From concrete waste to walls: An investigation of reclamation and digital technologies for new load-bearing structures

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Abstract. The research presented in this paper highlights current practices for the end-of-life of concrete and explores opportunities in using unaltered concrete rubbles from demolition for the digital construction of structural walls. Through research by iterative making performed by the authors, relevant upcycling processes and design strategies are identified and explored to shape new tectonics specific to reclaimed concrete rubbles with non-standard variable geometries. This iterative research proposes accessible and scalable digital processes to overcome the challenges inherent to this untapped construction material. Results from small-scale prototypes provide valuable insights for full-scale processes to advance the digitization of construction and alleviate its environmental impact.

1. Introduction

While technological solutions have been significantly developed to reduce the greenhouse gas emissions generated during the operation of buildings, much is still needed to reduce those caused by the construction and maintenance of buildings. Load-bearing structures and their construction process account for approximately 74% of embodied emissions in buildings [1]. Besides, the construction and demolition industry accounts for 33% of all waste by weight [2]. When excluding excavated soils, this waste comprises 64% of minerals and 26% of mixed waste [3]. New circular strategies, like reclaiming obsolete parts into new assemblies, offer opportunities to lower waste and embodied emissions.

In this context, architects and civil engineers are significant decision-makers. Still, they lack return on experience regarding appropriate aesthetic language and technical solutions when using reclaimed construction materials. Indeed, component reuse calls for new tectonics, i.e., new interrelations between intrinsic material nature, structural form, and construction process. Understanding the unique nature of reclaimed elements as a disruptive given, one may consider that a new consistency must be found through potentially-innovative geometric arrangements and construction methods.

While literature exists to optimize structural forms for reclaimed stocks of elements, little to no effort has been made to explore construction processes that are well-suited for reclaiming materials, particularly, while using widely available digital equipment to harness geometrical variability at industrial scale. Developing new « digital low-tech » construction methods while avoiding the skill and equipment requirements of high-end digital fabrication ensures productivity, safety, and scalability through digital means while aiming for accessibility.

This paper therefore includes an overview of the current end of life of concrete in section 2, the challenges inherent to reusing concrete rubbles in section 3 and the opportunities in overcoming these challenges for the construction of walls in section 4. In section 5, the physical explorations conducted by the authors are presented. Lastly the content of this paper is summarized in section 6.

2. End of life of reinforced concrete and its impacts

Besides excavated soils, concrete is the most wasted solid material, and the cement needed for its fabrication is responsible for 9% of anthropogenic gas emissions [5].

2.1. Concrete demolition

Once a building or an infrastructure is considered obsolete, demolition is still predominantly considered, and the materials, including reinforced concrete, become waste. Current circularity solutions for reinforced concrete are required but not enough to alleviate the environmental impact of reinforced concrete and the construction industry [6]. Due to the wet connections of cast-in-place concrete, such material is extracted with various tools: hydraulic demolition jaw, hydraulic ram, core saw, pneumatic jackhammer, circular diamond saw, hammer drill, demolition hammer, and diamond wire saw. Once extracted from the building or infrastructure, the concrete is in the state of rubbles of blocks, most of them with two recognizable parallel flat sides.

2.1.1. Concrete crushing

Most concrete waste is crushed down to be used as backfilling under transport infrastructures or as a small portion of aggregates in new concrete, a strategy called “recycling” [7]. Both end-of-life cycles rely on the energy-intensive crushing process: large pieces are broken down to fit the crusher intake, roughly 60x60x60cm, with the help of a hydraulic jaw and a loader, each requiring 25 litters of gasoline per hour. Crushers are large and heavy machines that can be moved on site, consume around 50 liters/hour, and produce gravel and aggregates of variable size. Within the crusher, rebars are separated from the concrete after crushing by a magnetic belt, while lighter non-concrete elements are diverged with air blowing from below. Using crushed concrete as aggregate in new concrete still requires more natural aggregate. Still, it most importantly requires the production of new cement, the most significant contributor to greenhouse gas emissions of the construction industry.

Figure 1. Tools and processes involved in the end of life of reinforced concrete.

2.1.2. Concrete sawing

Another increasingly explored circularity strategy is reusing concrete elements by sawing concrete elements and using them in new structures [8]. This solution has great potential for emissions savings and the availability of standardized elements. However, matching donor and receiving structures requires heavy logistical adaptations within an industry with large inertia.

2.1.3. Landfilling

Some pieces of concrete cannot be reused or recycled due to contamination, small particles, or the lack of recycling facilities and are disposed of in landfills or illegal dumpsites, depending on locality [9].

2.1.4. Unaltered rubbles as a construction material

The raw state of concrete after demolition and before crushing is never used as is in constructing structures. Most of the rubbles have two parallel flat sides, and are systematically downcycled. But reducing the intensity of their downcycling or even upcycling them yields environmental benefits [10]. Thus, using this altered material could prevent the energy-intensive processes previously mentioned and the constraints inherent to component reuse. Moreover, this induces a new set of tectonics and associated processes, to the condition of overcoming the challenges inherent to their processing.

3. Challenges for reusing concrete rubbles in structures

Using concrete rubbles in construction is challenging because of their non-standard and variable geometries. Currently, their reuse is limited to landscaping works known as “urbanite” in northern America. However, effectively utilizing this reclaimed thus low-carbon material for building structures presents several challenges. One of the major obstacles is the non-standard and variable geometry of the rubble elements resulting from the demolition process on various sites. Consequently, the non-uniform sourcing of material is a barrier for industry-scale applications.

The lack of traceability of concrete also generates many unknowns regarding the history of each element, particularly its fabrication, use, lifespan, and dismantlement. Moreover, the processes involved in concrete demolition depend on the economic condition of a locality, the availability of processing plants and tools in the vicinity, the proximity to naturally extracted minerals, and the logic inherent to the optimization of transport. The lack of information about the history of such elements deteriorates the knowledge and assumptions that can be drawn regarding their mechanical properties, as well as the intrinsic difference in technological value stemming from their original use and dimensioning. Lastly, concrete rubbles are often heavy pieces and cannot be easily altered like timber since they require specific machinery and skills.

4. Reusing irregular concrete rubbles through physical explorations

New technical solutions and skills are required to overcome the challenges of constructing with concrete rubbles, including at the design and structural verification stages. Like in retrofitting and strengthening, learning how to work with unknowns is necessary to foster a circular economy in construction. Despite working with assumptions, precise data is required to identify the expected reproducibility and similar construction techniques depending on assimilable material properties. In particular, such concrete pieces are suited for applications in compressive structures and are explored in walls for single-story buildings in the scope of this paper.

4.1. Traditional masonry

Exploiting the compressive capability of concrete rubbles in structures can draw valuable lessons in geometric stability from traditional dry masonry. However, the source stock differs significantly from stones since concrete rubbles often have two flat parallel sides. Moreover, conventional dry masonry is long and cumbersome and requires ample space to lay out and sort stones. These existing knowledge and constraints offer room for improvement, notably with digital sensing and packing strategies.

4.2. Working with existing non-standard geometry

Altering the source material to shape it to a desired fit usually helps stabilize and minimize voids and is traditionally employed in stereotomy and cyclopean masonry [11]. However, this strategy requires different processes and constraints. Altering the source geometry and shaping it into a desired form also perpetuate a fabrication process based on standardization and a linear economy. Conversely, accepting the initial geometry as is or altering it only partially to assemble it in new structures is a fabrication strategy with excellent development opportunities, following the examples using crooked logs [12], timber forks [13], and irregular boulders [14].

4.3. Construction machinery and the digital

Digital tools such as 3D scanners and industrial arms are well suited to harness geometrical variability for upcycling fabrication. However, considering the weight of concrete rubbles (from a few kilos to several tons) requires new technical solutions for their assembly. While extensive academic research in architecture has been developed for 6-axis industrial arms, these tools have lower payloads than rubble weight. They are, therefore, not suited for the positioning and assembly of concrete rubbles. Existing construction machinery have more significant payload capacity and can be digitized or even automatized [15]. However, the potentialities of merging pre-existing construction machinery with digital processes remain underexplored.

4.4. Digital low-tech
The use of 6-axis industrial arms and the early digitalization of excavators and cranes contains a high risk of alienation for professional of the construction industry. This risk comes from their high entry level for tools and skills compared to the undigitized construction industry. Yet, using digital processes precisely enables operations otherwise not feasible and to target an industrial scale. By utilizing a "digital low-tech" strategy that incorporates accessibility, resilience, affordability, and safety principles, digital technologies can be understandable and maintainable for individuals with limited technical proficiency. Thus, constructing walls from concrete rubble hints at new opportunities in lowering the entry barrier of digital processes by emphasizing the collaboration between humans and machines. Such collaboration exploits their respective assets and shapes complete processes based on the rational operation to be replicated across multiple construction sites and prefabrication halls.

4.5. New tectonics
The described challenges relate to the “new” properties of concrete rubbles to design and fabricate with. Therefore, these properties open the way for defining their associated structural forms and construction process, a triptych referred to as “tectonics” in architecture. Since tectonics are part of the design practices of architects, they convey more potential than abstract numbers of kilogram equivalent of carbon dioxide per square meter. Similarly, developing coherent construction using concrete rubbles address civil engineers eager to find lower-carbon concrete alternatives.

5. Physical experiments
Leveraging the opportunities for constructing walls from concrete rubbles to overcome the challenges inherent to such materials require iterative refinements of physical prototyping. The iterations allow to narrow suitable processes, geometric arrangements, connection types, sequence of assembly, etc., depending on the expected outcome and the context. Thus, a research by making is initiated by the authors through small-scale and full-scale prototypes, based on an analysis of the local construction industry. Each prototype results from a design brief and is analyzed through an assessment chart.

5.1. Geometrical characterization of concrete rubbles
The assembly of irregular and variable geometries with digital processes, while considering an industrial feasibility, prompts the need for more information regarding the characteristics of concrete rubbles. The authors have engaged several geometrical acquisitions in waste sorting plants to characterize the size of rubbles and their respective proportions in the total stock of concrete waste.

Figure 2. Scanning small-scale and full-scale rubbles with photogrammetry and LiDAR, and expected boundary detection from RGB images.

5.2. Physical experiments and results
Prototyping at a small scale allows the authors to verify the influence of various factors over stability and ease of implementation and anticipating physical needs for large-scale prototyping. The impact of

geometry over stability is explored through prototypes assembled flat on the ground then erected vertically (figure 3 (a)) stacking horizontally sub-nested rectangular panels (figure 3 (b)), with cross-walls (figure 3 (c)), as a discretized sinus in plan (figure 3 (d)), or stacking rubbles on their flat side (figure 3 (e)). Experimenting with various connection types, such as mortar, fasteners, and post-tensioning, also improves the overall geometric stiffness of the walls.

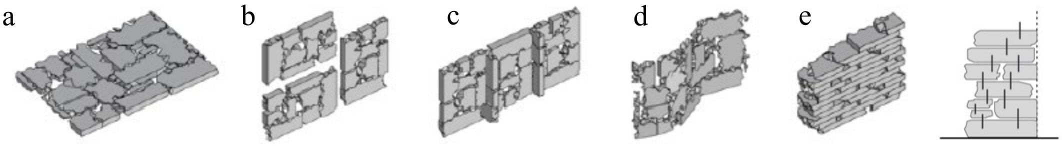

Figure 3. Geometric arrangement options for wall stability and section of connection strategy.

Moreover, the small-scale fabrication process allows us to explore the influence of several factors to inform the full-scale fabrication. These factors include the variation of spacing between rubbles, the method of acquisition of their geometry, the vector of insertion, and the sensitivity of light conditions for image-based detection of rubble geometry. The small-scale prototypes were executed using a desktop-size “GoFa” robotic arm with a custom end-effector. The image acquisition was achieved with a standard webcam looking top-down. The designs and packing of the walls were performed in Grasshopper using openNest, while the robotic planning and control was achieved with compas_fab and compas_rrc within Grasshopper.

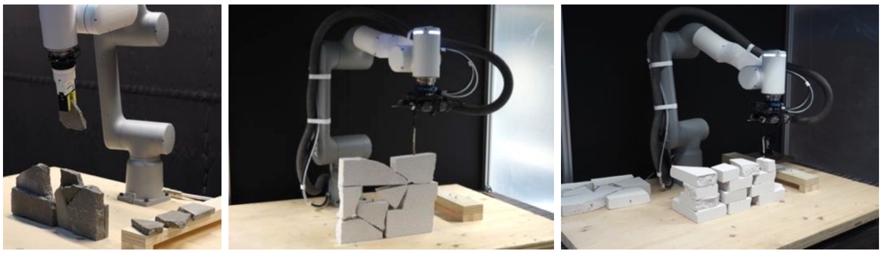

Figure 4. Three small-scale prototypes exploring various assembly strategies and tools.

5.3. Construction industry scalability

From the process and the outputs of the small-scale prototypes, adequate tools, processes, arrangement, sequence, and connections are retained to construct stable load-bearing walls at a 1:1 scale utilizing rubble from a nearby demolition site. To achieve this goal, the envisioned process integrates various approaches, such as leveraging existing construction machinery with high payloads, utilizing computer vision canny edge detection for rubble geometry detection, retaining design flexibility while minimizing layout space, ensuring robustness in case of breakage, minimizing alteration of the source material, and utilizing human collaboration for accurate rubble positioning. The stability criteria for the full-scale prototypes are guided by swiss norms on masonry walls.

5.4. Limitations and expected tectonics, and future research

The expected new tectonics stemming from concrete rubbles and accessible digital processes provide insights regarding architectural impact such as wall thickness, air tightness, assembly time, support for additional layers, etc. In most assembly processes, the developed solutions do not match current architectural and constructive practices. However, climate urgency impose a change in regulations and practices to minimize the production of new raw materials, which is embraced in this proposed process. Digital tools, although developed to be accessible, are not particularly crucial for the fabrication process we proposed, nor for the construction of walls using small size rubbles. Nevertheless, digital tools are critical for the geometry detection and packing of large concrete rubbles, especially while aiming for industrial applications. Therefore, accessible digital tools for the detection and stable packing of 2.5D concrete rubbles represent the area of research with the most potential.

6. Conclusion

As the construction industry is looking for sustainable solutions, the tremendous quantities of concrete rubbles are an opportunity to lower the amount of waste and the greenhouse gas emissions of this decisive industry. The construction of structure is the main contributor to these issues, which is why we propose the construction of walls from such concrete rubbles to drastically reduce the environmental impact of construction. We presented built examples of such walls at small-scale using digital processes to harness the geometrical variability of irregular minerals. However, digital tools currently developed in academic and industrial research are rather complex. This emphasizes the need for accessible digital processes, through "digital low-tech" research for these processes to reach an industrial scale. The construction of structure with this untapped material prompts the need for new processes and structural form, while their combination extends the range of tectonics. Because tectonics are the language of the designers of the built environment, this new definition explores the relationship between architecture, construction, and the environment.

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