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Unreinforced concrete masonry for circular construction

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Abstract

This paper proposes an effective approach to realise circular construction with concrete, and shows Unreinforced Masonry as a foundational building block for it.

The paper outlines the importance of circularity in building structures. It specifically focuses on the impact of circular construction with concrete on improving the sustainability of the built environment in a rapidly urbanising world economy. Subsequently, the relevance of principles of structural design and construction of unreinforced masonry to achieve circularity is articulated. Furthermore, the paper presents and summarises recent developments in the field of Unreinforced Concrete Masonry (URCM) including digital design tools to synthesise structurally efficient shapes, and low-waste digital fabrication techniques using lower-embodied-emission materials to realise the designed shapes. The paper exemplifies these using two physically realised, full-scale URCM footbridge prototypes and a commercially available, mass-customisable building floor element, called the Rippmann Floor System (RFS).

The paper also outlines the benefits of mainstream, industrial-scale adoption of the design and construction technologies for URCM, including accelerating the pathway to decarbonise the concrete industry. In summary, the paper argues that URCM provides a solution to significantly mitigate the carbon emissions associated with concrete and reduce the use of virgin resources whilst retaining its benefits such as widespread and cheap availability, endurance, fire safety, low maintenance requirements and recyclability.

Keywords Unreinforced masonry, Digital concrete, Circular construction

1 Circular concrete construction

Rapid urbanisation and climate change heighten the urgency to address the circularity of building construction (Block et al. 2020; Fivet & Brütting, 2020; Wangler et al. 2019). In this context, the widespread and relatively cheap availability of concrete, the low cost of the technological requirements for its use, and its beneficial material properties such as longevity, fire resistance, thermal activation, etc. make it an important material. However, the expected high volume use of concrete makes the associated carbon emissions, mainly stemming from the production of clinker for cement and exacerbated by the use of steel reinforcements, important to mitigate (Eds, 2021; Monteiro et al. 2017). In other words, decarbonisation of the concrete industry is critically important. This paper argues that if one were to view concrete as a synthetic stone, the pathway to its sustainable use can be unlocked by the design and construction paradigm of unreinforced masonry.

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1.1 Unreinforced concrete masonry

The whole life-cycle environmental impact of building structures is the sum of three principal components: (i) construction (manufacture and construction processes); (ii) operation (maintenance); and (iii) end of life (demolition or deconstruction) (Fieldson et al. 2009).

The so-called 9-R framework is often used to reason about circular economies (Van Buren et al. 2016). The Rs (*Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover energy)* span from refusing the use of carbon-emissive raw materials to the recovery of energy by incinerating residual flows. The Butterfly Diagram is used to visually explain the implications of each of the Rs in a circular economy (Fig. 1) (Braungart & McDonough, 2009; Foundation, 2019). In it, the so-called technical cycles outline distinct loops of circular use of resources. The smaller, inner loops advocate the maximal utilisation of manufactured products through the prolongation of their lifespan and continual reuse in manufactured form. Consequently, they are the most effective in reducing carbon and energy footprints of particular resources.

Digital Concrete (DC), defined as the digital design of structural parts and their robotic manufacture, aims to mitigate the high carbon emissions of concrete by reducing the volume of concrete used through better shape design and low-waste fabrication technologies (Wangler et al. 2016, 2019). Thus, DC acknowledges both that the demand for concrete is unlikely to subside due to the rapid urbanisation of the world and that concrete, despite its reputation, can be an ecological material given its low carbon footprint when normalised by volume of material.

Concrete can be seen as an artificial stone, a material with appreciable strength in compression but negligible in tension. Consequently, like stone, it is appropriate to shape concrete as a discretised masonry arch in compression and inappropriate to form it into a straight beam in bending. Following the motto "strength through geometry" and the principles of traditional unreinforced masonry construction, our proposal will show how translating the (lost) knowledge of the Gothic master builders into today's praxis results in truly sustainable, circular and economical structures in (unreinforced) concrete, addressing climate change by significantly reducing embodied emissions, utilising fewer single-use resources and minimising construction waste.

We can thus define Unreinforced Concrete Masonry (URCM) as the design and construction of unreinforced masonry structures using blocks of concrete that are synthetically produced using modern digital fabrication technologies. Defined thus, the URCM approach extends the Digital Concrete approach beyond reduced concrete consumption to.

– motivate the development and use of lower-strength, lower-carbon concrete;
– allow for reduced steel consumption by limiting tensile and flexural strength requirements through a compression-appropriate design of the global

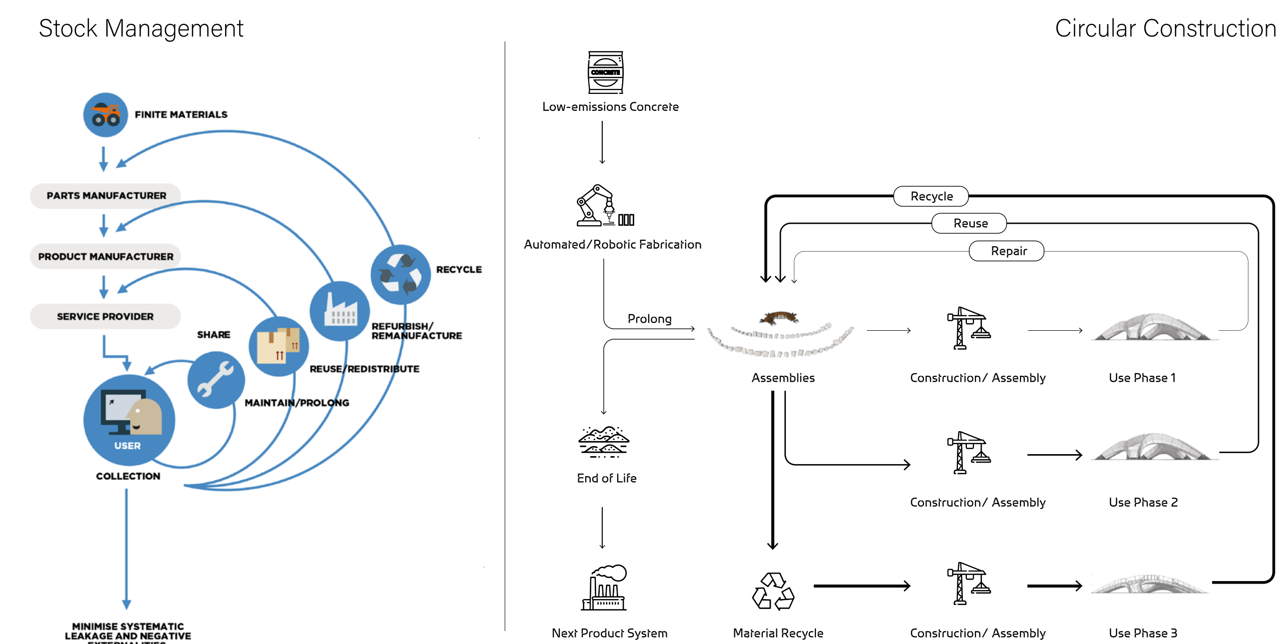

Fig. 1 Left—Technical cycles of the Butterfly diagram by Ellen McArthur foundation showing the loops corresponding to various circular strategies. The radius of the loop is invesrsely proportional to the effectiveness of the strategy, with the inner most ring being the most effective. Right – Translation of the Butterfly diagram for unreinforced concrete masonry structures. The line weight of the loops is inversely proportional to the effectives of the circular strategy, with prolongation of the lifespan of the structure being the most effective

shape of the structure, and the subsequent block discretisation and variable cross-sectional profiles of the blocks;
- mitigate the carbon footprint of concrete by extending the lifespan of concrete structures both due to low induced material fatigue and the elimination of embedded corrosion-prone reinforcement components; URCM structures can be repaired more easily as the separation of concrete and steel allows for straightforward maintenance strategies;
- enable the continued reuse of manufactured structural parts due to low induced stresses in the parts; continual reuse is possible due to the dry-assembled construction, glue-free connections, and thus non-destructive disassembly that URCM structures allow. Importantly, dry assembly can lead to an ideal, so-called integrated inverse manufacturing that balances the workload in the construction and disassembly phases. Integrated Inverse Manufacturing (IIM) is considered important to achieve closed-product life cycles. Closely related to IIM is the incorporation of disassembly aspects during the design phase, or so-called Design for Disassembly (DfD); and,
- allow for easy recycling of the concrete at the end of life of structural parts, with minimal construction and demolition waste (CDW). URCM enables easy and low-energy consumption recycling since it allows for both separation of concrete and steel materials and easy disassembly. Higher-quality recycled aggregates and repeatable recycling are two important parameters in achieving full, closed-loop recycling of concrete, similar to steel and plastics. Separation of materials by design, and thus the lack of embedded steel reinforcement in the URCM structures is aligned with both these features of closed-loop recycling.

In other words, URCM enables *Refuse*, *Reduce*, *Repair*, *Reuse* and *Recycle* principles of circular construction with concrete. The contributions of the paper stemming from these features of URCM are:

- elaboration of the relation between URCM and circular construction with concrete, particularly the 5-Rs as described above;
- exemplification of the circular construction principles using the technology demonstration projects:

  ○ The rib-stiffened funicular floor system, specifically its discrete version called the Rippman Floor System – RFS (Rippmann et al. 2018; Ranaudo, Van Mele and Block, 2021; Mata Falcón et al. 2022); and

  ○ The unreinforced 3D-concrete-printed masonry footbridges called Striatus and Striatus 2.0: Phoenix (Dell'Endice et al. 2021; Dell'Endice et al. 2023, 2024; Bhooshan, Shajay Bhooshan et al. 2022).

- the summary description of the mature ecosystem of design and engineering tools of the URCM paradigm; and,
- articulation of the value of URCM with regard to scalability, accessibility of technology, and the decarbonisation roadmap of the concrete industry (GCCA, 2022; Habert et al. 2020).

1.2 State of the art

The cohesive research work of the Block Research Group (BRG) at ETH Zurich since its inception in 2009 remains the most complete argumentation for an URCM-based circular construction (Rippmann et al. 2018; Block et al. 2019, 2020). The work of Catherine De Wolf argues both broadly for a framework of digital technologies that enable circular economies in the built environment, and more specifically for incorporation of whole life-cycle and embodied carbon emissions in structural design and engineering of buildings (Çetin et al. 2021; De Wolf et al. 2017). Recent work by the Structural Xploration Lab at EPF Lausanne provides arguments for the upcycled reuse of load-bearing structural concrete elements as opposed to the down-cycled reuse common in the concrete industry (Brütting, De Wolf and Fivet, 2019; Brütting et al. 2019a, 2019b). Their Re-crete demonstrator project also utilises the URCM paradigm, albeit with the masonry blocks consisting of concrete salvaged from disassembled floor slabs (Devènes et al. 2022). The reader is referred to Salama (2017) for guidelines, principles and a survey of the design of concrete buildings for disassembly.

The rib-stiffened floor by the BRG is a pioneering structural building element that embodies circular principles in its design and development (López et al. 2014; Liew et al. 2017; Ranaudo, Van Mele and Block, 2021; Mata Falcón et al. 2022). A result of more than a decade of research and computational tooling for integrated design, engineering and fabrication of unreinforced masonry, it has inspired other efforts, most prominently in the United Kingdom (Arup and World buisness Council, 2023; Oval et al. 2023).

Striatus and Phoenix, two unreinforced, 3D-concrete-printed, masonry arch bridges represent the most recent milestone in URCM (Bhooshan, Shajay Bhooshan et al. 2022; Dell'Endice et al. 2023, 2024). The projects demonstrate that with the integration of digital design and robotic fabrication technologies, the long span, low-carbon benefits of stone masonry can be fully extended to unreinforced masonry with 3DConcrete-Printed (3DCP) blocks, additionally reducing weight and waste. The projects also highlight that URCM extends the expressive aspects of unreinforced masonry, particularly in the structural and fabrication-informed design of each of its three significant parts: the global shape of the structure, its subsequent stereotomy and the textural articulation of the masonry blocks.

2 Concrete and circularity

Concrete is the most used construction material in the world (Ashby, 2012) After water, it is the most used substance on this planet. It is versatile, resilient, durable, cheap and easy to produce and use (Lehne & Preston, 2018). As a building material, it can achieve considerable strength and fire resistance, requires relatively low maintenance, and offers high design flexibility.

However, cement production (the main and most carbon-intensive ingredient of concrete) is currently responsible for 4% to 8% of global CO2 emissions (Lehne & Preston, 2018; Roser & Ritchie, 2021). It is also the biggest contributor to sand depletion, with estimated 60% to 75% of extracted sand worldwide being used for concrete production, causing severe damage to river beds and beaches (Smith, 2018). To reduce the carbon footprint of concrete, several strategies are being pursued by manufacturers and researchers (Habert et al. 2020). These include using alternative fuels for heating cement kilns, blending cement with less clinker or with supplementary cementitious materials (SCMs) that have lower emissions, and capturing and storing or utilising the carbon dioxide emitted from cement plants. For example, the Equivalent Carbon Coefficient (ECC) of a C20/25 concrete mix can be reduced by approximately 70% when substituting the cement type from CEM I to CEM III/B (Jones & Hammond, 2021).

Despite its environmental impact, concrete has one of the lowest embodied energy for unit mass among the most used construction materials, especially when low cement content is used (Ashby, 2012; Habert & Roussel, 2009; Jones & Hammond, 2021). The detrimental effects of concrete on the environment are then not only due to its material characteristics, but mostly due to the tremendous amount required by our society. For instance, the building sector, accounted for more than 11 billion tonnes of concrete consumption in 2010, and is estimated to consume up to 60 billion tonnes in 2060 (IEA, 2018; Smith, 2018). This can be easily appreciated through Eq. 1, which relates the Global Warming Potential (*GWP*) of a structure to the type of material and its mass (m) of its i parts. It is evident that reducing the environmental impact of concrete alone can only partially affect the GWP of the structure, and that reducing the amount of material used is equally important.

$$GWP = \sum_{i=0}^{n} \frac{ECC_i \times m_i}{t_i} \tag{1}$$

However, Eq. 1 only measures the GWP at construction, neglecting future contributions related to the choices made during the design phase. For example, a concrete structure with 1/10th of the GWP at construction might have the same long-term GWP if its lifespan is also 1/10th and needs to be fully rebuilt each time. Moreover, the equation cannot measure the consequences of the large amount of construction and demolition waste generated by a structure with a shorter lifespan. When evaluating the impact of a structure, it is then crucial to consider its technical performance over time and its End-of-Life (EoL) strategy (Müller et al. 2014).

2.1 The 5-R design guideline

It is complex to precisely quantify the considerations regarding the Global Warming Potential of structural elements made from concrete (De Wolf et al. 2020). However, the 9-R framework (Sect. 1.1) can used as a first approximation to guide design choices. In this context, the most significant levers to improve the circularity of construction with concrete are:

1. *Refuse*: prevent the use of high-carbon concrete mixes to mitigate non-optimal structural designs;
2. *Reduce*: decrease the amount of concrete placed in structurally unnecessary zones of the structure; Reduce: lower stresses due to alignment of material to thrust lines, resulting in more uniformly stressed sections, unlike the case of bending stresses that result in peaks and under-stressed areas.
3. *Reuse*: design concrete building components such that they can be reused in their original form as many times as possible, keeping the same mechanical performance;
4. *Repair*: design concrete elements that are more resistant to deterioration due to environmental factors such as weathering, corrosion, chemical attack, abrasion, or fatigue;

   Repair: separation of materials allows checking and if necessary (locally) replacing components increasing the lifespan of the structure; and,
5. *Recycle*: concrete can be recycled into aggregates for new concrete production or other applications such as road base, fill, or rubble. However, recycling concrete can also pose some challenges, such as removing contaminants, separating different types of materials, and ensuring the quality

and performance of recycled products. In the case of URCM, since no embedding of reinforcements in the components is required, they can be easily recycled and do not encounter corrosion issues, extending their lifespan.

A possible strategy to achieve the above was presented by Block et al. (2020) and summarised in the principle of *strength through geometry* and *material effectiveness*. In light of such principles, the first two points (*Refuse* and *Reduce*) are strictly related to structural geometry: shaping the structure such that the stresses are uniformly distributed and placing concrete only in the compression zones, can drastically reduce the use of material and foster the use of lower-strength, more sustainable concrete mixes. At the same time, *Repair* and *Recycle* can be promoted by the removal of embedded steel from concrete sections, which can increase the durability of the concrete elements and ease the recycling process. Lastly, *Reuse* can be obtained with the prefabrication of modular structural components that are easy to assemble and disassemble.

3 From URM to URCM

Strength through geometry and *material effectiveness* can be achieved through the application of unreinforced masonry (URM) principles in the structural design process. The 9-R framework (Sect. 1.1), and in particular the reduced 5R framework (Sect. 2.1) as applicable to the construction industry, has always been part of the history of unreinforced masonry (URM) structures, albeit for economic rather than environmental reasons (Fitchen, 1981). For example, it was common to reuse materials and components from demolished buildings or to extract the stone blocks from the construction site directly. In some cases, the structural design considered multiple requirements, like thermal mass or design features to capture wind streams for cooling, reducing the need for other materials. Such strategies were made possible by the structural principles of URM, mainly its discrete nature, the careful design of the global structural geometry and the stereotomy of each constituent masonry block. However, considering current regulations and building codes, the application of URM principles to the design of new structures must consider additional constraints and criteria. This section describes the relevant principles of URM that can be utilised in the design of Unreinforced Concrete Masonry (URCM) structures. It also highlights the challenges and opportunities of implementing URM-informed structures in modern building construction.

3.1 URM Principles

Geometry is the most relevant aspect of the structural behaviour of URM structures both at the scale of the global shape of the structure and at the scale of the discretised, individual blocks that constitute the structure.

The former—global shape of the structure—must be designed to follow funicular thrust networks and remain in compressive stress states under all loading conditions. Traditionally, funicular structures, such as arches and vaults, were designed with generous cross sections, in which, because of their mass, the self-weight was considerably higher than any other external load (Heyman, 1966). This resulted in negligible variations of the stress state under additional load cases, and stress level being one or two orders of magnitude lower than the strength of the material.

Appropriate geometry is equally crucial at the scale of the individual elements composing the structure, which are designed following specific stereotomy and discretisation rules. The discretisation plays an essential role in the mechanics of URM structures, whereby the interfaces between masonry blocks are designed to be as orthogonal as possible to the funicular flow of forces within the structure, allowing compression-only load paths that avoid bending (Mata Falcón et al. 2022). The discretisation also directly relates to the capacity of the structure to adapt to variations of the boundary conditions through differential movements of the components.

In the following paragraphs describe the challenges and opportunities related to the translation of traditional URM structural principles to Unreinforced Concrete Masonry (URCM), considering modern regulations and building codes.

3.2 Challenges

In the current context, where reducing material consumption, saving resources and decreasing the environmental impact are key aspects, the design of structures following URM structural principles faces new challenges.

URM structures traditionally relied on and benefited from thick sections (Section 3.1). Today, deep cross sections are not desirable because of architectural constraints and the need to reduce material consumption. Reduced sections in URCM structures have two main consequences:

i. Even though Heyman's hypothesis of infinite compressive capacity remains valid, the induced tensile stresses now need careful consideration. In other words, it remains generally valid that the compressive stress level within the structure is much lower than the strength of the material. However, the tensile stresses induced by the compression of thinner sections have to be carefully checked against the tensile strength of the unreinforced concrete (Dell'Endice et al. 2024) and,

ii. The self-weight of the structure is reduced, which implies that live loads tend to have a higher influence in the behaviour of the structure.

Furthermore, depending on the structural elements to be designed, a reduction of the cross-sections also has implications on requirements for fire and acoustic regulations.

Discretisation represents another challenge for designers. Questions about the correct size of the discretisation to be adopted or how to deal with the capacity of URM to adapt to settlements through small misalignments that could potentially not satisfy Servicability Limit State (SLS) requirements arise. As previously described (Sect. 3.1), discretisation is crucial for the correct behaviour of URM. The size and number of the blocks in the structure also affect fabrication and on-site productivity: more components might require more complex falsework and labour on-site, increasing assembly tolerances. Misalignments could not be an issue from the Ultimate Limit State (ULS) point of view but could potentially not satisfy some of the SLS criteria. On the other hand, increasing the size and reducing the number of individual components might locally trigger bending stresses. The resolution of discretisation also has an influence on the transportability of the components, which need to be handled after their fabrication and for the construction, and on the assembly strategy to be adopted. A compromise must be found that considers the requirements and constraints of each application.

Another factor limiting the direct use of URM in modern structures is the requirements (i.e., expectations) on the span-to-depth ratios of spanning structural elements. In modern reinforced concrete structures, slabs are usually dimensioned to have structural depths of about 1/20 to 1/30 of their maximum spans. However, for such shallow depths, continuous arches and vaults tend to behave more like beams and plates, with the occurrence of bending moments and, hence, the possibility of tension stresses in these elements (Ranaudo, Mele and Block, 2022). Although this does not affect the stability and ultimate behaviour of the structure, it might compromise their compliance with modern serviceability standards where cracks are to be avoided. However, the tension in shallow arches and vaults can be reduced by altering the self-stress state of these elements by, for example, precambering or introducing appropriate post-tensioning forces (Ranaudo, 2023).

Finally, other challenges involve the design of the joints between the components, which should preserve the capacity of masonry structures to accommodate moderate settlements without compromising the stability of the structure, but at the same time, improve alignments during the assembly (e.g. through registration keys or positive/negative interlocking) still only transferring compression forces. Joint design is also relevant to overcome stress concentrations due to geometrical imperfections deriving from fabrication imprecisions or assembly misalignments.

3.3 Opportunities

Historically, the design of URM structures relied on the knowledge of proportional rules by experienced master builders and used exclusively subtractive manufacturing techniques. Today, the combination of computational design tools and digital fabrication let us rediscover their use. The technological advancements also allow us to overcome the design and fabrication complexity of unreinforced masonry (URM) structures, which previously contributed to their decline.

From the structural design perspective, advanced structural analysis tools have been recently developed and made available to analyse the global stability of three-dimensional URM structures. These tools can deal with complex geometries and investigate their behaviour when subjected to variations of the boundary conditions (Avelino et al. 2021; Dell'Endice et al. 2021; Dell'Endice et al. 2022; Dell'Endice et al. 2023; Iannuzzo et al. 2021; Kao, Iannuzzo, et al. 2022; Kao, Ranaudo, et al. 2022; Kao, 2023; Maia Avelino, 2023). One strategy adopted by the authors to deal with the design of URCM is the combination of Discrete Element Modelling (DEM) and Finite Element Modelling (FEM) analyses, with the first providing the necessary information about the global kinematic behaviour of the structure and the latter describing the stress state of its elements (Dell'Endice et al. 2023).

From a fabrication perspective, digital fabrication allows us to overcome the practical limitations and low productivity challenges to the physical realisation of URM structures. Historically, the blocks were shaped through subtractive manufacturing processes, which required specialised skilled labour, time, financial resources and produced waste material. Stones were manually cut, and to reduce the workload, ad hoc strategies were adopted to reduce the number of uniquely shaped stones (Fitchen, 1981). The stereotomy of the voussoirs can now be parametrically modelled and, in the case of subtractive manufacturing, fabricated using CNC machines (Fallacara, 2006; Calvo Barentin et al. 2016; Rippmann et al. 2016). However, in the case of URCM that considers concrete as an "artificial" stone, additive manufacturing techniques such as 3D printing or casting can be used to precisely shape "synthetic" blocks, reducing material waste by placing the material only where needed. In the case of casting, architectural geometry and digital fabrication are relevant in the shaping and production of robust, material-efficient and costeffective moulds for the prefabrication of structural elements. Unreinforced concrete discrete components with specific shapes can be easily produced, and geometrical features such as holes or structural ribs can be considered in the mould design. It can be noted that difficulties with demolding and casting of very complex shapes remain, together with the handling and transportation of the components after curing.

With 3D Concrete Printing (3DCP), intricate interior cross-sectional features can be included, and additionally, shapes do not have to consider demoulding. On the other hand, constraints on what is printable without support material or from the robotic printing process have to be taken into account. For 3DCP, the mechanical properties of the concrete change due to the printing process, resulting in anisotropic behaviour. This should accounted for in the structural analysis of the components.

Finally, from a construction perspective, URM structures have always been challenging due to the need for curved falsework to support the dry-assembled structure until decentering. As such, the physical realisation of URCM structures requires new strategies that minimize the need or amount of curved falsework. In particular, the production of single-use elements for the falsework that follow the geometry of the intrados, can be reduced by adapting standardised reusable scaffolding systems commonly used in the construction industry (Dell'Endice et al. 2024). On the other hand, post-tensioning strategies with unbounded reversible tendons inserted in specific sleeves present an alternative for the activation of the structure after the assembly, reducing misalignments and increasing the robustness of the structure to variations of live loads.

4 Case studies

As detailed in the previously (Sect. 3), important aspects of URCM for circular construction are:

– Structural geometry and its discretisation:

  Structural design that includes compression-dominant global shape design, its transport and construction informed discretisation into concrete masonry blocks (stereotomy), and variable crosssection of blocks therein.

– *Fabrication:* Low-waste, low-carbon digital fabrication of individually customised concrete masonry blocks.
– *Construction and Disassembly:* Integration of aspects of both assembly and disassembly in the design phase of structures.

The three case-study projects described next demonstrate the maturity of the integrated design and construction technologies of URCM to effectively implement the aspects of design and construction above.

The cumulative research and development in URCM by the Block Research Group has meant not only that the exemplary projects are documented in detail, but the corresponding design technologies described therein are also assimilated into the Python-based, open-source computational framework COMPAS (Van Mele et al. 2017). The computational tools of URCM as incorporated into COMPAS currently are easy to use for exploring compression-dominant shapes of structures, or so-called form finding. The tools for URCM-informed discretisation of the form-found shapes are also incorporated into COMPAS, but require experience and expertise in geometry processing and computational design. Similarly, Discrete Element and Finite Element Modelling packages are also available for expert use. It can further be noted these state-of-the-art technologies are effectively disseminated through student and professional educational workshops based on the COMPAS framework.

4.1 Rippmann floor system (RFS)

The Rippmann Floor System (RFS) (Fig. 2) is a discretised concrete funicular floor (Liew et al. 2017; Rippmann et al. 2018; Ranaudo, Van Mele and Block, 2021; Ranaudo, 2023). It consists of a rib-stiffened shell designed to remain in a uniformly compressive state under the predominant load combination, and steel ties that resolve the horizontal thrust at the corner supports. The clear distinction of the compression (in the vault and ribs) and tension (in the ties) load paths allows *in primis* to place the most effective material where needed, namely, unreinforced concrete in zones of compression and steel in zones of tension. At the same time, it allows separating one material from the other. The discretisation of the floor is chosen to comply with logistical requirements, such as from fabrication, transport to site and installation, as well as to create structural hinges that reduce internal indeterminacy and help the control of the force flow. The modular design and the dry-jointed interfaces allow us to mount it, unmount it and possibly reuse it or replace it, as a whole or in parts.

The RFS is, as suggested by its name, a *system* and therefore can be adapted to specific boundary conditions,

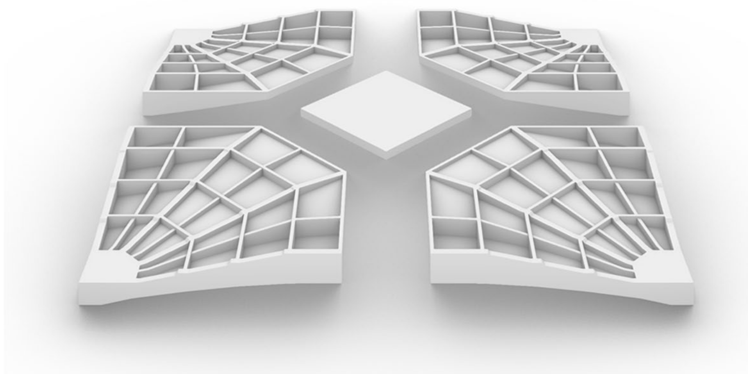

Fig. 2 Exploded view of the Rippmann Floor System (RFS), discretized into five elements. The prefabricated elements are installed on-site using reversible, compression-only connections, ensuring easy assembly and disassembly. The mono-material construction of the RFS removes the risk of corrosion and allows for efficient recycling at the end of its life. Courtesy of VAULTED AG

floor plans and substructures and appropriately designed to comply with additional architectural and structural requirements, such as fire resistance (REI) and acoustic performance. A a 6×6 m RFS prototype was built in Duebendorf, Switzerland (Fig. 3).

4.2 Striatus footbridge

Striatus, an arched masonry footbridge composed of 3D-concrete-printed (3DCP) blocks, exemplifies the extension of Digital Concrete, beyond shape efficiency, towards addressing additional aspects of circular

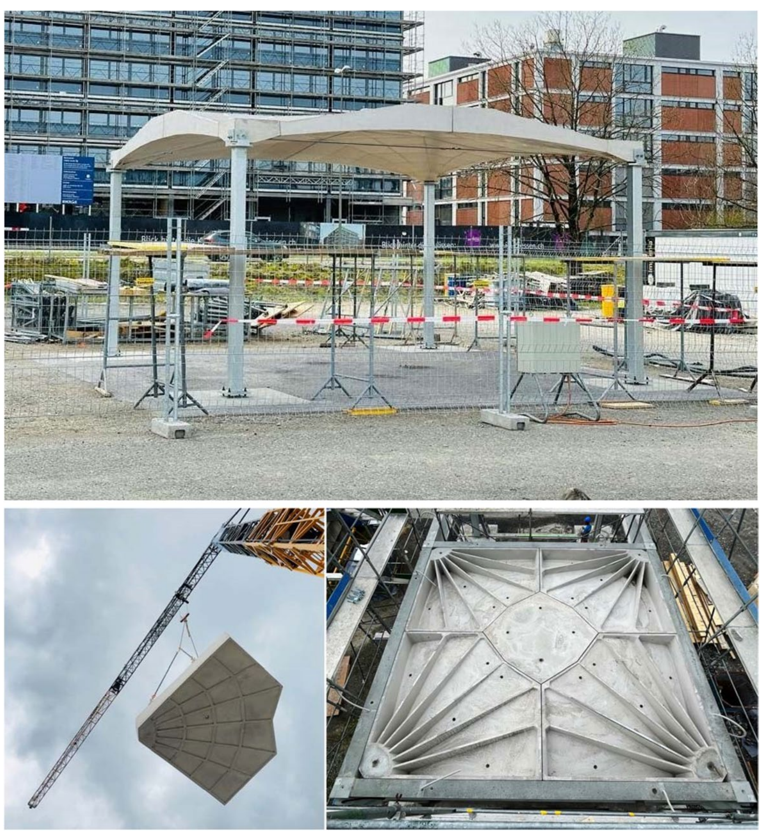

Fig. 3 A 6×6 m RFS under construction in Duebendorf, Switzerland. Photos: Top by Tom Van Mele, Bottom Left by Philippe Block, Bottom Right by Francesco Ranuado

Fig. 4 Striatus footbridge, photograph of the completed footbridge as exhibited for 6-months in Venice, 2022, prior to being completely disassembled and crushed to create new concrete printing 'ink'. Photos by naaro

construction with concrete (Bhooshan, Shajay Bhooshan et al. 2022; Dell'Endice et al. 2023) (Fig. 4).

Similarly to the Rippman Floor System, the design of the bridge explicitly utilises a URCM paradigm for circular construction with concrete. Striatus was designed to be dry-assembled and fully engage the 3DCP material structurally. Thus, the structure is discretised based on a proper unreinforced-masonry stereotomy (Rippmann et al. 2016). Furthermore, the printed blocks and print layers are aligned orthogonal to compressive force flows (Fig. 5). The bridge directly uses the hollow blocks as printed, without casting additional structural concrete in them.

Striatus addresses the following challenges of achieving both a structural design that will support the 5 R's and its materially effective physical realisation:

- Form finding of a global shape for the bridge that induces only compressive stresses in the material once physically realised (Fig. 6—left);
- Manufacturing URCM structures with variable cross-sectional thickness and structural ribbing to address both structural stability and efficiency (Fig. 6—right); and, ● Segmentation of URCM for assembly, transport, and disassembly.

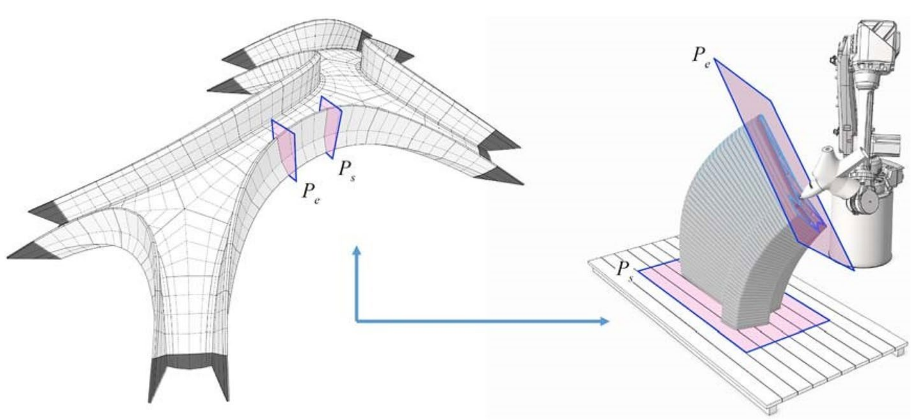

Fig. 5 URM-informed discretisation at the scale of the masonry blocks, i.e. the stereotomy, and the aligned placement of the print filament

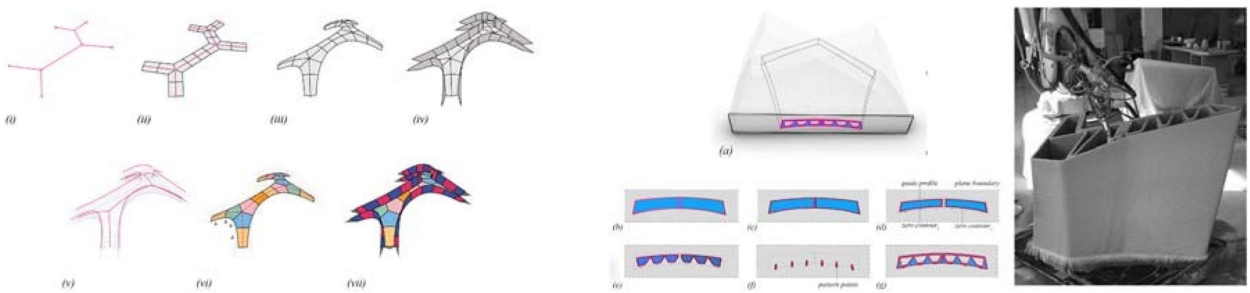

Fig. 6 URCM approach: unreinforced masonry design and physical realisation via individually customised, variable cross-section 3Dconcrete-printed blocks

Given the explicit URCM goals, the design and engineering toolchain used was similar to the one for the RFS (Sect. 4.1). The constrained form-finding procedure was built on the lineage of methods stemming from the Thrust Network Analysis (Block, Lachauer and Rippmann, 2014; Van Mele et al. 2014; Block et al. 2018). Similarly, the unreinforced-masonry-informed stereotomy extended the principles and techniques emanating from the design and construction of the Armadillo stone vault (Rippmann, 2016a, 2016b; Rippmann et al. 2016; V. Bhooshan et al. 2018). The stereotomy also considers aspects of transport, handling during assembly, etc. (Bhooshan, Shajay Bhooshan et al. 2022; Dell'Endice et al. 2023).

The variable cross-sectional design of each of the discretised concrete masonry blocks was achieved using innovations in image-based representations for geometry processing or specifically, the adaptation of features of so-called Functional Representation (S. Bhooshan et al. 2018; Bhooshan, Van Mele and Block, 2020; bhooshan et al. 2022) (Fig. 6—middle). Discrete-element modelling was used to evaluate the structural stability of the discrete, rigid blocks produced as an outcome of the stereotomy. Finite-element modelling was performed to verify the local bending stresses in the blocks.

4.3 Striatus 2.0: Phoenix footbridge

Striatus 2.0, called Phoenix, is the second iteration of the Striatus bridge, built in Lyon (France) in 2023. It was designed as a permanent structure, aiming to improve

Fig. 7 Stratus 2.0: Phoenix. URCM 3DCP permanent pedestrian bridge built in Lyon in 2023. Photo by Alessandro Dell'Endice

the circularity of 3DCP URM structures and address the critical challenges encountered during the fabrication and construction of Striatus (Fig. 7).

More in detail, the sustainability of the concrete ink was improved by reducing its nominal strength from 90 to 50 MPa, using fully recycled cement, and incorporating recycled aggregates from the disassembled Striatus blocks and local sand. The robustness of the URM system was improved by increasing the structural depth of the 3DCP blocks and by printing thicker layers. From a geometrical point of view, the number of blocks was almost doubled, and their dimensions halved, improving manoeuvrability and transportability and helping the fabrication process by reducing the curvature variation in each 3DCP block. Compared to Striatus, single-use falsework components were minimised by using standard re-usable commercial scaffolding towers. Overall, Phoenix represented a reduction of almost 25% of the CO_2 emissions in comparison to Striatus, and it represents a significant advancement in applying 3DCP and URCM principles for sustainable construction.

5 Conclusion

The paper argued for the importance of addressing circular construction with concrete, especially for the structural components of buildings. In this context, the relevance of and opportunities offered by an Unreinforced Concrete Masonry (URCM) paradigm were articulated. The paper then summarised the key milestones in the research and application of URCM design, fabrication and construction technologies, before highlighting their easy-to-extend, open-sourced availability via the COMPAS framework.

Specifically, the paper synthesised multi-decade research and development in unreinforced masonry into guiding principles that allow to reason about the design and physical realisation of circular concrete structures. The URCM approach articulates the importance of an unreinforced masonry paradigm to achieve each of three important aspects for circular concrete construction:

- digital shape design of structures that enable them to be realised and use significantly reduced carbon emissions, energy and material use, particularly virgin cement and steel;
- integrating aspects of construction and disassembly in the design phase of structures both for easy repair and reducing end-of-life carbon emissions and waste associated with demolition; and,—low carbon, low-waste digital fabrication and construction of structures so designed.

Thus, the proposed URCM approach provides a tangible path to decarbonise the concrete industry and thus pave the way for the sustainable use of concrete, both of which are critical for a rapidly urbanising world.

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