KNITCANDELA
CHALLENGING THE CONSTRUCTION, LOGISTICS, WASTE AND ECONOMY OF CONCRETE-SHELL FORMWORKS

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This paper describes the design, development, computational workflow, digital fabrication and construction of KnitCandela, a thin, undulating, concrete waffle shell built using a flexible formwork system featuring a custom, prefabricated knitted textile as shuttering and a form-found cable net as the main load-bearing formwork. The shell was developed by the Block Research Group at the Institute for Technology in Architecture of ETH Zurich in collaboration with the Computational Design Group of Zaha Hadid Architects (ZHCODE) as part of the first exhibition of Zaha Hadid Architects in Latin America. It was exhibited at the Museo Universitario Arte Contemporáneo (MUAC) in Mexico City between October 2018 and July 2019.

Designed as an homage to the Spanish-Mexican shell builder Félix Candela (1910-1997), the curved geometry of the shell is reminiscent of Candela's iconic restaurant in Xochimilco, while its fluid form and colourful interior surface are inspired by the traditional Jalisco dress. Candela relied on hyperbolic paraboloids to efficiently build curved concrete shells with reusable straight formwork elements. The design of KnitCandela breaks free of the constraints of ruled or developable surfaces. Instead, it demonstrates that complex concrete structures can be built at low economic and environmental cost through the strategic use of computational design and fabrication, combined with craftsmanship.

The five-tonne concrete shell (Fig. 1), with a surface area of 50m², was cast on a flexible cable-net and knitted fabric formwork, weighing just 55kg. Following a digitally-generated knitting pattern, the fully shaped, double-layered 3D-knitted shuttering of the formwork was produced in just 36 hours on a commonly available CNC knitting machine. Due to its lightness, it was easy and compact to transport to site. The load-bearing cable-net and knitted formwork was tensioned in a temporary timber/steel frame and coated with a special stiffening cement paste, developed at the Chair of Physical Chemistry of Building Materials at ETH Zurich. Fibre-reinforced concrete was manually applied to the formwork to realise a 3cm-thick shell with a quadrilateral grid of stiffening ribs with a height of 4cm.

Flexible Forming of Concrete

Doubly-curved, rib-stiffened shells offer an efficient load-bearing capacity but have complex geometry. As a result, their non-standard shapes can be challenging,

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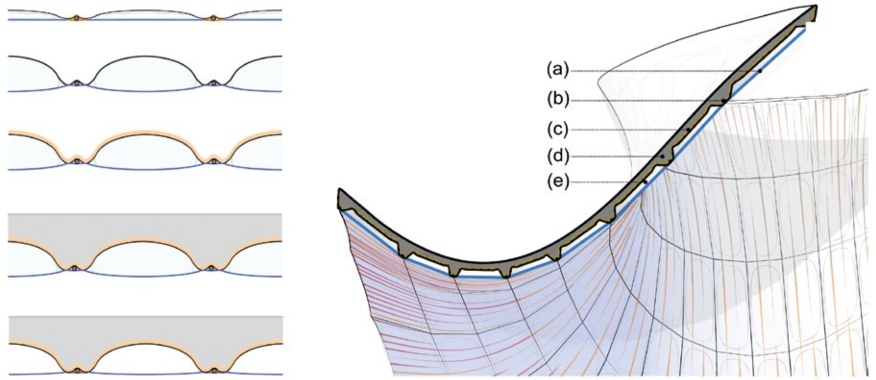

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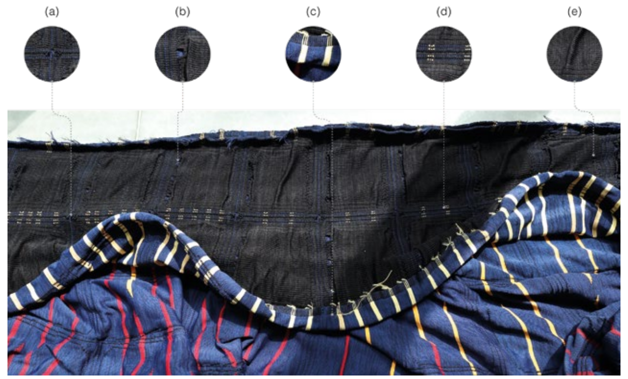

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expensive, wasteful and time-consuming to build with traditional formwork methods that rely on single-use cut timber or milled foam. These custom-fabricated formwork constructions account for approximately half to as much as two-thirds of a structure's cost (Garćia de Soto et al., 2018) and take a lot of time to manufacture, requiring months of carpentry or CNC milling (Søndergaard et al., 2018). Additionally, these rigid and often heavy moulds have to be held in place by scaffolding, needing foundations. As such, traditional approaches are not economically and ecologically viable for non-standard and doubly-curved structures.

Using a membrane or fabric can offer an alternative flexible forming system that needs minimal or no scaffolding (Veenendaal et al., 2011). As textiles are compact and light, they can be effortlessly transported to the construction site and have proven to be a waste-reducing solution to formworks for a wide range of building components (Hawkins et al., 2016). To achieve the desired geometry, textiles need to be tensioned into shape using rigs, frames or external supports (West, 2016). Tensioning may also be done using hybrid approaches where a cable net (Veenendal and Block, 2014; Méndez Echenagucia et al., 2019), bending-active elements (Lienhard and Knippers, 2015; Cuvilliers et al., 2017; Ramsgaard Thomsen et al., 2018) or inflatables (Ahlquist et al., 2017) form a self-supporting system with the textile. Fabric formwork systems generally use single-layered, woven fabrics with uniform texture and structural properties. To avoid wrinkles, their shaping and the integration of other features relies on the extensive tailoring and joining of different flat sheets of material.

In contrast to woven textiles, knitted materials can be tailored to non-developable and three-dimensional shapes, allowing for functional integration and the design of very specific properties without the need for gluing, welding or stitching. Therefore, using weft-knitted textiles as part of these flexible systems broadens the geometric possibilities and offers the opportunity for functional integration, which may result in simplified logistics on site.

Constraining the Design Space

The structure was designed as a 3cm-thick, anticlastic concrete shell with 4cm-high stiffening ribs in both directions, thus resulting in a doubly-curved waffle shell. The design of the structure's geometry was informed by the formwork system and resulting fabrication constraints. The formwork system behind KnitCandela was made up of a timber and steel tensioning frame, a load-bearing steel cable-net falsework, and a custom 3D-knitted textile shuttering.

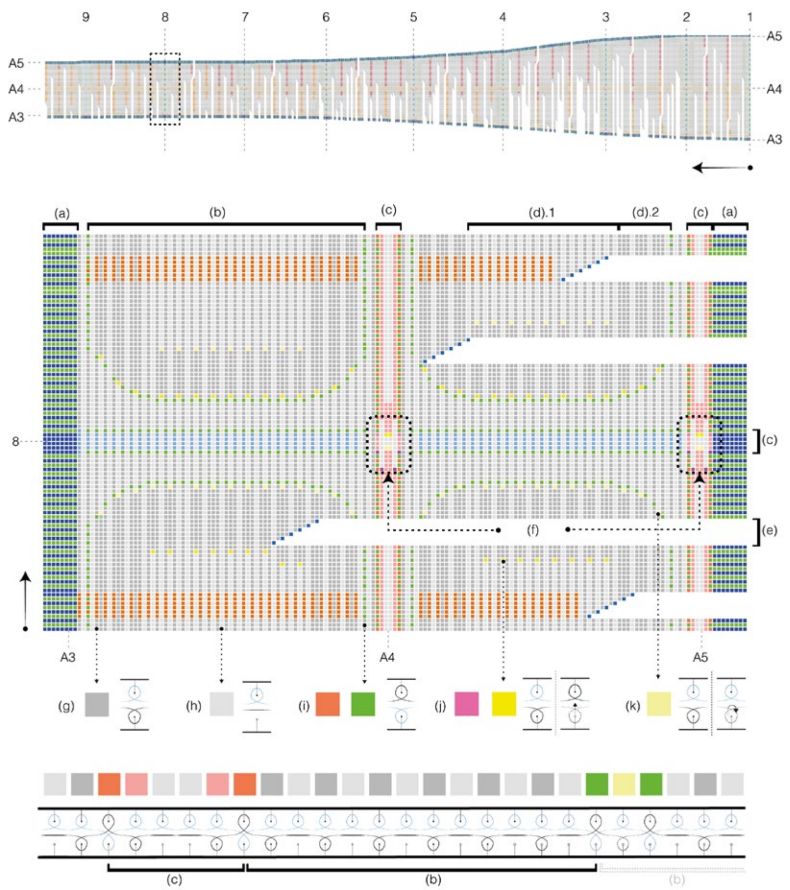
The system sought to investigate construction opportunities in terms of material and weight saving, streamlining logistics on- and off-site and exploring new aesthetic opportunities offered by using knitting. To demonstrate the integration and shaping possibilities of spatial knitting at an architectural scale, the knitted shuttering was designed to have channels and openings providing guidance and alignment for the load-bearing cable net; additionally, pockets were included to shape voids in the finished concrete structure to achieve material and weight savings. These cavities were obtained by inflating modelling balloons in the pockets. The construction steps and resulting waffle shell are shown in figure 2.

The densities of the knitted textile on both layers were carefully tailored to control to which side of the formwork the pocket would inflate and into what precise shape. The edge details were created by inserting steel rods into the edge-boundary channels and held up by laser-cut wooden profiles. The double-sided textile used as shuttering presented a decorative and technical layer, including

1. KnitCandela is a concrete waffle shell built using a lightweight, stay-in-place, cable-net and knitted fabric formwork. Photo: Angélica Ibarra.

2. Steps for creating the KnitCandela's concrete waffle-shell section (from top to bottom): (a) tensioning the two-layered knitted textile, and cable net; (b) inflating of the pockets; (c) coating the knitted shuttering with a fast-setting cement-paste layer; (d) casting of the concrete waffle shell; and (e) deflating of the pockets to form the voids.

3. Double-layered knitted textile produced in one piece, featuring an aesthetic front face and a technical back face that includes for controlling the position of cables, inflatables and edge detailing: (a) openings for the cable-net nodes; (b) openings for inserting balloons; (c) textile border for joining pieces together; (d) channels for cables; and (e) variable loop densities and sizes.



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4. Generated knitting pattern for Strip 2 showing the features and functions needed to achieve them: (a) seam detail; (b) pocket; (c) vertical and horizontal channels; (d) varied loop densities; (e) short row; (f) openings in channels at their intersection; (g) knit front and back (yarn 1 and yarn 2); (h) float front and knit back (yarn 1 and yarn 2); (i) knit front and back (yarn 2 and yarn 1); (j) knit front and back, then transfer front to back; and (k) knit front and back, then drop front stitch.

features for inserting, guiding and controlling the position of cables and inflatables, and is shown in figure 3.

From a fabrication point of view, the textile was only limited by the needle-bed width (1.3m) of the knitting machine (Steiger Libra 3.130). Taking advantage of the knitting machine's ability to create infinitely long pieces, the geometry was split into four long strips (16m-26m in length), resulting in a total of four seams over the entire surface.

The cable-net and knitted shuttering formwork, defining the final shell, was form-found using a target geometry that was defined through a series of design iterations with the goal of balancing the aesthetic and structural targets of the project. To keep the detailing of the formwork clean and simple, the topology of the cable net was restrained to a quad pattern, with closed continuous ring cables in the 'horizontal' and boundary-to-boundary cables in the 'vertical' direction.

Computational Knitting

A digital workflow was established for the project, which aided the iterative design and engineering process, the generation of the informed geometry (based on the fabrication and formwork system constraints), and the production of all needed manufacturing instructions and data. The entire workflow was developed using the COMPAS framework, an open-source computational framework for research and collaboration in architecture, engineering, fabrication and construction (Van Mele et al., 2017).

For producing a knitted textile, a knitting pattern is needed to drive the CNC machine. *compas_knit* (Popescu, 2019), a digital pipeline developed to automatically generate knitting patterns from a given 3D geometry, was used to produce the textile shuttering of KnitCandela. The generated knitting patterns were informed by the knitting direction and a target loop width and height, which for this project were determined to be 3.5mm and 2mm, based on pre-stressing tests. Patterns were generated in patches matching the quadrilaterals formed between cables. This not only made for a computationally less intensive process, but also naturally aligned the patterns to the cable directions which made the fabrication of their channels simpler and cleaner. After all 2D patch patterns were generated for a given strip, they were combined into one single pattern and the locations of the cables and decorative colour lines were automatically mapped on the combined pattern and marked with a colour code. Then a BMP-format pixel image was exported with each colour representing a predefined function (knit, transfer, drop stitch etc.) for the machine to perform (Fig. 4). Finally, the BMP image was imported into the machine's proprietary software, Model 9, where each colour was assigned a symbol from a library developed for this project.

Enhancing Craftsmanship

The concrete shell was constructed on site over a period of four weeks. The elements needed for the construction were fabricated in Mexico and Switzerland. The textile shuttering was fabricated at ETH Zurich, vacuum-packed and transported to Mexico in two suitcases, as regular checked luggage. The timber and steel frame for tensioning was fabricated in Mexico City.

To assemble the formwork, the four strips of textile were sewn together into one wider strip, and the cables inserted in the corresponding channels of the textile. Turnbuckles were attached to the ends of the cables and all nodes were

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temporarily fixed in place with zip ties. This package was then attached to the frame and tensioned into shape by gradually tightening the turnbuckles around the outer perimeter.

Given the tight schedule of the project and fabrication limitations, the tensioning rig was custom-designed to be easily manufactured with traditional methods and effortlessly assembled into a self-contained frame. The planar timber arches, built only out of standardly available profiles, were tilted into position and then braced by in-situ welded tubular steel profiles. The waffle shell's weight-saving cavities were created by inserting and inflating standard modelling balloons into the pockets of the double-layered textile. Laser-cut plywood edge profiles were attached to the cables (Fig. 5), then the fabric was folded over and the boundary spline was fixed to the profiles, ensuring a clean edge detail and a reference for the concrete thickness. The entire textile was sprayed with a thin, fast-setting cement-paste coating (Fig. 6). The Calcium Aluminate Cement (CAC) coating was designed to harden within two hours in ambient conditions, stiffening the textile to minimise local deformations when concrete was applied (Reiter, 2019).

With the formwork surface realised, glass-fibre-reinforced concrete was applied in three layers. First, all ribs were filled in; then, a second layer built up the thickness of the shell (Fig. 7); and, finally, a third finishing layer was applied and hand rendered smooth (Fig. 8). Finally, once the concrete cured, the cables were released from the frame to let the shell stand unsupported. The frame was dismantled and removed, while the pockets were deflated, leaving the textile in place and visible on the intrados of the structure (Fig. 10).

Increasing Productivity

Prototyping, design, engineering, fabrication and construction was carried out by multiple teams in Europe and Mexico over a period of three and a half months. The timber and steel frame was fabricated and assembled by construction workers in two weeks. In the meantime, once designed and generated, the knitted textile took only 36 hours of machine time to produce, with each of the four strips being a two-layered, weft-knitted textile produced in one manufacturing process. Due to the low weight (25kg) and compactness, the textile could be easily transported to the worksite. Installing the formwork in the frame and casting concrete took a total of two weeks, of which one week was dedicated to assembling the textile shuttering and cable-net falsework and an additional three days were dedicated to preparing the formwork for coating (tensioning, inserting and inflating balloons, and attaching and fixing the edge details). The cement-paste coating was sprayed onto the textile in two sessions of four hours. Finally, three layers of fibre-reinforced concrete were applied over the course of three days.

The digitally designed and fabricated textile provided integrated features for inserting and guiding elements such as cables and inflatables that helped shape the sophisticated mould. This not only made it possible to shape a mould that would otherwise require extensive milling (more than 750 hours or 3 months for a similar surface area, according to Gardiner et al., 2016) but also significantly simplified on-site logistics. An example of this being the pockets of the textile which shape individual cavities of different shapes and sizes using the same standard element (balloon). In this case, the standard balloons produced varied solutions through the

5. Attaching the laser-cut edge profiles to the steel cables of the tensioned formwork. Photo: Maria Verhulst.

6. Spraying the cement-paste coating on to one side of the tensioned formwork. Photo: Mariana Popescu.

7. Hand rendering of the concrete of the waffle shell. Photo: Mariana Popescu.

8. Fibre-reinforced concrete manually applied in layers and rendered smooth. Photo: Mariana Popescu.

9. Tensioned cable-net and knitted textile formwork needing minimal scaffolding. Photo: Maria Verhulst.

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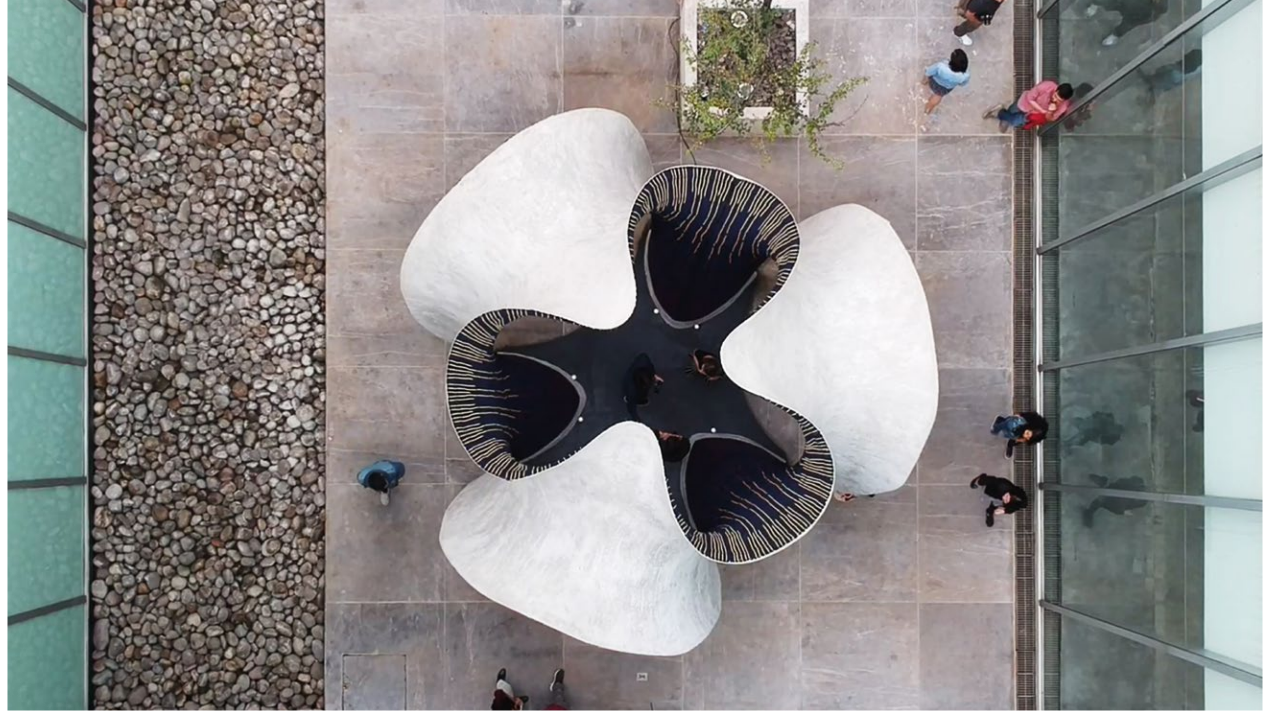

embedded properties of the textile. By including the construction intelligence within the custom textile, the need for extensive labelling could be avoided, placement errors reduced and the construction of the mould drastically sped up.

Realising a complex concrete structure in a short period of time was possible because of a streamlined design process complemented by a robust production pipeline such that the development could be pushed close to the start of construction. Moreover, on-site logistics was kept simple, drawing upon existing craftsmanship and bridging computational design, digital fabrication and crafts.

Relying on a computational approach using the open-source framework COMPAS, numerous structural and constructional iterations could be simulated digitally and physically prototyped thanks to the smooth connection to fabrication. This uncompromised digital chain allowed for an intense development cycle between multiple collaborating teams, resulting in the efficient structural design, engineering, digital fabrication, and construction of KnitCandela. The demonstrated design-to-production process presents an outlook towards a more integrated, research-driven architectural and engineering practice with increased productivity.

Discussion and Outlook

The KnitCandela prototype demonstrated that with an appropriate computational design and digital fabrication pipeline, knitted textiles can be easily produced. Furthermore, when combined with load-bearing elements, knitted textiles can be used to shape complex geometries at an architectural scale. Tensioning the cable-net and textile formwork in a timber frame removed the need for dense scaffolding to support heavy moulds from below (Fig. 9). Because of time and site constraints, the frame used for tensioning was custom-designed and fabricated for this project. However, a system relying on standard scaffolding elements could be developed, making the tensioning frame a reconfigurable and reusable part.

As a thoroughly efficient, ecologically conscious construction system, the stay-in-place mould for this complex structural geometry produced almost no waste. The minimal foundations and scaffolding required to realise KnitCandela's formwork give a glimpse of how the formwork for such expressive forms of significant size (50m²) can be designed, fabricated and realised with a minimal footprint, in a very short period of time (three and a half months) and at low cost (EUR 2,250, excluding labour and the external frame). The computationally designed, materially- and waste-efficient approach demonstrated in KnitCandela targets all those areas where project timelines and budgets often get out of control – transport and on-site logistics, manual labour (for the formwork fabrication and construction), installation costs, etc. – while also being an elegantly designed structure that embraces the aesthetic opportunities offered by the knitted textile. The system takes a step in confronting the challenges faced by the building industry today and offering practical, easily realisable solutions for a more sustainable way of building.

10. Top view of the KnitCandela pavilion showing its radial symmetry. Photo: Leo Bieling.

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