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Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell

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ABSTRACT

This paper describes the structural design, digital fabrication and construction of KnitCandela, a free-form, concrete waffle shell with KnitCrete, a falsework-less formwork approach using a custom prefabricated knitted textile as multi-functional, structural shuttering layer and a form-found cable net as the main load-bearing formwork. 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.

With a total weight of only 55 kg, the 50 m^2 formwork was easy and compact to transport. On site, the formwork was tensioned into a timber and steel rig, the pockets were inflated, and then coated with a thin layer of custom-developed, fast-setting cement paste. This paste served as a first stiffening layer for the textile, minimising the formwork's deformations during further concrete application. Fibre-reinforced concrete was manually applied onto the formwork to realise a 3 cm-thick shell with 4 cm-deep rib stiffeners.

The novel approach, for the first time applied at architectural scale in this project, enables the building of bespoke, doubly-curved geometries in concrete, with a fast construction time and minimal waste, while also reducing the cost and labour of manufacturing complex parts.

1. Introduction

KnitCandela is a thin, undulating, 50 m^2 concrete waffle shell built at the Museo Universitario Arte Contemporáneo (MUAC) in Mexico City as part of the first exhibition of Zaha Hadid Architects in Latin America in the fall of 2018. The 5 tonnes concrete shell was built using a 55 kg, flexible cable-net and knitted-fabric formwork tensioned into a timber and steel scaffolding frame. The design was developed by the Block Research Group at ETH Zurich in collaboration with the Computational Design Group of Zaha Hadid Architects (ZHCODE). Designed as a homage to the Spanish-Mexican shell builder Félix Candela (1910–1997), the curved geometry of the shell is reminiscent of Candela's restaurant in Xochimilco, while the fluid forms and colourful interior were inspired by the traditional Jalisco dress. Candela relied on hyperbolic paraboloids (hypars) to build doubly-curved concrete shells, because they are doubly-ruled surfaces. Ruled surfaces are curved geometries that can be described entirely by rulers, i.e. lines. Candela used this property to rationalise the formwork of his shells where the straight rulers are thin wooden beams. While they may be relatively easy to build, the geometrical variety of these doubly-curved surfaces is limited (to ruled surfaces) and relies on extensive scaffolding.

Through the use of novel computational design methods and a KnitCrete formwork, both of which will be presented in this paper, the range of buildable anticlastic (i.e. with negative Gaussian curvature) geometries can be expanded. Unlike Candela's work, there is no longer the need to rely solely on hyperbolic paraboloids to efficiently build doubly-curved concrete shells. Fig. 1 shows the plan and elevation of the built shell, providing the overall dimensions of the pavilion. The geometry of the pavilion's formwork, defining the final shell, was form-found with a force-density approach [25] using a target geometry. The target geometry was defined through a series of design iterations with the goal of balancing the aesthetical and structural targets of the project. Both the target geometry and the final geometry were designed using a non-uniform distribution of force densities, making the geometry neither based on hypars, nor on minimal surfaces [26].

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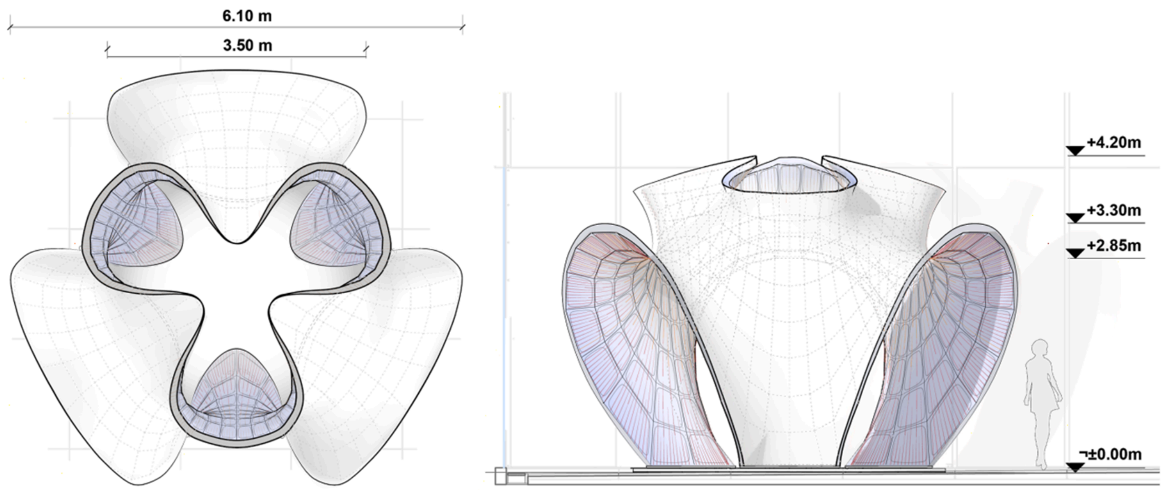

Fig. 1. Plan and elevation of the KnitCandela shell.

2. Background

With the building industry accounting for more than 35% of the global energy consumption and 40% of energy-related CO_2 emissions [2], lightweight construction is increasingly more important in the current climate context. This encourages the use of lighter materials and a reduction of the amount of material used for building structures, i.e. reducing the structural volume of a construction material [9]. The latter is especially important for concrete, which is the most widespread building material in global use [7,17].

Concrete's production relies heavily on the use of aggregates and freshwater, while the world's yearly cement production accounts for 6 to 8% of the global carbon-dioxide emissions [13]. According to Orr et al. [18], the embodied energy of a building is predicted to be the main energy consumption component by 2050. Therefore, it is not only important to reduce the amount of material used in terms of structural volume, but also the amount of material that is needed during construction.

For their stiffness, structures with less material can utilise their geometry and the placement of material where needed according to the natural flow of internal forces. Doubly-curved and rib-stiffened shells offer the possibility of increasing the load-bearing capabilities of a structure in a material efficient and economical way [3].

Though more materially efficient, their construction is challenging, especially as bespoke concrete elements built with traditional methods often use single-use timber or milled foam moulds. Formwork typically accounts for approximately 50% of the structure's cost; however, according to recent studies, the moulds used to cast custom, geometrically-

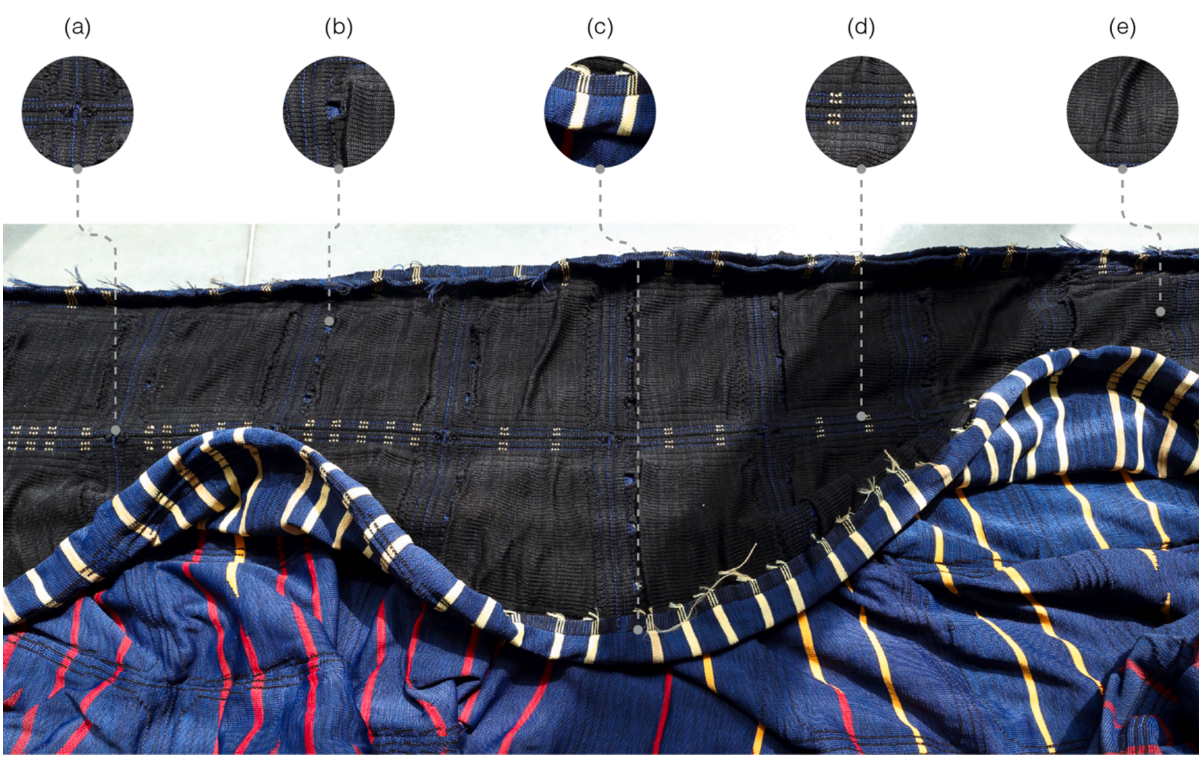

Fig. 2. Double-sided textile with included features: (a) openings for connecting the cables of the cable net; (b) openings for inserting balloons; (c) textile border for joining pieces together; (d) channels for cables; and (e) variable loop densities and sizes for controlled stretching (Photo: Maria Verhulst).

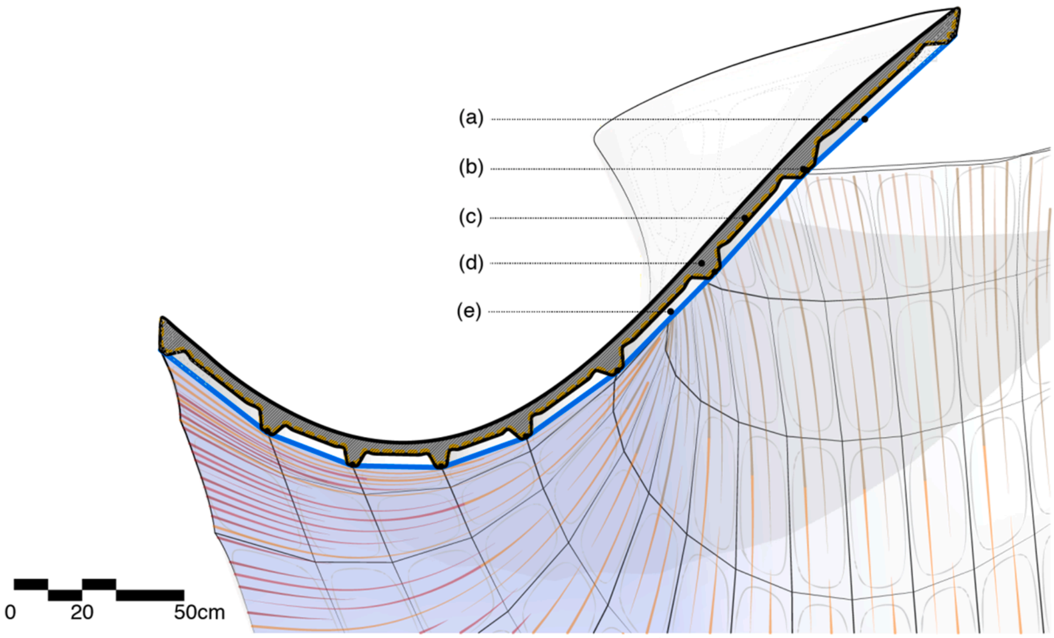

Fig. 3. Detail section through the pavilion showing the waffle shell, and the continuous 3 cm-thick shell with the 4 cm-deep stiffeners running in two principal directions: (a) two-layered knitted textile; (b) cable net; (c) fast-setting cement-paste coating; (d) concrete waffle shell; and (e) voids created by inflated pockets.

intricate structures accounts for more than 70% of the structure's construction cost, which is approximately three times higher than the cost of a standard structure [11].

Lightweight fabric formwork systems offer an alternative to traditional construction formwork systems [29]. By using a flexible membrane instead of a rigid formwork, textiles have proven to be a feasible solution for the creation of lightweight, waste-reducing formworks for a wide variety of complex building components [12]. Moreover, because of their compactness and light weight, they can be effortlessly transported to the construction site.

To achieve the desired geometry, textiles need to be tensioned into shape using rigs, frames and external supports [30]. Tensioning can also be done using hybrid approaches. Recent research has used a cable net [28], bending-active elements [23,14,8] or inflatables [5] to form a self-supporting system with the textile [22,29].

The NEST HiLo roof prototype, built at ETH Zurich, is the most recent example of a large-scale, thin concrete shell structure to be successfully built using a cable-net and woven-fabric formwork [6,16].

Fabric formwork systems generally use single-layered, woven fabrics with uniform texture and structural properties. To accommodate for tensioning and the insertion of auxiliary systems, textiles need to be fitted with functional details such as channels and openings. If wrinkles are to be avoided, the shaping and integration of other features relies on the extensive tailoring and joining of different flat sheets of material.

By contrast, knitted materials can be tailored to doubly-curved and three-dimensional shapes, allowing for the integration of features and the design of very specific properties without the need for glueing, welding or stitching several parts together.

They can be easily prefabricated using CNC knitting machines and therefore have the advantage of lowering the cost and manual labour in the manufacturing of such complex parts. In our approach, the tensioned textile is coated with a thin, high-performance cement paste [24,21]. This cement paste sufficiently stiffens the textile for further use, directly as a mould or as part of a scaffoldless formwork system. The ultra-lightweight moulds drastically reduce the need for additional support and scaffolding, and can simplify logistics on site. Such an approach is an innovative way of constructing doubly-curved geometries in concrete while addressing the consumption of resources and sustainability in construction. Some of the above-mentioned advantages of using such a system have already been explored through a variety of component-like prototypes such as complex nodes or branching structures, rib-stiffened surface configurations, waffle-shell configurations and a small-scale bridge prototype, built using a hybrid knitted-textile and bending-active glass-fibre rods as formwork [19,21].

The knitted fabric shuttering used for the construction of the KnitCandela shell (Fig. 2) further demonstrates the integration and shaping possibilities offered by knitting at the architectural scale. The included features are:

- a space fabric, i.e. a double-layered textile, with an aesthetic and a technical side;
- pockets for the insertion of inflatables to form cavities in the final shell;
- varied loop sizes and densities for controlling inflation depth;
- channels and openings for inserting cables and inflatables;
- seam detail/strategy to connect different knitted patches/parts; and,
- inclusion of edge detailing for guiding concrete finishing.

3. Design

The two layers of the textile fulfill different tasks. The visible aesthetic inner layer displays a colourful pattern, while the outer, technical layer includes features for inserting, guiding and controlling the position of the cables and other formwork elements. The pockets created between the two layers were inflated using standard modelling balloons, controlling their depth using different knit densities. After fixing the knitted shuttering surface with the fast-setting cementitious coating, local Mexican workers applied the fibre-reinforced concrete by hand. The inflated pockets became cavities in the cast concrete, forming a structurally-efficient ribbed shell.

3.1. System

The formwork system behind KnitCandela consisted of three elements:

- an external timber and steel scaffolding frame,
- a load-bearing, steel cable-net falsework, and

Fig. 4. Edge clamp solution: laser-cut plywood profile attached to the steel cable net, holding up the edge of the textile (Photo credit: Paola Figueroa).

- a custom 3D weft-knitted textile shuttering/mould.

The cable net was inserted in the textile and tensioned in the timber frame to form the formwork for the concrete casting.

The structure was designed as a 3 cm-thick concrete shell with 4 cm-deep stiffening ribs running in both directions, thus resulting in a waffle shell. The cavities shown in Fig. 3 are formed by inflating balloons inserted in the pockets designed in the knitted textile.

As with the KnitCrete bridge prototype detailed in Popescu et al. [19], strength is built-up in stages. The cavities of the waffle shell were formed by inflating the pockets, coating the top layer of the textile with the fast-setting cement-paste coating, and casting concrete onto the stiffened textile. Finally, when the concrete had hardened, the pockets were deflated, leaving the textile in place and visible on the inside of the structure.

The weft-knitted textile was not only used to guide the cables and keep the inflatables into position, but also to control the side and degree of inflation. Because the pockets and the properties of the textile control the size and inflation, standard balloons could be used for all cavities. This means custom solutions can be created with standard elements.

The edge details that were created by inserting steel rods into the edge/outside-boundary channels and held up by laser-cut wooden profiles (Fig. 4).

3.2. Form finding

The form finding of the KnitCrete formwork (the cable-net and knitted shuttering) and thus of the resulting shell was done using *compas_fofin*, the force density-based form-finding package (Van Mele 2019) of the COMPAS framework [27].

A target geometry for the form-finding process was defined through a series of design iterations with the goal of balancing the aesthetical and structural targets of the project. To keep the detailing of KnitCrete formwork clean and simple, the topology of the cable net follows a quad pattern, with closed continuous ring cables in the "horizontal" direction, and boundary-to-boundary cables in the opposite, "vertical" direction. The horizontal cables were used for generating prestress and the vertical cables to transfer the loads from boundary to boundary of the supporting structure.

Although the cable net was modelled with discrete cable segments rather than continuous horizontal and vertical cables, the force densities were controlled cable per cable, rather than segment per segment to obtain a smooth naturally curving geometry. The form finding was done while taking into account the weight of the resulting shell surface. Since each change in force density results in a new shell geometry, which in turn has a new weight, this is an iterative process.

In a first step, the force densities were modified without specific upper and lower bounds to freely sculpt the desired geometry. Afterwards, in a second step, the lowest possible force densities that still generated the same geometry were found through an optimisation process based on CVXPY [10,4], a Python-embedded modelling language for convex optimisation problems. This allowed to minimise the internal forces in the cable net, as well as the forces on the supporting structure. Since the designed geometry has high geometric stiffness due to high degrees of curvature, the required prestress could be kept very low.

As a last step of the form-finding process, the cables were materialised by choosing an appropriate cross section with respect to the internal forces from which then the initial unstressed length of the cables could be calculated.

3.3. Structural analysis

The structural analysis of the shell structure was performed with the *compas_fea* finite element package [15] of the COMPAS framework [27], using software Abaqus as the backend solver [1]. The compas_fea package allowed for an effective parametric exploration and structural analysis feedback loop, ideal for investigating the different shell geometries in the design process, as the quick return of analysis results fed further iterations of the form, and fitted the tight time schedule.

The shell and rib features of the KnitCandela structure were extracted from the CAD geometry and automatically added as shell finite elements in the structural model. The shell elements were given the target structural thickness, with additional self-weight loading added due to the expected additional concrete mass present from the fabrication method. Additional area loading was applied across the shell's surface

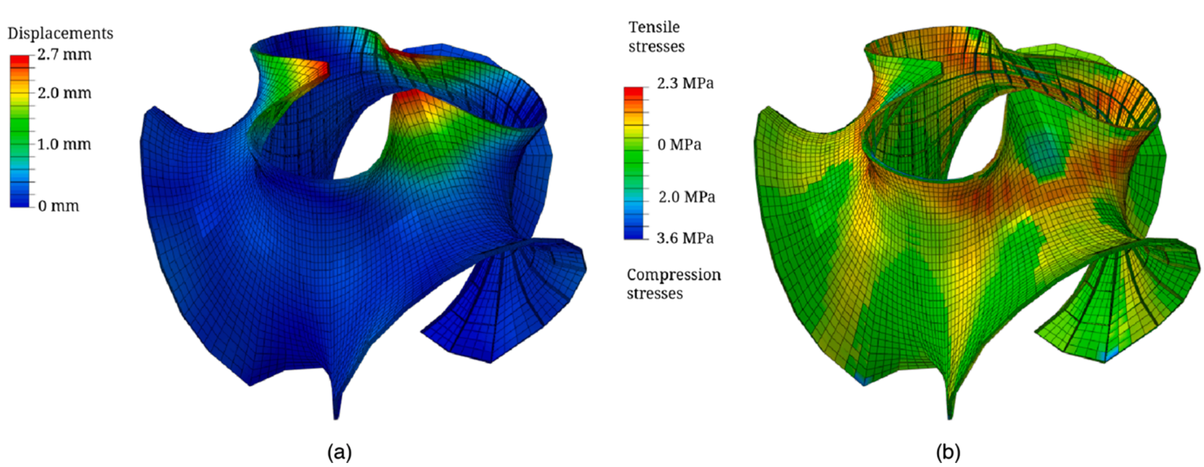

Fig. 5. Deflections and Tensile stresses: (a) deflections were analysed to be below 3 mm throughout the structure for all considered loading cases; (b) tensile stresses were kept below the design tensile material stress limit of 4 MPa, with the highest stresses predicted to occur in a hoop around the structure.

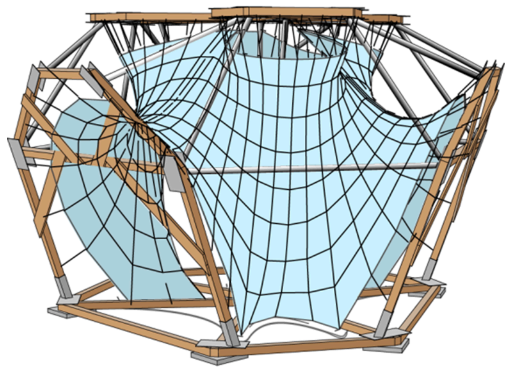

Fig. 6. Cable-net and textile formwork pre-stressed in a steel and timber frame.

area in various directions to simulate both potential wind pressure loading and other lateral loading on the structure such as from visitors. Boundary conditions were taken as pinned (fixed from translating) along the support lines, knowing that the stiff steel baseplate, which connects the touchdown points, would restrain any lateral movements and take any reaction forces. The lateral reaction forces were of low magnitude, below 20kN, due to the angle of approach to the supports, imparting relatively little demand on the steel baseplate.

Due to the efficient structural form that gains stiffness through its doubly-curved geometry, deflections were predicted to be small, with maximum deflections of 2.7 mm occurring at the cantilever tips, where they pinch together at the top of the structure (Fig. 5). The target for deflections was set to be under 3 mm.

Material modelling in the structural model was conservatively based on a low-strength concrete with compressive strength of 20 MPa, with some fiber reinforcement to reach a tensile strength of 6 MPa (factored down to 4 MPa). As the concrete was not further reinforced with traditional steel rebar, it was important to focus on limiting tensile stresses throughout the shell design and analyses. Tensile stresses were found to lie below the material design limit of 4 MPa, with a maximum of 2.3 MPa occurring as a hoop stress around the chest of the structure, caused by the cantilevers above. Compressive stresses were consistently low throughout the analyses, locally reaching no higher than 3.6 MPa at the support areas with the steel baseplate, significantly below the material's compressive capacity.

3.4. Frame and support structure

The structural concept of the supporting frame falsework was to make a self-stressed system that did not require any anchorage into the site ground structure. To accomplish this, the symmetry lines of the shell structure were exploited to cancel out lateral thrusts produced by the shell through self-equilibrating of the cable net's reaction forces transmitted through the steel baseplate. A combination of steel and timber struts and ties were arranged in a frame with rigid joints (Fig. 6). The structural frame design utilised compas_fea for generating analysis results, and linking them with the construction needs and constraints of the frame. The pairing of form-finding and structural analysis workflows, allowed for the direct application of the design cable-net reaction forces to the structural model as applied point loads.

To take the cable-net reaction forces from the flexible formwork to the rigid falsework, intermediate timber frame elements were designed to transfer the cable reaction forces at locations in space to connection points along the structural frame. Before applying the concrete, the tendency of the cable-net reaction forces to lift the steel baseplate up were counteracted by the weight of the plate itself, and of the frame structure pushing back down on beams. The governing criteria for the design of the falsework for supporting the prestressed cable elements was not necessarily the strength of the framing, but its stiffness. This was because small movements and construction or fabrication tolerances of the frame from its desired location could have led to large increases or decreases in the cable prestress forces. Therefore, generous safety factors on the cable-net reaction forces were used to account for sensitivity to deflections, and deflections were the main analysis results to be minimised. Turnbuckles allowed for the adjustments to the cable-net geometry on-site by lengthening or shortening the cables.

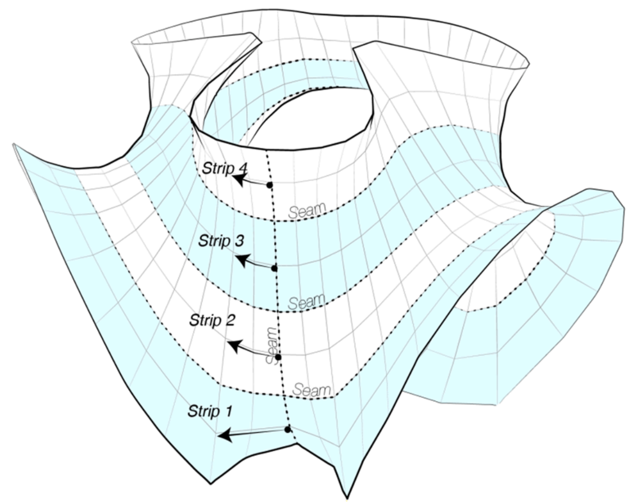

Fig. 7. Division of the shell's surface into four strips for fabrication showing the resulting three plus one seams.

4. Fabrication

The elements needed for the construction of the concrete shell were fabricated in Mexico and Switzerland. The textile shuttering, weighing 25 kg, was fabricated at ETH Zurich and transported to Mexico in two suitcases as checked luggage. The timber and steel frame for tensioning and the cables comprising the cable net were fabricated in Mexico City. This section will focus on the fabrication of the textile shuttering.

4.1. Geometry division for fabrication

The 50 m^2 textile shuttering that comprises KnitCandela's formwork, was made from long strips ranging from 16 m to 26 m in length, which in total took only 36 h to knit. Each of the four pieces was a double-layered, weft-knitted textile produced in one manufacturing process on a gauge 7 Steiger Libra 3.130 CNC flat-bed knitting machine. The textile dimensions were only limited in width by the machine's 1.3 m wide needle bed. The geometry was divided into strips to take advantage of the machine's possibility to create infinitely long pieces.

Fig. 7 shows the division of the shell geometry into the four pieces that were produced, with a total of four seams over the entire surface. Three long seams, between the parts, and one final seam, connecting the start and end of a part, form the tubular geometry. The seams were placed along cables both in longitudinal direction and for the final vertical seam.

4.2. Knitting principle

To produce a piece of textile, flat-bed weft-knitting machines use an array of needles (Fig. 8a) laid out onto two beds facing each other (Fig. 8b and c). With each pass of the machine carriage, one or more threads/yarns, brought by one or more yarn guides, is pulled by the needles through loops created in a previous pass, thus forming new loops. Various textile configurations can be achieved by alternating yarns, needles and the needle bed used during one pass of the machine carriage. A knitting pattern, describing the action of each needle during a pass of the carriage, is used as instruction for the CNC machine.

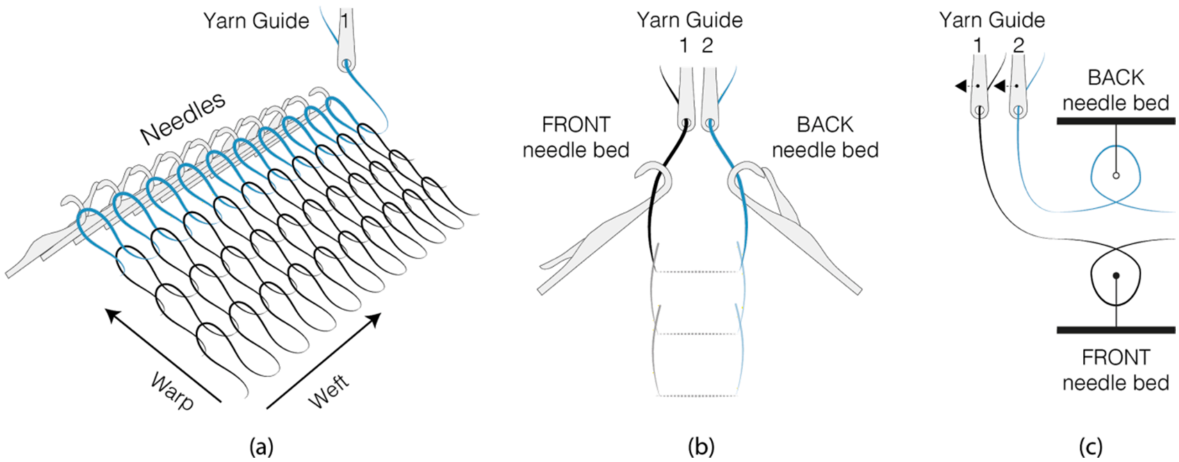

Fig. 8. Machine needle bed layout: (a) needle bed made up of an array of needles forming loops; (b) 'V' needle bed layout in flat knitting machines; (c) top view representation of needle bed.

Therefore, knitting patterns are 2D matrices (pixel grids) where each row represents a pass of the carriage and each entry in that row represents a pair of facing needles and their corresponding operations.

4.3. Pattern generation

Because the geometry was radially symmetrical, it was sufficient to generate the knitting patterns for a sixth of the surface. This was then mirrored and repeated to create the pattern for the full strip.

The knitting patterns were generated using the *compas_knit* package, an in-house tool developed for automated generation of knitting patterns for a given 3D geometry. A description of the automated knitting pattern generation is given in Popescu et al. [20] and Popescu [21].

Because knitting is a directional process that produces a textile with different properties in width (weft direction) and length (warp direction), a knitting direction needs to be chosen and a target loop size determined. The knitting direction was defined by splitting the geometry into strips. This loop size is dependent on a number of factors such as:

- machine gauge,
- yarn type and dimensions,
- tension used while knitting,
- chosen material formation (pockets, channels etc.), and
- desired prestress of the textile when tensioned in the rig.

To find the loop width and height parameters to be used in the pattern generation process, a series of textile prototypes were knitted. The textile prototypes helped to investigate the needed parameters, develop the material formation needed for the system, and to calibrate the pattern generator for the needed tension. In this case, the steel cable net was the main load-bearing component of the formwork. Therefore, the textile needed to be loose enough so as not to interfere with the tensioning of the cable net and tight enough to make a smooth inner surface and control the inflation of the balloons. The tightness was determined empirically by testing the interaction between the textile, cable net and inflatables in a 1:1 mock-up of part of the shell structure.

As the determined loop dimensions were very small (3.5 mm × 2 mm), to speed up the computational process, a larger unit was chosen for the pattern generation.

The final parameters for the pattern generator were as follows:

- width: 7 mm,
- height: 12 mm,
- spacing weft: 2, and
- spacing warp: 6;

where the spacing in the weft and warp directions represents the number of loops included in the generated 7 mm × 12 mm unit.

To generate the patterns, each strip was further split into patches coinciding with the quadrilaterals formed between cables. Generating the patterns in discrete patches makes the computation less intensive. Additionally, it naturally aligns the patterns to the cable directions, which makes the fabrication of the channels simpler.

After all patches of a given part were generated, the 2D patterns were combined into one single pattern. The locations of the cables and the coloured texture lines were automatically marked on the combined pattern with a colour code. The pattern for Strip 2 (Fig. 7), including the colour coding for the position of the cables and texture lines is shown in Fig. 9.

This pattern was then exported as a BMP format pixel image. Each colour zone on the pixelated diagram represents a predefined function for the machine to perform (e.g. knit front or back, transfer, drop stitch etc.). The BMP image was then imported into the machines' software, Model 9, where each colour was assigned a symbol from a library developed for this project.

The functions were programmed into the machine's software to create the different features of the knitted textile. In this case, needles on both beds of the knitting machine were used. Two different yarn guides would feed the needles on any given machine pass. One yarn guide fed the needles on the back bed and the other those on the front bed (Fig. 8b and c). A selection of the developed functions and an example pass of the machine carriage are shown in Fig. 9g–k.

Fig. 10 shows an example of the generated knitting pattern and the relationship with the corresponding front and back faces of the produced textile.

5. Construction

The concrete shell was constructed on site over a period of four weeks. First, the timber and steel frame was assembled and fitted with all of the hooks for hanging and tensioning the cable-net and knitted textile formwork (Fig. 11a). All of the cables were cut to the predefined length and laid out onto plotted drawings with each node intersection marked along the length of the cable.

These cables were inserted into the knitted textile shuttering and fitted with turnbuckles at the ends. This package was then attached to the supporting frame and taut into shape using the turnbuckles (Fig. 11b). Once tensioned, balloons were inserted into the textile's pockets, to create the waffle shell's weight-saving cavities, as described in Section 3.1 (Fig. 11c). The entire textile was sprayed with a cement-paste coating for stiffening (Fig. 11d), and then, concrete was applied

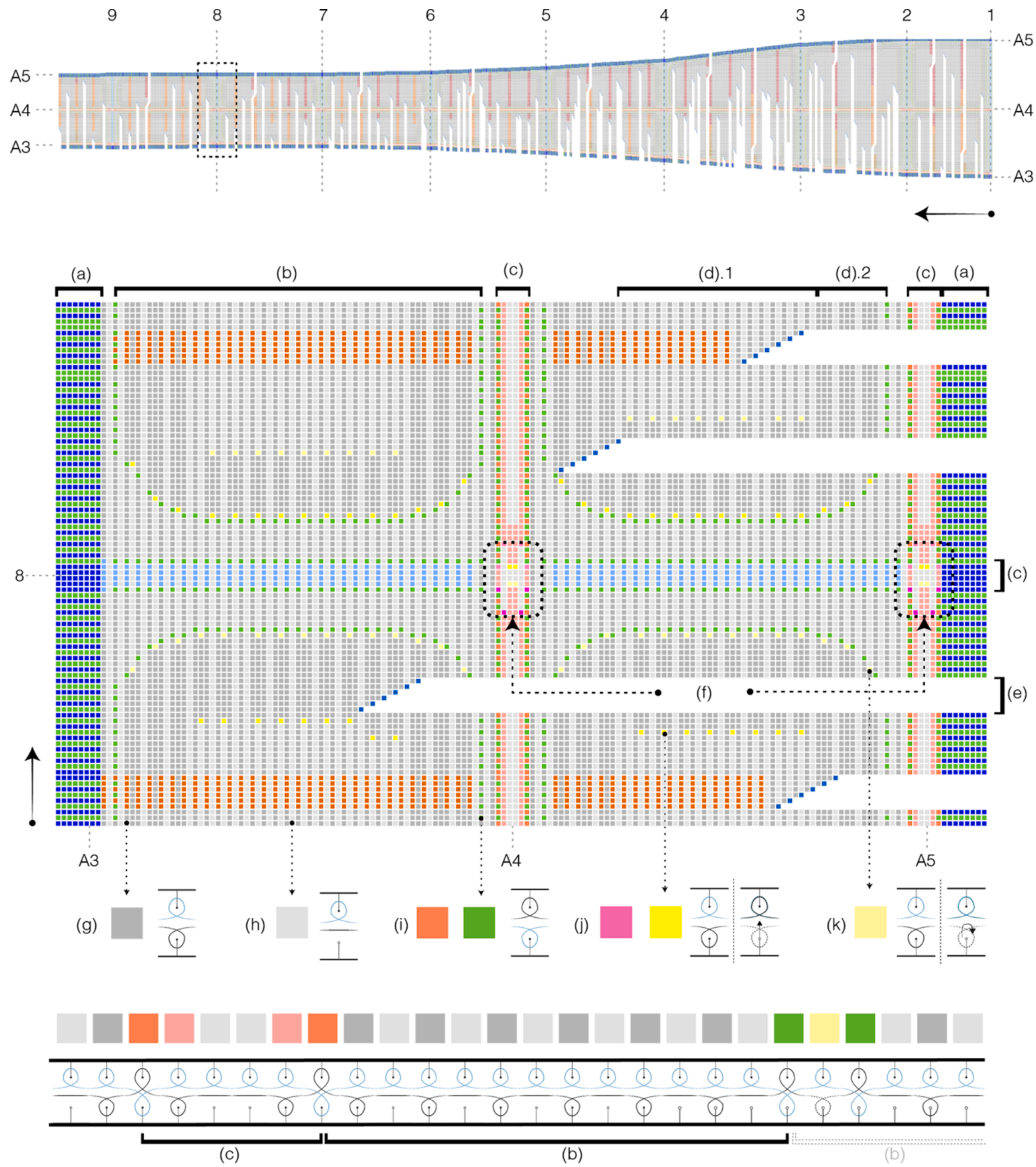

Fig. 9. Generated knitting pattern for Strip 2 showing the features and functions needed to achieve them: (a) seam detail; (b) pocket; (c) vertical and horizontal channels; (d) varied loop densities; (e) short row; (f) openings in channels at their intersection; (g) knit front and back (yarn 1 and yarn 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.

manually onto the formwork (Fig. 11e). Finally, once the concrete had hardened, the cables were released and the frame removed (Fig. 11f).

5.1. Frame assembly

The timber and steel frame for tensioning was built on site by local construction workers.

First, a temporary levelling slab was cast to form the base of the shell pavilion, and then the timber base frame was fixed onto the slab. Four steel tubular members, fixed to the middle of the base frame, supported the connected timber edge beams at the top of the frame. The three arched timber edge beams on the side of the frame were assembled flat on the ground and then raised into position.

Then, the arched timber edge beams and the top edge beams were connected by tubular steel profiles welded to steel plates and bolted to the joints of the arched timber boundary.

Finally, all hooks needed for hanging the cable-net and fabric formwork were fixed to the frame in their correct positions.

5.2. Formwork assembly

The formwork consisted of two elements, a cable-net falsework and a knitted textile shuttering. To assemble the formwork, the four strips of textile were sewn together into a long strip, and the cables inserted in

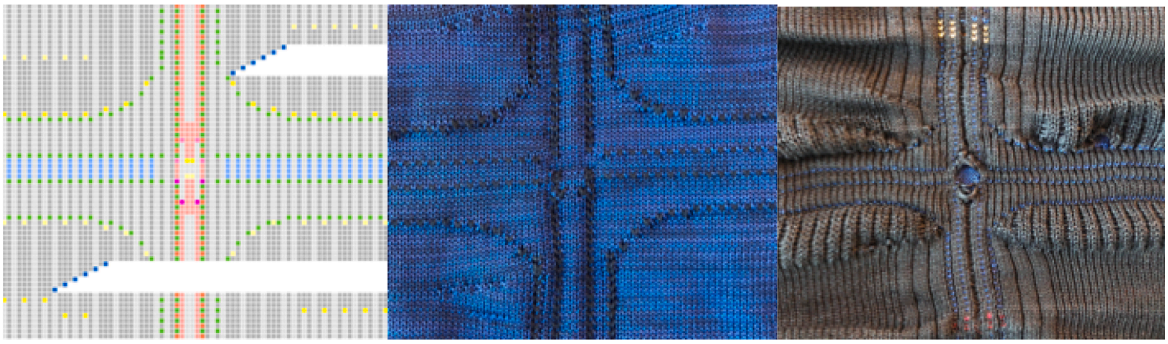

Fig. 10. Knitting pattern and corresponding textile front and back face.

the corresponding channels of the textile.

The long loop cables were inserted first, followed by the short cables. Then, as before, loops for attaching the cable net to the frame were formed on the ends of the short cables and turnbuckles attached to each one. Finally, all nodes were temporarily fixed in place with plastic zip ties.

5.3. Tensioning

The assembled cable net and textile were laid out around the central steel members of the scaffolding frame, as seen in Fig. 12a. The last vertical seam was sewn and the ends of the loop cables were connected using standard cable connectors.

The textile was then hoisted up by ropes tied to the top most nodes and the cable ends were connected to the corresponding hooks on the frame. Fig. 13b and c show the textile hanging from the top of the frame and the cables connected to their corresponding hooks. After securing the textile to the top of the frame, the ropes were removed and the opposite end of each cable was connected to the corresponding hooks on the frame arches (Fig. 12d).

The cable-net nodes were secured in place with rebar wires to ensure their position remained correct during tensioning.

The tensioning was performed by gradually tightening the turnbuckles around the outer perimeter. Fig. 12d shows the formwork secured to the frame and tensioned.

Once tensioned, modelling balloons were inserted into the textile's pockets to form the cavities within the concrete. The edge profiles described in Section 3 were attached and the edge detail was fixed in position.

5.4. Coating and concrete

Once fully assembled, the textile was sprayed with a thin fast-setting cement-paste coating [24]. The coating is based on a pumpable and set-regulated binary blend of calcium aluminate cement and hemihydrate, designed to be processable for 90 min in ambient conditions and to harden rapidly after spraying. Such a combination is needed to ensure that enough water remains for strength/stiffness build-up from cement hydration and that water is not lost due to drying. A standard progressive cavity mortar pump and air compressor were used as the material delivery system to the spraying nozzle. The coating was sprayed as a light mist (Fig. 13a) onto the entire textile forming a layer approximately 1 mm–1.5 mm thick (Fig. 13b). Glass-fibre-reinforced concrete was applied onto the coated formwork in three layers. First, all the ribs were filled in, and then a second layer built-up the thickness of the shell (Fig. 13c). Finally, a third, finishing layer was applied and hand rendered for a smooth finish (Fig. 13d).

5.5. Decentring

Ten days after casting, the shell was decoupled from the frame to stand unsupported, referred to as decentred. First, the tension in all cables was released by gradually untightening the turnbuckles. Then, the cables were unhooked from the timber frame in two groups. The shell was visually inspected for cracks at every step to make sure the structure was sound and not deforming excessively. Finally, the frame could be dismantled and removed.

6. Time, cost and transportation

The shell was designed, engineered, prototyped, fabricated and constructed over a period of three and a half months, of which one and a half months were dedicated to the fabrication and on-site construction.

The timber and steel frame was fabricated and constructed by construction workers in two weeks. In the meantime, the knitted textile took 36 h of machine time to produce and was transported easily to the worksite due to its low weight and compact size.

Table 1 shows an overview of the weight, cost and production time needed for the fabrication of hybrid cable-net and knitted fabric formwork, cement-paste coating and concreting.

Assembling the textile shuttering and cable-net falsework on-site took approximately one week. Once assembled, three more days were dedicated to the preparation of the formwork for coating and concrete casting. This included:

- tensioning of the cable net,
- inserting and inflating balloons, and
- inserting and fixing edge detail.

The cement-paste coating was sprayed onto the textile in two sessions of four hours over the course of two days. Finally, three layers of fibre-reinforced concrete were applied over the course of three days.

7. Discussion

The KnitCandela prototype demonstrated that with an appropriate computational design and digital fabrication pipeline, knitted textiles can be easily produced. Furthermore, when coupled with other load-bearing elements, knitted textiles can be used to shape complex geometries at the architectural scale.

7.1. Advantages

Tensioning the cable-net and textile formwork in a timber frame removed the need for dense scaffolding to support heavy moulds. Fig. 14 shows the sparseness of the employed forming systems by comparison to a traditional rigid one. The minimal foundations and scaffolding required to realise the formwork give a glimpse into how such forms can

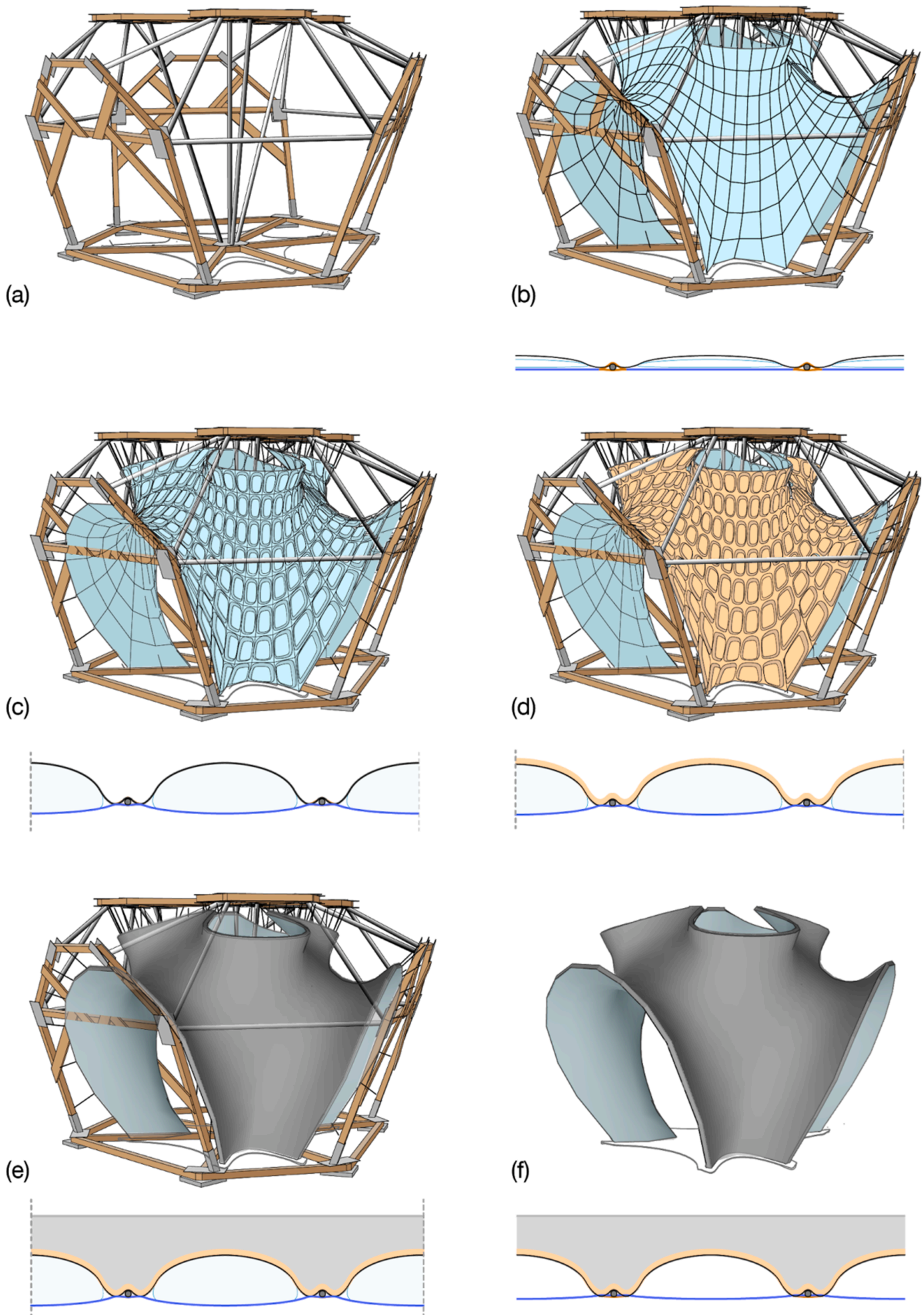

Fig. 11. Construction sequence of KnitCandela: (a) external tensioning frame; (b) tensioned cable-net and knitted textile; (c) inflated pockets to form cavities; (d) fast-setting cement paste coating; (e) concrete; (f) finished structure after decentering.

be realised with a minimal falsework and need for material.

Additionally, the use of a knitted textile offers advantages with respect to integrating features such as channels for guiding other structural elements and changing the surface texture, all in a single fabrication process. The inclusion of features such as guiding channels and pockets makes it possible not only to shape a mould that would otherwise require extensive milling but also to guide and place elements for construction without the need for complicated logistics and labelling of custom elements. An example of the simplified logistics are the pockets of the textile, which helped 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 embedded properties of the textile. This means custom solutions can be created with standard elements. The design and construction was carried out by multiple teams in Europe and Mexico over a period of 3.5 months. The intense development cycles, collaboration between multiple teams in

Fig. 12. Hoisting and tensioning of the hybrid cable-net and knitted textile formwork in the timber frame: (a) cable-net and textile formwork placed around centre supports of tensioning frame with ropes tied to nodes, (b) hoisted formwork fixed to the top of the tensioning frame, (c) connection between cables and frame and (d) formwork connected to all the frame hooks and tensioned into shape (Photo credits: (a)–(c) Lex Reiter, (d) Maria Verhulst).

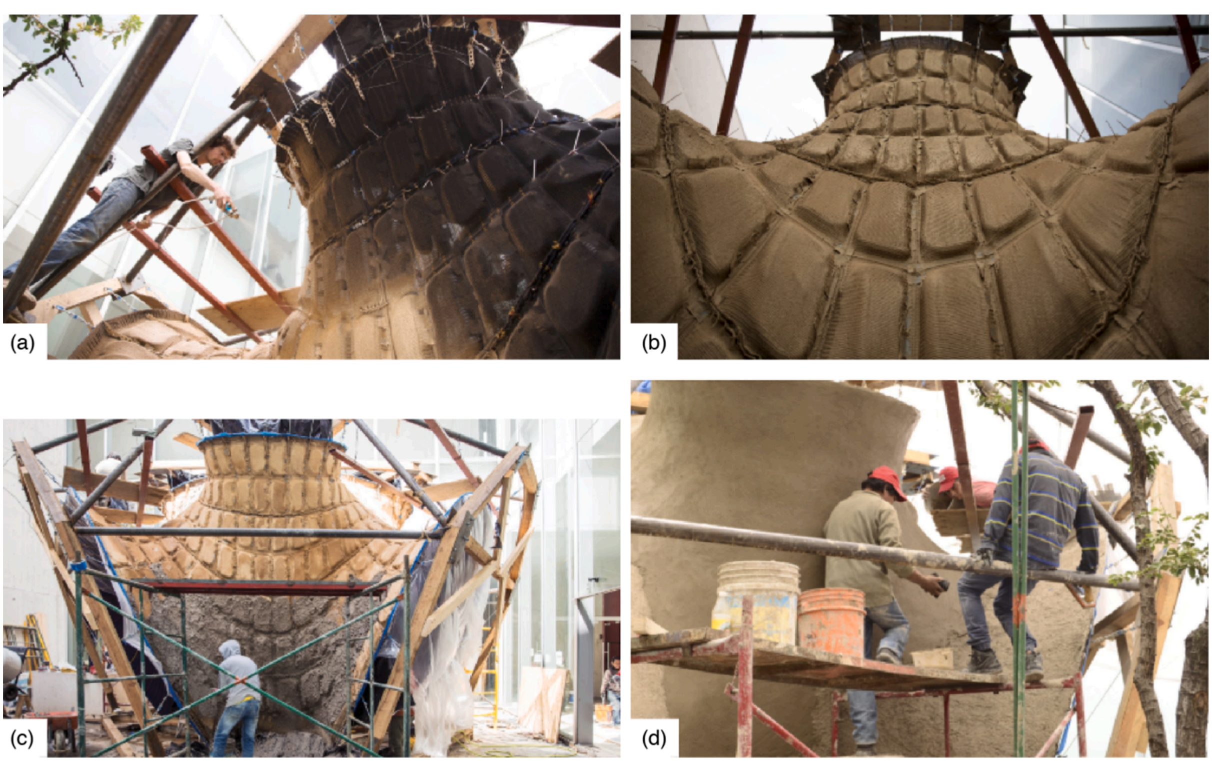

Fig. 13. Concreting steps: (a) spraying; (b) coated structure; (c) first concrete layer; (d), finishing (Photo credits: (a)–(c): Mariana Popescu, (d) Alicia Nahmad).

Table 1
Weight, cost and production/assembly time of KnitCandela's fabric formwork and concrete.

	Material	Mass kg	Cost EUR	Production or assembly time
Knitted textile	PES dtex 167× 30× 8	25	230	36 h
Cable net and connectors	Stainless steel 3 mm	30	1200	4 days
Balloons	4–5 cm diameter	N/A	230	1–2 days
Cement-paste coating	CAC based	200	220	2 days
Concrete (including labour)	Fibre reinforced	5000	5300	2–3 days
Tensioning frame (including CNC and labour)	Wood and steel	N/a	21,560	10–14 days

different locations and numerous structural and constructional iterations were realised with a building information modeling (BIM) approach using the open-source computational framework COMPAS. This made the structural design, engineering, digital fabrication, and construction of KnitCandela efficient. The design-to-production process, made possible by the streamlined computational strategy, presents an outlook toward a more integrated, research-driven architectural and engineering practice with increased productivity.

As an ecologically conscious construction system, KnitCandela utilises a stay-in-place mould that is practically zero-waste as the formwork becomes part of the structure and the tensioning frame could be reused. Because of the structural geometry, a doubly-curved 3 cm-thick shell with stiffening ribs with a depth of 4 cm running in both directions, fewer materials were required overall, making the project economical both in terms of financial costs and material or construction waste. Finally, rather than shipping heavy and high-volume formwork parts to site, the lightweight knit significantly reduces the carbon emissions from transport. This could be further improved by only delivering the needed fabrication data and manufacturing the textile locally.

7.2. Limitations and possible improvements

Given the tight schedule of the project and fabrication limitations, the frame used for tensioning was custom-designed and fabricated for this project. It was designed to be easily manufactured with traditional methods using standardly available timber and steel profiles, which could be effortlessly assembled into a self-contained frame. However, a system relying on standard scaffolding elements could be developed, making the tensioning frame a reconfigurable and reusable part. The NEST HiLo roof is an example of a flexible fabric formwork system using standard scaffolding and reusable elements that can serve as a model for further development of standard solutions. The full-scale prototype of the concrete shell roof and the final structure are built using the same scaffolding, frame and cable elements [16].

Tensile structures are ideal for creating fluid doubly-curved geometries, but need higher prestress or stronger coating for geometries with less curvature. Though the cavities of the waffle shell were easy to build using standard balloons, the geometry of the larger cavities, which were 0.5 m–0.75 m in size, were more difficult to control. Having large flat areas, these larger pockets were not stiff enough after coating to support the casting of concrete. In the future, to prevent the pockets from collapsing during casting, other geometries or other coating materials should be explored.

Using a flexible formwork system and textiles has some implications for the construction site and general handling. While the system is lighter, to avoid tears, it needs to be handled with particular care. During the assembly of the textile, a dry and relatively clean environment is preferable, especially if the textile is exposed as an aesthetic face layer in the finished structure.

7.3. Future work

Transforming the tensioned knitted formwork into a load-bearing concrete structure is a challenge that has been addressed to certain extents by the project presented in this paper. Given the advantages and limitations discussed in this section, future work can be centred around optimising the tensioning strategy for the system and investigating material opportunities both in terms of coating and the knitted textile

Fig. 14. Tensioned cable-net and knitted textile formwork and the minimal scaffolding needed (Photo credits: Maria Verhulst).

Fig. 15. Finished concrete shell showing the soft textile interior and the smooth concrete exterior (Photo credits: Angelica Ibarra).

itself.

In the future, we will investigate strategies for tensioning that use a standardised, reconfigurable or reusable frame. Textiles may be tensioned not only using a rigid external frame but also using integrated bending-active or inflatable systems. Therefore, the possibility of creating a hybrid and deployable system will also be investigated.

The behaviour of flexible systems is harder to predict than that of rigid formwork systems. Reaching the target geometry implies that there should be good on-site control mechanisms for the tensioning. This implies the development of simulation and control mechanisms to predict and guide the position of flexible elements to match spatial, strength and design requirements.

Finally, strategies for controlled and automated deposition of material need to be investigated as flexible formwork systems are more sensitive to local loading during construction. The use of unmanned aerial vehicles (UAVs) or other robotic systems could be considered for the cement-paste coating as well as the casting of concrete.

8. Conclusions

This paper described the design, engineering, digital fabrication and construction of KnitCandela (Fig. 15) using a flexible cable-net and knitted fabric formwork system. The structure shows the possibilities of using such an approach at the architectural scale and discusses the needed fabrication pipeline.

The custom-made computational design, engineering, and fabrication pipeline allowed for the automatic generation of the sophisticated knit pattern and enabled the realisation of the project in a very short time. The lightweight formwork was easy to transport, reduced the need for additional scaffolding and simplified logistics on the construction site. Furthermore, excluding the falsework frame, the total material cost of the 50 m^2 formwork was under EUR 2000.

The system has several potential benefits over traditional approaches to concrete formwork, as it is lightweight, easy to manufacture, highly transportable, quick to assemble and can significantly reduce the waste. The computationally designed, materially- and waste-efficient approach demonstrated in KnitCandela, targets those areas where project timelines and budgets need to be controlled: transport and on-site logistics, manual labour, installation costs, etc. The demonstrated system confronts the challenges faced by the building industry, offering practical, easily realisable solutions for a more sustainable way of building.

9. Full credits KnitCandela project

Detailed design and structural design

Block Research Group (BRG), ETH Zurich: Mariana Popescu, Matthias Rippmann, Tom Van Mele, Philippe Block

Sketch design and intrados pattern generation

Zaha Hadid Architects Computation and Design Group (ZHCODE): Filippo Nassetti, David Reeves, Marko Margeta, Shajay Bhooshan, Patrik Schumacher

Fabrication and construction

BRG: Mariana Popescu, Matthias Rippmann, Alessandro Dell'Endice, Cristian Calvo Barentin, Nora Ravanidou

Architecture Extrapolated (R-Ex): Alicia Nahmad Vazquez, Horacio Bibiano Vargas, Jose Manuel Diaz Sanchez, Asunción Zúñiga, Agustín Lozano Álvarez, Migue Juárez Antonio, Filiberto Juárez Antonio, Daniel Piña, Daniel Celin, Carlos Axel Pérez Cano, José Luis Naranjo Olivares, Everardo Hernández, Ramiro Tena.

Structural engineering

BRG: Andrew Liew, Tom Van Mele

Concrete development

Holcim Mexico: Jose Alfredo Rodriguez, Carlos Eduardo Juarez, Delia Peregrina Rizo

Site construction coordination

R-Ex: Alicia Nahmad Vazquez

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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