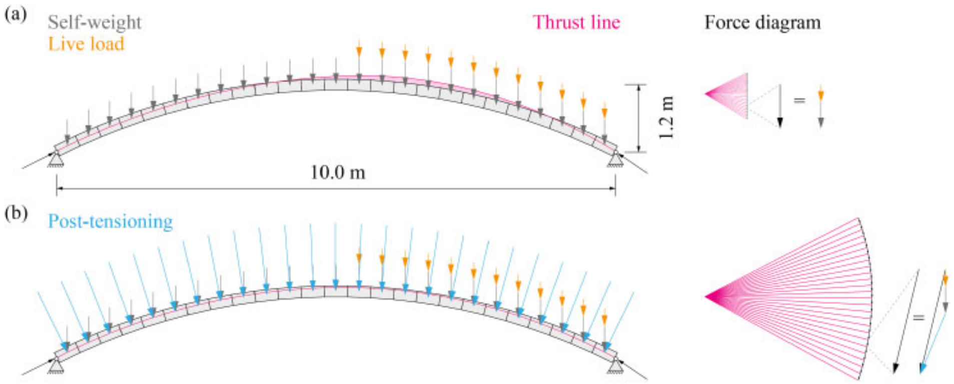

Figure 2. Post-tensioned segmental arch: (a) arch under self-weight and asymmetric live load, (b) arch subjected to post-tensioning. On the right side the corresponding force diagrams are shown.

2.2 *Material sourcing and preparation*

Building with reused elements adds additional complexity to the design process: it requires designing and building a new structure with the limitations and variety of the available element stock (Gorgolewski 2008). For example, the design must consider the dimensions and mechanical properties of stock elements that can be found at the desired time to fulfill all structural requirements. The span and rise of the Re:Crete arch were chosen such that it could be built with concrete blocks of 18 to 22 cm thickness and with typical concrete grades used in building construction.

After a "material hunt" at local demolition and landfill sites, the 25 blocks were eventually commissioned from a concrete sawing company that was working on a building transformation project. The RC blocks of size 120 × 40.5 × 20 cm were cut from a basement wall with diamond saws (Figure 3a and b). In a successive step, holes were drilled through each block to later receive the post-tensioning cables (Figure 3c).

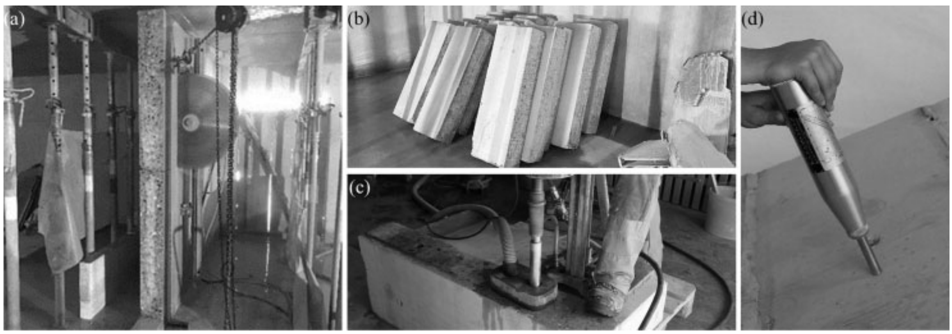

Figure 3. Cutting of a basement RC wall with a diamond saw, (b) stock of cut blocks, (c) drilling of holes for the post-tensioning cables, (d) rebound hammer testing.

A variety of methods are available to assess the mechanical properties of reclaimed concrete blocks: 1) referring to the code regulations that were in use at the time of the original construction, 2) destructive testing of bore cores, and 3) non-destructive testing, e.g. with a rebound hammer (Figure 3d). The latter option is considered sufficiently accurate and was employed on the blocks so that the arch could be reliably designed to not exceed the concrete compressive capacity.

2.3 *Detailed design*

The prototype is designed for self-weight and an (a-)symmetrically applied live load of 1.5 kN/m^2. The post-tensioning force is calibrated so that the complete concrete cross-section remains in compression under the considered loading. Two single-strand post-tensioning cables, protected within a PE duct, are employed, one in each of the two holes in the blocks. Because the RC blocks are cut orthogonally, mortar joints remedy the shift in angle between two adjacent square blocks of the arch. In addition, the mortar joints ensure good contact between blocks and compensate for sawing tolerances. Tension rods interconnect the arch springing points to mutually couple the arch thrust (Figure 1). In a practical application and when soil conditions allow it, typical gravity foundations would take the arch thrust.

Particular attention was given to designing the Re:Crete prototype so that it can be easily dismantled. The post-tensioning cables are unbonded and fixed in their stressed state with reversible anchors, thus cables can be reused after disassembly. The joint mortar is selected to be strong enough to withstand the compressive stresses induced by the arch thrust and the post-tensioning, but at the same time to be low adhesive to enable the separation of blocks at disassembly.

2.4 *Assembly*

The first step of the prototype assembly is the erection of a timber centering that temporarily supports the concrete blocks (Figure 4a). The centering is made of plywood panels that are CNC-milled into the polygonal arch shape and a supporting braced frame structure. Steel abutments and horizontal tension rods are placed at both sides of the centering. Next, the concrete blocks are placed onto the centering one by one whilst passing the post-tensioning cables and ducts through the holes in each block (Figure 5a and b). After all blocks are placed, the gaps between blocks

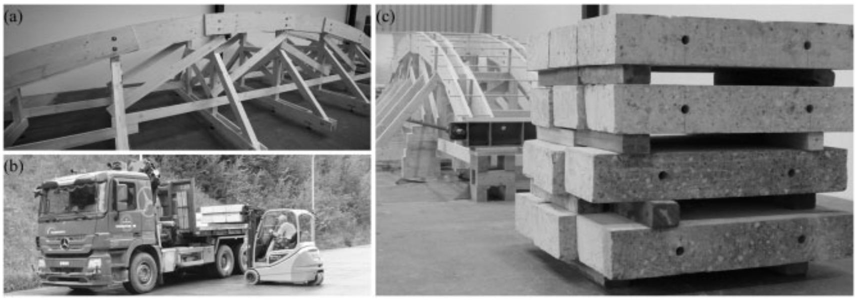

Figure 4. Assembly preparation: (a) the wooden centering, (b) RC blocks delivery, (c) a stack of RC blocks with holes for the post-tensioning cables, the centering in the background.

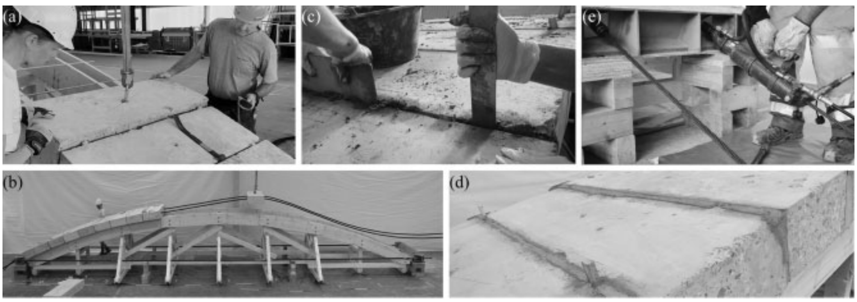

Figure 5. Assembly stages: (a) and (b) concrete blocks placement, (c) and (d) grouting joints with mortar, (e) post-tensioning with hydraulic jacks.

are grouted with lime-cement mortar (Figure 5c and d). After 14 days of curing, the cables are post-tensioned using hydraulic jacks (Figure 5e).

Through the post-tensioning step, the final structural behavior is established. The blocks are now self-supporting between the abutments and thus the centering can be lowered. At first, the centering is lowered by about 3 cm and used as a safeguard during the following load-testing (Figure 6a and b). The arch has been loaded with 1.8 tons of sandbags in total, corresponding to the design live load. The measured vertical deformations (Figure 6c) of <2 mm corresponded to the values that were computed via a FE Analysis. After the successful testing, the centering is removed entirely (Figure 1).

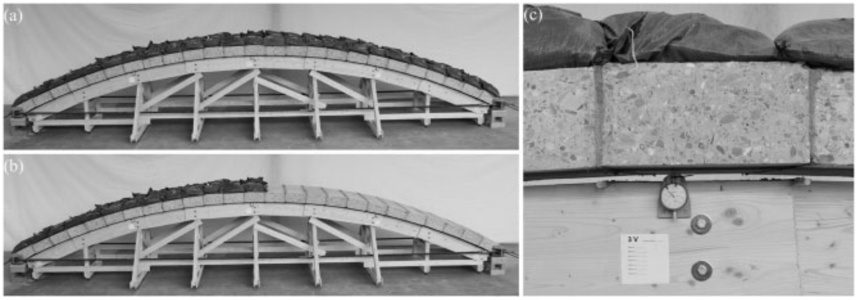

Figure 6. Load testing stage: (a) full span loading, (b) half span loading, (c) deformation measurement.

3 LIFE CYCLE ASSESSMENT

3.1 *Method*

Life Cycle Assessment (LCA) is a widely recognized method for assessing the environmental impacts of products (International Organisation for Standardisation 2006). LCA accounts for all substances exchanged with the environment during the production, construction, use, and end-of-life stages of a product. LCA has been applied to the reuse of structural steel components by Yeung et al. (2017) and combined with structural optimization by Brütting et al. (2020, 2019) and Küpfer et al. (2021). Asam (Asam 2007) carried out an LCA for the reuse of precast concrete.

The environmental footprint of the Re:Crete prototype is here compared to three alternative footbridge designs (Figure 7): a) a post-tensioned segmental arch with 25 blocks made of new concrete, b) a monolithic arch made of new concrete and with passive steel reinforcement, and c)

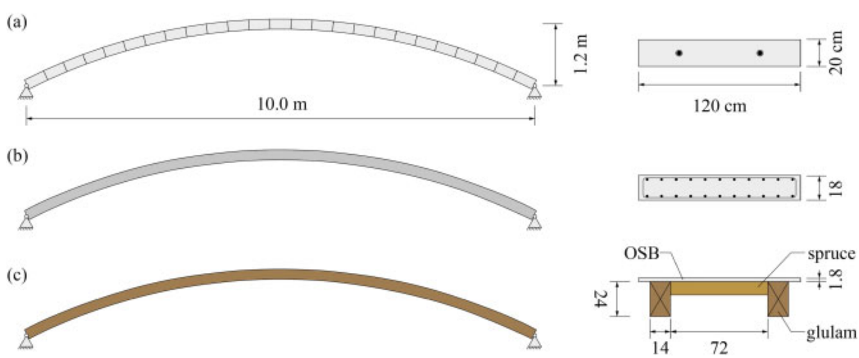

Figure 7. Alternative designs: (a) segmental arch made of new concrete blocks, (b) monolithic arch with passive steel reinforcement, and (c) timber arch.

a timber glulam arch. All alternatives are designed to fulfill the same demands on dimensions and loading as the Re:Crete prototype.

3.2 *System boundary and data collection*

The LCA considers the construction of the main load-bearing parts of the arches and includes the end-of-life phase of the obsolete structure used as a source for the reused elements. The operation, maintenance, and end-of-life stages of the footbridge are not considered. All processes related to the obsolete-structure demolition/selective deconstruction, elements preparation, resources extraction, material production, transportation, and construction work are included within the analysis. Abutments, foundations, and decking are excluded from the comparison as they are expected to be identical for all alternatives. For (a) and (b) a new timber formwork for new concrete casting is considered in addition to a timber centering.

Impact allocation for recycled and reused materials follows a cut-off approach (Ekvall and Tillman 1997; Schrijvers et al. 2016). In this approach, impacts associated to recycling or reuse processes are allocated to the product using the materials that result from these processes. Process emissions calculation is mainly based on on-site measurements (e.g. electricity use for diamond saw cutting and drilling) and the Swiss LCA database KBOB (2016).

3.3 *Results*

The bar chart in Figure 8 shows the embodied global warming potential (embodied carbon, in kgCO_2eq) of the Re:Crete prototype and the three design alternatives. The construction of the Re:Crete prototype emits 72% less greenhouse gas than the new concrete segmental arch and 65% less than the new monolithic arch. For new concrete segmental and monolithic arch, the obtained results would be approximately equivalent if recycled concrete aggregates replace natural aggregates in the new concrete mix (known as “recycling concrete”). The production CO_2eq emissions of new and recycling concrete are almost identical (Knoeri et al. 2013; Marinković et al. 2010). The timber alternative has an embodied CO_2eq similar to that of the Re:Crete prototype.

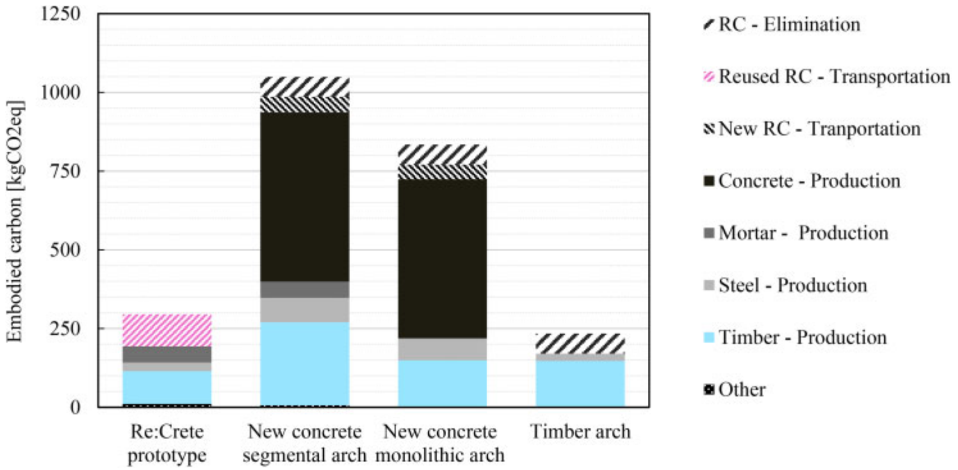

Figure 8. LCA results for the Re:Crete prototype and the three design alternatives.

In the case of the Re:Crete prototype, transport of the 25 RC blocks (Figure 8, pink) and the timber centering (blue) contribute the largest share of the total CO_2eq emissions with 35% and 34%, respectively. The production of mortar and steel post-tensioning cables represent 17% and 9%, respectively. Sawing of the concrete contributes only 2%. Evidently, the transport distance between deconstruction and assembly site of the reused RC blocks strongly influences the environmental footprint. Reducing as much as possible transport distances can make the Re:Crete prototype a competitive alternative to timber. Besides, reused RC elements could be transported for up to 600 km until emissions attributed to the Re:Crete prototype exceed those of the new concrete monolithic arch.

4 DISCUSSION AND CONCLUSION

The Re:Crete prototype demonstrates that employing reclaimed cast-in-place RC elements in new load-bearing systems can achieve the same structural performance as using new RC, whilst significantly reducing greenhouse gas emissions. However, this new design paradigm implies other design challenges that have successfully been overcome with this prototype: 1) time-constrained availability of material and coordination of the deconstruction, 2) unknown detailed material composition, 3) non-bespoke section properties, and 4) relatively large geometric variations of stock elements.

Building on this knowledge, future work will explore novel connection techniques to enable RC element reuse at a larger scale and will study structure types where elements are not only in pure compression but also subjected to bending, possibly making use of the passive steel reinforcement remaining within the cut elements. Preliminary LCA results show potentially large greenhouse gas emissions savings achievable through RC element reuse. In addition, reuse reduces resource use, delays the downcycling of RC, and avoids waste. The results also suggest that reusing concrete elements thus provides a new lower-bound benchmark for concrete construction in terms of environmental impact.

The Re:Crete footbridge prototype successfully combines concrete sawing, non-destructive mechanical testing, and post-tensioning, three well-known techniques that already existed in parallel. It establishes a novel way of designing and building structures made of reused RC elements, hence contributing to the large adoption of a circular economy by the construction industry. Hence, this pioneering work opens up the path for new research and innovation on RC element reuse, aiming at making the construction of concrete structures without pouring concrete the new normal.

AUTHOR CONTRIBUTIONS

JB initiated the Re:Crete footbridge project and carried out the structural design of the prototype with the support of MBM and JD. MBM organized the material procurement. All authors participated in the construction. CK computed the LCA with the help of JD. JD and JB wrote the first draft of the paper with CK, MBM, and CF actively contributing to the final version. All authors reviewed and approved the submitted version.

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