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Building in Concrete with an Ultra-lightweight Knitted Stay-in-place Formwork: Prototype of a Concrete Shell Bridge

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ABSTRACT

A novel formwork system is presented as a material saving, labour reducing and cost-effective solution for the casting of bespoke doubly curved concrete geometries. The approach uses a custom knit technical textile as a lightweight stay-in-place formwork with integrated solutions for the insertion of additional elements, and is fabricated as a nearly seamless fabric. Using weft knitting as the textile formation technique minimises the need for cutting patterns, sewing, welding or gluing, when compared to conventional weaving and gives the possibility to integrate channels, openings, have varying widths and directional material properties, thus broadening the geometric design space. The system has been tested through a small-scale concrete footbridge prototype, built using a pre-stressed hybrid knitted textile and a bending-active structure that acted as a waste-free, stay-in-place, self-supporting formwork. Through the gradual buildup of strength in thin layers of concrete, formwork deformations during casting were minimised. This allowed for low tensioning levels of the fabric and the possibility to use higher pressure (e.g. during shotcreting) in applying the subsequent concrete without intermediate support from below. The computational design and fabrication of the knitted textile formwork included integrated channels for the insertion of bending-active rods, tensioning ribbons and features for controlling the concrete casting. The analysis and process of increasing the stiffness of the lightweight and flexible formwork is presented. The hybrid approach results in an ultra-lightweight formwork that is easily transportable and significantly reduces the need for falsework support and scaffolding, which has many advantages on the construction site.

1. Introduction

Advancements in computational methods and CAD environments have enabled architects to easily explore intricate geometries, leading to the question of how to build these forms. While digital fabrication has created new opportunities for the fabrication of complex and unique forms, controlling the costs and using material efficiently in custom concrete construction still remains a challenge.

In the construction industry, the most common formwork solutions for simplifying the creation of single-curved concrete elements are reconfigurable modular systems such as the Peri Rundflex [1], RMD Kwikform Trapeze [2] and Doka H20 [3].

Formwork for doubly-curved surfaces is typically created from timber or foam by using subtractive fabrication methods [4]. Especially when the formwork is used only once, this results in excessive material waste and high costs of up to 75% of the total production costs of the concrete structure [5]. Furthermore, these formwork systems need significant falsework and scaffolding, which further reduces site accessibility and can impose additional demands on the foundations.

Various adaptive formwork systems have been investigated for more efficient manufacturing of bespoke concrete elements. For example, the doubly curved cladding elements of the Arnhem train station in The Netherlands, were manufactured using a flexible mould that could be reconfigured with linear actuators [6-8]. Other examples of adaptable systems are flexible moulds [9] combined with reshapable materials such as wax [10] and moulds made of milled frozen sand [11]. Typically, these kind of solutions are limited to moderately curved surfaces with no undercuts.

Other approaches to the fabrication of bespoke concrete elements use state-of-the-art 3D-printing technologies. Recent work by Contour Crafting [12], XTreeE [13] and D-Shape [14], and at Loughborough University [15], have demonstrated the potential of printing techniques involving layered extrusion and the deposition of concrete to reduce or even eliminate formwork altogether. However, the direct production of curved 3D-printed concrete elements is still relatively slow and requires further developments to overcome some of the remaining practical

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limitations. Furthermore, since with the current technology reinforcement cannot be introduced as part of the extrusion process, structural elements that are compliant with design standards such as Eurocodes cannot yet be produced. Therefore, 3D-printed concrete elements are mostly used as formwork components [16, 17].

3D printing is well-suited for the production of articulated sand or thin plastic moulds [18, 19]. While 3D-printed moulds offer geometrical freedom with relative ease [20], they are non-recyclable, heavy, need significant scaffolding, and add additional weight to the structure if used as lost or stay-in-place formwork. An alternative stay-in-place formwork system is MeshMould [21], which started as a 3D printing method that created a leaking formwork for concrete casting or spraying. It now uses a robotically-controlled wire bending and welding process to create a stay-in-place cage of steel reinforcements

The use of textiles as formwork for concrete has been investigated via many experimental works throughout the 20th century, but it has not yet been established as a common construction method [22]. However, recent renewed interest in this field has resulted in the development of fabric-formed concrete elements for various architectural and structural applications [23, 24]. An in depth overview of flexible formwork technologies and their current use is given by Hawkins et al. [25]

The NEST HiLo roof prototype is the most recent construction-scale example of a structure built with a flexible fabric formwork system [27]. The carbon-fibre reinforced concrete structure was built on a pre-stressed cable-net falsework with a tailored textile shuttering. The optimised and actively controlled formwork system allowed for the creation of a geometrically complex and highly efficient structure [28].

While these flexible systems can allow for an efficient construction without the traditional material and labour costs, they can be challenging in terms of layered integration, predicting and controlling the geometry while pouring the concrete, and for calculating the final deformed shape [29]. Furthermore, tensioned fabric systems are limited to anticlastic geometries, although further geometric freedom can be achieved when fabrics are combined with bending-active systems [30, 31] or inflatable components [32]. These additional flexible elements can internally support the textile formwork to create a hybrid structure that eliminates much of the need for falsework. They also enable the creation of synclastic-like geometries and self-stressed, stable formworks.

For the integration and layering of formwork systems, knitted textiles offer several advantages, such as good draping qualities, direct 3D shaping, simple integration of openings, and the possibility to locally customise material properties. Furthermore, knitting can be used to realise non-developable surfaces without patterning and discretisation schemes, and thus almost entirely without seams [33].

1.1. A stay-in-place hybrid formwork system

Combining the strengths of some of the previous work discussed above, this paper introduces a novel, flexible, stay-in-place, hybrid formwork system for the construction of concrete structures, that has the potential to eliminate the need for falsework and significantly reduce the amount of time, labour, and material involved in the production of complex concrete geometries.

The system uses a knitted fabric that is shaped and pre-stressed by flexible, bending-active elements and ties. Note that because of the use of *weft knitting*, local features such as channels and holes can be integrated into the very shape and structure of the fabric itself, without tedious and complex cutting patterns and therefore without the typical seams resulting from gluing, stitching or welding flat sheets of material together. These features can be used to integrate additional support and tensioning elements, and potentially structural reinforcement or building systems components.

After tensioning, the flexible knitted fabric is covered with thin layers of a high-strength cement paste until it is sufficiently stiff to be used as a self-supporting mould for traditional concrete casting or spraying.

The system's feasibility is demonstrated through the design, analysis and fabrication of a proof-of-concept prototype in the form of a small-scale concrete bridge.

Section 2 follows with an overview of the proposed novel formwork system and the prototype bridge design. Section 3 then explains the fabrication process and the necessary parameters taken into account for the design of the textile formwork. Section 4 gives details of the structural analysis for the formwork strength and stiffness. Section 5 describes the process of casting the structure using a gradual strength buildup through a cement-paste coating, an intermediate mortar layer and a final thicker concrete layer. The measured deformations as a result of applying the different layers are shown in Section 6. Finally, Section 7 concludes with the main outcomes of the research and discusses possible improvements to the system. Although the system presented in this paper focuses on structures dominated by membrane stresses, the method can be used on concrete elements that have significant bending components, given the required amount of rebar is added to the structure

2. Prototype design

The prototype is a small-scale bridge built using a custom weft knit textile which includes channels for inserting bending-active elements and ribbons. These bending and ribbon elements are used to tension the textile into the desired form and support it during the first layering of cement paste.

Fig. 1 shows an exploded axonometric view of the formwork system, which consists of the following components:

- The stay-in-place formwork layer is made of a custom knitted textile (c) with integrated channels for the insertion of shaping elements.
- The integrated shaping elements are bending-active rods (d) and tensioning ribbons (e), used to pre-stress the textile into the desired shape.
- Once the hybrid textile and bending-active layer is tensioned into shape, the formwork is made rigid using two separate thin and light layers of high-strength cement paste (f) and mortar (g).
- These paste and mortar layers are light enough not to load the structure excessively and provide sufficient strength and stiffness to support the final layer of structural concrete (h).

The bridge prototype was designed with a 2.10 m span, a width of 1.17 m at the supports, 0.60 m width at mid-span, and a rise of 0.26 m. The dimensions were limited by practical considerations of the available space and manoeuvrability within the concrete laboratory, and by the need to fit onto two Euro Pallets for transportation. The shape of the bridge was driven by the idea of creating an articulated geometry by tensioning a membrane into shape using an alternating combination of five 8 mm glass-fibre reinforced polymer (GFRP) bending-active rods and four 30 mm braided Aramid ribbons. This setup allowed for the shaping of ridges and valleys across the cross-section, which acted as a local stiffening scheme for the structure, increasing the structural depth through the corrugations (Fig. 2).

To reach the final design shown in Fig. 2, several variations were designed and analysed in a parametric study to evaluate their visual and structural performance, as well as the material use by comparing their weights. The effect of a variety of parameters was investigated, such as the number of valleys and ridges, the continuity of the geometric shape, the rise of the bridge, and the width of the mid-section. Some options were immediately discarded because they exceeded the obtainable curvature or length of the available bending-active elements. Straight interpolated ridge profiles were preferred over curved ones, as the tensioning system would provide straight surfaces between the ribbons and rods.

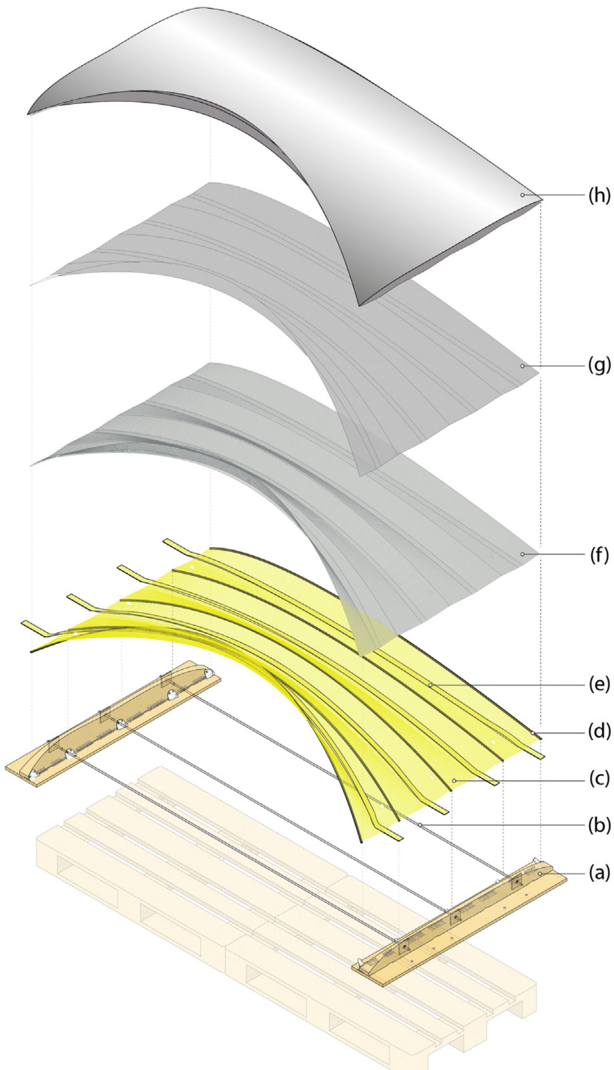

Fig. 1. Exploded view showing the layered formwork concept: (a) timber edge supports; (b) threaded-rod ties; (c) 3D knitted textile; (d) bending-active rod; (e) tensioning ribbon; (f) cement-paste coating; (g) mortar; and (h) structural concrete.

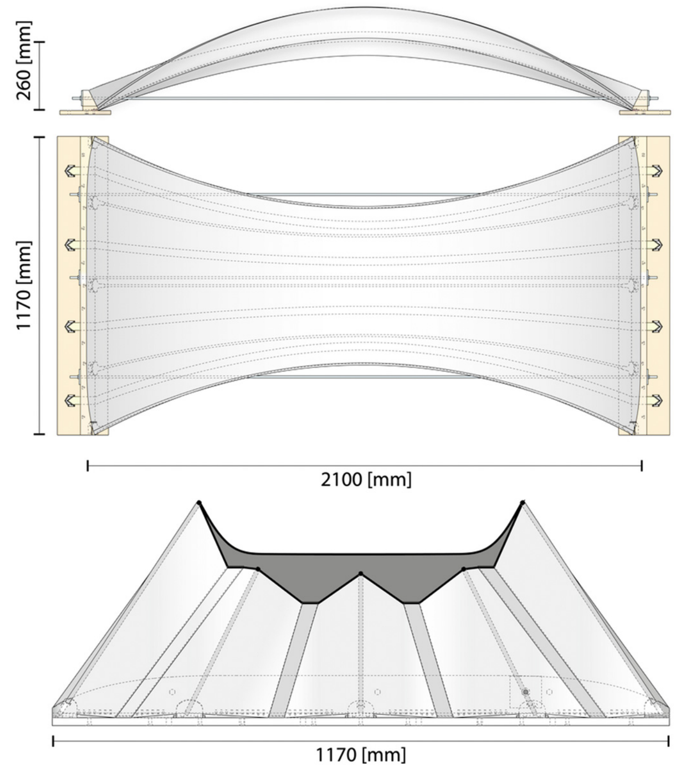

Fig. 2. Elevation, plan and cross-section views of the final bridge design.

3. Fabrication

This section describes the design, fabrication and assembly of the hybrid knitted textile and bending-active layer. The knitted part, described in Section 3.1, consisted of a custom knit textile with integrated channels for the insertion of the shaping elements. The shaping elements and tensioning system are described afterwards in Section 3.2.

3.1. Knitted textile

A knitting pattern is needed for the manufacturing of knitted textiles. Knitting is a directional process where the fabric is formed in a succession of rows consisting of several loops. A row is formed with each pass of the knitting machine carriage by needles pulling a strand of yarn through previously formed loops. Therefore, the knitting pattern can be described as a 2D step-by-step instruction diagram representing each loop to be formed by the knitting machine. Patterns are typically created manyally and this can be a time-consuming process. As knitting is most commonly used in the garment industry, the software solutions for generating patterns focus on repetition and known forms [35]. More automated solutions are needed in a bespoke architectural context, where geometries are not only much larger, but also more intricate and less repetitive. These solutions can rely on the use of developable surfaces for creating the patterns [36] or through mathematical descriptions [37]. However, to make use of all of the advantages that knitting has to offer, knitting patterns have to be created directly from a 3D input geometry in an automated way.

Fig. 3 shows an abstracted snippet of a knitting pattern. The pattern is a 2D grid representation where each square represents a loop to be created by the knitting machine. The rows highlighted in magenta are called *short rows* as loops are only formed on parts of the row. Through short rows, loops can be connected to non-consecutive rows shown as arrows in Fig. 3. This enables the shaping of knit textiles without the need for cutting and stitching.

The knitting pattern for the bridge was generated using the `compas_knit` package developed using the Python programming language and based on the COMPAS framework, an open-source computational framework for research in architecture, structures and digital fabrication [38]. The method generates the loop topology needed to create a given 3D geometry based on a given knitting direction and the target loop dimensions (height and width) [39]. Loop dimensions are dependent on a number of machining parameters, including: 1) the gauge of the knitting machine (the spacing between needles), 2) the knitting point (the depth of the needle within the bed when the loop is formed), 3) the yarn thickness, and 4) the tensioning of the yarn.

Before the knitting pattern could be generated, the loop geometry parameters needed to be determined. Sample material pieces of 60 loops in width by 100 loops in length were knit with the chosen yarn (Aramid 160 TEX) and tension settings on a computerised Brother KH-970, equipped with a second needle bed, also known as a *ribber* (Fig. 4). These small samples were then tensioned in a rig such that the stretched loop dimensions could be measured (Fig. 5).

Additional tests were carried out to determine the maximum hole size and surface texture such that the cement-paste coating would be optimal. Fig. 6 shows the behaviour of the coating on plain knit (left) and ribbed knit (right) samples. From these tests, it could be concluded

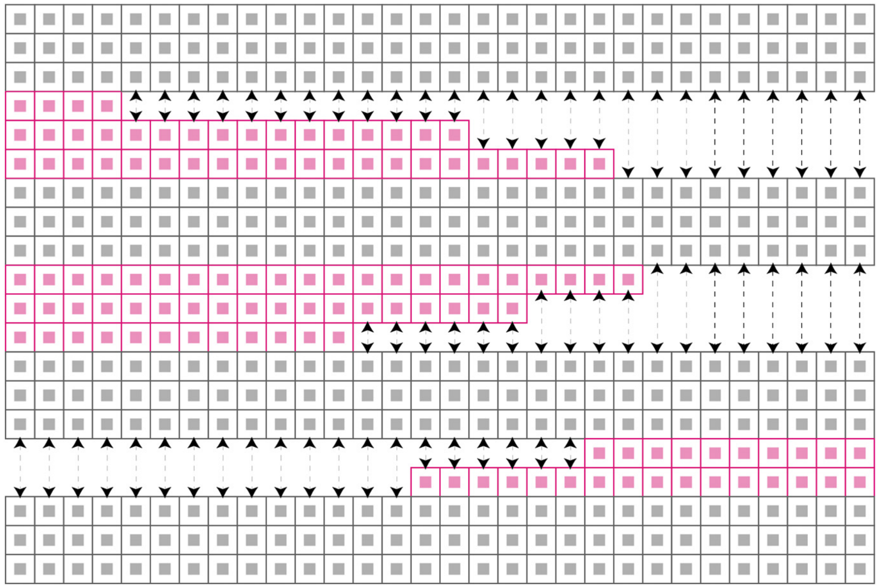

Fig. 3. Graphical representation of a knit pattern. Each square represents a loop to be knit by the machine. The loops marked in magenta depict short rows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Electronic knitting machine (Brother KH-970) equipped with ribber bed.

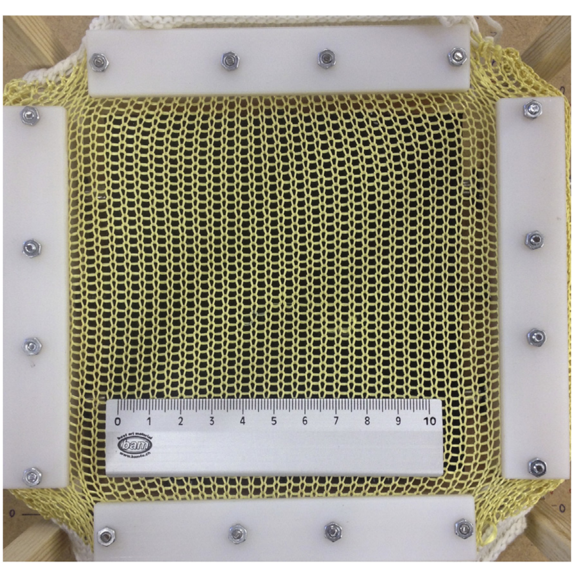

Fig. 5. Knit textile sample tensioned in a rig for measuring target loop sizes.

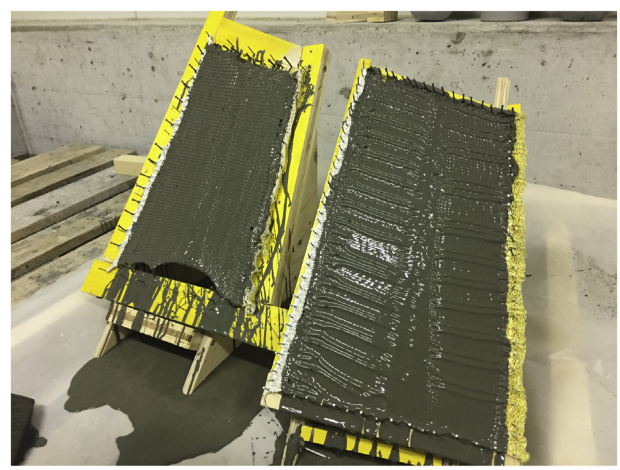

Fig. 6. Cement-paste coating tests for the calibration of the knit-pattern generation. left: plain knit; right: ribbed knit.

that the ribbed knit pattern performed better, as it inhibited the flow of the cement-paste, resulting in a better coverage of the textile. The textured surface also allowed for a better mechanical bond with the subsequent mortar layer. The coverage tests showed that for a ribbed surface, holes up to 5 mm in diameter could be coated with ease. As a result, a target loop dimension of 3.5 mm × 5 mm was chosen.

The integrated channels were knit using the ribber. In addition to the integrated channels for the tensioning ribbons and bending-active elements, the knitted textile also featured holes for the insertion of riveted markers. These markers provided registration points for measurement of the textile surface and physical offsets used for controlling the formwork concrete thickness. Openings were added to allow steel ties to pass through the shell surface. Fig. 7 shows the appearance of the untensioned textile with the GFRP rods, braided ribbons inserted into the channels, and the riveted markers.

The knitted textile was manufactured as three separate pieces, thus needing two stitched seams over the entire structure. The width of the pieces was limited by the width of the knitting machine. Knitting the textile in a single seamless piece would be possible using industrial grade knitting machines, which have needle beds up to 2.5 m [34].

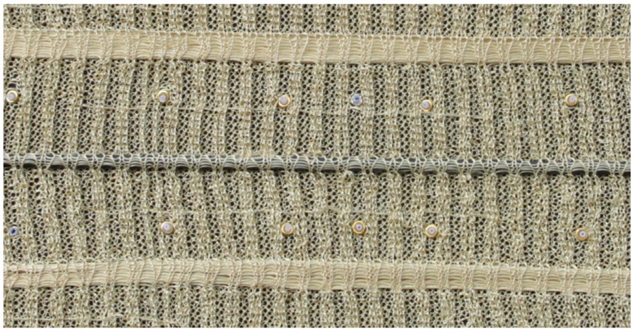

Fig. 7. Knitted textile with integrated channels and markers for concrete layer thickness control and spatial measurements.

Fig. 8 shows the generated knitting patterns and the layout of the three sections in the complete textile. The total weight of the textile amounted to only 433 g, which when combined with the tensioning ribbons, rods and registration markers was 900 g, less than 0.5% of the final total structural weight.

Fig. 9. Knitted textile layer of the formwork, tensioned into shape using GFRP rods to create ridges and Aramid ribbons as valleys.

3.2. Tensioning

The textile was tensioned using five hollow GFRP rods (8 mm outer diameter and 6 mm inner diameter) and four 30 mm-wide braided Aramid-fibre ribbons. Timber edge beams with a cross-section of

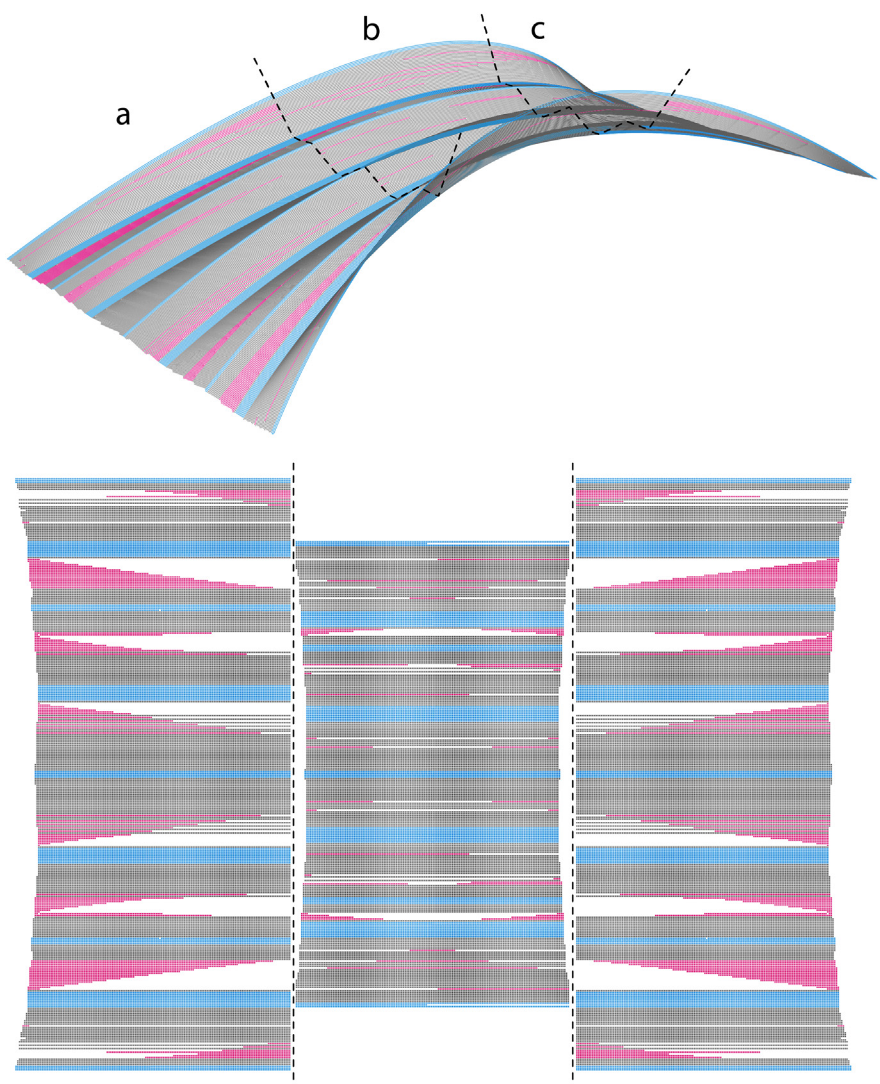

Fig. 8. Generated knit patterns and layout of the three pieces of fabric; Highlighted in blue are all of the locations of the channels for rods and ribbons and in magenta all the short rows enabling the gradual width changes of the knit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

60 mm × 80 mm formed the supports of the bridge. These were fitted with custom 3D-printed fixtures for clamping the GFRP rods into place, and slots underneath for passing the Aramid ribbons through, which were secured with ratchet straps fixed to the Euro-Pallets. The rods and ribbons were inserted into the knitted textile and the assembly was tensioned into shape. This was done by first placing all rods into their respective 3D-printed fixtures, fixing the textile to hooks fitted onto the edge beams and securing it in place with rubber "U" profiles. Finally, the ribbons were tensioned using the ratchet straps until the desired shape was achieved. Temporary GFRP struts were placed along the length of the bridge between the bending-active rods, to maintain the correct distance between rods and to prevent them from deflecting inwards due to post-tensioning. The resulting tensioned structure can be seen in Fig. 9.

4. Structural analysis

As the knitted textile formwork layer would have only a thin layer (a few mm) of applied high-strength cement paste and mortar layer, the structural form needed to be efficient to take the self-weight loading of the final concrete pour on top. The large span-to-thickness ratio (over 400) of the formwork layer required that stiffness be gained from a number of sources, so as not to have the possibility of local or global instability, or material failure in compression or tension. The structural stiffness of the formwork layer was gained by:

- The design of the bridge shape that, as a whole, provided geometric stiffness through its curvature and span-to-rise ratio.
- Structural corrugations, created by the alternating tie ribbon and bending-active rod elements, which increased the cross-sectional stiffness of the formwork layer from the increased effective structural depth.
- Steel tie rods, connecting the abutments of the bridge, allowed arching action to form, taking loads in compression as well as just purely bending.

The thickness of concrete for the formwork layer was to be determined, such that it could satisfy strength and stiffness requirements. This was performed by generating finite element models and analysing all of te prospective bridge variations with the help of the finite element package `compas_fea` of the COMPAS framework. The NURBS surfaces and meshes representing each bridge, and finally the chosen bridge design, were generated in Rhinoceros, and then a script created to extract their geometry and perform a structural analysis with `compas_fea` using the FEA software Abaqus as the backend solver [40]. The key features and assumptions of this scripted analysis were as follows:

- Each formwork surface was discretised into a mesh with approximately 10,000 quad faces. This number of quadrilateral elements was found to provide a good balance between the analysis times in the parametric analyses, and accurate finite element results provided by a sufficiently dense mesh.
- These faces were added as thin quadrilateral shell elements (S4 elements in Abaqus) in the structural model.
- Tie elements connected each bridge edgebeam, with the nodes at the ends of the bridge modelled with roller boundary support conditions.
- Self-weight loading of the formwork layer and the structural concrete layer were both included, with a safety factor of 1.35.
- The weight of structural concrete was applied as nodal loads based on the vertical distance between the formwork layer and top deck surface of the bridge, multiplied by the effective area around each node of the mesh.
- The first (lowest eigenvalue) buckling mode was examined to check the stiffness of the structure under the unfactored applied loads.

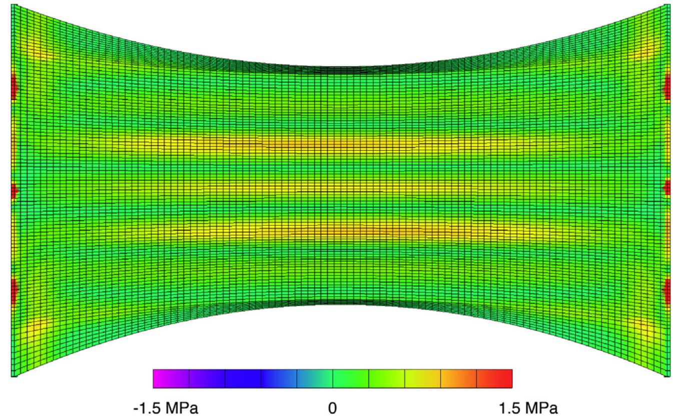

Fig. 10. Formwork layer: tensile stresses (positive) in the formwork layer were predicted to be below 1.5 MPa, under the action of all concrete self-weight loading.

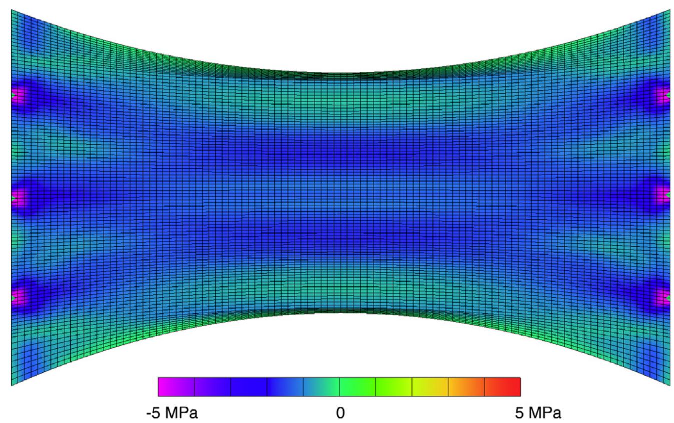

Fig. 11. Formwork layer: compressive stresses (negative) in the formwork layer were predicted to be below 5.0 MPa, under the action of all concrete self-weight loading.

- For the analysis, concrete with f_{ck} = 90 MPa (the characteristic 5% 28 day cylinder strength), based on Eurocode 2, was used as representative of the high-strength cement and mortar layers.

The analysis results showed that a thickness of 4 mm was sufficient to keep tensile stresses in the formwork layers below 1.5 MPa (Fig. 10) and compressive stresses below 5.0 MPa (Fig. 11). The 4 mm thickness appeared to be relatively stiff in a linear buckling analysis, with an eigenvalue of 18.5 for the fundamental buckling mode and with no obvious local failure modes (Fig. 12).

The final thicker concrete layer was also analysed. As this layer was

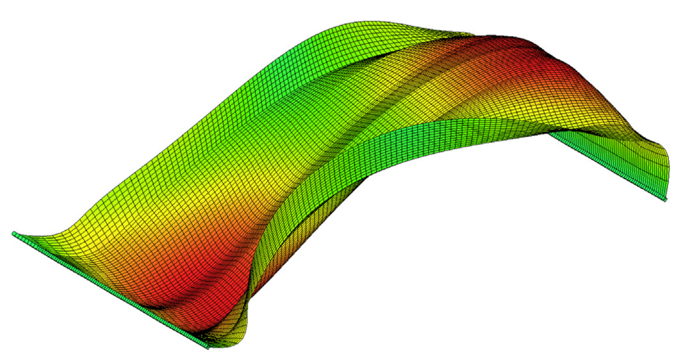

Fig. 12. Formwork layer: the lowest buckling mode shape took a global form with eigenvalue of 18.5 (ties omitted from the figure).

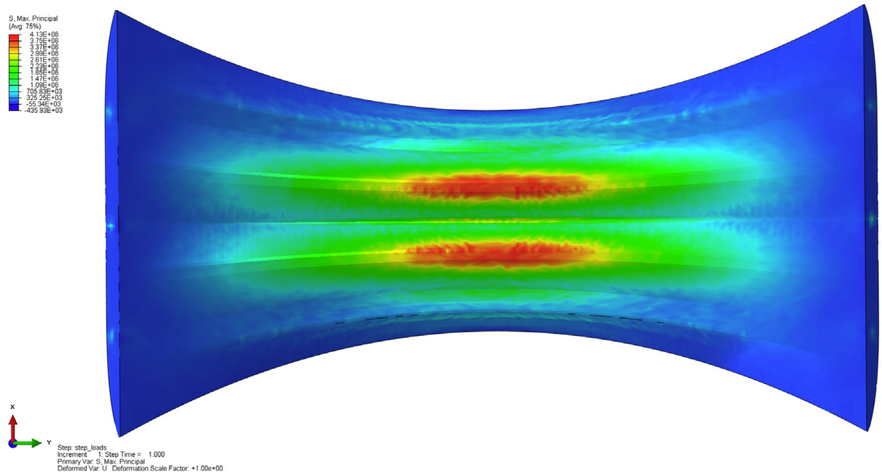

Fig. 13. Concrete layer: tensile stresses (positive) in the main concrete layer were predicted to be around 4.1 MPa, located on the underside of the bridge.

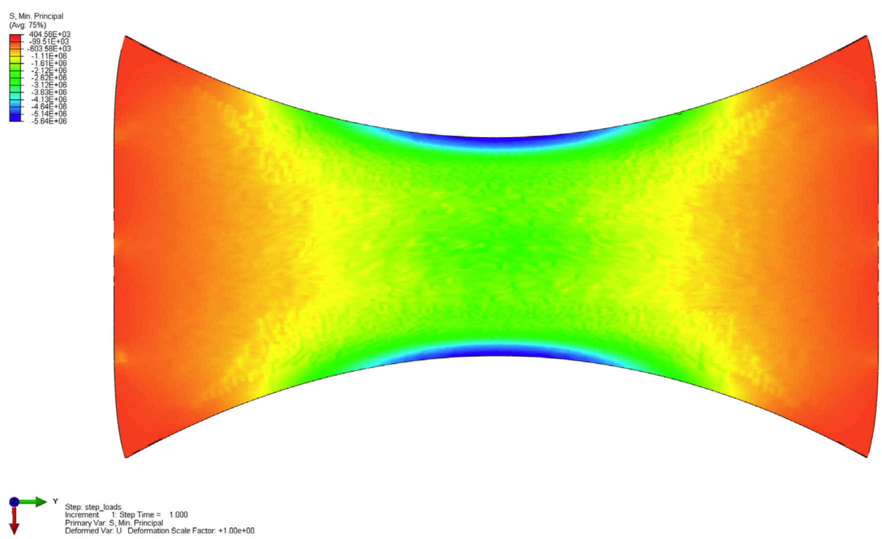

Fig. 14. Concrete layer: compressive stresses (negative) in the main concrete layer were predicted to be around 5.6 MPa, with highest stresses at the wings.

of non-uniform thickness and not thin, tetrahedron solid elements were used to represent the concrete volume. To create the tetrahedral elements, the formwork mesh was combined with an upper deck mesh and closing meshes at the wings and supports, to form a triangulated mesh representation of the outer surface. This surface was then discretised internally with `compas_fea` using TetGen (through the wrapper MeshPy). This resulted in approximately 140,000 elements for the analysis. Other key features of the modelling and analysis included: 1) the wooden end-blocks were explicitly modelled to spread the tie forces caused by the horizontal thrusts and avoid artificial stress concentrations; 2) a concentrated load of 5.0 kN was applied to a collection of nodes at mid-span, to act as an equivalent design point load; 3) the self-weight and imposed point load were additionally increased with a safety factor of 1.35; and 4) conservatively, no contribution of strength was assumed from the formwork layer (Figs. 13 and 14).

The results of the analysis showed that tensile stresses were highest on the underside of the bridge, at mid-span and at the troughs of the corrugations, where they peaked at 4.1 MPa. The compressive stresses were moderate at mid-span at 2.5 MPa, where most flexure occurs and the structure was relatively thin. Concentrations of 5.6 MPa were found at the wings where the stresses gathered due to the convergence of force flow, and then reduced towards the supports where there is more concrete mass. Displacements were naturally highest at mid-span, but still low at values around 0.6 mm.

5. Layered concrete buildup

Once tensioned, three separate concrete layers were applied to create the structure. The first layer, which directly coats the textile with a thin layer of cement paste (Fig. 1 (c)), is described in Section 5.1. After curing, this layer served as a stiffening layer for the textile, giving it enough strength to support the subsequent spraying of a mortar layer (Fig. 1 (d)). These two layers constituted the lightweight formwork upon which the final layer of concrete (Fig. 1 (e)) was cast.

5.1. Cement paste coating layer

The cement paste was a stable highly fluid suspension consisting of a blended ordinary Portland cement, a polycarboxylate ether based superplasticiser and stabilising nanoparticles. It was prepared using a mixer providing high shear rates and the water-to-binder ratio was 0.24. Using mini-spread flow tests with a cone of height 50 mm and diameter 50 mm according to Roussel et al. [41], spread diameters of more than 30 cm were measured on a humidified glass plate. The cement paste was applied on the textile as a coating using a small funnel and working in symmetrical strips along the length of the bridge, always starting from the middle and working towards the supports. The applied cement-paste coating amounted to approximately 12 kg, providing an average layer thickness of 1.5 mm including the thickness of

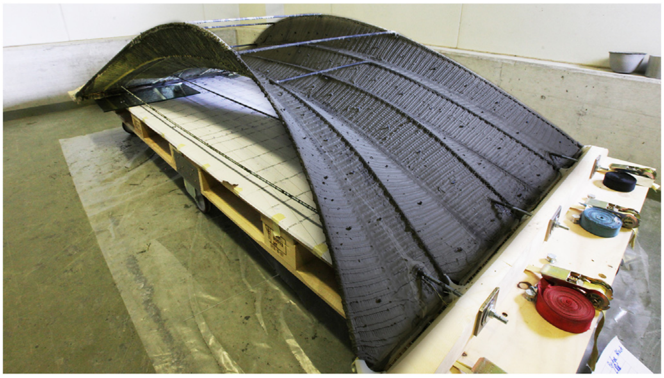

Fig. 15. Stiffened knitted textile after the cement-paste coating layer had hydrated.

the knitted textile. The majority of gaps formed by the stretched loops of the fabric were sealed by capillary action of the cement paste. However, some gaps in strongly inclined regions of the textile surface and where loop dimensions were largest, could not be sealed. The coating was cured for seven days in a climate chamber at 95% relative humidity and 20 °C, forming the stiffened textile formwork (Fig. 15), onto which the mortar layer was applied.

5.2. Textile-reinforced mortar layer

A commercial repair mortar was prepared in a forced action mixer and sprayed onto the stiffened textile formwork using pressurised air and a conveying pump (Fig. 16) in a climate chamber at 95% humidity and 20 °C. After spraying, strips of epoxy-coated carbon-fibre mesh (SBR coated mesh SITgrid008) were embedded manually into the mortar as a safety measure to provide some resistance to crack mouth opening during the concrete casting process step. The resulting mortar surface was roughened by hand to ensure an improved bond with the final concrete layer (Fig. 17). The resulting formwork layer had a thickness of roughly 4 mm and weighed approximately 40 kg. It could be confirmed that the rule of thumb that flow is prevented in gaps smaller than three times the largest aggregate holds true, as the mortar could not pass through the formwork, even for gaps that previously could not be sealed. The curing time for this layer was three days.

5.3. Structural concrete layer

The final layer consisted of an easy-to-compact steel-fibre reinforced concrete with a target yield stress of 1200 Pa according to Pierre et al. [42] (spread of 27 cm using an Abrams cone), providing the possibility to place approximately a 5 cm layer on a vertical wall section or 10 cm on an inclined plane of 30° inclination. The target yield stress

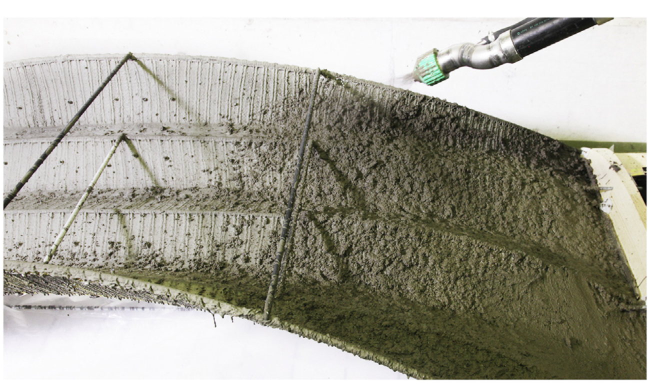

Fig. 16. Mortar spraying on to the coating-stiffened textile shell.

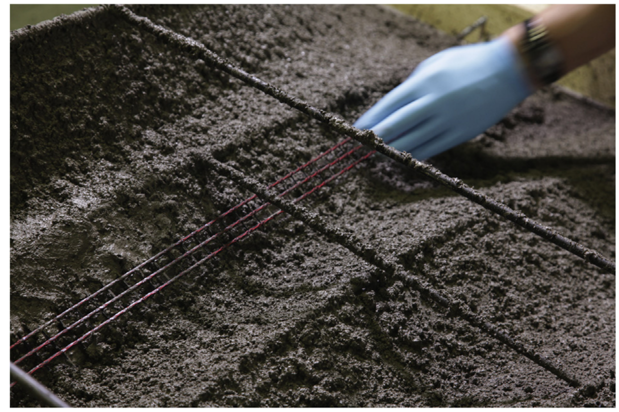

Fig. 17. Placement of epoxy coated carbon fibre reinforcement mesh.

was achieved during mixing by adjusting the aggregate solid volume fraction and measuring by slump test. The concrete consisted of 65% aggregates by total volume consisting of equal parts of 0–4 mm and 4–8 mm aggregates, 1% hooked steel fibres by total volume, an ordinary Portland cement, and a polycarboxylate ether-based superplasticiser, with a water-to-cement ratio of 0.38. A total of 150 L of this composition were prepared in a forced action mixer according to ASTM C192. Figs. 18 and 19 show the concrete casting process and the result immediately afterwards.

6. Measurements

The geometry of the structure was measured at each fabrication step using a grid of 391 reference points, which were placed every 10 cm along each bending-active element and ribbon, and at the mid-points between the bending-active rods and ribbons. Measurements were performed with a flush tape measure for the textile formwork and with a laser measure at every other step. Some points on axes 0–2 and 20–22 were excluded (see Fig. 20) as their height was too low to be registered. Each subsequent measurement was compared to the previous measurements, to assess the influence of the corresponding step in the fabrication process on the deformations and resulting geometry.

First, the rods and ribbons were inserted in the knitted textile. The hybrid structure was then placed into the supports and tensioned into shape, and the geometry measured using the flush tape measure. This measured state is considered as the initial geometry, which is to be checked against after the concrete layers were cast. The next measurements were taken to assess the effects of applying the cement-paste coating, which was performed 48 h after its application. The maximum deformation compared to the initial measured geometry before

Fig. 18. Manual casting of the final concrete layer onto the stiffened fabric formwork.

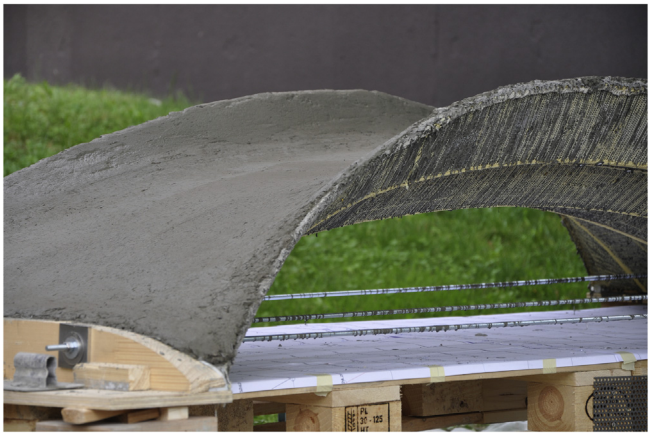

Fig. 19. Resulting concrete finish immediately after casting.

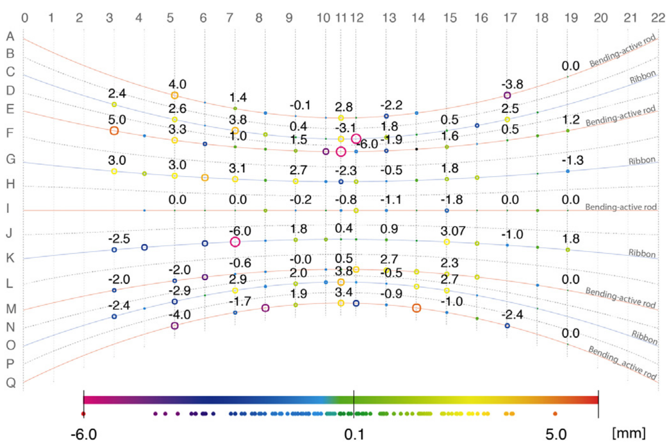

Fig. 20. Overall deformations after the cement paste coating with respect to the initial geometry, showing an average deviation of 0.1 mm.

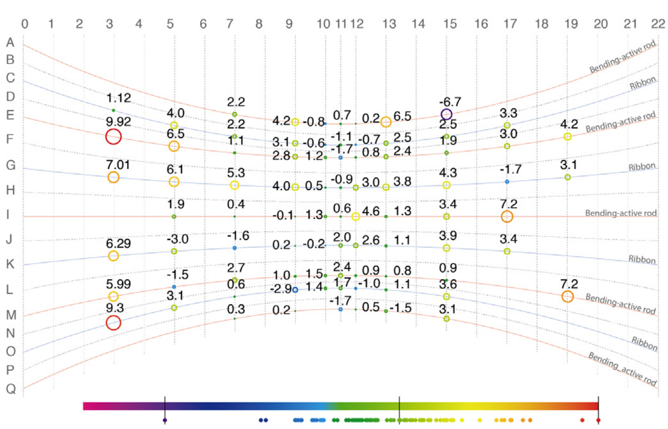

Fig. 21. Overall deformations of the formwork with respect to the initial geometry, showing an average deviation of 2 mm.

application of the paste was found to be 6.0 mm with an average of 0.1 mm across the prototype, as can be seen in Fig. 20.

Deviations following the application of the second mortar layer were in the range of 2–5 mm relative to the previous cement-paste coated geometry. The structure was then decoupled from the pallets before applying the final concrete layer, activating the steel ties for this heavier weight of concrete to be applied. The structure was measured again where no significant deformations were found (0.3 mm on average). Finally, a comparison was made between the measured geometry after the final concrete layer and the initial geometry. As shown in Fig. 21, the deviations are up to an absolute value of 9.9 mm and with an average of 2.0 mm. Due to the corrugated nature and unevenness of the formwork shell, as well as the manual placement of the laser measure, there were errors in the point measurements. The measurements of the cement coating and mortar layer compared well to the initial geometry, proving that a flexible fabric geometry that is stiffened in layers, provides a feasible formwork strategy with low deformations.

7. Conclusions

The results presented in this paper demonstrated the use of a bespoke knitted textile as a shape-giving formwork through a small-scale bridge prototype (Fig. 22). The prototype was built to investigate the possibility of constructing a concrete structure using a self-supporting tailored knitted textile formwork in combination with bending-active elements and stiffened using cement paste and mortar. The implications of this approach are far-reaching in contrast with many traditional formwork systems. When scaled-up, other than significant waste reduction, this method grants increased site accessibility, reduced labour and fewer or lighter foundations.

The system has several potential benefits over traditional approaches to concrete formwork, as it is lightweight, easy to manufacture, highly transportable and quick to assemble. Additionally, the use of a knitted textile offers extended 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. Furthermore, the stay-in-place knitted formwork used in this paper could later be extended to act as structural reinforcement as an integrated formwork, forming a composite cross-section.

The knit-pattern generation worked well, producing the designed geometry of the formwork in its tensioned state. For this, it was important to calibrate the pattern with material tests that took into account the desired machine setting and material behaviour when combined with the cement-paste coating. The orientation of the ribbed texture on the textile surface played an important role, as it helped with bonding in the cement paste coating process. This texture was most effective when the ripples were orthogonal to the principle flow direction of the liquid cement paste. Furthermore, the ribs provided improved bonding with the subsequent thicker mortar layer. The corrugated nature of the cross-section was structurally advantageous and the textured bottom surface was well-suited for applying subsequent cover. This bottom surface could also be rendered to have various functional or desirable aesthetic qualities.

Through the application of a thin layer of cement paste on the knitted textile, the fabric formwork was stiffened sufficiently to support the application of the incoming thicker concrete layers, while maintaining the original shape of the tensioned textile.A two step process was needed for the buildup of the formwork layer as the coating could not be directly applied in one pass to the needed thickness of 4 mm. At larger scales, an optimisation of the layering process can be explored to reduce the number of application steps. One solution could be the use of a spacer fabric, which would increase the initial coated thickness. Measurements performed on the structure after each step of the fabrication process showed that deformations as a result of coating, spraying and concrete casting were low, at only 2 mm on average. Moreover, tensioning stresses can be kept low as the thin coating does not place significant load on the knit.

The surface finish of the mortar layer was sufficiently rough to obtain a good bond between the mortar layer and final concrete layer,

Fig. 22. Overview images of the finished bridge prototype.

thus avoiding slip at the interface. Such bond behaviour could be incorporated into structural designs where the formwork and structural layers are intended to act compositely. When the formwork layer is influenced heavily by tensile stresses, sufficient tensile strength through reinforcement fibres or meshes will be needed to absorb any forces and moments, and to avoid local concrete cracking.

Scaling-up the system could be approached in two different ways: by scaling the entire system, or by the construction and assembly of multiple smaller components. For the latter solution the system is already considered at scale; remaining challenges relate to the assembly of the discrete components and their mechanical connections. However, to scale-up the entire system and directly use it on site, the coating process, which currently depends on a climate chamber, and the control of the pre-stressed textile and bending-active elements for larger spans, needs to be developed further.

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