KNITNERVI
LIGHTNESS AND TAILORED MATERIALITY FOR FLEXIBLE CONCRETE CONSTRUCTION

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The significant impact of the construction sector on the environment demands a rethinking of design and construction practices towards more sustainable solutions. While reinforced concrete is the most commonly selected construction material due to its affordability and durability, its excessive use is a major contributor to global CO2 emissions and resource depletion (Lehne and Preston, 2018).

This paper describes the design, development, and construction of the *KnitNervi* prototype (Figs. 1, 2), which proposes an integrated flexible formwork system with bending-active falsework and 3D-knitted shuttering. The prototype was built for the Technoscape: The Architecture of Engineering exhibition, which ran from October 2022 to April 2023 at the MAXXI Museum in Rome, Italy (Casciato and Ciorra, 2023). The demonstrator was installed in the museum's entrance piazza and celebrated expressive and efficient structures, and interdisciplinary co-development in architecture, engineering, and construction. *KnitNervi* reimagines the compression-only dome structure of the Palazzetto dello Sport as a funnel-shaped (concrete) skeleton with a droplet-shaped central support.

The structure has a 9m outer diameter and a 3.5m inner diameter on plan, and stands at 3.3m tall. The structural skeleton is made up of a diagrid of compressive prismatic ribs connected to a boundary ring in tension. Due to the temporary nature of the installation, concrete was not cast into the diagrid rib structure. Rather, the focus of the demonstrator was on further developing a formwork system using 3D-knitted textiles, which is deployed using elastic bending to reduce the number of supports required and the amount of waste produced during construction, and to integrate controlled knitting detailing for both fabrication and construction. The absence of cast concrete on site allowed non-specialist visitors to the exhibition to see how structures are built up with a translucent textile, offering an 'x-ray through the structure' effect.

Alternative forming strategies

In current design and construction practices, the overuse of reinforced concrete largely derives from relying on it to provide structural performance through material strength, especially for large rectilinear spans. In contrast, structurally informed, compression-dominant, doubly curved, and rib-stiffened geometries can achieve the same performance with significant reduction in material use by

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obtaining their strength from their structure geometry rather than material strength (Block *et al.*, 2020). However, their articulated, non-standard geometry gives rise to construction challenges such as costly, materially wasteful moulds, and difficult to place and shape custom reinforcement. As such, conventional construction approaches can be among the primary obstacles for implementing materially efficient designs. As a result, innovative formwork solutions are needed.

To address these challenges, this paper presents a flexible formwork system developed as an alternative to traditional formwork solutions. Using a flexible membrane in formwork assembly offers new possibilities in structural, architectural, and manufacturing applications through simple means (West, 2016). The use of flexible formwork technologies relying on tensioned fabrics as moulds for concrete has been explored and successfully used since the late 1800s. An extensive overview of flexible formwork technologies is given by Hawkins *et al.* (2016). The system presented in this paper is an evolution of the KnitCrete flexible formwork system using 3D-knitted textiles (Popescu *et al.*, 2021). The approach represents an improvement over previous work through integrating the reinforcement and eliminating custom single-use external supports. This is achieved using a bending-active grid-shell as stay-in-place falsework in combination with a 3D-knitted shuttering to jointly create the formwork for a ribbed concrete structure.

Active bending allows slender elements to undergo elastic deformation and form 3D curved geometries without the need for additional intermediate supports (Lienhard, 2014). While flexible formworks based on tensile systems only allow for anticlastic geometries, using an active bending falsework allows for both anticlastic and synclastic geometries. Several explorations have been conducted on bending-active falseworks, including the use of textile shuttering and grid-shells (Tang and Pedreschi, 2015; Cuvilliers *et al.*, 2017). Combining bending-active systems with knitted textile membranes brings additional challenges in terms of simulating and modelling their hybrid interaction. These types of hybrid systems have been explored and developed in various demonstrators (Ramsgaard Thomsen *et al.*, 2018; Ramsgaard Thomsen *et al.*, 2015; Ahlquist *et al.*, 2013).

Integrated structure and formwork

The double-layered grid-shell structure is created by elastically bending slender straight rebars, eliminating the need for falsework. Its locked-in curved geometry provides sufficient stiffness while supporting the textile shuttering and ultimately being integrated into the concrete grid-shell as reinforcement. The structure of the bending-active grid-shell is determined through a form-finding process carried out with SOFiSTiK. The lengths and crossing positions of the splines serve as input for the third-order analysis, which equilibrates the system to achieve the form-found shape (Scheder-Bieschin *et al.*, 2022).

1. KnitNervi: Inner view of finished formwork system demonstrator. © Mariana Popescu.

2. Finished KnitNervi demonstrator at the MAXXI Museum in Rome. © Minu Lee.


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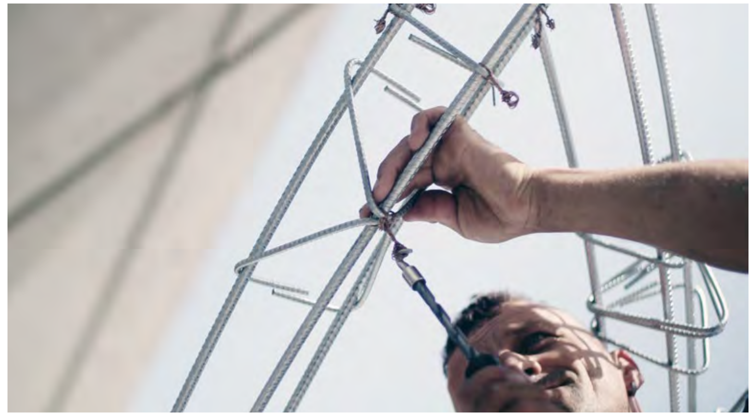
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3. Birds-eye view of the bending-active grid-shell during assembly. © Serban Bodea.

4. Assembly of grid-shell stirrups during construction of KnitNervi's bending-active grid-shell. © Thom-de-Bie.

5. Bending-active rebar grid-shell of the KnitNervi demonstrator. © Thom-de-Bie.

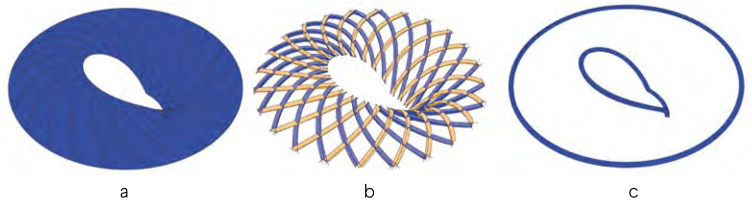
6. Measurement of bending-active grid-shell after assembly. © Thom-de-Bie.

The shell's diagrid structure is made up of triangular rebar cages (referred to as ribs) radially positioned in two opposing directions. The cross-section of these ribs consists of three splines laid out as a pair on top and a single spline at the bottom (Fig. 8a). To ensure sufficient stiffness and shape control, the two layers are connected with stirrups. Inclined, triangulating stirrups are used as shear-connectors between the top and bottom splines, while additional orthogonal stirrups maintain a consistent spacing between the longitudinal rebar splines. Together with the longitudinal splines, the stirrups create the rebar cage that remains in place as reinforcement for the concrete ribs. Akin to standard rebar spacers in construction, a simple custom 3D-printed spacer is fitted onto the rebar cage (Fig. 8a) to help tension the knitted textile shuttering into shape at the desired distance between shuttering and reinforcement. In a final tensioned state, the textile is coated with an eco-friendly clear resin that provides sufficient stiffness for concrete to be cast into the ribs without significant deformation of the formwork.

Production streamlining

A fundamental component of designing and fabricating such systems is an integrative design-to-fabrication workflow. By developing and using open and versatile computational framework COMPAS (Van Mele *et al.*, 2022), fabrication constraints are considered both in the form-finding and further engineering of the bending-active falsework's geometry (Scheder-Bieschin *et al.*, 2023) and the design and fabrication of the 3D-knitted shuttering.

The construction process of *KnitNervi* can be divided globally into two parts: 1) build-up of the bending-active grid-shell forming the rebar cage, and 2) build-up and assembly of the knitted shuttering. Each of these parts in turn consisted of two phases – a prefabrication and an in-situ assembly phase. In both cases, the prefabrication phase was geared towards creating a compact, lightweight, and easy-to-transport kit-of-parts to swiftly assemble on site.



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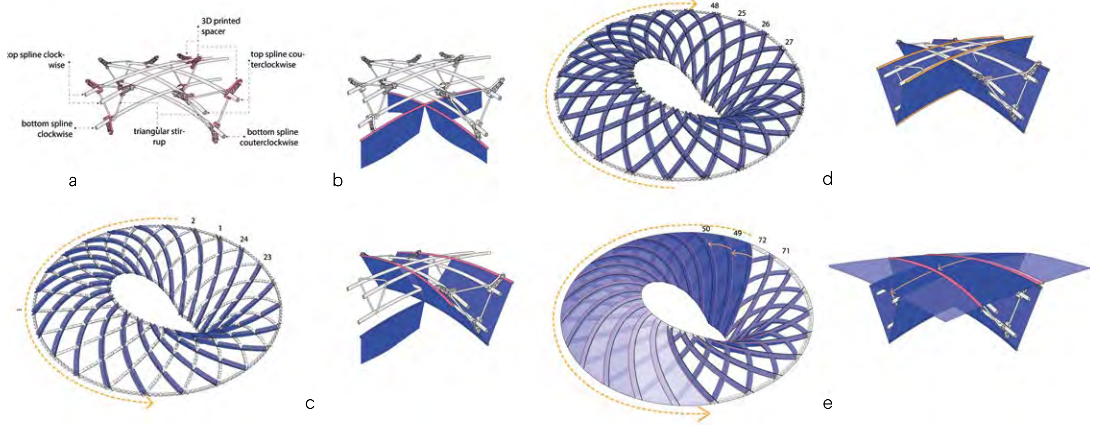
7. Segmentation for production of the textile shuttering: a) 24 segments for the top surface spanning between two ribs, b) 24 rib segments in clockwise direction (yellow) and 24 rib segments in counterclockwise direction (blue), and c) edge-ring segments.



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8. Sequence of attaching textile shuttering to the structure: a) attaching 3D printed spacers onto the rebar splines, b) attaching rib segments in both directions to the bottom spline, c) attaching rib segments in counterclockwise direction, d) attaching rib segments in clockwise direction, and e) attaching top surface.

Grid-shell falsework

The structure's main skeleton consists of two prefabricated boundary edge-rings, connected by bending-active grid-shell ribs. All fabrication data for the structure was derived from the computational model (Scheder-Bieschin *et al.*, 2022). The rebars, triangular stirrups, and edge-rings were prefabricated as a kit-of-parts. While the rebar splines were cut to size and stirrups were bent, the inner and outer edge-rings were prefabricated in two and six segments, respectively, by guiding splines through jig plates to maintain the desired shape. Each segment was then welded together using spline connectors.

To assemble the shell on site, scaffolding props were installed to support the grid-shell's inner and outer edge-ring segments. Telescopic props were used to adjust their height. The grid-shell ribs were then installed by sequentially connecting rebar splines to both edge rings (Fig. 3). This process began by attaching the top two splines of the triangular rib section in both directions and connecting them at marked crossings using rebar ties (Fig. 4).

While the stirrups were left hanging from the top splines in their respective sections, the lower spline was inserted through and connected to the edge-rings. Similar to the top layer, the bottom splines were connected at the marked crossings using rebar ties. Once all the elements were in place, the stirrups were moved into position along the splines and tied using rebar ties to ensure a consistent spacing and lock the grid-shell into shape (Fig. 5).

A total station was used to accurately align the structure according to the designed geometry. Measurements were taken at different stages of the assembly, including aligning the position of the edge-rings, monitoring the shape development of the grid-shell towards the desired form, and assessing the precision of the completed structure (Scheder-Bieschin *et al.*, 2023) (Fig. 6). These measurements also provided input for the fabrication pipeline of the knitted textile shuttering.

Knitted shuttering

Measurement data collected from the assembled grid-shell falsework was used to adjust and fine-tune the fabrication of knitted textile components. The ready-to-go streamlined production pipeline, coupled with on-site measured data, enabled a just-in-time delivery approach, ensuring that each component was manufactured precisely to fit its intended location in the structure.

The shuttering's 3D surface was defined using curves representing the correct offset from the primary grid-shell structure. This included a top-layer surface that covered the entire area of the demonstrator, including a membrane between the diagrid members, and bottom surfaces for the triangular ribs in both directions.

For production purposes, the geometry was divided into 24 parts along the radial direction of the diagrid ribs in a counterclockwise direction. Each segment corresponded to the distance between two adjacent ribs. The entire demonstrator was made up of a total of 74 knitted parts: 24 parts for the top surface (Fig. 7a), 24 parts for the clockwise direction of rib segments (yellow in Fig. 7b), 24 parts for the counterclockwise direction of the rib segments (blue in Fig. 7b), and two parts for the edge-ring segments (Fig. 7c).

Aside from addressing fabrication size limitations, this segmentation also facilitated on-site handling and allowed for construction with a minimal number of workers. Additionally, it reduced computational intensity for generating the fabrication files and contributed to a better-controlled workflow. The textile design and production workflows are described in more detail in the following section.

Once produced, the textile parts were ready to be installed. First, thin rods were passed through channels in the textile while still on the ground, and ropes were placed in channels corresponding to the rib intersections. To tension the textile shuttering onto the grid-shell, 3D-printed spacers were fitted onto the falsework structure along all splines (Fig. 8a). These spacers were designed to easily clip onto the rebars with 'feet' that locked them into the right angle when inserted next to the distancing stirrups. Each spacer had three grippers into which the guide bars of the textile parts could be snapped. This allowed adjacent textile parts to fit perfectly next to each other without the need for sewing. This strategy enabled the structure to be disassembled into the constituent kit-of-parts without the need for cutting.

Attaching the textile shuttering to the structure was done in a specific sequence. First, the rib segments in the counterclockwise direction were attached to the bottom spline, leaving the sides hanging. Then, the rib segments in the clockwise direction were attached to the bottom splines (Figs. 8b, 9). The sides of the rib segments were then raised and attached to the structure using rods passed through channels in the textile (Fig. 8c). The same procedure was applied to raise the sides of the counterclockwise rib segments (Fig. 8d). With all sides of

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9. Textile rib segments attached and hanging from the bottom splines of the grid-shell. © Mariana Popescu.

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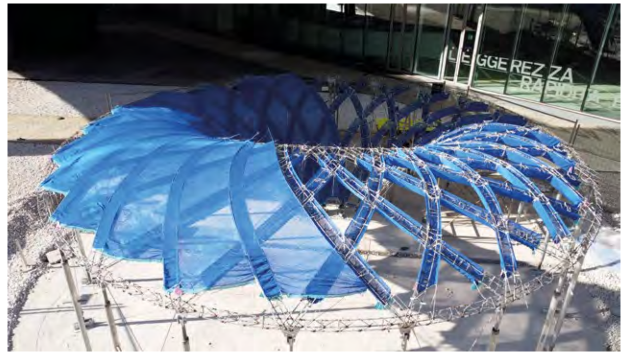
10. Assembly of 3D-knitted textile on bending-active grid-shell. © Achilleas Xydis.



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11. Birds-eye view of knitted textile during assembly. © Mariana Popescu.

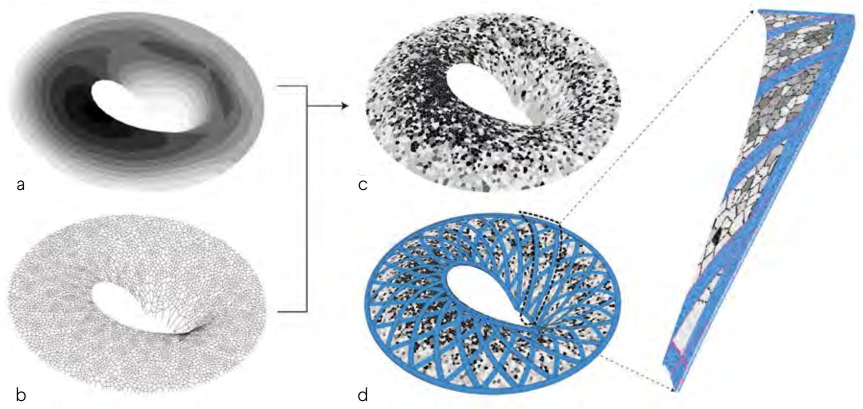
the rib segments raised, the node crossings were adjusted into position and tied with ropes previously inserted in channels at the intersection edges of the textile. After attaching and tying all the ribs, the top surfaces were placed into position in a radial sequence (Figs. 8e, 10, 11). Finally, the edge-ring rib segments were attached in the same way as the diagrid rib segments.

Controlled material properties

The textile's texture, density, and overall stitch-level architecture were designed with a hierarchy of functions. The rib sections, which would serve as formwork for casting concrete, have a denser texture, while the interstitial surfaces not used for casting were designed with a pattern of varying local densities. The distinction between porous and dense regions on the knitted surface is based on a conceptual definition of light and dark zones. The design intent was to have denser, more massive, and less transparent areas close to the ground and the periphery, while the areas close to the centre of the surface were designed to be lighter and porous. These zones were defined in Grasshopper3D using custom line and point magnetic fields that represented the desired level of transparency in each region (Fig. 12a).

Once the light/dark zones were established, the shuttering surface was divided into polygonal regions of various sizes. The regions labelled as 'dark' were subdivided into smaller regions compared with the 'light' zones (Fig. 12b). Each polygonal region was assigned a porosity value between 20% and 80%, which was represented in the model by the lightness of the grey colour assigned to each region (Fig. 12c). A darker grey indicated a higher porosity of the corresponding knitted surface.

The knitting patterns for each of the 74 parts were generated using the compas_knit package, as described in Popescu *et al.* (2017) and Popescu (2019). The patterns were colour-coded to mark functional features, such as channels, as well as regions of different porosity (Fig. 12d). The patterns were exported as BMP-format images (Fig. 13a) and post-processed using a custom Python script before being imported into the proprietary machine software. The post-processing aimed to transition from a pixel image where colour zones represent different porosity areas to a pixel image where each colour represents a distinct operation for the machine. This was done in two post-processing steps. Each pixel within the generated patterns represented a 4-loop-by-4-loop region on the machine. As such, the first step was to refine the pixels in the image to represent each needle position on the machine instead of a 4 x 4 region (Fig. 13b). In the second post-processing step, transfer stitches (Fig. 13d) were added to populate large interlock stitch (Fig. 13c) regions based on the assigned porosity value. These transfer stitches form a small hole within the produced textile, thus creating variations in the local density of the pattern.



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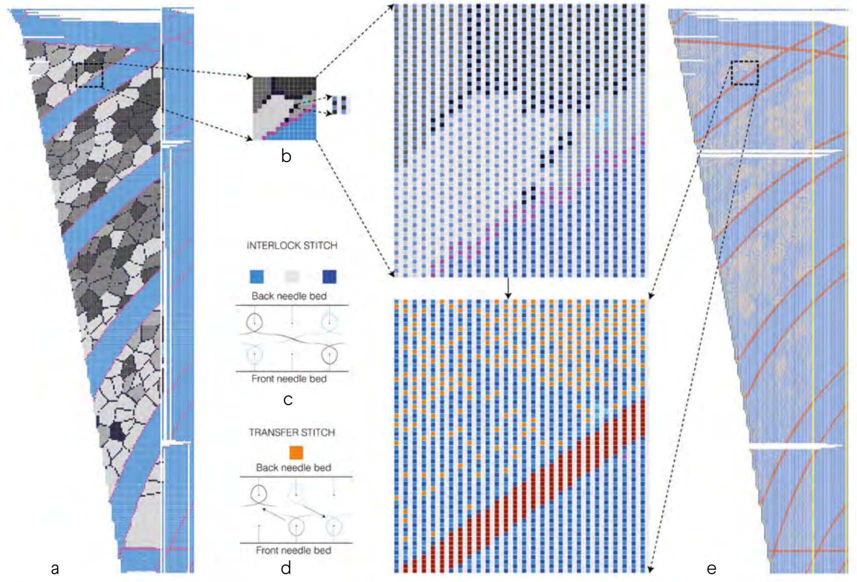

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12. Density regions and 3D-generated knitting patterns: a) fields representing desired transparency levels, b) polygonal regions for defining porosity values based on regions, c) porosity regions, and d) generated knitting patterns in 3D.

13. 2D knitting patterns and their refinement: a) 2D knitting pattern exported as BMP, b) first refinement step where each pixel is further represented as a 4x4-pixel pattern representing machine operations, c) interlock stitch operations, d) transfer stitch operation, and e) final post-processed image to be imported into machine software.

14. Detailed inner view of textile of finished KnitNervi demonstrator. © Mariana Popescu.

The post-processed BMP image (Fig. 13e) was then imported into the CNC knitting machine's software, where each colour was assigned a symbol from a custom-made library. Machine instructions were generated by translating each symbol into a distinct machine operation and combination of settings. The instruction files were used to fabricate the parts on a Steiger Vega T 3.130 CNC weft-knitting machine.

Discussion and outlook

The system described in this paper presents a computational workflow for the design and fabrication of flexible formwork systems. Such systems have the potential to address the challenges of forming and reinforcing complex structural geometry, as showcased on the ribbed shell formwork of the *KnitNervi* demonstrator (Fig. 15). The proposed structure combines design, structural engineering, and fabrication, integrating reinforcement and knitted shuttering into a single stay-in-place formwork. It eliminates the need for expensive custom moulds and pre-bent rebar cages. Additionally, the system is lightweight, self-contained, and self-supporting. It can be flat-packed for transport and easily deployed using a kit-of-parts approach, without the need for cranes or other heavy equipment. The construction process for both the rebar skeleton and knitted shuttering followed standard strategies and used common construction site tools. It involved a small team of skilled workers and was completed in two two-week sessions. However, working with such systems requires precision and diligence in construction, as well as a delicate touch and a rethink of building site accessibility. The sequencing of the build-up was crucial, making the process more vulnerable to mistakes. In this context, construction crews for such structures need to have an affinity for meticulous work and patience.

In light of the choice not to cast concrete into the structure, the demonstrator was unable to provide a full validation of the construction system for casting. In spite of this limitation, preliminary tests were conducted to assess the system's ability to withstand

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hydrostatic pressure during casting. Triangular-section beams, measuring 1.5m in height, were successfully cast vertically in one go, displaying zero or minimal deformation. In addition, a node section was cast and showcased in the exhibition. These tests demonstrated the feasibility of the approach for casting purposes; however, further investigation is required to determine the casting sequencing for the entire geometry.

With the ultimate goal of casting the structure, the design and assembly methods of the demonstrator were developed not only to be easy to assemble but also to allow disassembly into its constituent parts such that it could be rebuilt in a permanent location. This approach reflects on future-proof strategies with modularity and reuse in mind. By creating a shuttering that can be easily disassembled, there is potential to separate the stay-in-place knitted shuttering part of the formwork from the structure once it is cast, and potentially reuse it in the future.

Efficient computational pipelines for design have enabled the effortless extraction of fabrication data. This makes it possible to produce a kit-of-parts and split the construction of the grid-shell and knitted shuttering. This split provides time for waiting for a measurement of the as-built geometry, which is then used as input for fabricating the textile. The textile is measured and produced to fit accordingly.

Overall, by breaking away from standardisation paradigms, this demonstrator highlights the importance of sustainable construction practices and enables the building of expressive and efficient concrete structures. By using innovative design and manufacturing techniques, and addressing the challenges of materialisation, this flexible formwork approach could eventually help reduce the environmental impact of the construction industry.

15. Birds-eye view of finished KnitNervi demonstrator. © Mariana Popescu.

Acknowledgements

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TU Delft: Mariana Popescu, Nikoletta Christidi

Project and site construction coordination
ETHZ BRG: Serban Bodea
TU Delft: Mariana Popescu

Sponsors

NCCR Digital Fabrication, ETH Zürich; Debrunner Acifer; Doka Switzerland; Doka Italy; Pletscher Metallbau AG; Jakob Rope Systems; NOWN; Symme3D

The research presented in this paper was supported by the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement # 51NF40-141853).

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