Development of Knitted Moulds With Variable-Length Spacers for Non-Repetitive Building Envelope Tiles

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Abstract. Integrating non-repetitive geometries into building envelopes enhances thermal efficiency, reduces energy use, and transforms façades from passive barriers into performative systems. However, current fabrication processes for building envelope tiles with complex geometries remain costly, labour-intensive, and reliant on non-recyclable moulds, limiting their environmental and economic viability. These limitations highlight the need for a more sustainable and adaptable method for producing non-repetitive architectural elements. This study proposes a digital workflow for the design and fabrication of complex morphology building tiles using knitted stay-in-place spacer moulds. The method employs a double-bed industrial knitting machine to produce variable-length spacer structures that control tile thickness and localized inflation. A computational workflow combining Processing, Rhino/Grasshopper simulation, and M1plus knitting software enables the direct translation of surface geometries into fabrication instructions. This workflow is demonstrated through the production and casting of knitted tiles featuring a variety of three-dimensional morphologies, which closely align with their digital simulations. The results confirm the feasibility of this approach for fabricating intricate, self-supporting forms without external fixtures, establishing a foundation for performative and computationally integrated architectural fabrication.

Keywords. Computerized Knitting, 3D Knitted Formwork, Building Envelope Tiles, Non-Repetitive Tile, Knitted Fabric Spacers

1. Introduction

Modern building envelopes predominantly consist of repetitive elements serving a singular function as barriers between interior and exterior spaces (Grobman et al., 2023). While effective for enclosure, these envelopes often lack the ability to enhance environmental performance or ecological engagement. Incorporating building

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envelopes with intricate geometries and non-repetitive elements can significantly improve structural thermal performance, reduce energy consumption, and mitigate airflow, thus expanding their role beyond passive separation (Hershcovich et al., 2021). Current manufacturing processes of façades, which include intricate geometries and non-repetitive tiles, are often costly, labor-intensive, time-consuming, and dependent on non-recyclable moulds, limiting their scalability and environmental viability (Austern et al., 2022). The cost of these moulds can add up to 60% of a tile's total cost and have a negative environmental impact (Nawy, 2008). While 3D printing offers an alternative by eliminating the need for formwork, it remains time-consuming and costly. Thus, there is still a need for a more sustainable method to design and fabricate complex, non-repetitive geometry elements, particularly for building envelopes.

A novel approach to develop and fabricate complex morphology building tiles was previously demonstrated by Sterman et al. (Sterman et al., 2025), who used knitted stay-in-place moulds as formwork for casting tiles. In their workflow, tubular fabrics combined with tuck stitches that connect the front and back faces of the fabric were utilized. The work produced a bump-like geometry and employed a jig to fix the mould during casting. Even though the workflow proved viable in developing and fabricating intricate 3D geometries, it still lacks control over tile thickness and relies on external fixtures while casting.

In this study, we developed a novel computational knitting method of varying length crosslink spacer structures, incorporating an innovative digital methodology for both design and fabrication of stay-in-place moulds with complex morphological elements. The variable-length spacers enable the control of the tile's thickness and finer adjustments of the inflated geometry. Additionally, we eliminate the need for using a jig, enabling the production of a variety of shapes without relying on external fixtures.

In our approach, the cement-based composites are cast directly into a spacer textile, utilizing the technical adaptability of spacer structures to control the tile's morphology through adjustments to the spacer length parameter. Diverse morphological outcomes are enabled by the use of a double-bed knitting machine to create precise fabrications of these spacers and parametric variations of their lengths.

Our goal is to develop a computational workflow for the design and fabrication of stay-in-place spacer moulds, allowing users to automatically translate a surface geometry into knitting instruction files and simulate their design before casting. Our approach is demonstrated in a series of cast tiles, utilizing a variety of fabric spacer lengths to achieve a range of complex morphologies.

This work contributes a computational framework that functions as both a creative and functional tool for performative and sustainable architectural design. By shifting from repetitive, mono-functional façades towards textured, ecologically active building envelopes, this study introduces a new methodological approach for fabricating complex morphological tiles. Furthermore, it establishes a foundation for future exploration into scaling this technique, while advancing the design-to-fabrication workflow for wider implementation within architectural practice.

2. Background and State of the Art

Fabric formwork systems offer a lightweight, waste-reducing solution for complex building components. Surface textile moulds are mainly used to create shell structures, requiring only a single forming surface for concrete casting. The geometry of the mould is determined by the interaction between the applied forces and the internal stresses within the formwork. When casting concrete shells, the formwork may either hang under the weight of the concrete, be mechanically prestressed, or be supported by air pressure or actuators (Hawkins et al., 2016), as exemplified in Popescu et al.'s Knit Candela project, which showcases structural design and digital fabrication for a concrete waffle shell (Popescu et al., 2021). Concrete in a filled mould creates hydrostatic pressure on the formwork, adjusting its shape to withstand the load. The final casting shape can be controlled by prestressing the formwork or choosing specific stiffness characteristics for the knitted structure (Hawkins et al., 2016), as exemplified through research conducted at the University of Michigan, which examined the dynamic interaction between knitted formwork and fresh concrete, focusing on how different yarn types and knit structures affect casting characteristics (Slocum, 2021). However, research utilizing both techniques has yet to develop a solution for creating 3D double-layer complex-walled designs using knitting. Current approaches focus on single 3D layers that require multiple material sprays in a labor-intensive process or simple cylindrical column moulds.

A specific textile form that is used for construction is spacer fabric. Spacer fabrics are three-dimensional (3D) fibrous structures consisting of two separate substrates joined by either spacer yarns or layered fabric (Dejene & Gudayu, 2024). Recent studies have demonstrated the beneficial use of spacer structures as reinforcement for concrete structures. Cement-based materials are brittle in nature and are therefore combined in practice with reinforcement, conventionally with steel rods or with fibres. Research has shown that textiles with adequate geometric configurations can enhance the mechanical performance of cement composites more effectively than singular yarns. This improvement is attributed to the stronger fabric-cement bond achieved through mechanical anchoring, which arises from the fabric's structural arrangement (Di Prisco et al., 2004). By incorporating 3D spacer fabrics as reinforcement, the tensile performance and impact resistance of cementitious composites are significantly enhanced, exhibiting high energy absorption capacities, high resilience and durability, and better crack control compared with traditional fibre-reinforced composites (Liu et al., 2023). Fabric spacers' 3D architecture allows reinforcement throughout the entire thickness of the concrete element, while utilizing the flexibility of the knitting machine to produce spacer structures with varying widths. Using spacer fabrics as inner reinforcement offers the advantages of improved mechanical properties, reduced material consumption, and lightweight, durable composites suitable for various construction applications (Adosi et al., 2021). This is also demonstrated in a study by Roye et al. (2004), who produced spacer fabrics with variable spacer lengths and cross-sectional profiles, allowing for a tailored reinforcement geometry for specific concrete applications, thus optimizing stress distribution and improving structural performance. Although the ability to fabricate complex, geometrically tailored textile formwork in a single process minimizes the need for additional layers or post-processing (Roye & Gries, 2007) no research was found to demonstrate the use of spacer fabrics as filled moulds, utilizing variable length spacers to produce complex morphological elements.

In our approach, we address these gaps by utilizing the spacer textile externally as a mould for the building tile and cast directly into it, while modifying the tile width using the varying spacer lengths. This allows us to create building tiles with complex morphology elements, while eliminating the need for an additional disposable mould.

3. Methodology

The 3D knitted stay-in-place moulds are fabricated using a Karl Mayer Stoll ADF 530 double-bed industrial knitting, with a multi-filament nylon 6/6 yarn, which assists in creating a sealed surface and preventing the casting material from leaking through the fabric. In this preliminary stage, the selected tiles were cast with gypsum to assess the inflation of the knitted moulds and the 3D geometries created using the crosslink-spacer structures.

3.1. DEVELOPMENT OF CROSSLINK FABRIC SPACERS

3.1.1. Crosslink Spacer Fabrics

For this study, we developed a new method to produce variable-length spacer structures that connect the front and rear faces of the tubular knitted fabric. These spacers are based on combining two spacer techniques, layered fabric spacers (also known as crosslink spacers), and pile yarn spacers (Figure 1). Crosslink spacers are traditionally produced through specialized weaving techniques that involve dividing warp yarns into multiple systems and weaving them into interwoven crosslink structures, while pile yarn spacers are produced by independently knitting two outer layers on separate beds and inserting the pile yarn between them using tuck stitches, which hold the layers at a set distance (Dejene & Gudayu, 2024).

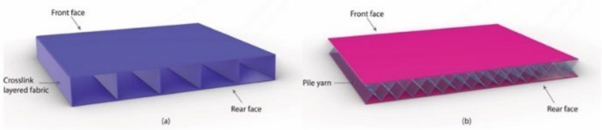

Figure 1: Spacer fabric - (a) crosslink layered fabric spacer; (b) pile yarn spacer

In our method, we adopt the concept of interconnecting the two outer fabric layers through additional knitted structures, while employing the double-bed configuration to produce two parallel layers and the ability to vary spacer lengths. The knitting instructions combine tubular knitting and defined sections of partial knitting on the front bed to create the crosslink spacers. The structure of the spacer is defined as one knitted loop and one float, maintaining every other loop on the front needle bed to maintain continuous knitting and prevent the formation of a hole. After knitting several rows, the knitted loops are transferred to the rear bed, therefore connecting the spacer between the front face and the rear face of the textile (figure 2).

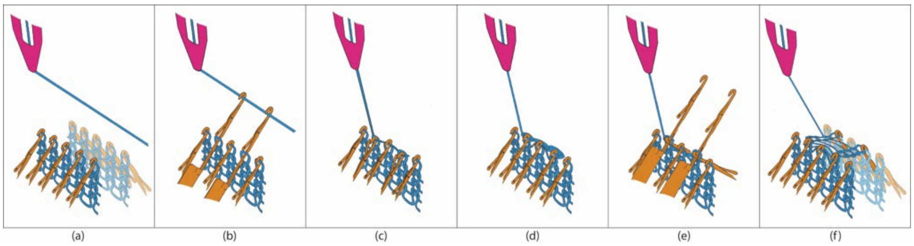

Figure 2: Crosslink spacer (knit-float structure) knitting process - (a) tubular knitting; (b) every other needle (in spacer) is working; (c) threading of loops (first row); (d) process of knit-float; (e) transfer of knitted loops from front to rear needles; (f) end of spacer loops transferred to rear needles

3.1.2. Color-based Interface for Controlling Spacer Length

The knitting program is planned using the Color Arrangement (CA), the M1plus parametric design module, which seeks colors in the knitting map and assigns stitches accordingly. In the knitting program, each section of the knitting structure is defined by a specific color, allocated to the corresponding knitting instructions defined by the CA. The partial knitting spacer structures are defined in the program as three rows of a selected color, corresponding to the CA color, in which the number of rows knitted on the front bed is defined. After which, transfer rows are defined (Figure 3). Each spacer is defined in a different color, specifying the number of rows knitted, resulting in different lengths of each spacer structure, thus affecting the distance between the two faces of the stay-in-place mould once cast.

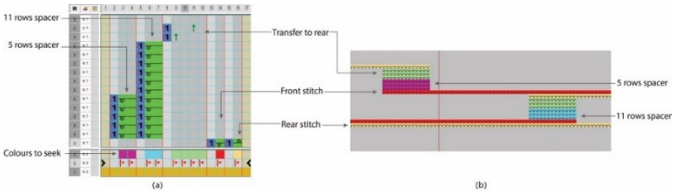

Figure 3: (a) Color arrangement for seeking and assigning spacers; (b) knitting map of spacers

3.1.3. Maximal Spacer Length Study

To determine the maximal length possible for the spacer structure, several iterations with various spacer lengths were knitted, starting from 5 rows to a maximum of 63 rows (Figure 4). Knitting on the ADF 530 with a gauge of 10, a notable limitation was the length of the spacer. When knitting a large number of rows, the knitted spacer would hover over the needle bed, and while transferring the loops from the front to the rear needle bed, the spacer may be caught in the needles, therefore preventing the spacer from performing in its full-length potential. To overcome this limitation, different parameters were altered and examined through this process, including the stitch length of each section (the tension in which the yarn is being pulled on the needles), the tubular structure, the spacer rows, the transfer of loops and the additional rows knitted to place the yarn carriers in the next spacer position, the fabric take down force and the knitting speed. The results improved when altering these parameters;

however, the longest spacer we were able to achieve was of 45 rows, producing a spacer of 50 mm in length. The shortest spacer of 5 rows resulted in a length of 5 mm.

Figure 4: Varying crosslink spacer lengths

3.2. DEVELOPMENT OF THE KNITTED MOULD

3.2.1. Mould development

The mould, fabricated using the double bed configuration and based on a tubular knitting structure, is sealed on all edges of the shape, except for an opening at the top to pour the casting material. Modeled on the same knitting instruction as presented in the study by Sterman et al (2025), throughout the knitting map, the CA seeks and assigns plain knit stitches for the tubular section, and back tuck stitches to the boundary section. While the machine knits the mould's rear face, every three knitting rows it transfers a loop to the back needle bed and forms the tuck stitch, which lays the loop on a back needle. This action connects the front and back faces of the fabric in this specific location, forming a boundary on the edges of the mould, preventing leakage of the casting material and helping to maintain the overall shape while casting (Figure 5). The fabricated mould's measurements are 30 cm by 30 cm, containing 112 spacers throughout the shape, and takes about 20 minutes to be knitted.

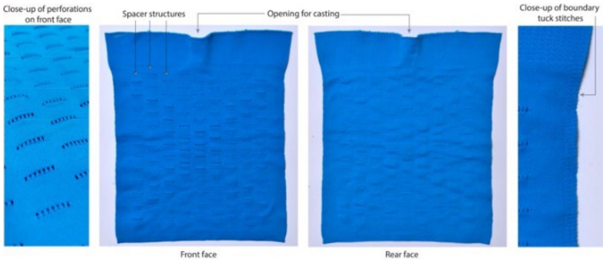

Figure 5: Knitted mould front and back face

3.2.2. Casting process

The casting process is conducted on a vibrating platform to ensure material distribution. The mixture is poured through a funnel and a plastic tube, which is placed within the top hole of the mould. The varying lengths of the crosslink spacers allow for varying inflation throughout the mould, creating a geometry on the front of the mould. The technique used to knit the spacer structures resulted in perforations on the front face of the textile, where the loops were transferred from the front to the rear needle bed. To minimize leakage during casting, we placed the face of the textile with the holes facing down and added sand to the gypsum to create a thicker mixture.

3.3. DESIGN TOOL AND WORKFLOW

In this study, we examine the effect of the varying length of the spacer structures on the creation of 3D geometries on the front face of the tile, while maintaining the width and location of the spacers in the knitting map fixed. At a later stage of the research, we intend to examine the effect of varying these parameters on the morphologies created while casting. We created a digital design tool implemented in Processing to assist users in designing the variable-length spacer knitting plans. The design tool allows users to input a greyscale image as a height map and receive a colour-coded knitting map, which can be used as input for the knitting machine software. The tool is based on a tile map defining the location of the spacers, and a given knitting map defining the shape of the knitted mould and the location of the spacer structures (Figure 6). Each colour in the map is predefined in the corresponding CA file, while each spacer colour corresponds to a different spacer length. According to the input grey-scale image, the design tool remaps the colour scale from white to black as numbers between 0 to 1, black pixels corresponding with a spacer colour of forty-five rows, and the white pixels to a spacer colour of 5 rows. In between, the various spacer lengths are assigned according to the proximity to the numbers between 0.1 and 0.9, to spacers constructed from 11, 15, 21, 25, 31, 35, and 41 rows, respectively

First, the tool applies the relevant box colours to the tile map, then aligns the colours with the corresponding spacer structures in the knitting map. The workflow results in a bitmap which is based on the given knitting map, while all spacer pixels are coloured in the defined colour corresponding to the varying lengths. Using this tool, users can produce knitting instructions of various geometries, controlling the maximum and minimum inflation of the tile by placing black, grey or white pixels in various locations.

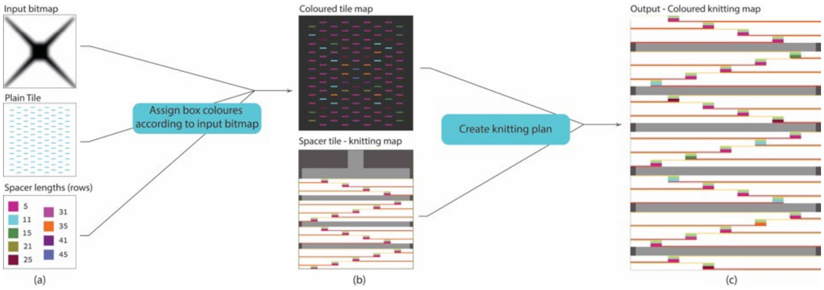

Figure 6: Design tool workflow - (a) input grey-scale BMP applied on plain tile, according to predefined colours of spacer lengths; (b) coloured tile map, applied to spacer tile knitting map; (c) output colour-coded knitting map of the spacer tile for M1plus.

3.3.1. Simulation

In addition to the colour-coded image of the knitting map, an additional tool produces a simulation output of the tile once inflated. The simulation of the inflated shapes is embedded using Kangaroo (http://kangaroo3d.com). Based on the grey-scale image and the location of the spacer structures throughout the knitted mould, the tool generates a coloured mesh. The physics engine simulation is based on dividing the mesh into edges and simulating each edge as a spring. The spring value defines the maximal stretch of the loop, determined by the loop length parameter defined in the fabrication process and by the specific yarn being used. The vertices of the mesh are defined by the different coloured spacers, creating anchors in different lengths (corresponding with the number of rows as predefined in the CA). Thus, these anchors will not be affected by inflation. During the simulation, a global pressure force is applied to the mesh, lifting the vertices and constructing the inflated geometry.

4. Results

Various configurations of stay-in-place tiles with various 3D morphologies were created, featuring varying lengths of spacers which control the inflation of the tiles (Figure 7). An additional hexagonal tile was fabricated and cast to exemplify the use of spacers and the casting process in a non-rectilinear knitted mould (Figure 8), demonstrating the flexibility of the proposed method in fabricating tiles of varying shapes and scales, eliminating the need for external fixtures while enabling the production of complex geometries through an adaptable knitting and casting process.

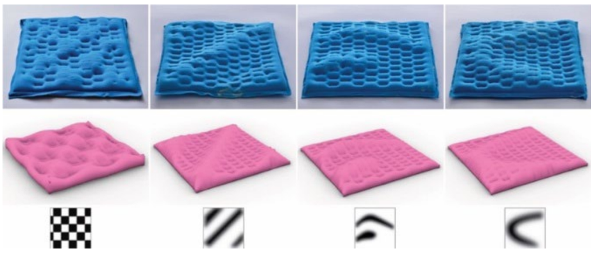

Figure 7: Examples of cast tiles input bitmaps (down), simulation (middle) and physical models (up)

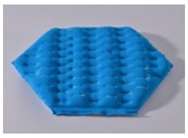

Figure 8: Physical cast hexagonal tile

To validate the simulation tool, the physical cast moulds were scanned and compared with the digital simulation (Figure 9). The comparison highlights the similarities between the simulation and the physical tile in terms of volume and geometry, with a difference of up to 13 mm in tile width, which may be attributed to material leakage during casting.

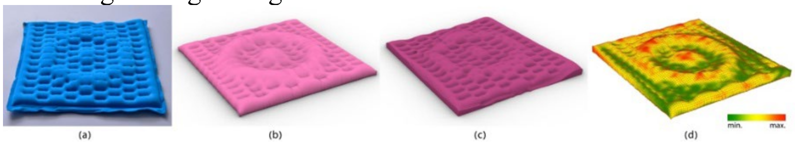

Figure 9: (a) cast tile; (b) simulation; (c) scanned tile; (d) comparison between simulation and scanned tile, green symbolizing full alignment while red symbolizing discrepancies

5. Discussion and Future Work

In this preliminary stage, the selected tiles were cast with gypsum to evaluate the inflation behavior of the knitted moulds and the resulting 3D geometries. The results demonstrate the success of this method in producing complex morphologies and its potential scalability for generating diverse tile shapes, suited to various architectural applications. This approach also offers opportunities for ecological adaptation by accommodating multi-species integration through features such as cavities, perforations, and protrusions. Future research will focus on developing a definitive cementitious mixture, conducting durability and viability tests, and refining the fabrication process to prevent perforations during spacer knitting. Additionally, the design tool may be further developed to enable the planning and simulation of complete façade systems, including tile division and geometric distribution, while also estimating the volume and weight of cast tiles to optimize material use and enhance precision in casting preparation.

6. Conclusion

This study presents a novel methodology and workflow for the design, simulation and fabrication of 3D stay-in-place knitted spacer moulds for building envelope tiles. The results demonstrate the feasibility of devising and producing complex geometries through variable spacer lengths. Multiple tile configurations, including circular, checkered, diagonal, and curved morphologies, were fabricated to examine the limitations of spacer variations and their effect on tile inflation and form generation. A non-rectangular tile further validated the casting process and confirmed the technique's adaptability to non-rectilinear geometries. A customized simulation workflow using Kangaroo effectively modelled differential inflation across the tile based on bitmap input. Further research is required to refine spacer fabrication, particularly in forming perforations on the front face of the fabric and explore the use of biodegradable materials to enhance the method’s contribution to sustainability.

This research contributes an innovative workflow that utilizes computational knitting to produce stay-in-place variable-length spacer moulds, enabling the creation of complex, non-repetitive building tiles through an efficient and fully integrated design-to-production workflow. The method allows users to automatically generate knitting instructions from a simple grey-scale height map, bridging digital design and material fabrication.

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Attribution Statement

ChatPDF (http://www.chatpdf.com) was used to extract and summarize relevant information for background review.

References

Adosi, B., Mirjalili, S. A., Adresi, M., Tulliani, J.-M., & Antonaci, P. (2021). Experimental Evaluation of Tensile Performance of Aluminate Cement Composite Reinforced with Weft Knitted Fabrics as a Function of Curing Temperature. *Polymers*, *13*(24), 4385. https://doi.org/10.3390/polym13244385

Austern, G., Capeluto, I. G., & Grobman, Y. J. (2022). Real-time fabrication analysis: A method for evaluating fabrication constraints of complex concrete shapes. *Architectural Science Review*, *65*(6), 421–435. https://doi.org/10.1080/00038628.2022.2107992

Dejene, B. K., & Gudayu, A. D. (2024). Exploring the potential of 3D woven and knitted spacer fabrics in technical textiles: A critical review. *Journal of Industrial Textiles*, *54*, 15280837241253614. https://doi.org/10.1177/15280837241253614

Di Prisco, M., Felicetti, R., & Plizzari, G. A. (with Symposium RILEM sur les bétons renforcés de fibre). (2004). *Fibre-reinforced concretes: Proceedings of the sixth International RILEM symposium, [20-22 September, 2004, Varenna, Italy]*. RILEM publications.

Grobman, Y. J., Weisser, W., Shwartz, A., Ludwig, F., Kozlovsky, R., Ferdman, A., Perini, K., Hauck, T. E., Selvan, S. U., Saroglou, S. (Tanya), Barath, S., Schloter, M., & Windorfer, L. (2023). Architectural Multispecies Building Design: Concepts, Challenges, and Design Process. *Sustainability*, *15*(21), 15480. https://doi.org/10.3390/su152115480

Hawkins, W. J., Herrmann, M., Ibell, T. J., Kromoser, B., Michaelski, A., Orr, J. J., Pedreschi, R., Pronk, A., Schipper, H. R., Shepherd, P., Veenendaal, D., Wansdronk, R., & West, M. (2016). Flexible formwork technologies – a state of the art review. *Structural Concrete*, *17*(6), 911–935. https://doi.org/10.1002/suco.201600117

Hershcovich, C., Van Hout, R., Rinsky, V., Laufer, M., & Grobman, Y. J. (2021). Thermal performance of sculptured tiles for building envelopes. *Building and Environment*, *197*, 107809. https://doi.org/10.1016/j.buildenv.2021.107809

Liu, S., Ma, X., Ma, Y., Chen, Z., Dong, Z., & Ma, P. (2023). Review on the design and application of concrete canvas reinforced with spacer fabric. *Journal of Engineered Fibers and Fabrics*, *18*, 15589250231152591. https://doi.org/10.1177/15589250231152591

Nawy, E. G. (Ed.). (2008). *Concrete construction engineering handbook* (Second edition). CRC Press. https://doi.org/10.1201/9781420007657

Popescu, M., Rippmann, M., Liew, A., Reiter, L., Flatt, R. J., Van Mele, T., & Block, P. (2021). Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell. *Structures*, *31*, 1287–1299. https://doi.org/10.1016/j.istruc.2020.02.013

Roye, A., & Gries, T. (2007). 3-D Textiles for Advanced Cement Based Matrix Reinforcement. *Journal of Industrial Textiles*, *37*(2), 163–173. https://doi.org/10.1177/1528083707078136

Slocum, B. (Ed.). (2021). *Distributed proximities: Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture. Volume 1: Technical papers, keynote conversations*. Association for Computer Aided Design in Architecture, Philadelphia, Association for Computer Aided Design in Architecture (ACADIA).

Sterman, Y., Grobman, Y. J., & Goldfeld, Y. (2025). Developing a Computational Design to Fabrication Method for 3D Knitted Stay-in-Place Moulds for Building Envelopes Tiles. In H. Chai, D. W. N. Bao, Z. Guo, & P. F. Yuan (Eds.), *Symbiotic Intelligence* (pp. 67–76). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-3433-0_7