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Unfold Form

A curved-crease unfoldable formwork for a corrugated fan-vaulted floor

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Abstract

To address the urgent challenges faced by the construction industry of reducing carbon emissions while meeting the demand for new floor area, innovating floor systems offers high potential as slabs are structurally highly inefficient and mass dominant. Unreinforced vaulted floor systems offer a promising strategy through their geometric stiffness. However, the drawback commonly lies in the expensive and wasteful formworks for such non-standard geometry, furthermore often relying on digital fabrication, which is not available in emerging markets where there is the highest need. In response, this research introduces a low-tech, low-cost, material-efficient, lightweight, compactly transportable, rapidly deployable, self-supporting, and reusable formwork solution. Unfoldable curved-creased bending-active plates with textile hinges enable the in-situ construction of unreinforced corrugated fan-vaulted floor systems. The curved creases provide shape control, while the corrugations provide stiffening and translate into concrete rib articulations to enhance material efficiency. This paper focuses on validating the system through a demonstrator. The system, its co-design methods, and its fabrication and construction are presented. By employing structural geometry for both formwork and resulting shell floor, as opposed to wasteful moulds and inefficient slabs, the system could reduce the environmental impact of the construction industry.

Keywords: curved-crease unfolding, bending-active plates, deployable formwork, corrugated shell, vaulted floor system, in-situ construction, low-tech, structural geometry.

1 Introduction

1.1 Motivation

The construction industry faces the challenge of having to significantly reduce its tremendous carbon emissions while urgently providing nearly double the existing floor area by 2050 [1]. Innovation in floor systems has the most potential for impact considering that slabs constitute approximately half of the mass of multi-storey buildings [2] and are structurally highly inefficient. A rethinking based on the principles of the Gothic master builders teaches us to use strength through structural geometry. This effective principle is applied to vaulted floor systems through the introduction of a thin funicular unreinforced concrete shell with local stiffening articulations [3]. Mainly subject to low compressive stresses, these enable savings on reinforcement steel and concrete mass, additionally allowing lower strength, hence a lower cement ratio [3].

However, the drawback of construction of such non-standard geometry commonly lies in expensive, wasteful, bulky, and single-use formworks. Additionally, most custom formwork strategies rely on high-tech digital fabrication methods; however, the majority of the 2050-projected demand for floor area lies in economically less developed countries [1], where these tools are commonly unavailable. Consequently, formwork strategies with a universal approach using low-tech, low-cost materials, machinery and equipment could be applied in a wide range of regions, increasing their potential impact drastically.

The aim of this research is a low-tech, cost- and material-efficient, compact, and reusable formwork system that enables the in-situ construction of structurally efficient vaulted floors. Key to this innovation is that the formation of the formwork is based on a simple geometric principle. And equally to the shell, the formwork achieves its strength through geometry.

1.2 Curved-crease unfolding

The active bending of plates allows the efficient construction of lightweight, curved structures without using formwork or digital fabrication [4]. However, the shape of unconstrained bending-active plates is limited to the Elastica curve, and they undergo large deformations and risk stability failure under external loads [5]. Instead, with curved-crease folding (CCF), the plate's curvature is controlled by the crease shape (Fig. 1a), offering high geometric control and an intriguing design space [6]. Moreover, the mutual restraint of the adjacent plates improves structural performance significantly (Fig. 1b) [5]. Consequently, curved-crease-folded bending-active plates can be taken beyond the realm of installations to architectural-scale structural applications [7], [8]. However, their plate thickness lies beyond foldability, which necessitates the assembly of separate plates with curved hinges.

Since the plates must be joined regardless, the structure can be joined from stacked plates along curved creases into a flat-folded configuration, which is then unfolded. This concept was introduced with the terminology of Curved-Crease Unfolding (CCU) along with its geometric principles by Scheder-Bieschin et al. [9]. In the classic CCF, a flat assembly is folded from a large element into a more compact spatial configuration. Whereas in CCU, flat-folded plates can be unfolded rapidly from a compact state with an accordion-like mechanism into a double-curved, corrugated structure with extended design possibilities. Hence, this material-efficient structure is highly suitable as a formwork system for a shell with corrugated ribs as stiffening articulations, as conceptually demonstrated in Scheder-Bieschin et al. [5].

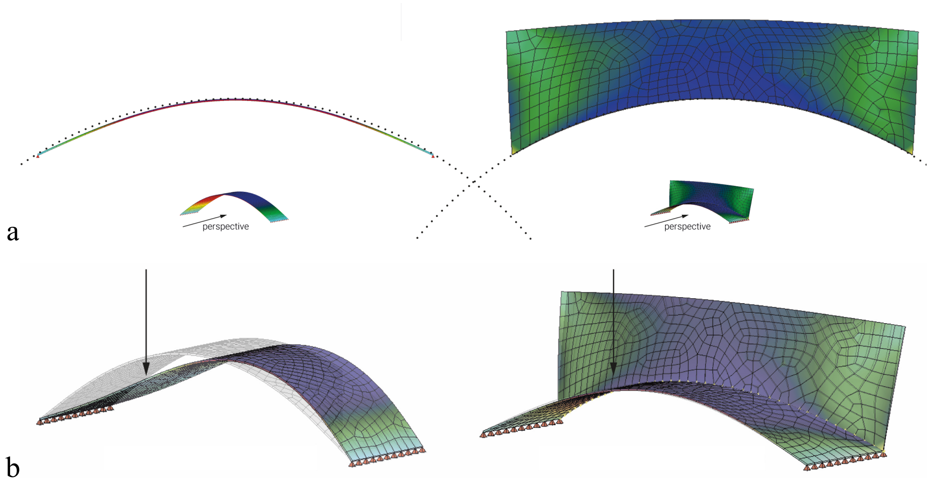

Fig. 1: Principle of (a) shape control and (b) stiffening of curved-crease unfolding shown based on a single bending-active plate (left) and curved-crease folded plates (right) [5]

1.3 Vision of "Unfold Form"

The vision of this research is to apply the principles of CCU bending-active plates as a reusable formwork for the in-situ construction of a compression-only, unreinforced-concrete, fan-vaulted floor. The core principles of the "Unfold Form" construction system are at a geometric, structural and design level: i) the geometric control of the creases with informed curvature allows the controlled shaping of a funicular shell geometry; ii) the resulting corrugations with their static height provide geometric stiffness for the formwork but also result in stiffening ribs in the concrete shell; and, iii) these geometric unfolding and structural schemes eventuate in the intriguing aesthetics of a fan-vaulted rib layout of the thin-shell floor inspired by the iconic King's College Chapel in Cambridge.

The advantages of the construction system, as depicted in Figure 2, are a simple 2D prefabrication process based on low-tech machinery and low-cost materials. It offers flat-packed, compact transport to the construction site and the rapid, on-site deployment through the CCU unfolding mechanism into a lightweight, self-supporting, material-efficient formwork. This formwork is robust and walkable to cast in-situ a material-efficient, unreinforced concrete shell. Lastly, the reusability of the formwork enhances ecological and economic sustainability.

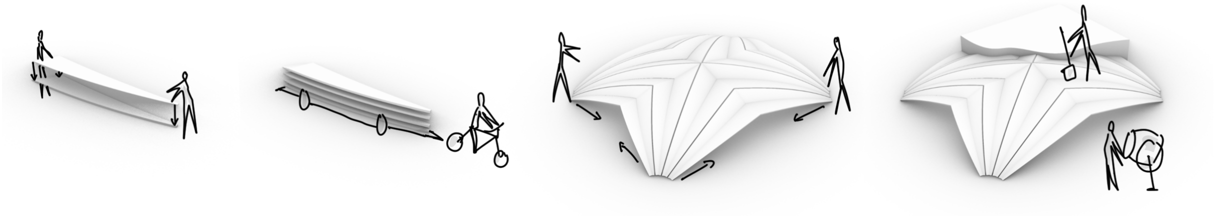

Fig. 2: Vision of the “Unfold Form” formwork system (from left to right): simple 2D prefabrication, flat-packed transport, rapid in-situ deployment, and easy and safe concrete casting

This research focuses on validating this vision through a half-scale demonstrator. The translation of the system’s core principles necessitates the integrative design of geometry, engineering, and fabrication. The paper first introduces the system design (Section 2), followed by a brief overview of the computational design workflow (Section 3), a description of the prefabrication, including the challenging design of the curved hinges, the construction and the result (Section 4), and concludes with an outlook on the potentials of “Unfold Form” (Section 5).

2 System

The “Unfold Form” construction system consists of a flat-packed formwork that unfolds to form a fan-vaulted concrete shell with corrugated ribs, which serves as the load-bearing structure of a vaulted floor system. The demonstrator is realised at half-scale of a housing unit and spans 3 metres by 1.8 metres. The proportions of this module are based on the golden ratio; however, these are flexible and could, for example, also be square in plan. The height of the floor buildup varies between 40 cm at its supports at its four corners and 18 cm at the centre crown. With over 70% of the floor depth below 25cm, including the flooring, overall storey heights would not increase, rendering the system applicable to the building sector.

The formwork system (Fig. 3a) consists of the curved-crease unfoldable plates that support and shape the concrete (Fig. 3d) and a supporting frame substructure (Fig. 3b,c). The CCU system is composed of four parts (Fig. 3e), two identical and two mirrored ones, that unfold (Fig. 3d) to cover the four symmetric quadrants of the fan vault. Each part is assembled from fourteen planar plates of 8mm poplar plywood. Plywood is highly suitable for bending-active structures [10], furthermore, its orthotropy is oriented such that its lower stiffness aligns with the direction of active bending and its higher stiffness with the ruling directions.

The CCU plates are connected and covered with an industrial woven polyester textile tailored from fourteen developable textile strips. The resulting curved textile hinges allow the simultaneous unfolding and active bending. As the hinge design in the proof-of-concept prototype [5], the textile is wrapped around the edges such that the adhesive bond is subject to tangential forces instead of debonding normal forces while the centre of rotation is located around the seam (Fig. 3h). A one-sided PVC coating of the textile ensures a clean concrete surface finish and robustness for reuse in multiple casting cycles, while the non-coated surface ensures better adhesion to the plywood plates.

The four elements of the CCU system are vertically supported in situ at the four corners with simple props and thrust against the capitals of the columns. These capitals are connected with tension ties that restrain the horizontal thrust during the casting process and later of the resulting vaulted structure. In a real-world construction case, these could be hidden in walls or replaced by buttresses. The four CCU parts are actuated when restrained within the capitals and the supporting frame substructure. The frame is made of 24mm plywood plates and connects to the CCU system with industrial velcro fasteners to ensure a rapid and reversible connection for multiple casting cycles. The frame's zigzag-shaped plates along the crown lines (Fig. 3c) and the ledges along the perimeter help to precisely position, support, and stiffen the four parts, while the sidewalls (Fig. 3b) provide a mould for the wet concrete along the sides. The formwork system has no counter-mould for simplicity of fabrication.

The corrugated vaulted shape of the formwork forms the intrados of the concrete shell, while the extrados is shaped manually into a continuous surface (Fig. 4a). Consequently, the resulting fan-vaulted shell has stiffening ribs with triangular cross-sections. These secure the structural height to provide geometric stiffness against asymmetric loads. The ribs vary the structural height of the concrete shell between 4 cm to 13.5 cm at the deepest rib at the centre. As the funicular geometry of the formwork and hence the concrete shell ensures primarily compressive stresses, the concrete shell is unreinforced, saving material and simplifying construction separation of parts for end-of-life recycling.

The "Unfold Form" floor system is completed with a dry fill for load distribution, insulation and horizontal levelling (Fig. 4b). Its dry nature allows for fast processing time and circular reuse. The floor finishing layers are composed of a fibre board for additional insulation (Fig. 4c), a dry screed for additional load distribution (Fig. 4d), and a rubber floor finish (Fig. 4e).

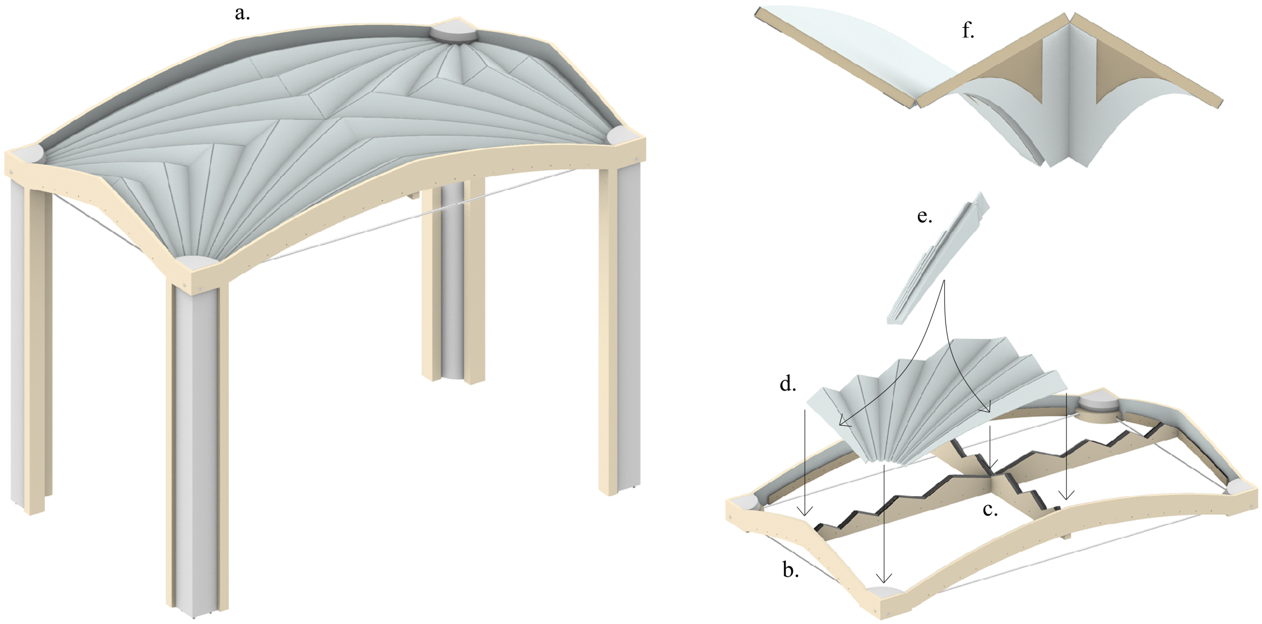

Fig. 3: System design of (a) the "Unfold Form" formwork: (b) side walls with side ledges, (c) crown plates, (d) unfolded CCU quarters, (e) folded CCU quarters, and (f) a closeup of the curved textile hinge design

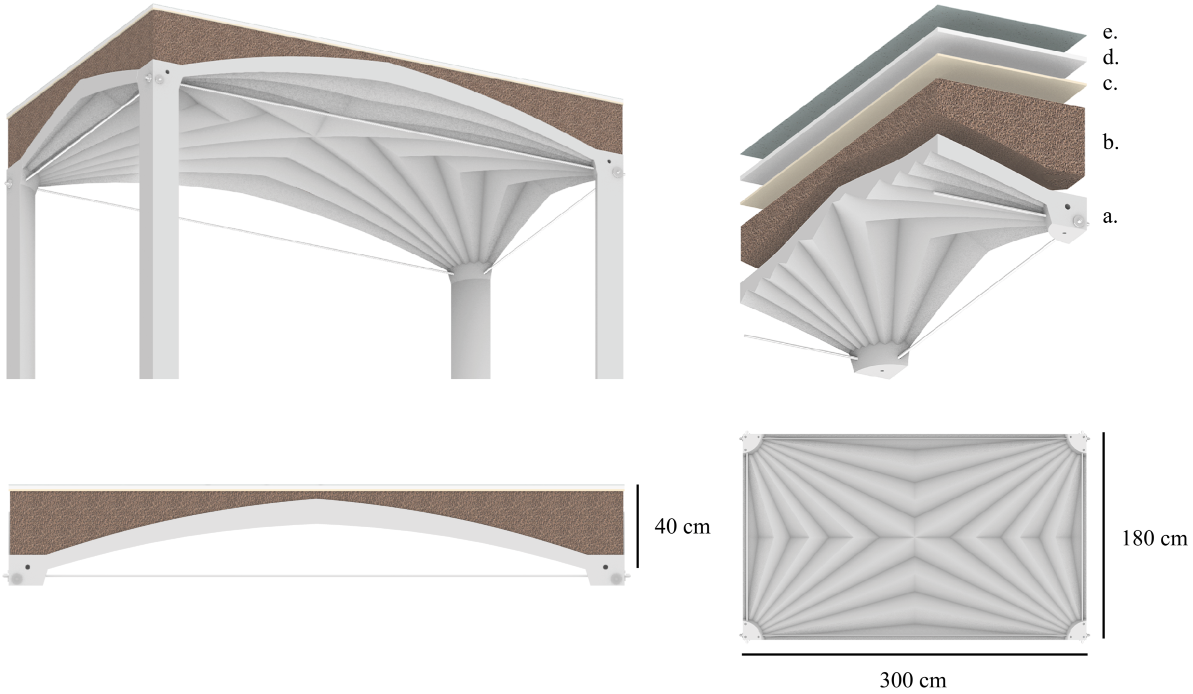

Fig. 4: System design of the "Unfold Form" floor system with (a) fan-vaulted shell and floor build-up with (b) dry fill, (c) fibre boards, (d) dry-screed, and (e) rubber floor finish

3 Geometric and structural co-design

The Unfold Form construction system emerges from an iterative and integrative computational co-design process that encompasses geometric, structural, and fabrication constraints for both the highly interdependent formwork and shell structure (Fig. 5). The design optimisation was achieved through a parametric sensitivity analysis evaluated against these constraints [11].

The geometric design commences with the form finding of the funicular target geometry based on a fan-vault pattern (Fig. 5a), utilising the Thrust Network Optimisation package from COMPAS [12]. The funicular target is translated along the curved-crease unfolded principle with the reflection method [9] into the corrugated bending-active plate geometry of the formwork (Fig. 5b) such that the thrust curves are contained within the kern of the shell structure [11]. The shell geometry is defined by the CCU formwork at its intrados and by a minimum thickness of 4 cm to its continuous extrados.

The structural design verifies this geometric design of the funicular shell with the Finite Element software SOFiSTiK [13]. The serviceability and ultimate limit state (SLS and ULS) are analysed along with a push-over analysis to determine the optimal iteration of the parametric design space. The formwork as well is analysed for SLS and ULS plus a buckling analysis is performed to capture potential snap-through behaviour. It is modelled with spring connections along the curved-crease hinges and includes the internal stresses from the bending-active actuation.

The fabrication design reconciles reciprocal constraints from both the formwork and shell and integrates the detailing from the prototyping process. Finally, the 2D geometry of the formwork plates and textile strips is computed through the simulation of the close-folding of the CCU mechanism and exported along with all other formwork components as fabrication data.

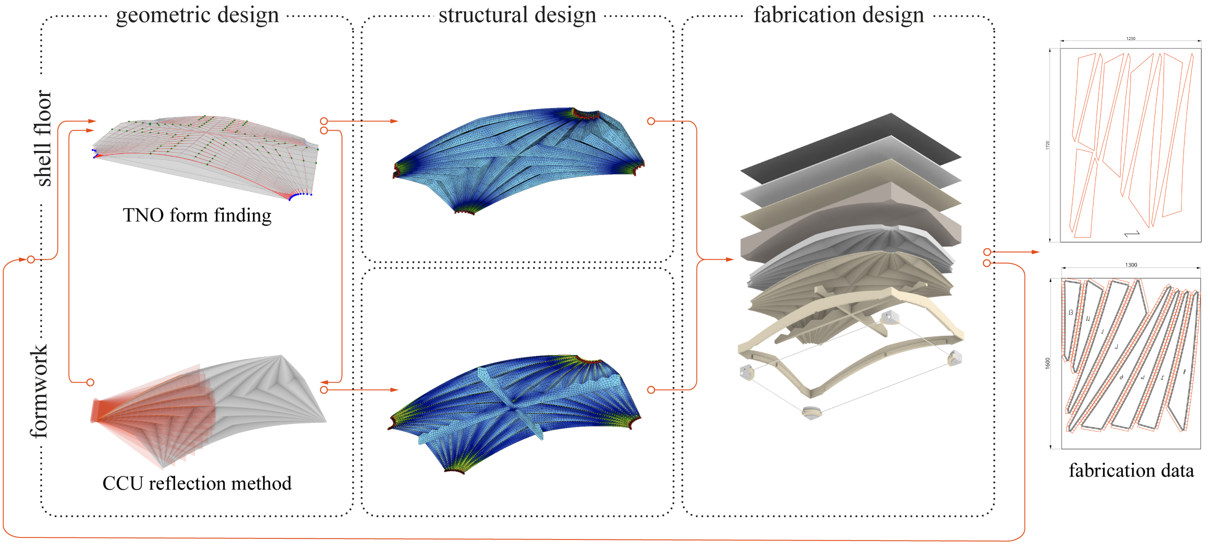

Fig. 5: Simplified integrative co-design workflow of the "Unfold Form" construction system

4 Fabrication and construction

The fabrication data from the high-tech design process are transferred to the low-tech fabrication process. The fabrication process is highly informed by an extensive prototyping and material development phase with the primary challenge of flexible yet structural and sealed hinges for rapid deployment, as well as a generally robust formwork solution for reusability and in-situ application.

4.1 Prefabrication

The prefabrication of the CCU formwork quarters commences with the cutting of the textile strips and plywood plates into their simple 2D cutting patterns. This process can be adapted to the context, from high-tech tools such as CNC machines (Fig. 6a) to low-tech tools such as a combination of paper stencils and a jigsaw. The textile strips are sewn together using a regular sewing machine with an industrial thread (Fig. 6b). The timber plates are adhered to the tailored textile using standard double-sided tape (Fig. 6c). The textile perimeter flaps are wrapped around the plate's edges and fixed with staples, guaranteeing a low-cost and effective fastener.

Fig. 6: Prefabrication of the CCU formwork: (a) cutting of the plywood plates,
(b) sewing of the textile strips, and (c) assembly of the CCU system

This prefabrication results in the four compactly flat-packed, lightweight formwork elements weighing only 6 kg each. It is based on a time-effective, simple, low-tech, yet precise production. Likewise, the elements of the formwork frame require simple 2D processing of plywood only. The total kit of parts of the formwork (Fig. 7a) is so flat-packed and compact that it can be transported even on a Vespa (Fig. 9b).

4.2 On-site assembly

On site, the frame is rapidly assembled in a plug-and-play manner due to hinges and reversible bolted connections (Fig. 7b). The CCU formwork quarters are instantly deployed and reversibly connected to the side ledges and zigzag-shaped crown plates through the industrial velcro strip (Fig. 7c). The low-tech system results in a robust and walkable formwork onto which the shell can be directly cast without further steps (Fig. 8a). Its complex structural geometry achieves high geometric precision as evidenced by scanning measurements.

Due to safety regulations of the research environment at ETH Zurich, the in-situ construction scenario could only be simulated at a height of 70 cm. After casting, the floor was lifted onto the intended 2-metre-high columns.

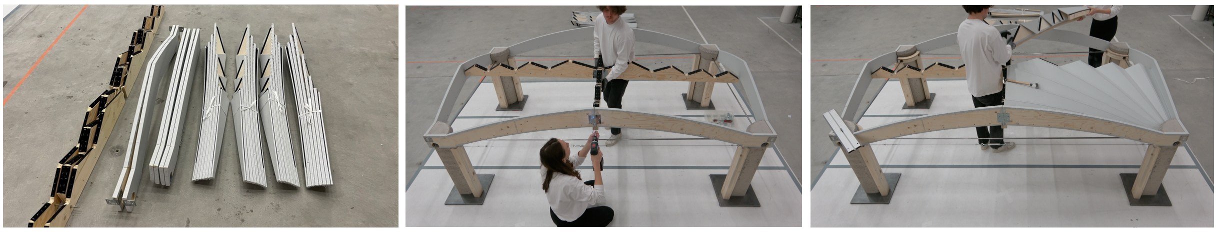

Fig. 7: On-site assembly of the formwork: (a) kit of parts, (b) formwork frame, and (c) deployment of the CCU quarters

4.3 Concrete casting

The single-sided mould with a vaulted extrados requires a concrete mix design with a non-fluid consistency such that it can be shaped by masonry trowels yet with sufficient workability for compacting and surface finish quality. This mix design was calibrated in experiments prior to concrete casting by tweaking the sensitive water-cement ratio. The use of renewable kenaf fibres improves consistency, shrinkage cracking, and flexural strength [14]. Even though the single-sided mould typology demands manual shaping of the extrados, the key advantages, compared to a system with counter-mould, are to circumvent the tremendous hydrostatic pressure and additional weight against the resulting uplift.

The concrete casting was carried out in two batches: a first layer to carefully compact the ribs with vibrating needles (Fig. 8b), and a second layer for the continuous shell. The extrados was compacted and formed with vibrating trowels following custom-made timber guides to control the shell's thickness (Fig. 8c). The casting process took approximately two hours, a time frame that could be significantly optimised in the future.

Fig. 8: Concrete casting: (a) underside of formwork, (b) filling of the triangular-shaped ribs, and (c) manual shaping of the shell's extrados with masonry trowels

4.4 Decentring and reuse

After three days of curing, the concrete shell can be decentred already, a time-efficient optimisation over conventional reinforced concrete slabs. This is due to the low compressive stresses of the funicular geometry and the absence of bond requirements with reinforcement. The "Unfold Form" system is designed such that decentring is highly intuitive and rapid and with reversible connections only to guarantee many cycles of reuse. After removal of the formwork frame by releasing the velcro connections, the CCU quarters can be easily removed from the concrete surface (Fig. 9a) thanks to their flexibility and PVC coating, making release agents obsolete. The elements can be rapidly refolded into their compact state and reused after a quick cleaning. The floor system was cast three times already without any noticeable wear, demonstrating the reusability of the formwork system. Many more cycles of reuse are anticipated.

Fig. 9: (a) Decentring of the CCU quarters, and (b) transport of the formwork on a Vespa for reuse

4.5 Final floor system of fan-vaulted shell

After further concrete curing, the floor system is completed with the build-up described in Section 2 and shown in Figure 4. This process followed conventional state-of-the-art practices for flooring systems.

The floor system drew inspiration from Gothic structural principles. Its ceiling, the exposed intrados of the shell, shows a highly intriguing architectural expression with its crisp corrugations, particularly when subject to light (Fig. 10). Its fan-vaulted ribs accentuate the vaulted sense of space while providing the structural height for stiffening against asymmetric loads. This expressive, elegant form is not despite but because of the constraints of structural efficiency and fabrication economy.

Fig. 10: Final "Unfold Form" floor system

5 Conclusion and outlook

This research presents a construction system for an innovative floor to address the urgent challenges faced by the construction industry of reducing carbon emissions while meeting the large demand for new floor area. The system's core innovation lies in the use of curved-crease unfolding (CCU) of bending-active plates as a reusable formwork for the in-situ construction of unreinforced fan-vaulted concrete shells. The curved creases provide shape control beyond the bending-active Elastica into the funicular shape while the corrugations provide stiffening and translate into concrete rib articulations that enhance material efficiency.

The successful realisation of a building-scale demonstrator showcases the viability of the "Unfold Form" system. Key advantages of the novel formwork system include its simple, low-cost, low-tech, and gender-equal prefabrication – gender-equal as many prefabrication tasks were executed by a pregnant woman, ultimately fostering a more inclusive construction industry; its extremely light weight of 24 kg and flat-packed state to be transported even on a Vespa; its instant deployability on site with high geometric precision; its material-efficient, self-supporting, robust, walkable, and geometrically-complex structure; and its reusability after only a few days. The resulting unreinforced shell gains its stiffness from its funicular and ribbed geometry drawing inspiration from gothic masterpieces. Compared to a conventional slab, it significantly reduces concrete mass and eliminates the need for reinforcement, except the minimal tension ties, which saves cost, embodied carbon, and rebar placement, as well as facilitates the separation of parts at its end of life.

The architectural outlook of the "Unfold Form" floor system is its application in multiple bays, for example, in housing units, arcades, or collonaded warehouses as done by Nervi. Since the CCU system is geometrically versatile, other proportions of spans are feasible. Furthermore, its design freedom also allows other typologies, such as corrugated funnel columns or barrel vaults [5], [9]. The scalability of the formwork and shell system is to be investigated through structural simulations [11] and prototyping. Furthermore, studies could focus on the beneficial effect of the corrugated vaulted ribs on room acoustics.

The outlook for the materialisation of the formwork ranges from using more natural textiles, such as hemp, to GFRP or steel, depending on the sustainability goal, anticipated reuse cycles, technological context, and scale. For the fan-vaulted shell, conventional concrete could be replaced with concrete with a non-cement binder or other liquid-to-solid materials with low strength and embodied carbon to enhance sustainability further.

The outlook on the application of the "Unfold Form" system ranges from high-tech contexts, benefitting from its aesthetics and efficiency, to predominantly less economically developed countries, benefiting from its independence from high-tech means. This is because the expressive shape, the efficient structural form, and the simple fabrication of the system are solely based on geometric principles. These geometric principles are designed with a computational co-design workflow and translated into low-tech construction. By employing structural geometry for both formwork and shell, as opposed to wasteful moulds and structurally inefficient slabs, the system aims to contribute to mitigating the environmental impact of the construction industry.

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