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Concrete rubble as a new construction material: panorama of applications to known structural typologies

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Abstract
Concrete rubble is among the most wasted materials worldwide. In this paper, we present a panorama of the upcycling potential of disused concrete rubble as construction material for new low-carbon structures. We identify 15 existing structural applications of concrete rubble reuse, 6 of which are currently supported with full-scale built demonstrators. Through analysis of 10 site visits and 19 interviews, we identify 7 opportunities (e.g., related to cheapness, sustainability, and localness) and 9 limitations (e.g., related to disparity and uncertainty) linked to this untapped material, and we compare them to those of stone and newly-produced concrete. Possible processing and assembly strategies specific to concrete rubble pieces are also documented. An analysis of the applicability of concrete rubble to 19 structural typologies highlights solutions that are technically possible, structurally relevant, and sustainably convenient. The analysis coupled with the review of full-scale precedents highlight the diversity and extent of remaining solutions to be explored. Wall and vault applications are detailed through structural design explorations encompassing 185 processing strategies and functional requirements. The authors identify foundations and retaining walls as environmentally convenient applications, surface-active compression structures as structurally relevant applications; and highlight readily implementable solutions, such as gabions walls.

Keywords: concrete rubble, debris, demolition, typologies, demonstrators, construction

1. Introduction
Concrete rubble from the demolition of buildings and infrastructures represents the most wasted material on earth besides excavated soils. In most situations, it is either landfilled or downcycled through energy-intensive crushing [1]. Concrete is also the most predominantly used material worldwide [2]. Cement production alone accounts for 8-9% of yearly greenhouse gas emissions [3]. The main application of concrete is the construction of structures. In buildings, structures are responsible for most embodied CO_2 emissions [4]. Concrete rubble produced during the demolition of structures is either landfilled or crushed to be used as a backfill or partial substitute of aggregate in new concrete, which does not diminish the greenhouse gas emissions related to the production of this new concrete [5]. While a number of academic prototypes have explored the direct reuse of concrete rubble as a construction material, there is no known panorama of possible structural applications of such material. Despite the expected environmental benefits of reusing such untapped resource for the sustainable construction of structures, the small number of established solutions hinders prospects of applicability in the construction industry. A panorama of possibilities and known precedents can help alleviate this issue.

2. Scope

This study tackles the use of demolition concrete without downcycling it as aggregates. In this context, downcycling is defined as a decrease in structural utilization of concrete from demolition, usually through crushing. In opposition, upcycling is the increase in structural utilization of such waste. This research addresses the use of concrete rubble of longest dimension comprised between 20 and 150cm and considers the potential use of additional materials and geometry alteration (except crushing). Moreover, the reuse targeted in this research is explored in a tool-agnostic way, such that tool limitations or capabilities are not critical requirements for potential built solutions.

3. Research objectives

This paper seeks to provide an overview of the upcycling potential of concrete rubble from demolition and its application in structures. To this end, we aim to characterize the opportunities and limitations of concrete rubble and identify possible, relevant, and optimal structural systems that can be built leveraging those capabilities. Furthermore, we seek to identify readily implementable solutions and solutions that require further exploration and/or physical experimentation.

4. Methods

Firstly, we reference precedents and built demonstrators of concrete rubble reuse through a literature review. To our knowledge, this review is the first gathering of concrete rubble reuse examples.

Secondly, ten site visits to demolition sites and recycling centres in Switzerland, coupled with nineteen interviews with Swiss stakeholders of the concrete demolition and recycling industry, provide the data for an analysis of the existing conditions of concrete rubble. Currently undocumented as a construction material, the opportunities and limitations of this “new” material for the construction of structures are identified using this qualitative data and compared to construction materials available in Switzerland. As concrete rubble can be situated the intersection of irregular stone and cast concrete (reinforced or not), opportunities are compared to those of irregular sandstone, and limitations to those of recycled reinforced concrete. Only the best or equally performing attributes are detailed for opportunities and only worse properties for the limitations.

Thirdly, using this data complemented by a review of the literature, we identify adequate processing and assembly strategies for using concrete debris as a construction material. Geometrical features and material properties are used to cluster the possible strategies.

Fourthly, based on structural typologies identified by Engel [6] and Muttoni [7], we conduct a multi-criteria analysis to unearth the possible applications of concrete rubble. The structural typologies are clustered by the predominant nature of their internal stresses: compression, tension, or both. Among these categories, the typologies considered for comparison are based on structural principles (e.g. walls, vaults, trusses) rather than on their composed assembly (e.g. domino structure, beam grid). The comparison of applicability is based on a single category of rubble pieces, characterized by unaltered flat reinforced concrete rubble units with thickness comprised between 15 and 40 cm and object-oriented bounding box dimensions comprised between 20 and 150 cm. The planar boundaries of the flat pieces are considered irregular and mostly convex. Internal rebars are assumed bidirectional at orthogonal direction, oriented parallel to the object-oriented minimum bounding box, and spaced by 3cm from each of the two predominant flat faces. A high bending and shear capacity is considered along the flat plane of each rubble unit, while an average bending capacity is considered normal to the flat plane in both directions. The shear and bending resistance of their assembly depend on the assembly strategy. While the pieces are considered as extruded surfaces, the structures they compose can be volume-based (e.g., foundations and retaining wall), surface-based (e.g., wall and vault) or line-based (e.g., truss and beam). The applicability of this subset of concrete rubble to existing structural typologies is qualified regarding the reutilization intensity (compared to concrete waste as flat surface rubble pieces), the reclaimed structural capacity (use of original compressive + tensile resistance) and the freedom of new structures’ geometry (control of bounding and internal geometry).

Lastly, our research investigates the design of walls and vaults for upcycling concrete rubble. We develop design exploration by crossing 185 parameters: processing methods developed in section 5.3 (supplemented by processing capabilities of off-site facilities, tools), constructive know-how (e.g., concrete casting, dry masonry, post-tensioning), and requirements (e.g., structural need, context, flatness, airtightness, use, thermal performance, acoustic performance, adaptability, reversibility, and more). Merging such parameters attempts to tackle the diversity of needs and capabilities of the construction industry. The extent of exploration encompasses geometry, material property, construction process, and visual appearance. To identify gaps in the research of upcycling solutions for concrete debris, we localize the known precedents and built demonstrators of section 5.1 in the multi-criteria analysis and design explorations. This allows the recognition of readily implementable solutions and the ones requiring further investigation.

5. Results

5.1.Known examples and demonstrators

Reusing concrete rubble pieces for the construction of structures is underexplored. However, few built examples exist. Hereafter, we detail all known explorations and built demonstrators reusing concrete rubble in new structures without downcycling it as aggregates. The most prominent application of demolition concrete in new structures is the construction of small landscaping walls mostly in the United States of America [8] and, more recently, by Bellastock in Paris (France) [9]. This practice, with low academic documentation depicts broken concrete as *urbanite* (most likely a contraction of *urban granite*) and uses it by stacking rubble units on their flat faces. While concrete from demolition is indeed reused, the structural needs of new structures are low, thus failing to be coined as upcycling. Another example of reuse of concrete rubble without upcycling is the coastal shoreline protection at Gaza Beach [10]. Gradually ramping up the structural utilization of concrete rubble pieces, ongoing research at the laboratory for Earthquake Engineering and Structural Dynamics, EPFL [11] substitute stone in manual irregular masonry by small and lightweight rubble from concrete demolition to study their behavior under compression and shear loads. Similar walls but dry stacked are achieved by Rickhoff et al. at small scale using a robotic arm for placement [12]. Using heavier debris too heavy to be lifted by hand, Cliffhord et al. constructed a wall as an exhibition piece in Seoul (South Korea) [13] by robotically carving each piece. Such use of expensive tools is also seen in a retention wall in Oberglatt (Switzerland) built by Johns et al. [14] with stone boulders using an automated excavator, and was previously explored as a freestanding wall in Zurich by Wermelinger et al. [15]. Also tackling heavy rubble but leveraging affordable construction tools, Grangeot et al. developed new upcycling methods and built demonstrators [16], pictured on Figure 1.

Figure 1: Demonstrators built by Grangeot et al. for the upcycling of concrete rubble into walls

Further exploring structural design using concrete rubble but without full-scale demonstrators, Marshall provides computational arrangement options for paneled walls [17] and bridges [18], Khalil Yaqoob Al Khayat explores applications to post-tensioned trusses and jampacked columns [19] and a design studio at TU Darmstadt explores the "Design With Debris" through the making of 3D printed connectors [20].

These examples highlight a diversity of upcycling design solutions possible using concrete rubble while providing isolated applications to known structural typologies. However, there is no known panorama of the structural potential and limitation offered by this material. This limits the identification of its prospective quantitative applicability to current structural typologies. Besides, the examples show a possibility to invent new typologies leveraging the specific properties of demolition concrete.

5.2. Sources of concrete rubble

Concrete debris is predominantly the outcome of demolition. The proportion of concrete rubble stemming from demolition of infrastructures or buildings vary per country based on trends of construction typology, preservation policies, etc. In Switzerland, the site visits and interview highlight that concrete rubble from demolition is mostly produced by hammering, crushing, or saw-cutting. Additional concrete demolition techniques include hydro jetting, splitting, blasting, wrecking ball and more. Concrete demolition is often carried out using hydraulic excavators equipped with crushers, while other means exist but are less frequent [21] Demolition by hydraulic crusher is the most common concrete demolition practice in Switzerland as it preserves partial structural integrity of building structures during demolition. It minimizes risks of collateral damages while being faster than saw-cutting and, hence, cheaper. The concrete is separated from other building layers on demolition sites, to direct each material waste to adequate paths for end-of-life. When concrete considered for recycling is irreversibly bonded with components in other materials (rebars, connections, casings, electrical conduits, etc), it is also sent to concrete recycling centres where it is separated after hammering and/or crushing. In Switzerland, any hazardous contaminant is removed before demolition.

Regardless of the demolition method, the outcome is predominantly the production of rubble pieces. Depending on parameters such as potential onsite recycling, transport optimization, operating skills, configuration of the structure to be demolished and accessibility, the geometry of concrete debris can vary significantly. However, common geometric features include parallel flat sides due to the initial use of concrete in structures made of thick surfaces. This flatness is predominant for large rubble units (above 80cm of longest dimension) and less frequent for smaller ones, generating panel-like elements. Flat pieces have irregular and regular bounding geometries, while non-flat pieces are a mix of irregular convex volumes and prismatic elements (cylinders, elongated parallelepiped) or broken parts of them, whether hollow or solid. Unreinforced or highly reinforced source concrete is often extracted in large pieces to avoid long onsite processing. However, if transportation is challenging or costly, rubble pieces, whether reinforced of not, are downsized to maximum 60cm of longest dimension to minimize void in transportation containers and to limit pre-crushing in recycling centers.

5.3. Opportunities and limitations of using concrete rubble in structures

Compared to other concrete reuse strategies using saw-cutting, the reuse of concrete as rubble without downcycling it as aggregates offers many advantages balanced by weaknesses [22]. The results of the analysis of the ten site visits and nineteen interviews highlight seven opportunities and nine limitations of using such original construction material instead of stone and concrete, respectively:

5.3.1. Opportunities

- Concrete rubble is a cheap material. It is given to recycling centres, often with compensation to avoid the high cost of landfilling. Using concrete rubble as a primary material can therefore be highly economical and even generate profit.
- Concrete rubble is a low-carbon material. When considered waste, any upcycling strategy without energy-intensive reprocessing leverages past embodied greenhouse gas emissions.

- Concrete rubble is a local material. In Switzerland, since concrete recycling centres are distributed to decrease transport distance from demolition sites, local and plentiful sources of concrete rubble are available all year. Directly reusing concrete rubble near its demolition site further reduces its embodied energy.
- Concrete rubble is a reclaimed material unconstrained by the dynamics of deconstruction sites. The biggest drag of sourcing and reusing materials from disused constructions is the heavy impact on the selective and careful deconstruction and its timeline. Instead, reusing the outcome of traditional demolition circumvents this issue, as it is less careful to the material.
- Concrete rubble is an adaptable material. Due to the size of fragments, usually smaller than room-size structural elements, their reconfiguration allows for freedom of the new structure geometry in terms of dimensions and the rubble pieces' positions, orientations, and connectivity.
- Concrete rubble is a potential material substitute for stone. After trimming potential rebar outcroppings, the compressive behaviour and the inert property of concrete rubble can be leveraged to be used as a stone for all its compressive applications without detrimental extraction methods.
- Concrete rubble with rebar is a bending-resistant and shear-resistant material. Beyond the compressive resistance of concrete rubble, allowing stone-like applications, the internal rebar can be leveraged to increase the tensile and flexural resistance of concrete, allowing more applications.

5.3.2. Limitations

- Due to the sectioning of rebar during demolition and their unknown layout, leveraging rebar action is challenging. This results in uncertain and variable tensile, shear, and bending capacity.
- The non-uniform sourcing of concrete rubble in recycling centres compromises the clustering of material and geometric properties. Conversely, using fragments from a unique demolition site provides more uniform geometries.
- Concrete rubble pieces have irregular geometries besides flat sides and straight edges. Describing the non-standard geometry of broken edges and faces with primitives is challenging.
- Concrete rubble pieces are often smaller than room-size structural elements, requiring their challenging assembly for meaningful upcycling. Their reassembly is challenging because of their irregular and variable geometries and because many arrangements are possible yet not convenient.
- Due to the high density of concrete, rubble units are heavy. Lifting and positioning them by hand is limited to lightweight rubble pieces, while heavier ones require machines.
- Due to the toughness of concrete, rubble pieces are long to process using drilling or cutting tools.
- During demolition, existing connections, if any, are often not preserved, encumbering reassembly.
- Most properties of concrete rubble pieces are uncertain, requiring assumptions or testing for reuse. Uncertainties cover fabrication (rebar layout, diameter and resistance, concrete composition, and strength), past use (static and dynamic loads, wearing, exposition), and dismantlement (method, care).
- Not knowing the previous use of individual concrete rubble pieces provides invisible disparities of cultural and technological values. These differences of embedded value complexify the design choices of designers and the potentially streamlined processes of constructors.

5.4. Processing and assembly strategies

Based on the intrinsic properties of concrete rubble pieces and their reuse opportunities, several processing strategies are considered and pictured in Figure 2. The difference between subtraction and division lies in the generation of two or more geometries, which are controlled through division, while subtraction only considers a single remaining and controlled geometry.

The processing methods can be achieved through grinding, cutting, carving, chiseling, drilling, hydrojetting, pouring, or hammering. The energy required for such processing can be manual, electric, pneumatic, or thermic and be operated by humans or machines. Relevant tools for processing and assembly, along with their accessibility, are detailed in another article [15]. While these methods can alter the geometry of each rubble unit for structural purposes, they can also be used for aesthetic work. Some rubble pieces have emerging rebars which can be cut, straightened, or bent.

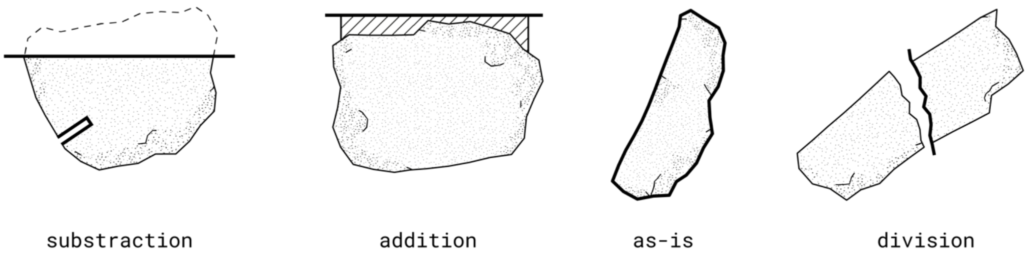

Figure 2: Categories of processing methods for concrete rubble

Leveraging the previously described processing methods, examples of assembly strategies for concrete rubble pieces, whether processed or not, are illustrated in Figure 3. Additionally, combining or extending such assembly strategies (for example, assembly by pearling as explored by Khalil Yaqoob Al Khayat) further expands the realm of capabilities. Possible added materials are diverse and not detailed in this article, but they should encompass the structural requirements of the overall structures and tolerances in assembling non-standard geometries. Potential rebar connections can either be dry (weaved) or irreversible (poured, welded).

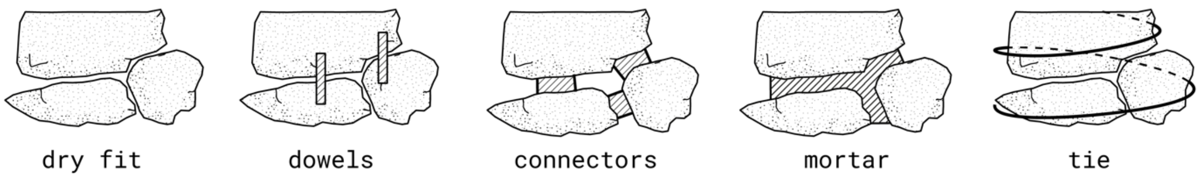

Figure 3: Categories of assembly methods for concrete rubble

5.5. Comparative applications of concrete rubble to structural typologies

The results of our multi-criteria analysis of the applicability of concrete rubble to 19 structural typologies extracted from the literature are illustrated in Figure 4. These non-exhaustive but representative examples also include precedents identified in the literature review. Retaining walls and foundations result as convenient for their structural adequation to the structural capabilities of demolition concrete, but most importantly for their capacity to capture the biggest amount of waste and thus avoided emissions. The results show that the potential applicability to various structural typologies is wide and with various degrees of relevance, and that only a limited portion of structural typologies.

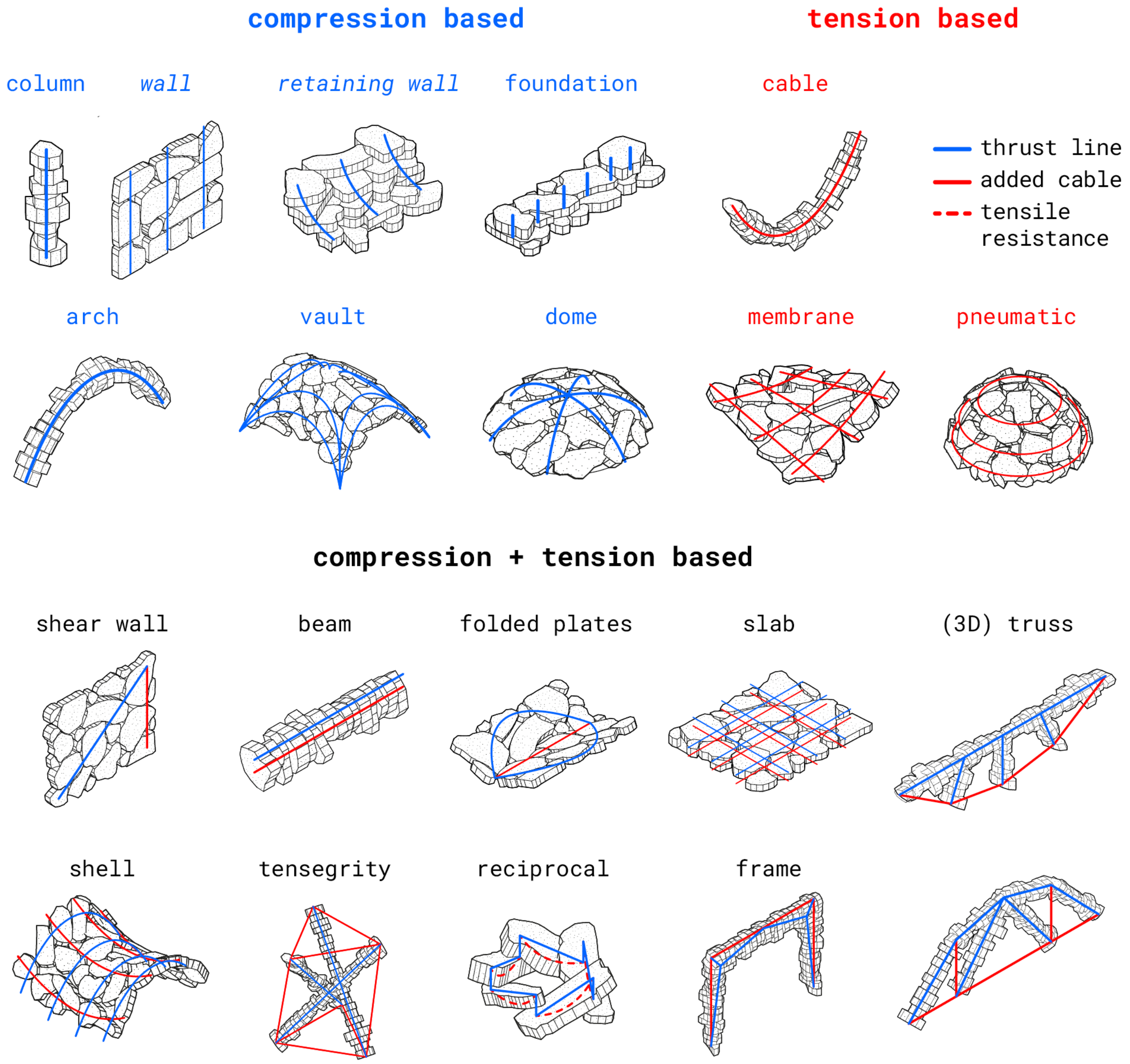

Figure 4: Applicability of concrete rubble per pre-existing structural typology. Typologies explored at full-scale are in italic.

5.6. Design explorations

From the identified applications of concrete rubble to known structural typologies, we develop walls and vaults through design explorations to expand the realm of constructive possibilities for new structures and to open the field of available structural expressions.

5.6.1 Walls

Due to the material and geometric similarities of concrete rubble and stone, many of the presented design explorations for walls presented in Figure 5 relate to knowledge and literature on masonry and dry masonry. Depending on the required slenderness and structural capacity, rubble units assimilated to bricks in their morphology can be oriented along six possible orientations: header, stretcher, rowlock, shiner, soldier, and sailor [23], while respecting masonry rules of art [24]. Irregular pieces light enough to be positioned by hand can also be used in an opus incertum [25] or gabions cages. Tightly packed arrangements with flat surfaces can be informed by historic examples of "pierre banchée" and cyclopean masonry [26]. Another example of an original solution stemming from such design exploration is the prefabrication of walls as horizontal puzzles and then rotated upwards using a tilting table. From these explorations, we identify gabion cages as an easy and ready-to-be-implemented solution with no added processes or tools, despite being largely underdeveloped. However, we do not know the impact of broken concrete toxicity on outdoor applications.

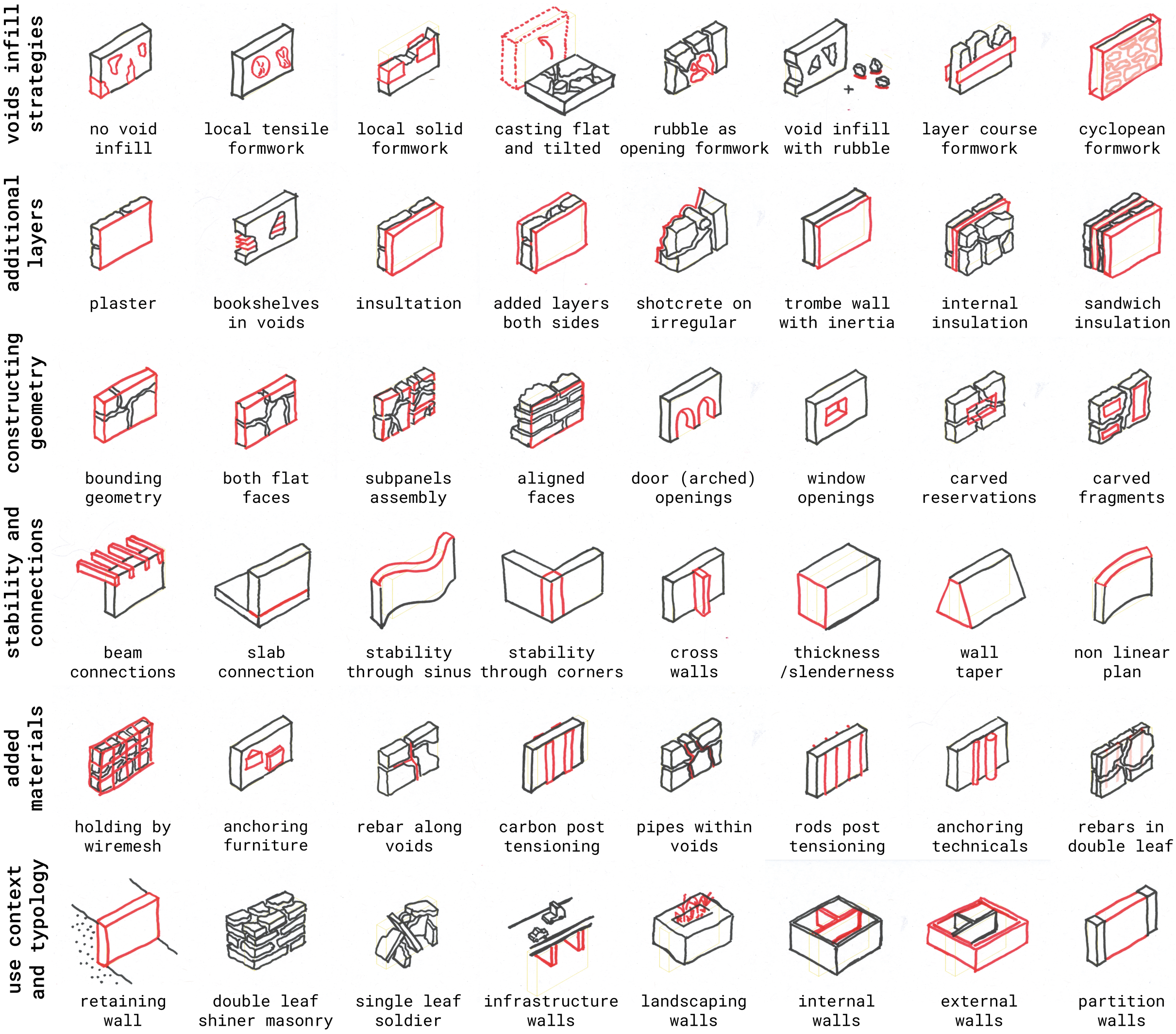

Figure 5: Selection of categorized design options for walls from concrete rubble. The design features of interest are highlighted in red. They provide initial examples of the vast diversity of architectural, structural and constructive solutions which can be developed from such untapped construction.

5.6.2 Vaults

The design explorations of vaults made of reclaimed concrete rubble can equally draw lessons from irregular dry-stone masonry, besides from the specific state of the art for vaults, e.g. geometric form-finding, Guastavino vaulting, centring methods, and patterns. The application of stone masonry principles to vaults allows the use of methods and tools developed for walls made of reclaimed concrete rubble to be translated by geometric wrapping while incorporating additional constraints. Most of the additional constraints stem from the need to span unsupported spaces, prompting the use of temporary supports or interlocking geometry. Besides traditional vault design and geometric optimisation, the arrangement of irregular rubble must be optimised to incorporate the discretisation of planar elements of various dimensions hence variable angles between them, while ensuring the line of thrust remains within material thickness. If not, the presence of internal rebars could be leveraged to allow shell behavior. An exploration of the construction of an unreinforced doubly curved vault, shown in Figure 6, highlights the challenge of standardising the falsework despite variable dimensions of elements while providing planar support to fill voids.

Figure 6: Collage by Grangeot of the prefabricated construction of an unreinforced masonry vault made of large flat demolition concrete rubble. The collage is used as an experimentation tool to plan constructive solutions.

6. Discussion

As material properties directly influence structural forms, one can wonder if new typologies are required to develop a convenient use of concrete rubble. Only through physical making and refinements will such an answer arise, perhaps even in distant futures, from the collaboration of architects with engineers. This is particularly important as the applicability to the known structural typologies is dependent on the effective distribution of the stock of concrete from demolition and their distinctive properties. To the authors' knowledge, no study exists regarding the geometrical characterization of concrete rubble from demolition and their distribution of sizes, flatness, and "ashlarness". Johns et al. provide preliminary insights despite being mixed with more that 91% of gneiss boulder stones and mixed erratics [13]. While recycling centres have metrics about the proportion of oversized rubbles to be fitted in their crusher, such estimation is highly imprecise.

7. Conclusions

In this paper, the applicability of concrete rubble from demolition to diverse structural typologies has been identified and explored through design options of walls and vaults. The opportunities and limitations of concrete rubble compared to stone and concrete, respectively, have been highlighted. The multi-criteria analysis of this study shows that concrete rubble is best suited for retention walls and foundations, while surface-active structures could have relevant applications. Moreover, more diverse structures remain unexplored. Construction know-how exists to construct structures from concrete rubble, and new ones could emerge in parallel to structural typologies suited explicitly for such unconventional construction material. Moreover, we highlight that built demonstrators are scarce, but there is a need to explore this reuse strategy further. Lastly, we sustain that some solutions for concrete rubble reuse are readily implementable with no additional processes or tools, such as gabion walls or stone substitutes in irregular masonry using lightweight rubble pieces, given toxicity precautions.

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