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. At the same time, however, they pose a new challenge to the field of computational design and fabrication. KnitCandela introduces a new approach to this challenge by using a flexible knitted fabric as shuttering material, which allows for a high degree of geometric freedom and the creation of complex shapes without the need for expensive and time-consuming traditional formwork elements. This approach not only reduces the cost and environmental impact of the construction process but also opens up new possibilities for the design and fabrication of concrete structures.
expensive, wasteful and time-consuming to build with traditional formwork systems that rely on single-use carpentry or CNC milling. Custom-crafted formwork accounts for approximately half to as much as two-thirds of a structure’s cost (Estrada et al., 2018) and takes a lot of time to manufacture, requiring months of carpentry or CNC milling (Søndergaard et al., 2018). Additionally, these rigid and heavy forms have to be held in place by scaffolding, needing substantial 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 (Veenendal et al., 2013). 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., 2010). To achieve the desired geometry, textiles need to be tensioned into shape using raps, frames or external supports (West, 2016). Tensioning may also be done using hybrid approaches where a cable net (Veenendal and Block, 2014; Méndez et al., 2017) form a self-supporting system with the textile. To demonstrate the integration and shaping possibilities of spatial knitting at an architectural scale, the knitted shuttering was fabricated at ETH Zurich, vacuum-packed and transported to Mexico in two suitcases, as regular mail is not possible for constructing formwork. From a fabrication point of view, the textile was only limited by the needle bed width (13.2 cm) of the knitting machine (Scotia Línea 3 120). Taking advantage of the knitting machine’s ability to create infinitely long pieces, the geometry was split into four long strips (18m-26m in length), resulting in a total of four seams for joining pieces together. Numerical knitting, pattern for strip 2 showing the back face and the technical back face that includes for controlling the position of cables: (a) seam detail; (b) pocket; (c) vertical and horizontal cables; (d) 3D geometry, was used to produce the textile shuttering and collaboration in architecture, engineering, fabrication and construction (Van Mele et al., 2017).

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 (Poppens, 2019), a digital pipeline developed to automatically generate knitting patterns from a given 3D geometry, was used to generate the knitting system KnitCandela. The generated knitting patterns were informed by the knitting direction and target length and width, which for this project were determined to be 3.5mm and 2mm, based on pre-testing tests. Patterns were generated in patches matching the quadrilaterals formed between cables. This not only made for a computationally less complex process, but also naturally aligned the patterns to the cable directions which made the fabrication of their channels simpler and cleaner. After all 42 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 5, 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. This facilitates the construction was fabricated in Mexico and Switzerland. The textile shuttering was created at EHT Zurich, vacuum-packed and transported to Mexico in two suitcases, as regular checked luggage. The timber and steel frame for the structure was manufactured in two sections and assembled on site with the concrete shuttering. The timber framework was attached to the ends of the cables and all nodes were
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 steps being a two-layered, well-knit textile produced in one manufacturing process. Due to its low weight (2.5 kg) 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
embodied properties of the textile. By including the construction intelligence within the custom textile, the need for extensive labelling could be avoided, allowing for greater adaptability and reusability of the constructional iterations could be simulated digitally and physically prototyped thanks to the smooth connection to a state of the art review’.


Zaharakis And Arches 2016. ‘ stiffness and ductility of knit structures’.

KnitCandela pavilion

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