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A Cable-Net and Fabric Formwork System for the Construction of Concrete Shells: Design, Fabrication and Construction of a Full Scale Prototype

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ABSTRACT

This paper describes the construction of a thin-shell concrete roof with a novel cable-net and fabric formwork system. The system consists of a fabric shuttering installed on a cable-net structure, which is tensioned from stiff boundary beams supported by standard scaffolding props. The cable-net is made from 2015 uniquely sized cables and rods, connected by 953 steel nodes. A specific non-uniform distribution of prestress was computed, such that under the weight of the wet concrete the cable-net sags into the desired shape of the final concrete shell.

All of the elements of the formwork system were digitally fabricated by specialised industry partners in Switzerland. After the installation of the boundary structure, the cable-net was tensioned with the prescribed non-uniform prestress. An on-site shape control system was used to minimise deviations between the as-built geometry and the digital model. Starting from the lower supports, the concrete was sprayed on the flexible formwork from two aerial platforms in a carefully planned sequence.

The construction of the shell together with partners from industry was a proof-of-concept demonstration of the formwork system, showing that concrete shells with complex doubly curved geometry can be built efficiently and with minimal material waste in a real-world context.

1. Introduction

Shell structures can significantly reduce the amount of material required to cover large spans, potentially decreasing the costs and embodied emissions produced by the construction industry [1]. However, although shell structures can be very efficient structural forms, they can also be quite demanding to construct due to their complex geometry. Concrete is the most commonly used material for the construction of continuous shells, since it is a material that can be easily moulded into any shape. The complexity lies in the fabrication of the formwork system. Rigid formworks require large amounts of material and manual labour, making them expensive and time consuming to build. Recently, flexible fabric formworks have been the subject of extensive research, since they have the potential to create non-standard geometries while significantly reducing material use [2,3].

This paper presents a cable-net and fabric formwork system [4,5] used in the construction of a thin, carbon-fibre-mesh-reinforced concrete shell structure. The cable-net and fabric formwork system improves on traditional formwork structures for doubly curved surfaces, which are most typically comprised of custom timber carpentry or milled foam, by using mostly reusable components. The cable-net is a network of individual steel cable segments and rods connected by steel nodes. It is tensioned from a reusable timber boundary beam, which in turn is supported by conventional steel scaffolding elements. The prestressed cable-net is designed to deform under the weight of the wet concrete into the desired shape of the structure. The specific, non-uniform distribution of forces to achieve this is found by means of an optimisation process and applied to the actual cable-net in multiple stages using an on-site control system [6].

The construction of this complex, anticlastic, thin concrete shell was the final proof-of-concept step in the development of the construction system to be used for the roof of the NEST HiLo unit [7] and functioned as a dress rehearsal for all the partners involved.

1.1. The NEST HiLo unit

HiLo is a research and innovation unit designed as a collaborative and flexible workspace, to be built in 2019 on the NEST building of the

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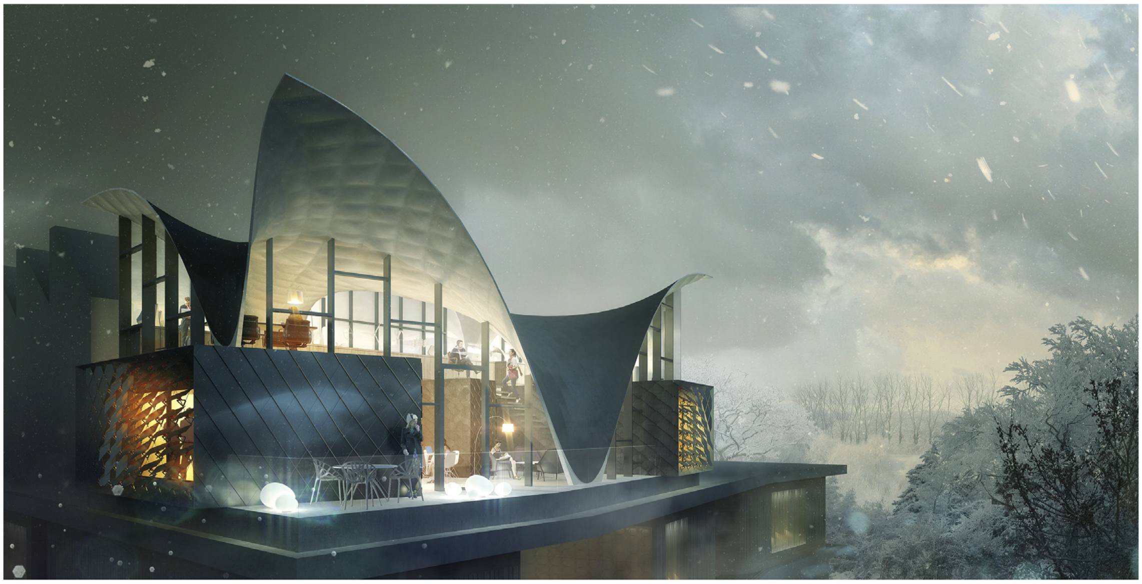

Fig. 1. The HiLo research unit showing the roof located on top of the NEST building.

Swiss Federal Laboratories for Materials Science and Technology (Empa) in Dübendorf, Switzerland (Fig. 1). NEST, which stands for Next Evolution of Sustainable Technologies (for the building industry), is a modular research and demonstration platform. NEST consists of a central backbone that contains basic services and access for a series of exchangeable research units, such as HiLo, with the purpose of introducing novel materials and components to the construction industry and enabling the testing of innovative systems under real-world conditions. The aim of the HiLo unit is to demonstrate how embodied and operational energy in buildings can be drastically reduced by combining lightweight concrete structures, appropriate fabrication and construction methods with low-energy building systems [7].

1.2. The HiLo roof

The most visible innovation presented in HiLo is the roof, which is a carbon-fibre-mesh-reinforced, concrete sandwich shell structure with integrated hydronic heating and cooling [8] and thin-film photovoltaic systems [9,10]. With a surface area of approximately 160 m^2 and covering an open space of roughly 120 m^2, the HiLo roof has an anticlastic doubly curved shape and is supported around the perimeter in five locations on two levels.

This paper describes the construction of a full-scale prototype of the HiLo roof in 2017 in the Robotic Fabrication Lab of the Institute of Technology in Architecture at ETH Zürich. The development and realisation of this prototype focused on the lower concrete layer of the sandwich construction. The objective was to evaluate the feasibility of the cable-net and fabric formwork system for the construction of such a large and complex shell structure, with real constraints and with the involvement of partners from the construction industry.

1.3. Paper outline

The paper is structured as follows. Section 2 describes the cable-net and fabric formwork system and how it addresses fabrication and construction tolerances via a custom-developed control system. Section 3 details the design and analysis process that was employed for the cable-net. Section 4 shows the fabrication process for all of the components used in the formwork system, and Section 5 describes the construction process of the roof itself. Finally, Section 6 draws upon the paper's conclusions.

2. Cable-net and fabric formwork system

The cable-net and fabric formwork system (Fig. 2) consists of the following components: (a) reusable steel scaffolding, (b) timber boundary beams, (c) steel cable-net, (d) fabric shuttering, (e) and edge clamps. After the carbon-fibre-mesh reinforcement (f) is connected to the nodes of the cable-net, the concrete is sprayed onto the formwork (g). Layers (a) to (e) are removed once the concrete has cured.

The system works by tensioning the cable-net between the timber boundary beams and connecting the fabric shuttering on top, making up the formwork that gives shape to the concrete. The tensioned cable-net is an efficient and entirely reusable structure, capable of supporting the weight of the concrete with minimal use of material. The ability of the cable-net to achieve sufficient stiffness to support the concrete with acceptable tensioning forces is tied to the geometry and curvature of the target shape. For this reason, the design of the cable-net is strictly related to the design of the desired concrete shell, and vice versa.

Fabric is used as the shuttering material for several reasons: it provides an appealing surface finish to the final concrete with minimal use of material and without the need for a release agent; it is flexible and can be patterned to adapt to the complex geometries of shell structures with minimal labour; and it is easy to store and transport to site. The edge clamps create the boundary of the concrete mould. They are fabricated from flat CNC-milled timber strips. Two strips are used to clamp the cable-net and fabric, and a third is installed perpendicular to the formwork surface.

2.1. Cable-net nodes and ties

The cable-net is made of steel ties and node connections. The ties are individual, uniquely sized steel cables and rods, all cut to a specific length to be stretched into the designed shape in its loaded state. The cables and rods are connected via a specially designed system of nodes (Fig. 3). These nodes connect the tie segments while providing the degrees of freedom required for the final shape.

The nodes are designed to serve many functions during the construction process. The node rings have a bridge element passing through their centres that allows for the anchoring of a threaded rod in the perpendicular direction of the shell in each node location. This threaded rod penetrates the fabric at precut locations where it is clamped to the node, ensuring the correct placement of the fabric. It also clamps the carbon-fibre-mesh reinforcement at specified heights

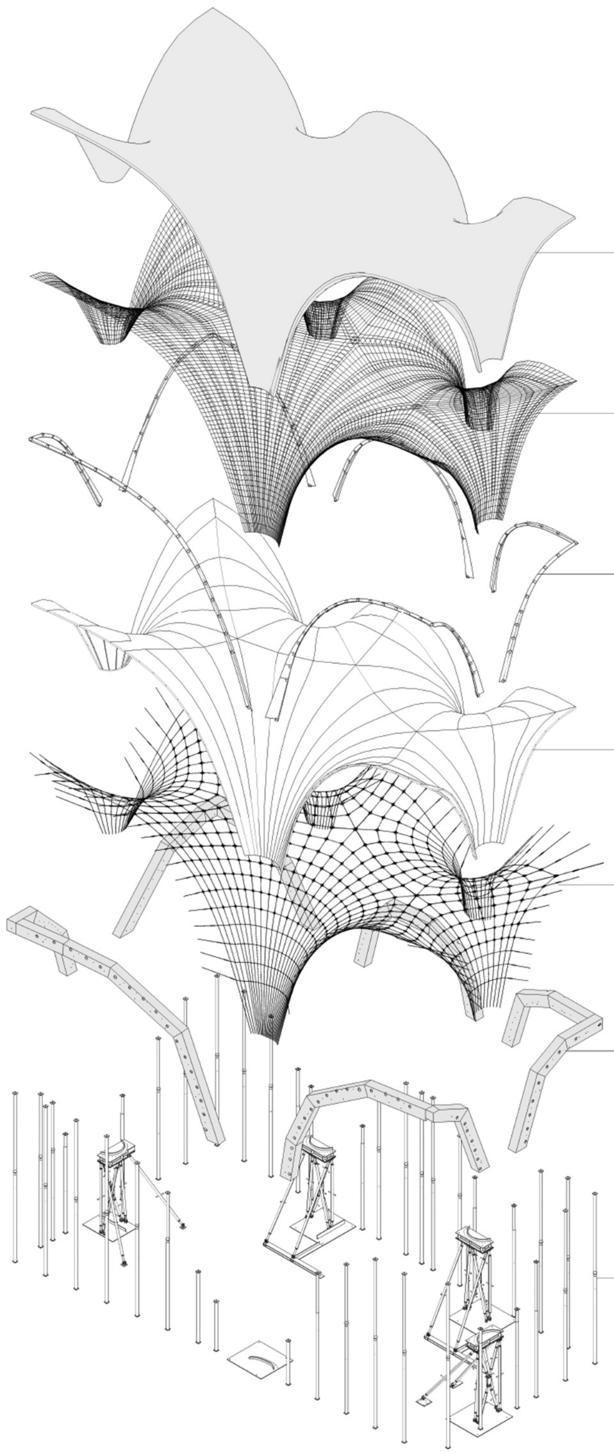

Fig. 2. Axonometric view of the cable-net and fabric formwork system showing (a) the reusable scaffolding, (b) boundary beams, (c) cable-net, (d) fabric, (e) edge clamps, (f) carbon-fibre reinforcement and (g) sprayed concrete.

and serves as a depth indicator for the spraying of the concrete layer.

Each node's central threaded rod holds two small black spheres spaced at defined distances beneath the fabric shuttering. These spheres are used to measure the as-built location of each node via a photogrammetry based measurement system with sub-millimetre accuracy. The location of the spheres is important for the on-site control system, which will be described in Section 2.4.

2.2. Fabric shuttering

A woven polypropylene fabric is used as shuttering. This fabric provides a unique texture to the concrete finish. The fabric spans the distance between the cables, supporting the wet concrete and sagging under the weight, creating a "pillowing" effect that is part of the shell's aesthetic appearance. However, the additional weight caused by this sagging must be limited for structural reasons. To do so, the fabric is designed to be slightly smaller than the actual cable-net geometry. The prestress induced by stretching it between the cables limits the pillowing and resulting extra weight.

The moisture content of the concrete during curing must be controlled to minimise the formation of cracks. This is particularly important for thin shells that have a high surface area to volume ratio. For this reason, the shuttering must not allow too much water to filter out. This was ensured by adding a plastic layer beneath the woven polypropylene fabric.

2.3. Scaffolding

The scaffolding required for the cable-net and fabric formwork system comprised of a timber boundary beam, cable ties and standard scaffolding props. The timber beam is required to anchor the boundary cables at precise locations and provide a stiff edge condition from which to tension the cables. The standard steel scaffolding props and ties support the boundary beam in the precise location in space.

Since the cable-net pulls inwards on the boundary beam, the forces can be taken to the ground in tension if the bracing props are placed on the outside of the beam or in compression if they are placed on the inside. Ideally, the forces would be taken to the ground in tension (Fig. 4b), as the bracing members can then be as long as required without buckling concerns. Additionally, having the bracing elements on the outside has the advantage of leaving the space under the cable-net available for work in the preparation of the concrete or other construction uses. As shown in Fig. 1, the site of the HiLo unit does not allow for props or cables to be anchored on the outside as the shell is to be constructed at the corner point of the fourth floor of the NEST building. For this reason, the bracing elements have to be placed on the inside of the boundary beam and thus work in compression (Fig. 4a).

2.4. Tensioning mechanism and control system

It is necessary for the cable-net to assume a shape that is close to the digitally designed "target" model, to eliminate uncertainty about the behaviour of the final shell with regards to its engineered strength and stability. Although all components of the formwork system are fabricated and assembled to a high degree of precision, fabrication and construction tolerances are unavoidable. Since even small changes in the boundary conditions or deviations from the designed lengths of the cable segments can have significant consequences for the geometry and stress state of the cable-net structure, a control system was developed to be able to adjust the boundary conditions such that the measured, as-built state matches the designed geometry as closely as possible [6].

The control process requires three steps:

1. The measurement of the as-built geometry and calculation of the real stress state of the cable-net. The geometry is recorded by the positions of the black spherical markers at the nodes (Fig. 3), as measured by an image-based theodolite system and associated custom software [11,12]. The measurements also provide the normal direction of the cable-net geometry at each node. This information is important for the accurate reconstruction of the geometry.
2. The use of a control algorithm to derive a new set of cable lengths for the boundary cables connected to the timber beam, such that the resulting equilibrium shape is closer to the target, without exceeding

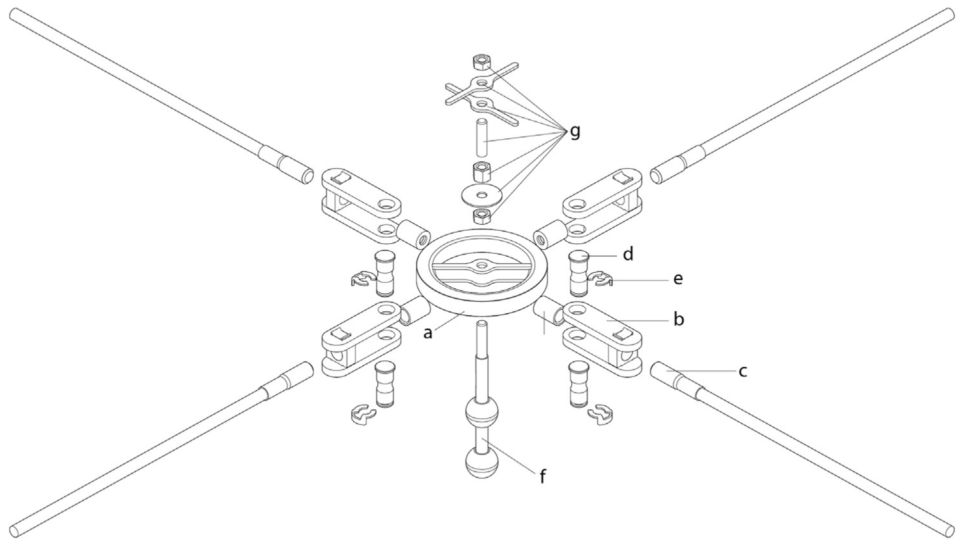

Fig. 3. Exploded axonometric view of the node component showing: (a) ring, (b) brackets, (c) ties, (d) pins, (e) clips, (f) threaded rod with measurement markers and (g) threaded rod with fabric and reinforcement anchoring parts.

the material stress limits of the components. For practical reasons, only the lengths of the boundary rods can be modified.

3. The tightening of the boundary cables anchored at the timber beam to achieve the prescribed lengths. The boundary cables terminate into threaded rods that can be tightened against the boundary frame using simple nuts and washers.

The control algorithm is based on a Differential Evolution optimisation solver [13], as implemented in the numerical package of the COMPAS framework [14]. The degrees of freedom of the optimisation problem are the unstressed lengths of the boundary edges. A Dynamic Relaxation model is used to calculate the equilibrium state and stresses in the structure, and the objective function is the mean norm between the simulated cable-net and the measured geometry. Solutions with stresses beyond acceptable elastic material limits are penalised out of the optimisation.

3. Cable-net form finding and analysis

The anticlastic geometry of the HiLo roof is required to balance aesthetic, functional and structural requirements and constraints, such as head clearance along evacuation routes, solar orientation for electricity production, maximum deformation of the cantilevers in relation to the glass facade, etc. A preliminary design of the shell was developed using a multi-objective optimisation process as described in [7], where the number and location of the supports, as well as the overall shape of the structure were determined.

The preliminary design was reworked to incorporate the latest requirements and architectural decision. This process was carried out using the data-structures and algorithms for patterning, smoothing, fitting and structural analysis available in the COMPAS framework [14].

The process was comprised of the following main steps:

1. Define the pattern of the cable-net that will be used in the formwork.
2. Define a feasible target shell geometry using this cable-net as a form finding mechanism.
3. Design a balanced cable-net layout on the target taking into account geometric constraints related to features of the space below.
4. Find a distribution of forces for the designed cable-net geometry that

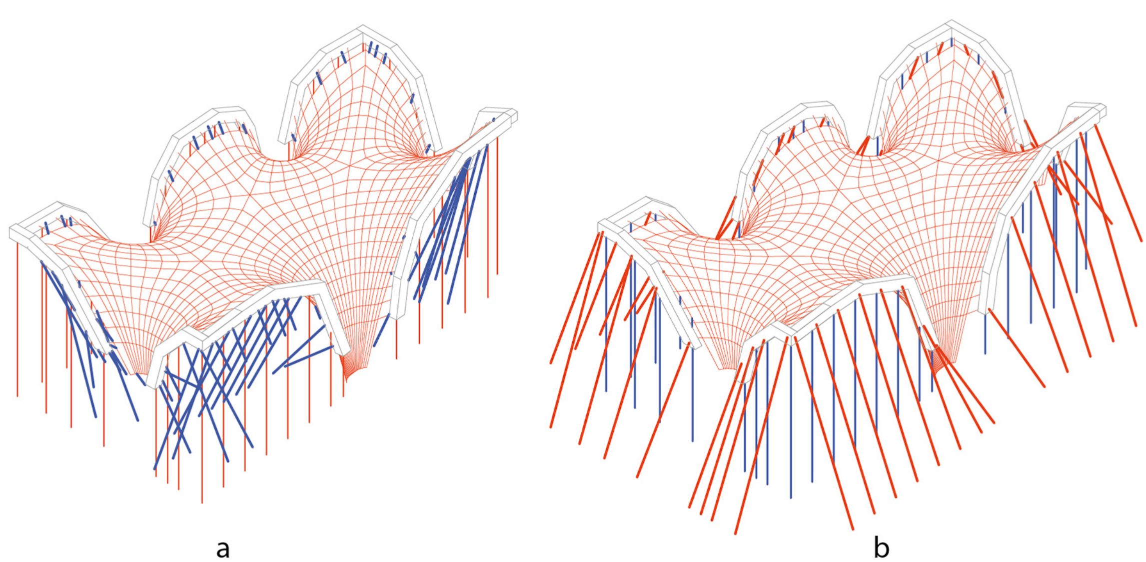

Fig. 4. Scaffolding props for the roof prototype on the inside of the boundary beams (a) in compression (blue), and outside (b) in tension (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

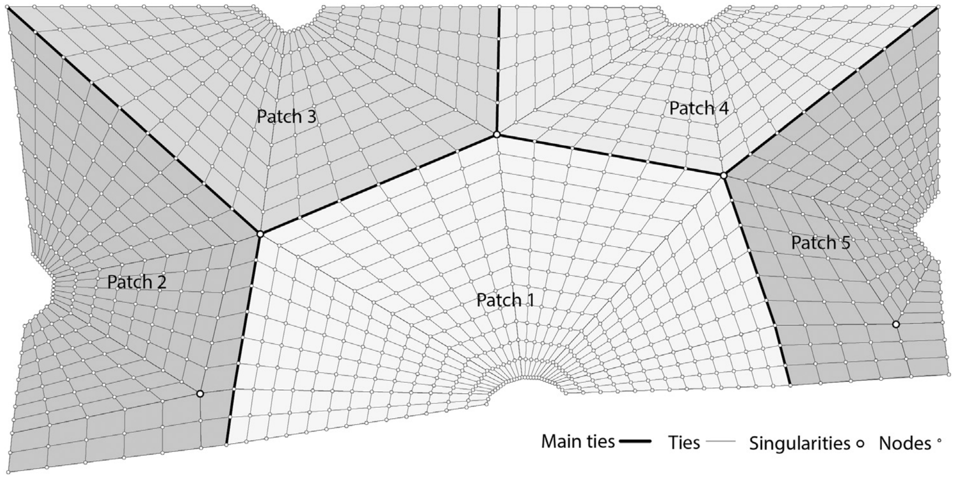

Fig. 5. HiLo roof cable-net pattern.

matches the target shell geometry as closely as possible when loaded with wet concrete.

The structural analysis and fabrication design of the cable-net were developed simultaneously as part of an integrated process until an optimal solution was found. This was necessary because requirements of one process served as constraints for the other and vice versa. For example, the bounds on the force densities for the form finding procedure were derived from the allowable stress in the elements that were sized based on constraints related to the fabrication and assembly process.

3.1. Pattern design

The pattern of the cable-net structure is a quad mesh consisting of five patches and with five extraordinary vertices (singularities), as shown in Fig. 5. Each patch creates a funnel towards its corresponding support and thus the lowest anchoring points of the net, while the boundaries between the patches create a set of main structural lines connected to the highest anchoring points. These main lines (spine), which control the overall geometry of the cable-net, are largely responsible for generating prestress and carry the bulk of the forces generated from the weight of the concrete. The density of the pattern is designed to reduce the number of tie segments and nodes, as well as control costs and fabrication time and avoid congestion of the funnels towards the supports while maintaining acceptably small face sizes in the central regions of the net. Controlling the size of the faces is important because it influences the magnitude of the pillowing of the fabric shuttering between the cables and thus the amount of additional, non-structural dead load carried by the shell. The resulting cable-net pattern has 94 anchor points, 2015 cable or rod segments, 957 faces, and 953 nodes.

3.2. Target geometry

Having defined the topology, density and connectivity of the cable elements, the target mesh was generated. The mesh geometry was designed manually using an interactive form-finding tool based on the force density method as implemented in COMPAS, following as closely as possible the preliminary design. The mesh was subsequently subdivided and smoothened. For this purpose, a smoothing algorithm was applied that works by moving the vertices to the average location of the centroids of the surrounding faces, weighted by the respective face areas. Specific groups of cable elements were constrained to straight lines corresponding to the HiLo unit's glass facade to be installed underneath (Fig. 6). This not only significantly simplifies the connections between the glass and the concrete, but also allows for the glass to be cleanly integrated in between the pillows of the surface and never across.

3.3. Distribution of prestress

A cable-net is an anticlastic, form-active system with tensile force members and thus no bending capacity. Form-active systems change geometry under the influence of applied loads to reach a new equilibrium state. To limit potentially large displacements, anticlastic systems can be prestressed. Theoretically, prestress could be increased until it fully negates the effects of the applied loads, but practical limitations on element sizes, foundations and anchoring points require an equilibrium state to be found within reasonable bounds.

For the formwork system, a specific non-uniform distribution of prestress was determined that allows the cable-net to deflect under the weight of the wet concrete into the desired shape of the shell, without exceeding the capacity of the members at any stage of the construction sequence. The allowable forces in the system are limited by the maximum size of the components of the cable-net resulting from constraints related to the fabrication process and the required degrees of freedom at the nodes, and by the magnitude of the reaction forces that can be taken by the supporting scaffolding structure. In addition, the forces are distributed such that they yield a smooth spatial layout of cables, as these leave a clear imprint on the bottom surface of the shell and thus be visible from below. Finally, the continuous lines of cables corresponding to the glass facade below should be perfectly straight in plan as described above.

The process of finding the non-uniform distribution of prestress consisted of the following steps:

1. The cable-net mesh is remapped to the target geometry while allowing its vertices to slide over this mesh and along the constraint curves corresponding to the boundaries and the facade lines, until a balanced distribution of faces is obtained.
2. A fitting procedure is used to find a distribution of forces, within the bounds determined by the maximum element and reaction forces, that minimises the difference between the corresponding equilibrium state and the current target geometry of the shell. This is a convex optimisation problem, which was solved with an iterative procedure built using CVXPY [15].
3. The resulting geometry from the fitting process must be post-processed with the purpose of eliminating residual forces and smoothing the final geometry.

Fig. 6 shows the non-uniform distribution of prestress that resulted

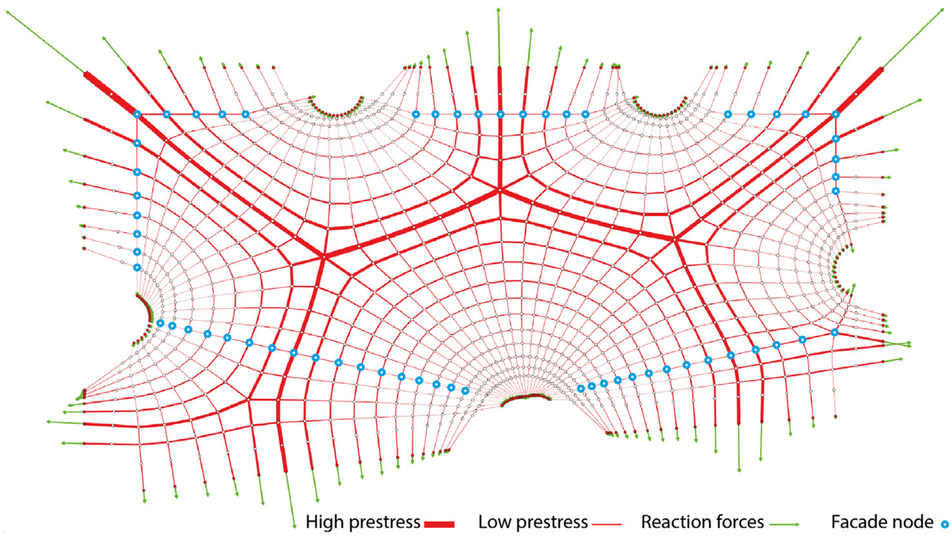

Fig. 6. Non-uniform distribution of prestress resulting from the fitting and optimisation process.

from the fitting process. It shows that the highest prestressed members are those along the spine of the cable-net, and those immediately adjacent. Fig. 6 also shows that the resulting geometry respects the facade line constraints, as required by the project.

3.4. Cable-net analysis

The cable-net geometry resulting from the form-finding process corresponds to the prestressed and loaded structure. It was then necessary to determine the unstressed geometry as well as the prestressed geometry without the load of the concrete. This can only be done once the materials and sizes of all of the cable-net components have been determined. An iterative sizing and analysis process is required to determine the appropriate sizes for all members in all loading cases, as it is not necessarily the case that the highest stresses are present in the loaded state for all members. This was done with the use of a cable-net structural model based on Dynamic Relaxation.

As shown in Fig. 7, five main types of elements were used to materialise the cable-net: 6 mm ø steel cables, 8 mm ø steel cables, 8 mm ø steel rods, 9 mm ø steel rods, and double 10 mm ø steel rods. The cable material model was based on a bi-linear stress-strain curve with two stages represented by $E_1 = 50.45$ GPa and $E_2 = 72.50$ GPa. The solid steel rods used a linear elastic material model with $E = 210$ GPa. For the self-weight of the cable-net, the weights of the nodes and brackets, as well as the cables and rods, were all collected together as nodal loads. The weight of the fabric membrane was also added as equivalent nodal loads based on the tributary area around each node and the unit weight of the membrane.

For the Dynamic Relaxation structural model, a tolerance of 1 N on the nodal residual forces was used for the static equilibrium of the cable-net, which when compared to the applied force values at the nodes, was accurate to the order of 0.1–0.5 %.

4. Fabrication

The success of the cable-net and fabric formwork system relies on the accurate fabrication of precise cable and rod elements, node components, fabric shuttering and timber boundary beams. For this reason, these elements were digitally fabricated by specialised industrial partners in Switzerland. These partners participated in the planning of most of the components to improve precision, reduce cost, and insure that everything could be fabricated with their machines. This section describes the digital fabrication processes of the main elements of the cable-net and fabric formwork system.

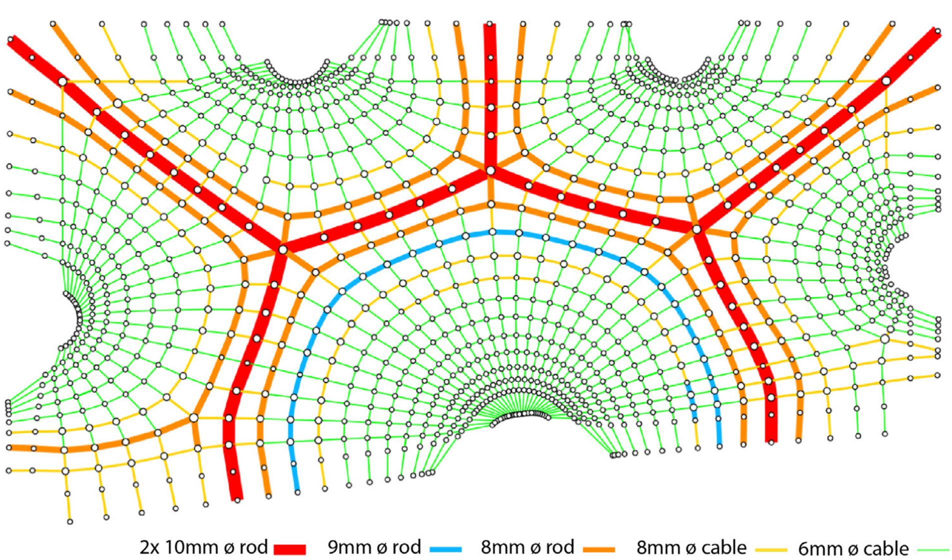

Fig. 7. The Network data-structure contained important fabrication information, as highlighted by the colours of the differently sized cables/rods, brackets and node rings. This information was used to create the materialised structural model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Cable-net fabrication (a) cables being cut to size, (b) node ring being milled.

4.1. Cable-net

Each individual cable was cut to its unique length (Fig. 8a) and then swaged and labeled. The cables were connected to the rings by means of brackets. These were designed to be made from flat steel sheets and pressed into their final configurations. The use of flat sheets reduced the price of the brackets considerably without any loss of functionality. The sizes of the brackets were the result of both the force magnitudes and the dimensions of the rings to which they connected.

The nodes were materialised as rings. There were four distinct types with diameters of 65 mm, 90 mm, 95 mm and 115 mm determined both by strength, fabrication and assembly constraints. To achieve the highest precision possible, and to ensure the required structural strength, the rings were milled from solid stainless steel discs (Fig. 8b). This digital machining process also allowed for the profile of the ring to be customised to maximise the cross-sectional area while still allowing for sufficient rotation of the ties to achieve the required angles. The largest node ring was used for the six-valent nodes of the cable-net.

4.2. Fabric shuttering

The fabric shuttering was shaped into the doubly curved geometry of the shell structure using machine cut fabric segments, all sewn into one single piece according to a predefined pattern with a specific amount of size compensation to generate a level of prestress that minimises sagging to the desired extent (Fig. 9). The seams of the fabric were aligned with the geometry of the cable-net to avoid leaving an additional imprint in the exposed concrete finish. The pattern was also constrained by the size of the fabric rolls and by the limitations of the CNC cutting machine. Finally, flaps were added to the sides of the segments to secure the fabric to the cable-net by wrapping around the cables on the underside of the shuttering. The flaps were discretised with small cuts at the locations of the nodes.

4.3. Timber boundary beams

Glulam timber boundary beams were fabricated using a 5-axis CNC mill. First bounding box cuts were made using a large robotic blade saw (Fig. 10a). Afterwards, at each anchor point a cylindrical hole was drilled through the beams for the boundary rods to pass through (Fig. 10b). At the outer edge, anchor planes were drilled into the beam at an angle perpendicular to the cable axis, ensuring that the cables would not bend after the net was tensioned and loaded (Fig. 10c). Perforations were also made for the beams to be connected to each other at their ends by bolted steel plates.

5. Construction

The HiLo roof prototype was constructed inside the Robotics Fabrication Lab of the Institute of Technology in Architecture at ETH Zürich over the course of five months (Fig. 11). The construction process consisted of: 1) the erection of the steel scaffolding members, 2) the hoisting and installation of the timber boundary beams, 3) the hoisting and anchoring of the cable-net and the fabric shuttering, 4) the tensioning of the cable-net, 5) the use of the control system to direct the cable-net closer to the designed target shape, 6) the installation of the

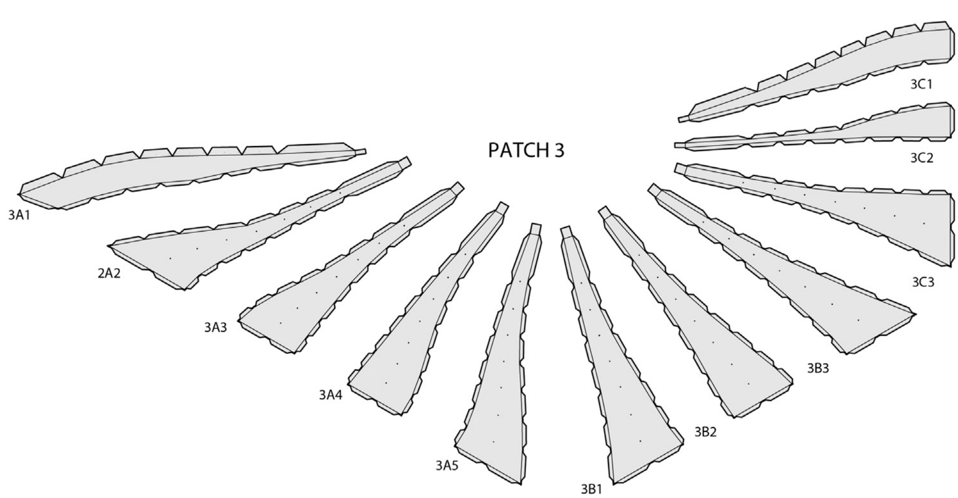

Fig. 9. Fabric shuttering pattern for Patch 3, showing flaps used to attach the fabric to the cable-net.

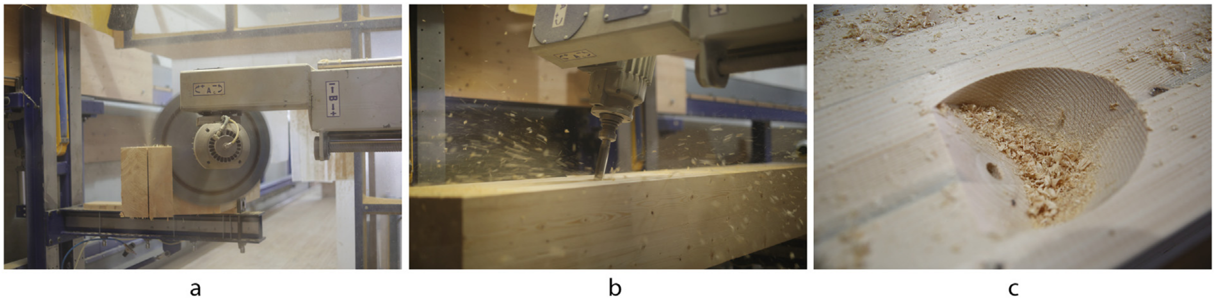

Fig. 10. Timber boundary beam fabrication. (a) Raw glulam cuts for initial sizing, (b) milling of anchoring plane for the cable-net, (c) finalised anchor point with perforation for the cables.

carbon-fibre reinforcement, and, finally, 7) the concrete spraying. Each of these steps are described in more detail in this section.

5.1. Scaffolding, boundary beams and steel supports

The scaffolding consisted of vertical props, vertical ties and diagonal props. The vertical props were installed first to support the timber boundary beams. The beams arrived on the construction site as single straight sections and were assembled on the ground using splicing steel plates and bolts. Once assembled, the beams were hoisted on top of the vertical props and connected using the precise anchoring positions etched into the wood. The scaffolding system's boundary edge was completed by bracing the beams using the diagonal props and vertical ties. All of these members were installed with the use of small forklifts and a spider crane. The standard scaffolding elements were bolted into the ground with M20 steel bolts.

The elevated supports for the touchdowns of the shell at the mezzanine level were made of custom steel landing plates and reusable scaffolding props. These elements had to be positioned with a high degree of precision as some of the cable-net anchors were located on these supports.

5.2. Cable-net and fabric installation

The installation of the cablenet and fabric was strongly influenced by the prototype's location within the confines of the Robotic Fabrication Hall, which precluded the use of a crane and demanded the exclusive use of aerial platforms to maneuver workers into the high anchoring positions. The cable-net was assembled into segments on the ground. The size and weight of the sub-assemblies were limited by the maximum amount that could be handled by two workers. The spine elements were assembled first and hoisted to their anchoring locations. The rest of the cable-net was then attached to that spine, segment by segment.

The fabric was delivered as one single element, making it difficult to handle without causing damage. For this reason, the fabric was rolled up, hoisted onto the spine of the cable-net, and then unrolled from the centre outwards towards the touchdown supports. The fabric was then attached to the cable-net at each node and the flaps stapled under the cables to fix it into position.

5.3. Target shape approximation by means of the control system

To achieve the required unloaded initial state of the system that allows the cable-net to deflect into the geometry of the final shell under the weight of the wet concrete, the boundary conditions were adjusted by using the on-site control system.

First, the boundary cables were set to the designed length in the digital model. The resulting real geometry was measured and compared to the designed version. Then, the deviations between the measured geometry and the digital model were compensated by adjusting the boundary conditions according to predictions made by the control

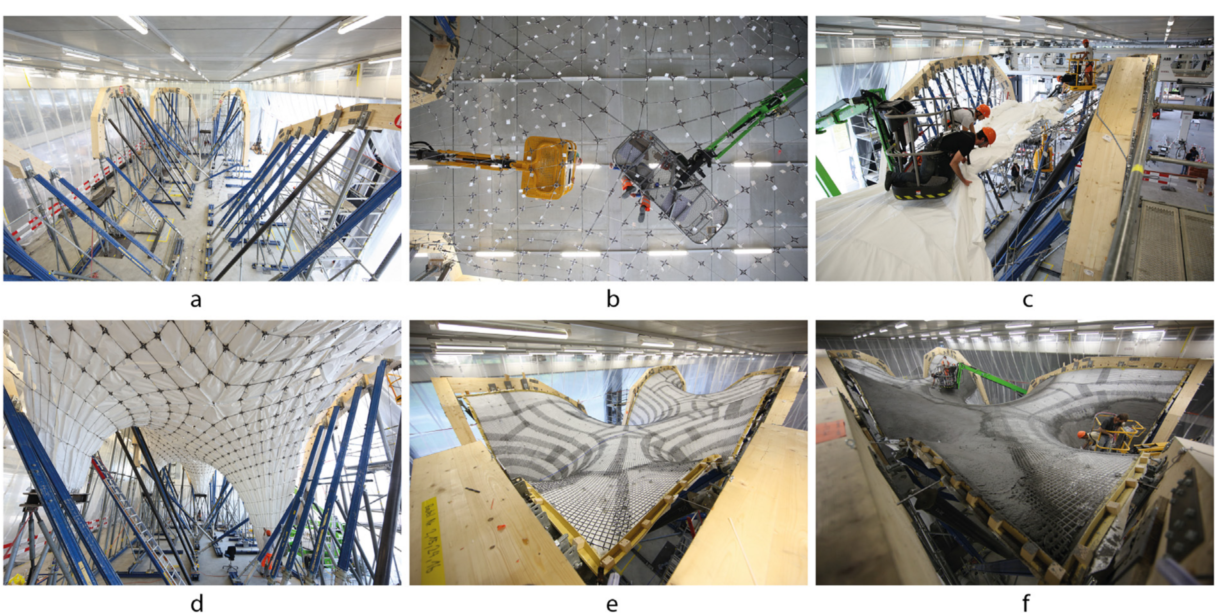

Fig. 11. Prototype construction sequence. a) Scaffolding and boundary beam, b) cable-net, c) fabric shuttering, d) tensioned system, e) reinforcement and f) concrete spraying.

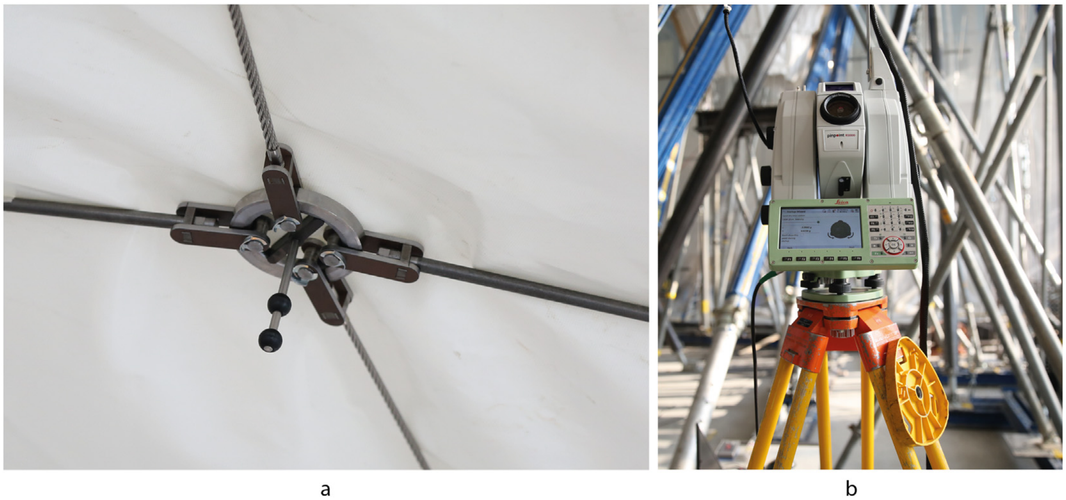

Fig. 12. A cable-net node with the two measurement spheres (a) and one of the Leica total stations used to record spatial coordinates (b).

algorithm.

Spatial point cloud data was recorded by the positions of the black spherical markers at the nodes (Fig. 13a) and circular stickers on the boundary beams, as measured by the image-based theodolite system (Fig. 12b). This system uses total stations with modified industrial CCD cameras inserted in place of the eyepiece and is able to provide sub-millimetre accuracy.

Post-processing was required on the raw data, which provided the coordinates of the spherical markers that were successfully recorded during each measurement session. First, data was filtered to ignore nodes that had only one measurement point, i.e. one sphere instead of two. When two points were present, the difference vector and the know distance to the centre of the rings could be used to determine the exact position of the nodes.

The Differential Evolution control algorithm described in Section 2.4 was used with a population of 20 individuals and an evolution with 2000 generations. The optimisation used the lengths of the boundary ties as variables, with a maximum adjustment of ± 25 mm. The equilibrium of the cable-net was calculated by the materialised model described in Section 3.4, with the objective function of the control algorithm being the minimisation of the mean norm between the simulated cable-net and the target or measured geometry. Any solutions with tie stresses that exceeded 600 MPa, where the cable material would start to yield, were penalised in the optimisation.

The initial spatial measurements of the cable-net showed that the mean deviations, or norms of the physical cable-net compared to the digital target shape, were 64 mm, with most deviations occurring around the northern side and around the main spine elements. The base-state with mean norm deviation of 64 mm is plotted in Fig. 13a, showing norms above 100 mm in red, 75–100 mm in orange, 50–75 mm in yellow, and all others in green. After only one round of the control process, mean norms reduced from 64 mm to 45 mm as plotted in Fig. 13b, where the majority of the improvements were found at the centre of the cable-net. Only one round of the control process was possible due to time constraints, and not all of the prescribed tightening was done due to problems with the anchor design of the main cables. With an improved method to tighten the boundary elements and with additional time for another control round, the 45 mm norms could have been reduced further to get the cable-net closer to the desired geometry.

5.4. Edge clamps

The edge clamps were delivered as a series of flat, CNC-cut, 3 mm MDF strips, cut to the required geometry and coated to avoid water absorption during concrete curing. The clamps were designed to be installed on top of the cable-net and to tightly secure the fabric between two strips that are oriented in the tangential direction of the surface. On top of the tangential strips, an additional strip was installed in the direction normal to the surface to stop the concrete from overflowing and precisely shape the edge of the shell.

5.5. Carbon-fibre reinforcement

The carbon-fibre mats were provided as 1.2 × 5 m flat panels. The panels can be bent in one direction up to a radius of curvature of 1 m. In order to successfully install them into position and adapt them to the doubly-curved shape of the HiLo roof, they were patterned and cut. The selected patterns took into account the curvature of the shell, placing the main axis of the mats in the direction of the highest curvature. Additionally, to guarantee a continuous tensile capacity, the carbon-

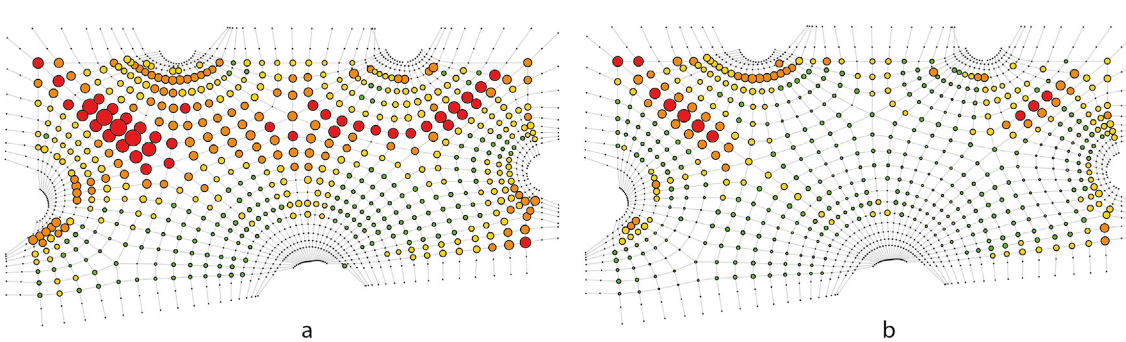

Fig. 13. Norm deviations between target shape and measured states, (a) the starting state of the cable-net, (b) the controlled state of the cable-net after one tightening sequence. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Fig. 14. The finalised HiLo roof Prototype.

fibre mats overlapped each other on all sides by at least 20 cm.

5.6. Concrete spraying

Given the complex geometry of the structure, the best possible method for the application of the concrete was spraying from aerial platforms. A concrete material was designed to be sprayable onto the fabric formwork even at near vertical orientations. The concrete was mixed on-site in small batches and pumped into long plastic hoses at low pressures to avoid damaging the fabric. Workers applied the concrete to cover the entire surface of the shell structure, using the threaded rods at each node as guides to achieve the desired concrete thickness. The deposited concrete did not always penetrate the carbon-fibre mats sufficiently for good bond and cover. To reduce the formation of air voids, a vibrating trowel was used to push and compact the concrete through and around the reinforcement.

The entire shell was sprayed in one continuous process with the intention of avoiding the formation of cold joints in the concrete. Due to the use of only two pumps and mixing stations, combined with frequent blockages in the hoses, the process was not as efficient as planned, lasting for a total of 36 h instead of the estimated 12.

5.7. Shell decentering

The concrete was left to cure for 15 days before the scaffolding was removed. This process started by detaching the nodes from the concrete and consequently releasing the tension on the cables by loosening them from the boundary beams. At this point in time, with the cable-net no longer supporting the concrete, the shell structure was free-stranding with no external forces acting on the boundary beams or scaffolding. These final scaffolding members were disconnected from their anchors on the ground and removed using small forklifts and spider cranes.

6. Conclusions

This paper presented the design, development and construction of a full-scale prototype of a thin concrete shell built with a cable-net and fabric formwork system. The construction of the prototype served as a proof of concept experiment of the novel construction system under real-world conditions (Fig. 14). It was shown that, using this system, it was possible to build the shell with considerable efficiency and precision. With the exception of the fabric and edge clamps, all of the elements of the formwork system are completely reusable, significantly reducing the material waste associated with shell construction. The custom-designed node of the cable-net simplified the installation of the fabric shuttering and carbon-fibre-mesh reinforcement, and thereby facilitated the on-site logistics during the construction of the shell structure. A geometry control system was employed to steer the shape of the formwork towards the designed shape. Although the entire experiment was a success, the construction of the prototype revealed the following potential areas of improvement:

- Precise control over the tightening or loosening of the boundary rods is essential to the success of the control system. However, the high forces in the boundary elements of the spine of the net were very difficult to apply manually.
- The designed concrete mix proved to be difficult to work with in high volumes, requiring long mixing times for small batches. This caused the spraying process to be slow and prone to hose blockages, causing the spraying time to be much longer than anticipated.
- The use of two layers of fabric (one for texture and another for moisture control) proved to be cumbersome during its installation.

These issues will be considered in an updated version of the system for the construction of the HiLo roof in 2019. The construction process lasted for 5 months, including several interruptions due to necessary on-the-fly adjustments to the system and related delays in supply of material and components. The construction process was also slowed due to the location of the prototype in the RFL and the inability to use a crane in this tight space. The construction time for the roof in for the HiLo site was estimated at three and a half months.

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Appendix A. Making of the HiLo roof prototype

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