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A path towards off-site automated fabrication of segmented concrete shells as building floors

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Abstract

Concrete shells are a more sustainable alternative than plates as building floors, thanks to their effective use of concrete in compression. Although the construction of these geometrically complex structures becomes more challenging, off-site automated fabrication offers solutions to efficiently produce a shell in segments before assembling it on site. The segmentation of the shell provides the opportunity for deconstruction, reuse and reconfiguration for a circular economy of construction. This paper presents a path towards the realisation of this vision, highlighting the dialogue between the structural objectives and the construction technologies, informing the development of the structural system and its production. Actuated reconfigurable moulds, robotic concrete spraying and robotic filament winding are explored to automate the prefabrication of segmented concrete shells. The production systems and some prototype samples are shown to present the current state of development.

Keywords: concrete shells, sustainability, circular construction, automated construction, digital fabrication, robotics, digital concrete, reconfigurable mould, robotic concrete spraying, robotic filament winding.

1. Introduction

This paper presents the on-going investigation of the Automating Concrete Construction (ACORN) research project, whose primary goal is to drive the acceptance of a new culture in the construction industry to enhance sector-wide sustainability, following the UK Construction 2025 objectives, to use enough material and no more.

1.1. Sustainable concrete structures

The construction industry accounts for nearly 50% of the UK's carbon emissions [1]. Cement production itself causes around 7% of the global greenhouse emissions [2], though this impact is due to the popularity of concrete as a construction material and its extensive use. Indeed, concrete has a low embodied carbon density compared to other construction materials: 0.2 kgCO_2e/kg for unreinforced precast concrete versus 2.5 kgCO_2e/kg for steel, and even 0.2-0.5 kgCO_2e/kg for timber products (excluding carbon sequestration) in the UK [3].
However, structural designers need to use concrete more effectively by favouring a compressive behaviour, as opposed to a bending behaviour. Slabs represent around 60% of the structural mass in a building, therefore, designing thin shells instead of thick flat plates offers a promise for high carbon savings [4] [5]. Under the variety of load cases a slab experiences, a shell may

work *mainly* in compression, instead of *purely* in compression, and require a light amount of reinforcement. Indeed, reinforcement usually accounts for two thirds of the carbon contribution of reinforced-concrete flat slabs [5], due to the bending behaviour of plates and the high standardisation of their reinforcement.

Concrete has an irreducible carbon content due to the chemical reaction of Portland cement unless industry-scale substitutes are found. Concrete structures must be designed for deconstruction and reuse, in a cradle-to-cradle instead of a cradle-to-grave approach, to achieve a zero-carbon industry thanks to circular construction. To do so, monolithic concrete structures resulting from in-situ casting or grouting pose a serious challenge as an economically and sustainably viable model.

1.2. Off-site automated construction

A shell is more complex to build than a prismatic plate, which can be formed from timber or steel panels. A pitfall to avoid in the design and construction of shells is to reduce the embodied carbon from raw material supply but to ruin it with an increase in the embodied carbon from fabrication.

Providing a formwork that follows these doubly curved shapes requires precision and customisation. Off-site automated construction, benefiting from affordable robotics and reusable and reconfigurable systems, provides the opportunity for mass-customisation with reduced carbon and waste. For instance, the leading technology in the field of digital concrete fabrication, 3D printing, has a positive impact when building complex shapes, despite some remaining challenges to become a widely adopted solution [6] [7]. Other automation technologies appear promising for the digital fabrication of concrete shells, namely actuated moulds and robotic shotcrete.

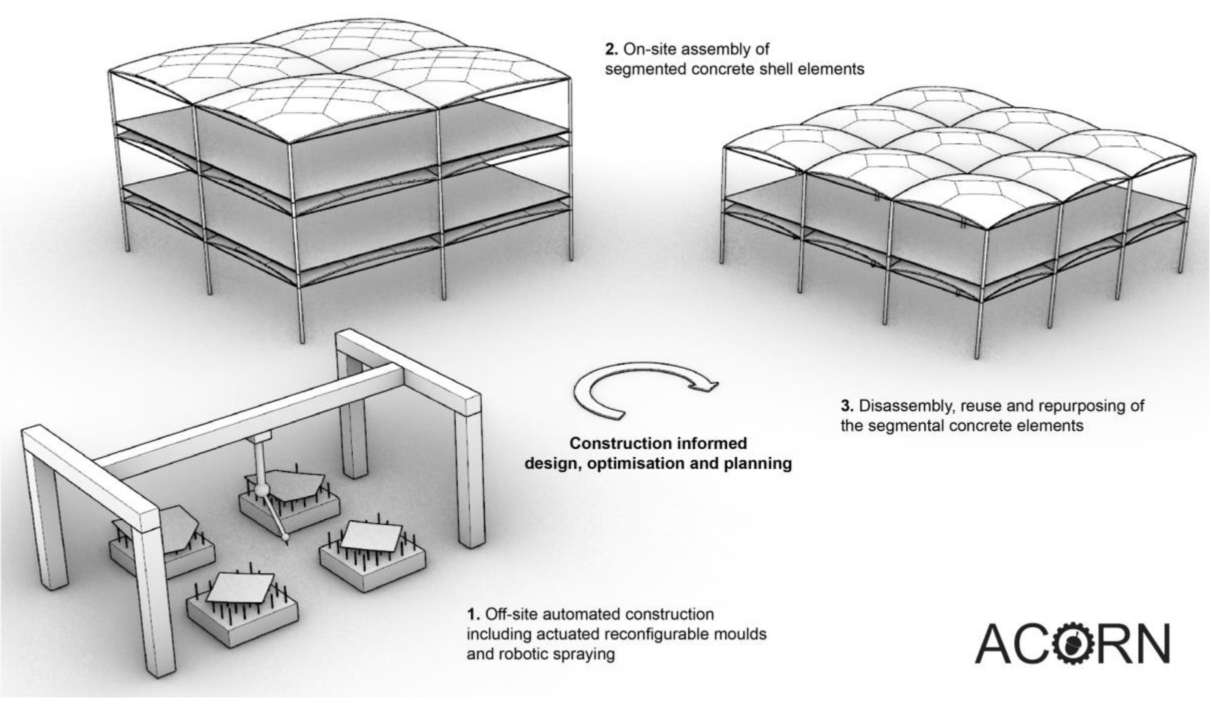

Figure 1: The approach of ACORN: off-site automated fabrication and on-site assembly of segmented concrete structures. The segments can be disassembled and reassembled at the end-of-life of the building. These construction aspects inform the design of the structure with data supporting construction planning.

1.3. Outline

This paper presents the approach of the ACORN project to build shells as building floors, illustrated in Figure 1 with off-site automated construction and on-site assembly, deconstruction and reassembly, supported by computational design and planning. Section 2 presents the proposed structural system of segmented concrete shells, informed by the sustainability and construction objectives. Section 3 details the fabrication strategy, including reconfigurable moulds as formwork, robotic concrete spraying for casting and robotic filament winding for reinforcement. Section 4 provides an insight into the state of development of the project, showing the production systems and some prototype samples.

2. Structural system

This section presents the proposed structural system of a segmented concrete shell structure to replace plates as building floors, informed by fabrication, transport and assembly constraints.

2.1. Shell structures as building slabs

Plates rely on bending to carry loads, which requires thickness and reinforcement due to the tensile forces. Shells rely on both a membrane behaviour and a bending behaviour, thanks to their curvature and their supports admitting horizontal reaction, through external thrust or internal ties. Through careful form finding, the shell can follow a funicular shape, which guarantees a compression-only behaviour for a specific load case, like the permanent loads, according to the lower-bound theorem of plasticity theory. Parametric exploration provides a design space of such shapes to explore, informed by project requirements, see Figure 2.
However, the integration of various requirements, like having planar boundaries, induces deviation from the funicular shape. Moreover, as slabs experience a wide range of live loads, including asymmetrical surface loads and point loads, a shell may perform only *predominantly* in compression. Figure 2 highlights the first principal direction with the positive tensile stresses in blue and the negative compressive stresses in red on the external layers of the shell. The capacity of shells to provide this variety of load paths must be supported by a plastic behaviour. To change from concrete's brittle behaviour to a ductile behaviour, short fibres are included in the concrete mix (see Section 3.3). To carry higher tensile loads and enable a local bending capacity, optimised tensile reinforcement is added to the mould (see Section 3.4).

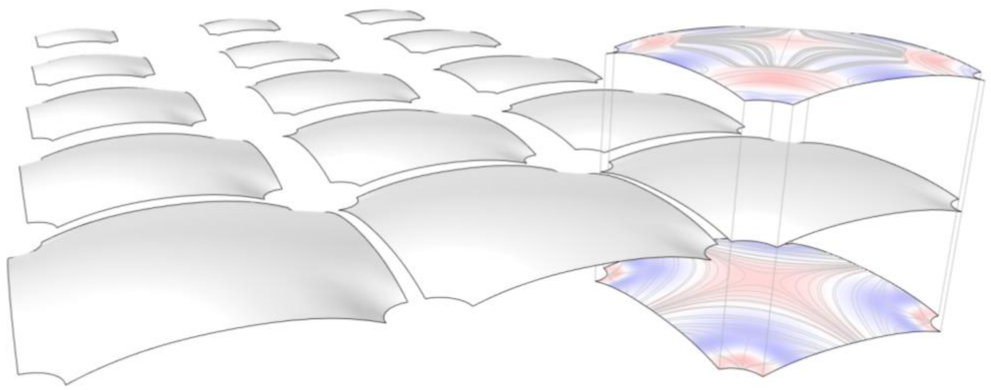

Figure 2: Shell design derived from parametric funicular form finding to provide a compression-*only* behaviour for the primary load case before the integration of project requirements, and structural analysis to check the compression-*dominant* behaviour for the secondary load cases. The coloured map shows the first principal direction on the external layers of the shell, with the positive tension in blue and the negative compression in red.

2.2. Structure segmentation for fabrication and transport

To build these structures off-site (detailed in Section 3), logistic constraints forbid to design the shell as a monolithic structure, as would be cast on site. Therefore, the shell must be segmented for off-site fabrication before transportation and on-site assembly, as in Figure 3a for a 9-segment shell. The main constraint is transport, with the inner dimensions of a classic lorry being around 12 m x 4 m x 2 m, pushing towards segmentation of the shell into strips. However, another important constraint is the size of the mould. The larger the mould, the more efficient the production, the simpler the assembly on-site and the better the structural integrity of the shell, though the higher the investment in the mould and the harder the nesting of the segments in the lorry. Moreover, as the interfaces are the weakest parts of the structure, the segmentation is informed by the force flow to have the forces as orthogonal as possible to the interface, as for a stone vault, to prevent sliding failure.

A segmented shell requires more care in its fabrication to guarantee both precision and tolerance for on-site assembly, particularly at the interfaces. The interfaces are planar, to simplify fabrication and assembly, and the orientation is vertical, because following the surface's normal would generally create warped elements. Boundary keys provide geometrical guides for partial interlocking during assembly, shown in Figure 3b. These keys follow a specific assembly kinematic, based on the local slope between adjacent segments. The lower segments, starting from the supports, are assembled first and then the other segments are added, from the lowest to the highest ones, with their convex part fitting in the concave part of the lower adjacent segments. The keys favour a compression contact and prevent sliding failure at these interfaces in the critical direction. In Figure 3, the boundaries are lower than the central part and are therefore assembled first. Temporary props are needed to provide structural equilibrium.

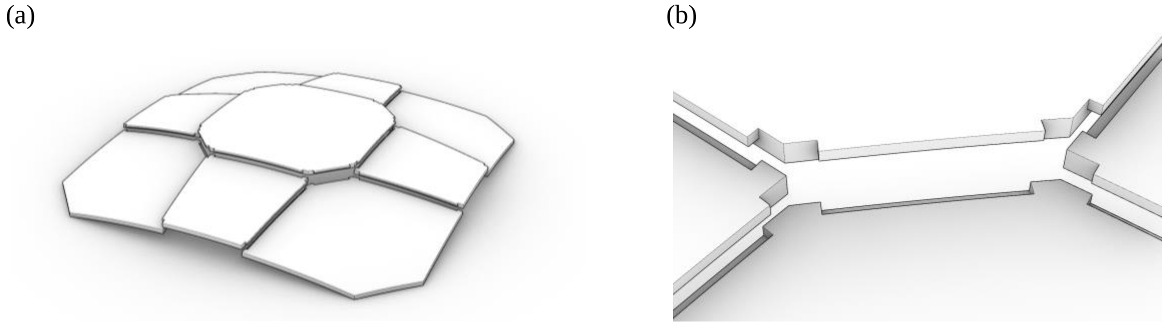

Figure 3: A shell segmentation informed by the force flow, the maximum dimensions of the mould and other construction requirements. (a) The assembly sequence following the increasing height with adjacent segments aligning thanks to (b) geometrical keys that act as assembly guides and prevent from sliding failure in the critical direction.

2.3. Deconstruction, reassembly and repurposing

The segmentation of shell structures presents an opportunity for deconstruction and reassembly, instead of demolition, by keeping the connection between the segments simple and reversible. Simple interfaces holding via compression are ideal. With grouting excluded and bolts used only where absolutely necessary, disassembly requires only re-propping of the segments. However, a compression-only interface changes the structural behaviour and must be accounted for during structural analysis.

The shell segments can be disassembled and reassembled for reuse in another building if their structural integrity is preserved. Strategies for repurposing the segments to projects with different requirements, in terms of load or span for instance, would allow upcycling of these components, via strengthening or reconfiguration, as illustrated in Figure 4.

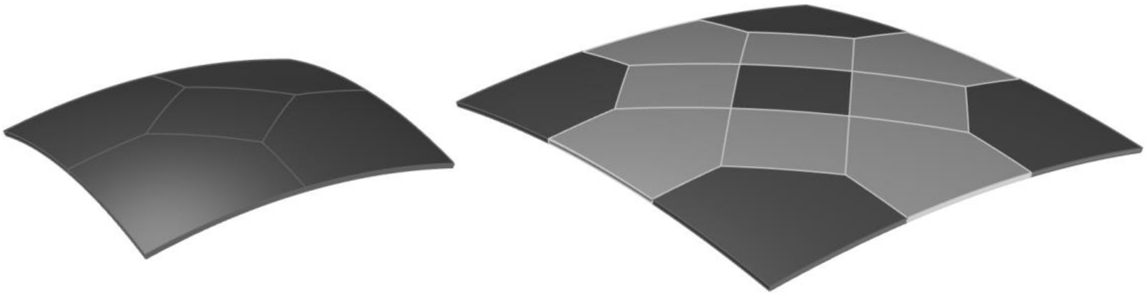

Figure 4: Reusing shell segments in different configurations to upcycle the structure into a new building. The five segments in dark grey are reused and combined with eight other segments in light grey to increase the span, thanks to resilience in the design.

These environmental, structural and construction objectives are informed by and inform the development of the fabrication strategies to enable the design [8] and production of this structural system.

3. Fabrication strategy

This section develops the strategy for the production of the segmented shell, prefabricated off-site, relying on digital fabrication technology, with a reconfigurable mould system, robotic concrete spraying and robotic filament winding of reinforcement.

3.2. Actuated, reconfigurable mould as formwork

The principal fabrication consideration to build a concrete shell is the formwork, as formwork materials can account for around 75% of the cost of doubly-curved structures [9]. Several strategies exist to form a shell on-site, such as timber, membrane or foam formwork, among others, but they are generally designed for a specific shape and for a single use. Reconfigurable moulds, that consist of a set of vertical pins whose heights are adjusted to support a flexible formwork to cast a material, are common for composite structures. The Kuwait Airport shows an application of such reconfigurable moulds by ADAPA, controlled by actuators to form the concrete panels bracing a steel frame [10], suitable for off-site fabrication of concrete segments. Our formwork system is modular, based on four 1 m x 1 m units that can be assembled to create a 2 m x 2 m or a 1 m x 4 m mould. The actuated pins form an array that supports a flexible formwork consisting of flexible strips in a four-way (orthogonal and diagonal) grid. These strips can slide across the pins, allowing reconfiguration and limiting the transversal loads on the actuators. The dimensions of the strips result from a trade-off between flexibility, to bend following the curvature of the shell, and stiffness, to support the fresh concrete. The behaviour of the flexible formwork is modelled using large-deformation structural analysis to find the best fit to the target shape.

The accuracy at the segment interfaces for assembly is provided by a rigid timber polygonal frame. The planar sides are cut from a timber board and are easy to assemble, disassemble and reuse. The boundary keys are formed using additional timber elements to create the concave and convex parts. A membrane is stretched below the frame and supported by the rods to complete the flexible formwork system.

3.3. Robotic concrete spraying for casting

Pouring concrete onto the curved mould would result in the concrete sliding down the slope, if the workability of the concrete mix is too high or if the concrete is vibrated, and requires extensive and careful manual work to achieve the variable target thickness. Spraying, on the other hand, directly sticks and compacts the concrete on the curved surface without the need for vibration, while also controlling the slurry output. Short fibres are included in the mix to provide a ductile behaviour for a plastic redistribution of the loads. To increase the quality of the spray process and of the shell, by controlling the spray distance and the spray orientation, a robotic arm drives the spray gun over the large surface [11] [12], see Figure 5.

Unlike in tunnelling applications, concrete loss due to rebound is limited in the context of a factory using a robotic process and downward spraying. To control the thickness across the curved formwork, the robotic trajectory is based on the ortho-geodesic curves of the surface, with a constant distance between the curves [11], highlighted by the constant overlaps between the spray circles in Figure 5. The variable thickness distribution dictates the number of passes. The shell segment is sprayed in a convex position, upside-down relative to its final position. This momentary inversion reduces the movement needed from the robot and solves reach problems (Figure 6a). The hydrostatic pressure of the concrete on the boundary frame is also reduced, allowing it to be thinner with a controlled deflection. The membrane deflects downward under the loading, following a funicular shape. Although this funicular shape during casting is not the mirror of the final shell once assembled, the local sagging between the rods better fits the shape of the element in a convex position than in a concave position (Figure 6b).

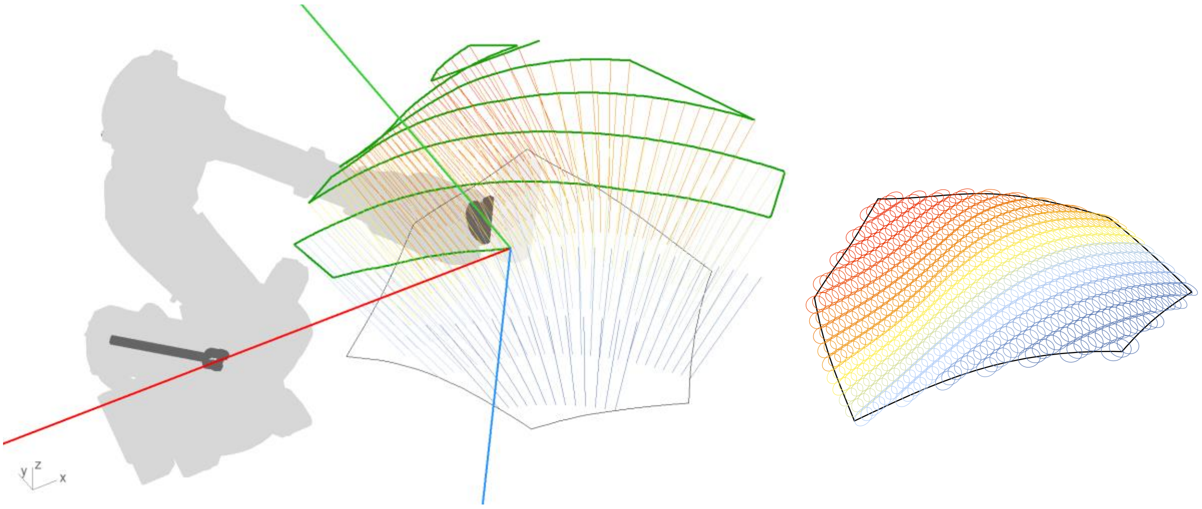

Figure 5: Robotic spray path based on ortho-geodesic curves, which provide a constant spacing between adjacent passes, highlighted by the constant overlaps between the spray circles. The colour gradient illustrates the spray progression.

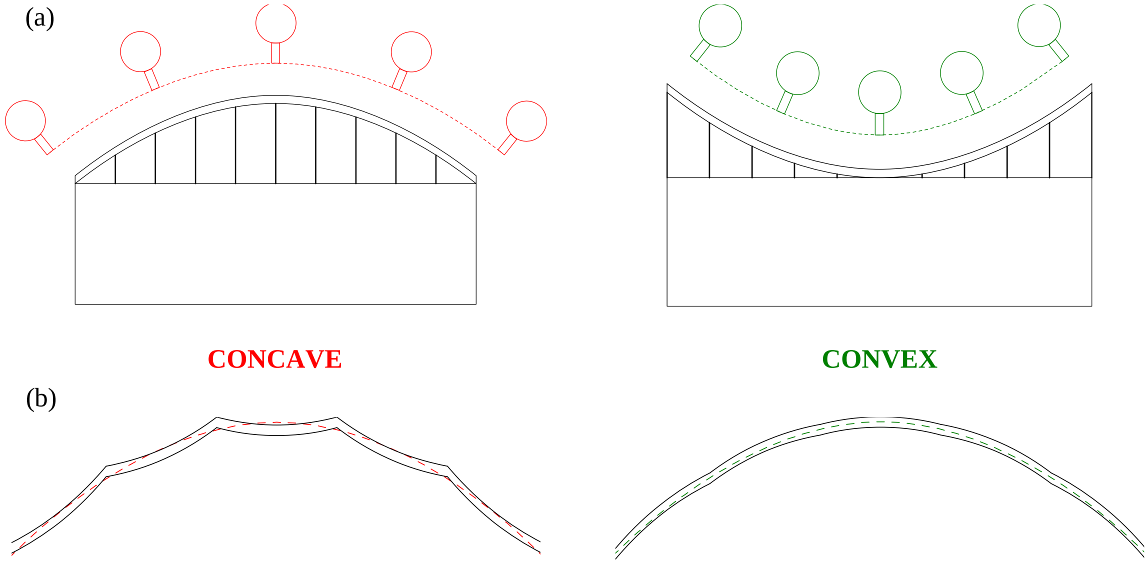

Figure 6: The shell segments are cast in a convex position instead of their final concave positions. The benefits include (a) smaller movements of the robotic arm to spray the segment on the reconfigurable mould and (b) a better fit to the target geometry despite the deflection of the flexible formwork, to embed a thrust line, shown as a dashed curve, within the shell's thickness to obtain a compression behaviour.

3.4. Robotic filament winding for reinforcement

Although a well-designed shell works mainly in compression, the variety of load cases experienced by a shell and the potential deviation from a funicular shape require tensile reinforcement. For a shell as in Figure 2, spanning a square on-plan and supported at the four corners, the transverse directions to the main compressive forces along the boundaries and the diagonals may require local reinforcement. The reinforcement of concrete structures classically accounts for about two thirds of the carbon cost of its cement content [5]. The bending behaviour is the main reason, but the high rationalisation of stiff steel rebar mats and cages assembled manually is an impediment to leverage optimisation of reinforcement layouts. Robotic filament winding is popular in the automotive and aerospace industry, where weight is critical, to produce complex composite shapes [13]. Composites are common in the construction industry for concrete repair, and robotic filament winding is finding applications for fibre shells [15] or beam reinforcement [16]. Previous digital work by ACORN applies layout optimisation [17] to robotic filament winding of reinforcement of concrete structures using strut-and-tie modelling [18]. Figure 7 shows this digital workflow, including layout optimisation of the ground structure of the strut-and-tie model, and materialisation and path planning of the robotic trajectory for continuous filament winding. The reinforcement layout is produced before concreting. The composite filament is coated with resin as it is wound around nodes attached to a grid of vertical pins. Once the resin has set, the layout is slid off the pins and added to the casting formwork. To form a curved reinforcement layout, the nodes are clamped at different heights on their respective pins.

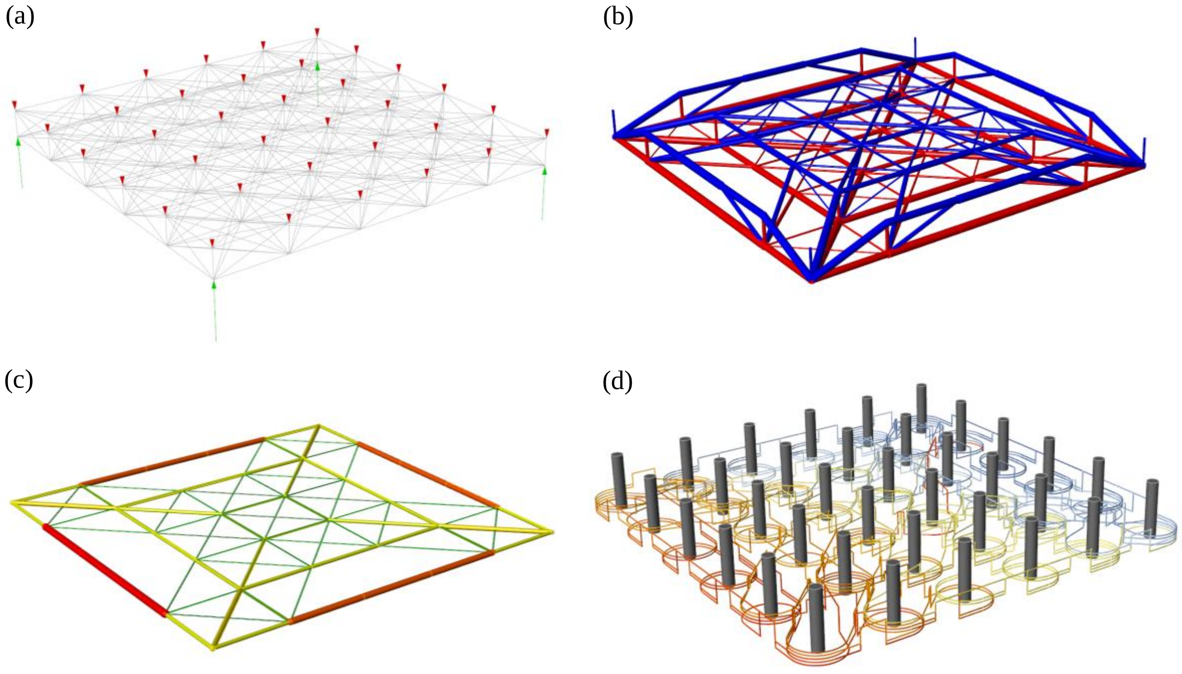

Figure 7: Digital workflow for the design, optimisation and materialisation of a robotically-wound optimised reinforcement layout. (a) Ground structure with loads in red and supports in green. (b) Optimised strut-and-tie model with compression in blue and tension in red. (c) Eulerian multigraph of filament passes per tensile strut of the bottom layer. The Eulerian property guarantees the existence of a continuous path visiting each edge of the multigraph. The colour gradient displays the number of passes per edge, i.e. the number of duplicates edges. (d) Robotic winding trajectory around the vertical pins avoiding collisions between the different elements. The colour gradient displays the winding progression.

3.5. State of development

At the time of writing, the production systems were delivered, and several prototype samples had been produced, as shown in Figure 8. The reconfigurable mould on Figure 8a was built by the workshop of the Department of Engineering at the University of Cambridge and consists of a 3 x 3 grid of pins spaced by 33 cm and with a maximum travel height of 40 cm. The pins support a compact network of strips sliding through the connecting nodes to allow reconfiguration. Figure 8b shows the connection between the PS9000i GRC spray station by Power-Sprays and the ABB IRB 6400R robotic arm, with a 2.8 m reach and a 200 kg payload, for robotic concrete spraying.

The 0.4 m² hexagonal frame made of timber elements shown in Figure 8c integrates the boundary keys and is designed for simple assembly and reuse. The prototype concrete segments in Figure 8d were manually cast upside-down on the reconfigurable mould and combined to form part of a full shell.

The 3D-printed node prototypes on Figure 8e slide on the pins and are maintained by clamps before receiving the filament in their channel during winding, and slid off after the resin has cured. The 65 cm x 65 cm CFRP filament reinforcement on Figure 8f, based on layout optimisation, was robotically wound around a 6 x 6 grid of vertical pins.

Future prototypes will combine the different technologies to produce a shell composed of reinforced segments sprayed on the reconfigurable mould.

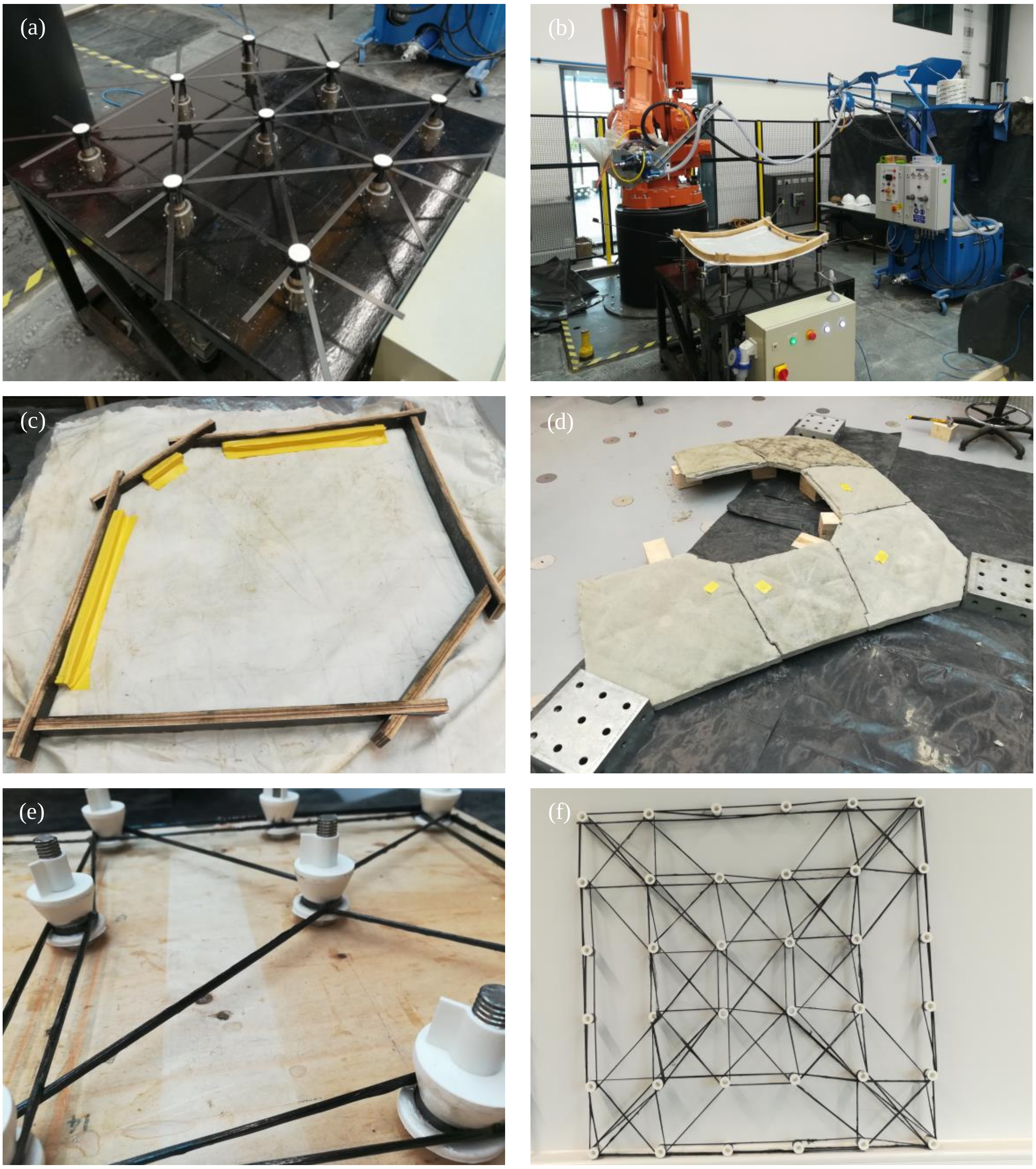

Figure 8: State of development with (a) the first module of the reconfigurable mould, (b) the robotic arm and spray station for robotic concrete spraying, (c) a reusable timber frame connected by slots and integrating boundary keys, (d) shell segments cast on the reconfigurable mould and combining into part of a shell, (e) a node detail for filament winding around a grid of pins, and (f) an optimised, robotically wound reinforcement layout.

4. Conclusion

Concrete shells as building floors offer a high potential for reducing the environmental impact of the construction industry. However, the savings in embodied carbon of the structural material should not be lost in the formwork material and labour. This paper has presented a framework for the off-site fabrication of concrete shells using automation and robotics, thanks to well-established digital fabrication technology, reconfigurable moulds, robotic concrete spraying and filament winding. The shell is prefabricated in segments to allow transportation and assembly on-site. The connections allow for deconstruction and reassembly, opposed to destruction, so that they can be reused at the end of the building's life. Different samples and prototypes have presented the current state of the project. Later, this framework will be applied on a full-scale demonstrator to validate the approach.

Acknowledgements

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