IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

When low strength materials meet funicular structures: a sustainable clay floor structure solution for emerging contexts

To cite this article: Cristián Calvo Barentin *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 042024

IOP Conf. Series: Earth and Environmental Science **588** (2020) 042024 doi:10.1088/1755-1315/588/4/042024

When low strength materials meet funicular structures: a sustainable clay floor structure solution for emerging contexts

Cristián Calvo Barentin[1,4], Ioannis-Athanasios Zornatzis[1,5], Gnanli Landrou[2], Thibault Demoulin[3], Guillaume Habert[2] and Philippe Block[1]

[1] ETH Zurich, Institute of Technology in Architecture, Block Research Group, Stefano-Franscini-Platz 1, 8093 Zurich , Switzerland

[2] ETH Zurich, Institute of Construction and Infrastructure Management, Chair of Sustainable Construction, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

[3] ETH Zurich, Institute for Building Materials, Physical Chemistry of Building Materials, Stefano-Franscini-Platz 3, 8093 Zurich, Switzerland

[4] calvo@arch.ethz.ch, [5] johnz@student.ethz.ch

Abstract. The inevitable expansion of the built environment due to the rapid growth of the urban population in emerging contexts poses a great challenge for the sustainable development of local communities. This problem could be faced by providing adequate multistorey building solutions while using sustainable and eco-friendly materials, preferably from renewable or upcycled and locally available sources. These materials tend to have lower mechanical properties than those commonly used in conventional structures and therefore not adequate for elements subjected to bending such as floor slabs. This challenge can be met by improving the strength of the locally available materials and/or using geometries specifically designed to lower the structural stresses such as funicular structures. In this study, a novel clay-based cementless material is used. Different mixtures and additives were tested to achieve similar processing advantages as concrete. A parabolic arched floor element is designed based on a parametric analysis using graphic statics to reduce structural stresses and weight. The fabrication system is based on reusable formworks in which locally available earth is used as part of the mould. A four meters span arched floor is built to analyse its structural behaviour and to evaluate the proposed fabrication method.

1. Introduction

Crises are sometimes a fertile ground for innovation. Creative solutions typically emerge when humanity is pushed out of its comfort zone and radical changes are needed. Throughout its history, humanity has had to adapt repeatedly to alterations in its habitat. Many times as a result of the impact of human productive activities. In ancient Greece, warfare led to the necessity for large quantities of wood for the production of ships and metal processing, thus favoring alternatives in the construction of buildings [1]. The lack of easily extractable material sources, such as wood, triggered innovation to adapt the craftsmanship of clay, stone, and marble to building construction. The masonry arch was clearly an effective and efficient way to use locally abundant but brittle materials, in horizontal spanning structures.

IOP Conf. Series: Earth and Environmental Science **588** (2020) 042024 doi:10.1088/1755-1315/588/4/042024

1.1. Rapid growth of urban areas in the big south

The United Nations Department of Economic and Social Affairs estimates that by 2035 the urban population will have increased by over 1.1 billion people [2]. In emerging contexts of the big south, such as India, Egypt or Nigeria, the population in some urban agglomerations is expected to increase by more than 10 million in the next 15 years (Figure 1). Providing them with adequate housing and infrastructure will require urban areas to grow considerably in both size and density.

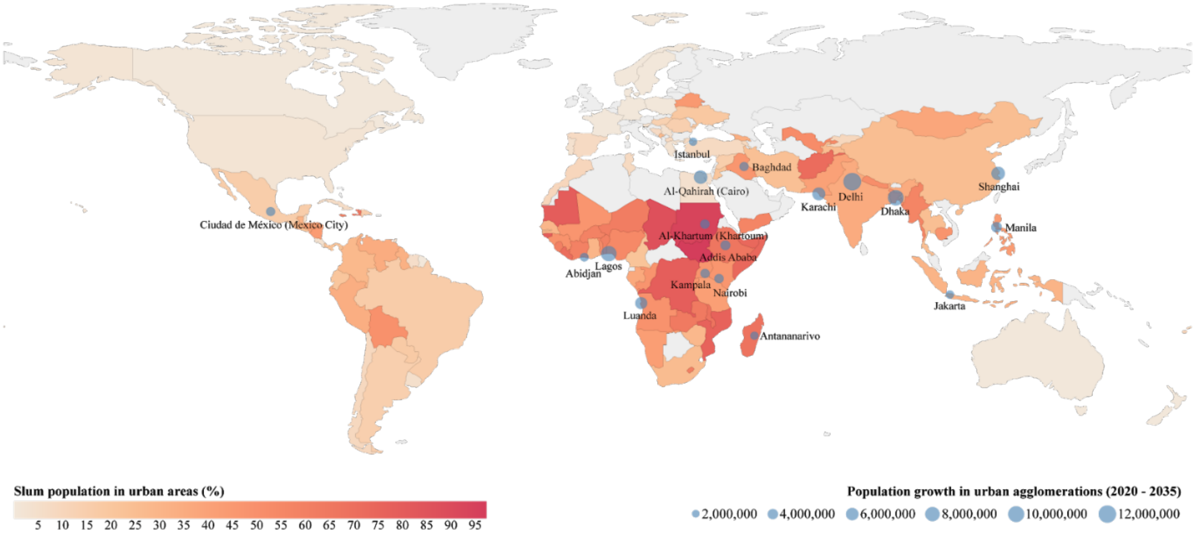

Figure 1. The blue circles represent the urban agglomerations that will grow by more than 2 million people in the next 15 years [2]. The colour scale illustrates the percentage of urban population living in informal settlements [3].

1.2. *Environmental impact of construction.*

Conventional building production processes are very harmful to the environment. By 2035, over 80 billion m^2 of new building space will be constructed and/or re-constructed worldwide, representing an area equivalent to roughly 60% of the existing global building stock [4]. This rapid expansion poses a great threat to the environment since the construction industry is one of the biggest contributors to environmental crises, mainly to climate change, energy consumption, waste production, and resource depletion. To reduce the environmental impact of the construction industry, it is simply not possible to build in the future as we currently do.

One way to reduce the environmental impact of these processes is to advocate for the effective use of materials in structures. The choice on the materials and how they work in the structure is based on effectively using their full potential according to their mechanical properties [5]. This approach makes it possible to save material, to decouple structural functions, thus avoiding the use of composite materials that are normally difficult to recycle, and to expand the range of materials that can be used due to lower mechanical requirements. The latter opens the possibility for the use of locally-sourced materials with low environmental impact on building structures. This potential diversification in building materials could help reduce the carbon footprint of buildings and decrease the pressure on ecosystems in extractive areas around the globe.

Another aspect to take into account is the waste generated throughout the life cycle of the buildings, during the construction and especially the demolition stage. Through the use of biodegradable or easily recyclable materials, it is possible to migrate from a linear to a circular approach, where waste is not considered the end of a cycle but inputs for a new cycle [6].

1.3. Floor structures
Even in a medium-height, multi-storey building, floor structures can represent up to 50% of the total design loads [7]. Most of the floor systems commonly used today are analyzed as elements that act in bending, and because of this they generally require large volumes of materials with good tensile and compressive strength. A good example of this are reinforced concrete slabs, where steel reinforcement is embedded in the concrete to increase the tensile capacity of the floor structure. This results in heavy composite structures that are difficult to recycle at the end of their life because of the difficulty of separating them into their constituent parts. Typically, reinforced concrete elements end up in landfills or are crushed into small pieces to remove the reinforcement and then use them as a downcycled aggregate of poor quality.

1.3.1. The arch as a solution. Arched floor systems were the most commonly used floors until mid 19th century [8]. They are structurally more efficient than current floor systems because of their shell action in compression. This resulted in a considerable reduction of the material used and in significantly lower stresses than found in modern conventional floor slabs. The use of these floor systems was largely abandoned in the late 19th century after the rise of reinforced concrete slabs. One of the key reasons for this shift was the simplicity and familiarity in the construction process of these new methods compared with arched floor systems, which depending on the availability of skilled labor, may need complex and time-consuming formwork.

Recently, renewed attention has been given to arched floor systems due to the possible benefits that their use would bring to reduce the environmental impact of buildings. Liew et al. [9] explored the incorporation of stiffeners and tension ties in the design of unreinforced concrete arched floor structures to reduce self-weight. This translates into a reduction in the mass of these by up to 70% compared to conventional reinforced concrete floor slabs (Figure 2a). Block et al. [10] (Figure 2b) and Rippmann et al. [11] (Figure 2c) combined the above with the use of alternative materials with lower mechanical properties than concrete.

Figure 2. (a) Rib-stiffened arched floor, (b) Prototype made by combining tile vaulting with cement-stabilized, soil-pressed bricks, using locally-available soil and (c) 3D printed prototype using sand bonded by phenolic binders

1.3.2. Advantages in the use of the arch. Arches are material-effective structures. The material is placed only in a cross-section that follows a parabolic trajectory to initiate internal compressive stresses instead of flexural stresses. By using the material effectively where is only required, it is possible to save a large volume of material compared to conventional floor structures [12].

Stresses in arched structures are usually low, and therefore no high-strength materials are required. Just materials with limited compression strength and almost no tensile capacity. These materials are generally friendlier with the environment and with a much lower embodied carbon coefficient than materials commonly used in buildings [13].

1.4. The solution.
The aim of this research is to develop a design process that generates scalable, compression-only solutions for structural floor components and to propose a simple and low-tech fabrication method for an emerging context using a novel clay-based cementless material. To counteract possible limitations

related to high costs, resources availability, access to state-of-the-art fabrication technologies, lack of skilled labor and low mechanical properties of locally sourced material, this study is based on two main premises: "effective use of materials" and "simplicity in construction".

The proposed solution is aligned with UN-demarcated SDGs 9, 11 and 13 as follows: within SDG 9 it is aligned with target 9.2, because the proposed fabrication method and the material promote an inclusive and sustainable industry through locally-sourced materials and local labor. Within SDG 11 it is aligned with target 11.1, in that it helps to ensure access to affordable housing and with target 11.6, which seeks to reduce the adverse environmental impact per capita of cities. Within SDG 13 it is aligned with target 13.3, which seeks to improve capacity to mitigate climate change.

2. Methods

2.1. Material

The original mixture was developed by Oxara, a spin-off of ETH Zurich. It composes of clay, silt and fine aggregates up to 4 mm and of two admixtures that improve the workability of the paste at fresh state and accelerate its hardening [14]. One of the challenges of this research is to produce a mixture with similar processing advantages to concrete, having a low yield stress in its fresh state to facilitate its placement and yet a high enough compressive strength after hardening.

This material is developed with the aim of providing an affordable and sustainable solution for building construction by using clay, which is a locally sourced and fully recyclable material, to replace clinker as a binder.

2.1.1. Development. The material has to be fluid enough to be poured into a given formwork, and yet avoid cracking during the hardening phase. Different solid volume fractions, water content and admixture proportions are tested. The option of adding fibres is also investigated to help minimize the propagation of drying shrinkage cracks. In this case, natural straw is used, but given local availability, any bio-based alternative is applicable (Figure 3).

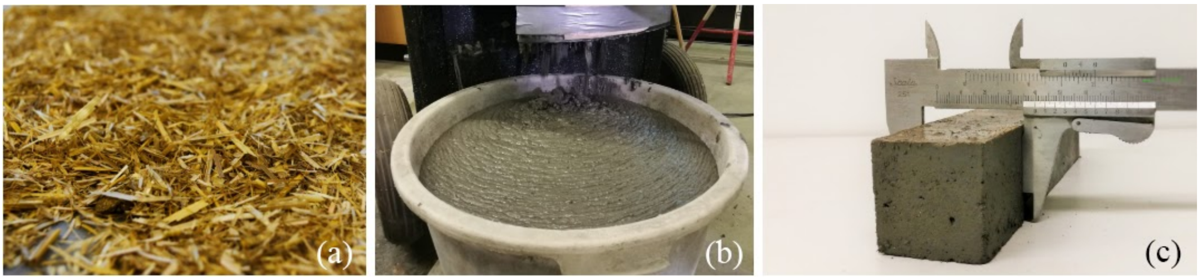

Figure 3. (a) Straw fibers, (b) Mixing process and (c) Testing prism.

2.2. Design of the floor structure

The design concept of the floor structure is based on a simple, single-curved barrel vault as a series of parallel parabolic unreinforced arched beams placed on an existing frame (Figure 4). The horizontal equilibrium is resolved with a tension tie. This makes the use of steel reinforcement unnecessary for the stability of the structure, thus reducing its carbon footprint and facilitating recycling. Spandrel walls are considered to provide adequate structural depth for multiple loading conditions, such as additional concentrated loads.

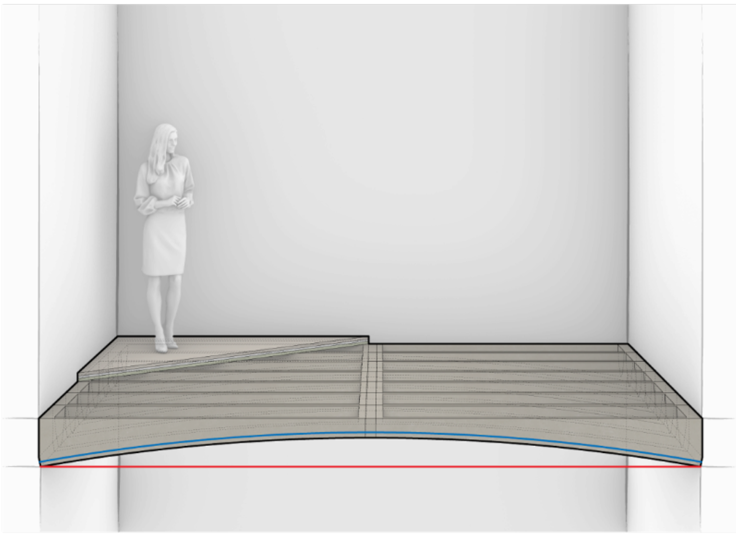

Figure 4. 3D visualization of the floor structure concept.

This study examines a modular approach with molded arched beams joined by control interfaces to form the final floor structure (Figure 5).

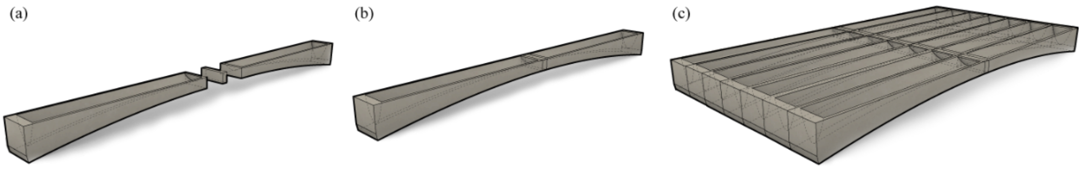

Figure 5. 3D visualization of the modular concept. (a) Constituent parts of a module, (b) Assembled module and (c) Floor structure consisting of modules arranged next to each other.

2.2.1. Form finding. The structure is analysed as a two-dimensional segmental arch on pin supports on both sides and subject to a uniform distributed load. The form-finding process to find a funicular geometry is done with Graphic Statics. This analytical method is based on the reciprocal relationship between form and forces, and where equilibrium is described using force vectors and closed force polygons [12]. Figure 5 illustrates the parametric model used for the form-finding process where a span, a rise ratio (ratio between span and height of the parabola) and a load magnitude are given.

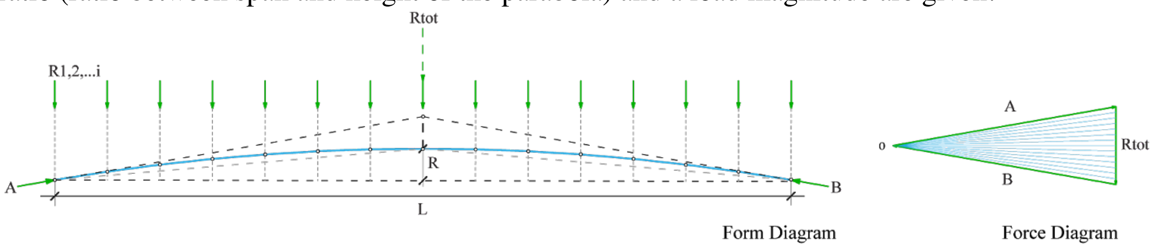

Figure 5. Parametric model used for the form-finding process.

2.2.2. Structural analysis. A parametric model based on Graphic Statics is used for the limited state analysis. Figure 6 illustrates the parametric model and the parameters considered for the analysis, which are: the mechanical properties of the material, the geometry of the arc, its thickness, the structural depth, the magnitude of the distributed load and the magnitude and location of a concentrated load. A proposed structure is safe if the shape of the obtained thrust lines are contained within the longitudinal section of the structure. And if the cross section of the arc allows for the maximum stress concentration found along the thrust line considering safety factors and the mechanical properties of the material.

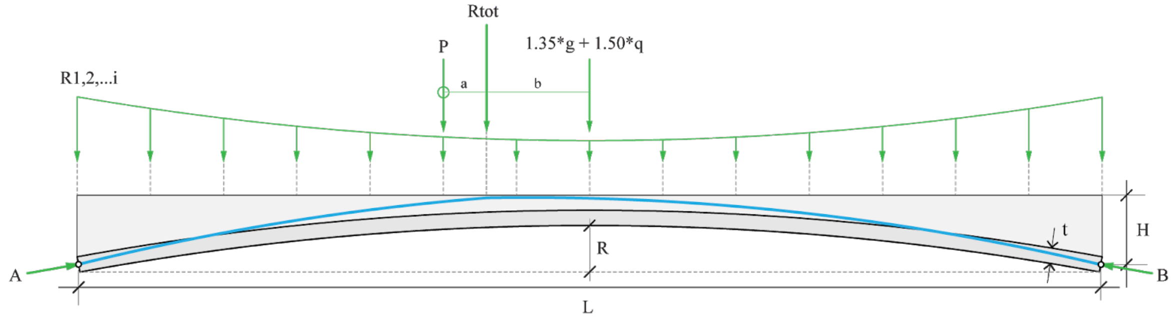

Figure 6. The parametric model used for the structural analysis of a given funicular geometry.

2.3. Fabrication
The successful implementation of the proposed fabrication method in emerging contexts relies on the involvement of the local labor. The process requires no previous knowledge or skill set. Each module is to be fabricated on site and casted in a reusable formwork. Simple techniques to ensure the quality control of the system are introduced, whilst the design accounts for tolerances in favor of safety during construction. Figure 7 shows an exploded view of the fabrication system.

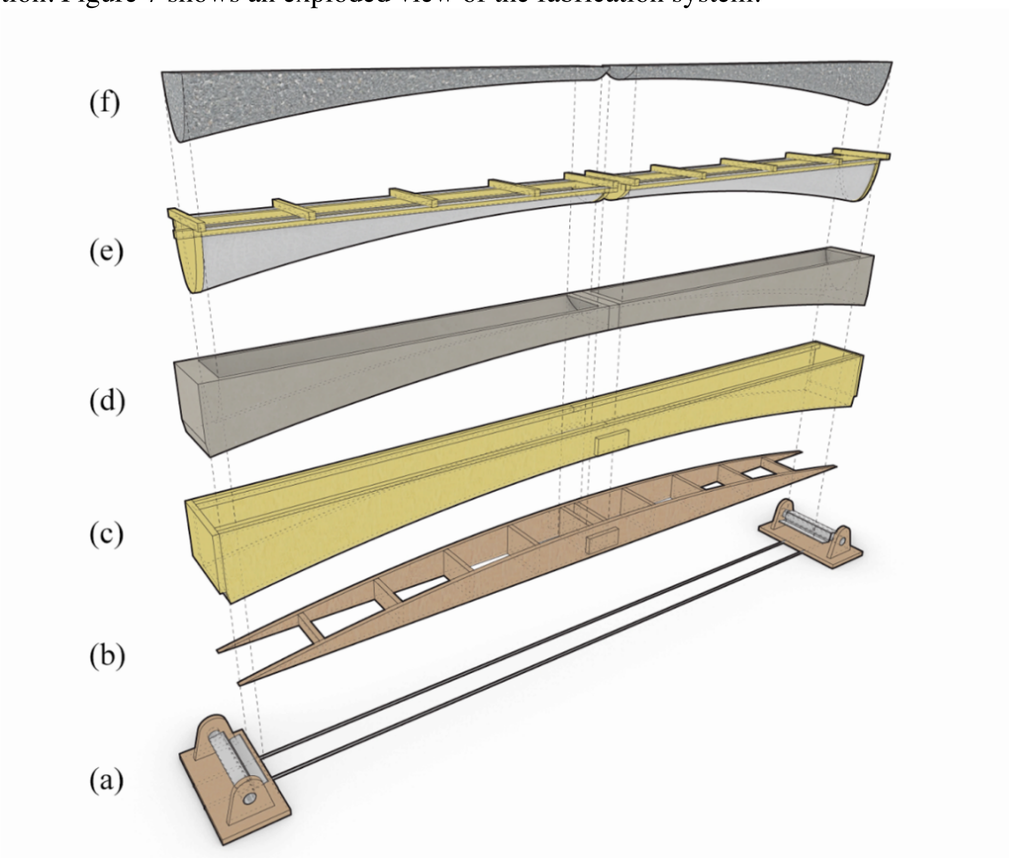

Figure 7. Exploded view of the fabrication with the layers as follows: (a) Pin supports connected with tension ties, (b) Scaffolding, (c) wooden formwork, (d) casted arched beam, (e) fabric formwork stiffened with timber elements for the floor voids and rib formations, and (f) locally sourced soil or gravel fill. (The lateral boards of the formwork are removed after two days to enhance the drying process and avoid cracking due to friction.)

3. Results

3.1. Material
Three testing prisms of 16x4x4 cm were created for measuring the strength and shrinkage for each of the thirteen different mix designs, whilst the evaluation of the workability is based on the results of the slump flow test in each case. The strength is tested in both compression and bending (three-point flexural geometry). The properties of the chosen mixture, that includes natural fibres, are: 3.4 MPa in compression, 0.9 MPa in bending, and a density of 2.2 g/cm3 with an average linear shrinkage of 1.71%.

3.2. Prototype
Three prototypes of span of 4 m, a structural depth of 30 cm, a width of 30 cm, a shell thickness of 6 cm, and a rise of 18 cm are fabricated sequentially to evaluate the fabrication process, the structural stability of the proposed design and to implement identified improvements (Figure 8).

Figure 8. Four meter span prototype

3.3. FE analysis
A finite element analysis is performed via the compas_fea package of the COMPAS framework [15] to analyse the ultimate limit state and serviceability limit state of the proposed structure (Figure 9). The stress-strain curve of concrete is used, since aspects of the mechanical behaviour of the material are not yet studied in depth. For the selected span of 4.0 m, the deflections must not exceed 1.6 cm. The post-processing of the simulation results shows satisfactory values under the serviceability factored loads with vertical deflections up to approximately 0.8 cm.

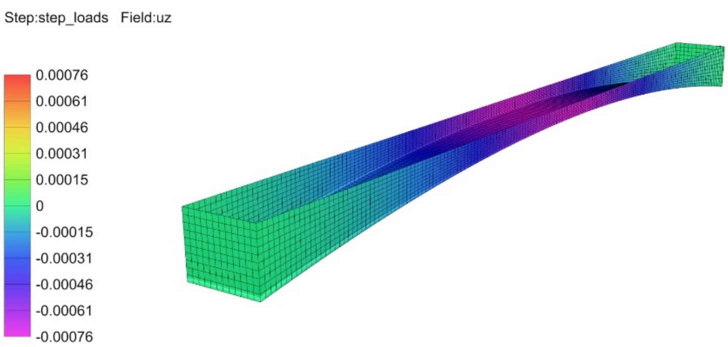

Figure 9. Structural analysis performed via the compas_fea package [15].

4. Conclusions
To make the proposed solution scalable in the coming years, the final simulated service and loading conditions should be verified with experimental data. Load tests are needed to assess the structural

behaviour through load displacement curves and to determine the minimum load under which a collapse mechanism occurs. Further material development is needed to solve problems of unwanted pre-cracking and to improve mechanical properties, with a focus on the definition of the stress-strain curve. Future work should also examine alternatives to increase capacity under cyclic and lateral loads through double-curved, equal stress solutions. Durability issues related to exposure to outdoor conditions and fire must also be addressed.

Another aspect to be covered is to produce an element of horizontal ground expansion that is not only structurally sound, but also inspires confidence despite scattered regulations and a strong bias towards unconventional building materials.

This study presents the implementation of 2D Graphic Statics for a parametric form-finding method of parabolic arched beams. The results are analysed via Finite Modelling Analysis. The method is applied for the design of statically determinate unreinforced arched beam subject to a limit state analysis. Such compression-only geometries allow the efficient use of locally available recycled materials that have low bending and tensile capacity, thus reducing costs and the environmental impact of flooring systems. A low-tech fabrication method using locally sourced materials is proposed to address the need for adequate and affordable solutions in an emerging context. A novel earthen mixture is further developed for the proposed structures. The feasibility of the fabrication process is evaluated and improvements are identified and implemented through three sequential iterations.

References

[1] Addis B 2007 Building: 3,000 Years of Design, Engineering, and Construction (London: Phaidon Press)
[2] United Nations 2018 World Urbanization Prospects: The 2018 Revision (New York: United Nations)
[3] UN Habitat 2014 Global Urban Indicators Database 2014 (Nairobi: United Nations)
[4] Architecture 2030 2014 Roadmap to zero emissions, the built environment in a global transformation to zero emissions (Santa Fe: Architecture 2030)
[5] Block P, Van Mele T, Rippmann M, Ranaudo F, Calvo Barentin C, and Paulson N 2020 Redefining Structural Art: Strategies, necessities and opportunities The Struct. Eng. **98** 66-72
[6] Webster K 2017 The Circular Economy: A Wealth of Flows (Cowes: Ellen MacArthur Foundation Publishing)
[7] Block P, Calvo Barentin C, Ranaudo F, and Paulson 2019 Imposing Challenges, Disruptive Changes: Rethinking the Floor Slab The Materials Book (berlin: Ruby press)
[8] Kidder F and Nolan T 1911 Building construction and superintendence vol 1 (New York : W T Comstock)
[9] Liew A, López López D, Van Mele T and Block P 2017 Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor Eng. Struct. **137** 323-35
[10] Block P, DeJong M, Davis L and Ochsendorf J 2010 Tile vaulted systems for low-cost construction in Africa J. African Tech. Dev. Forum **7** 4-13
[11] Rippmann M, Liew A, Van Mele T and Block P 2018 Design, fabrication and testing of discrete 3D sand-printed floor prototype Mat. Today Comm. **15** 254-9
[12] Block P, Van Mele T, Rippmann M and Paulson N 2017 Beyond Bending - Reimagining Compression Shells (Munich: Detail)
[13] Ashby M 2013 Materials and the Environment (Oxford: Elsevier)
[14] Landrou G 2018 Developement of Self-Compacting Clay Concrete (Zurich: ETH Zurich)
[15] Liew A and Van Mele T 2017 COMPAS: A framework for computational research in architecture and structures. COMPAS_FEA package (compas-dev.github.io/compas_fea/)