A MODULUS-BASED ENCODING METHOD FOR CONTINUOUS GRADIENT PATTERN IN ARCHITECTURAL KNITTED FABRICS

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Abstract. In the realm of lightweight materials in architecture, knitting as a discrete additive method has enabled the creation of functionally graded material (FGM). For the current research in encoding methods for knitting FGM materials, researchers tend to focus on a limited number of surface transitions to study localized material traits. However, designing at an architectural scale demands multiple hierarchical structures for smooth transitions due to amplified performance differences, resulting in a complex system. Thus, organizing knitting units during encoding becomes crucial. This paper proposes a modulus-based encoding method for architectural knitting FGM materials, accommodating various surface types to create continuous gradient patterns. Based on the Grasshopper platform and STOLL machines, the method translates 3D models into machine encoding by using BMP (Bitmap) graphics. The method was successfully applied in a workshop in Tongji University. This research explores the fabrication of knitting FGM materials with multi-patterns in architecture, aiming to inspire innovative applications of fabrics in architecture.

Keywords. Structural Grading Model, Functionally Graded Material, Knitted fabrics, Encoding Method, Architectural Design

1. Introduction

Lightweight composite materials have garnered significant attention in architectural design, and have been widely applied in outdoor installations (Liu et al., 2022), spatial partitions (Sinke et al., 2023), and casting templates (Popescu et al., 2021). Their inherent variability in physical properties allows for the possibility of diverse material characteristics by combining architectural design requirements with structural or formal demands. Functionally graded material (FGM) in the realm of composite materials, owing to their continuous variations in material composition and properties, offer higher-resolution customization in form and structure. This, in turn, enhances the

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efficiency of material utilization (Naebe & Shirvanimoghaddam, 2016).

The emergence of the additive manufacturing (AM) technique has made the realization of FGM possible. Giselle Hsiang Loh et al. introduced the term functionally graded additive manufacturing (FGAM)(Loh et al., 2018). FGAM enables the differentiation of material manufacturing processes, ensuring physical continuity while introducing property discontinuities. For lightweight materials in architecture, knitting structures serve as an additive manufacturing approach formed by the accumulation of numerous discrete stitches. This fabrication technique has already showcased various successful applications in architectural spaces, such as the Zoirotia (Sinke et al., 2023) and Isoropi (Tamke et al., 2021). Additionally, it has found relevance in adaptive wearable devices (Granberry et al., 2019). However, traditional FGM processing methods have struggled to uniformly alter geometric patterns in knitted fabrics, resulting in limited developments in textile composite materials (Mohan et al., 2017). The commercialization of modern flat knitting machines like the STOLL machine, equipped with high-resolution grid-based digital interfaces, enables the pixelated decomposition of overall fabric forms, allowing the customization of the structure of each knitted unit within a single fabrication act, enabling a more controlled and liberated material distribution state.

While pioneering new technologies, the primary challenges encountered in developing knitting FGM include strategies for gradation and encoding methods. Several scholars have researched fabric gradation strategies. For instance, Huy Do et al. used single jersey stitch patterns with two different knitting parameters to create gradient knitted textiles (Do et al., 2020). For the logic for gradation, it varies among projects. Martin Tamke et al. segmented structures into four surface types, thus developing four line-drawing algorithms capable of mapping surface designs onto arbitrary input grids (Granberry et al., 2019). However, in this study, the transition boundaries between patterns did not achieve uniform blending. Yuliya Sinke et al. proposed an encoding method based on two yarn colors and two structural densities by using the dithering technique (Sinke et al., 2023). Furthermore, the research suggests exploring richer gradient structures within monochrome for more comprehensive conclusions, which inspired this paper. In terms of encoding conversion methods, determining the scaling ratio between programming dimensions and actual dimensions remains a common challenge. Approaches involving machine learning (Thomsen et al., 2019) and physical prototyping methods have been referenced to address this issue (Granberry et al., 2019).

According to the literature research, it is observed that existing researchers tend to employ a limited number of surface types for the knitting FGM encoding process. By reducing the size of the fabric and the number of surface types, more accurate localized properties of the material could be obtained. However, driven by considerations of surface variation effects and performance possibilities, the design of large-scale architectural installations requires a diverse range of surface types to participate in the structural transition system. This necessitates a method capable of comprehensive planning for multiple surface patterns involved in the transition during the encoding process, addressing both macro-level grading boundary control and micro-level knitting interconnection possibilities. Additionally, research into multi-pattern gradients makes it possible for a more universally designed mechanism for gradients possible. Therefore, this research attempts to propose a universal holistic organization and encoding method applicable to various surface types in architectural FGM fabrics, aiming to generate continuous and natural gradient patterns within a single material.

2. Proposal

This research aims to introduce a modulus-based encoding method for architectural fabric structural with FGMs. The method relies on 2D knitting fabrics and is based on Grasshopper platform and STOLL machine. The STOLL machine is equipped with M1 Plus software, where machine actions are represented by colors. Color templates are able to be set by using color arrangement feature, which are then utilized to generate weaving information through BMP (Bitmap) images. Based on Yige Liu et al.'s encoding programming (Liu et al., 2020), this method proposes three stages for getting BMP images of multiple gradient patterns.

In the first stage, pattern selection involves choosing the distribution of surface types based on design intention. Surface types are primarily determined by two factors: form requirements and fabrication needs. Form requirements include structural performance and aesthetic appearance, such as transparency. Fabrication needs stem from factors such as positions for cables.

In the second stage, the number of grid overlays has to be determined based on the quantity of surface types involved in transformation of material properties. A unit grid should be firstly defined as the foundation for various pattern grids. The size of the unit grid should be determined through experiments. Then, a multiplicative relationship on the modulus needs to be established for the various types of patterns. In other words, the size of the cell grid occupied by each pattern module needs to be defined. Subsequently, all pattern grids are overlaid as layers on the overall fabric in the same coordinate system for subsequent processing.

The third stage involves specifying the stitch type within the grids for different pattern categories, each assigned a distinct color. The absence of color indicates the absence of knitting actions within that unit. Once all stitch colors within the fabric outline are defined, a BMP image is generated. This BMP image is then compatible with STOLL flat knitting machines using the integrated M1 Plus software, producing machine-readable pattern information.

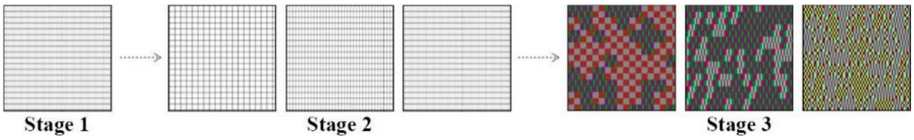

Figure 1. An illustration of the method proposed

3. Case Study

The method proposed in the research was applied in a workshop in Tongji University. The objective of the workshop was to erect a pavilion integrating timber structures with knitting facade (see Figure 2). How to encode knitting information with various patterns through modular-based approach becomes a central concern for this research. The process can be divided into two stages: design and fabrication. The design stage primarily involves the specification of morphology design, pattern design, and encoding process. The fabrication stage focuses on the assembly of the knitting fabrics and the wooden structures.

3.1. MORPHOLOGY DESIGN

The morphology of the knitting fabrics primarily relies on the wooden structures. An elastic fabric that formes a tubular textile around the timber structure was generated by using the Kangaroo plugin in Grasshopper. The upper and lower beams of the wooden structures served as anchor points for kangaroo. Parameters like strength were adjusted to get a surface align with the wooden structures. Based on the overall morphology, the surface should be discretized due to the fabrication requirements. Considering the constraints of the STOLL machine, the width of each facet to be knitted must not exceed 1 meter. In this process, designers identified control points based on the timber structure, dividing the surface into 16 parts along the axis.

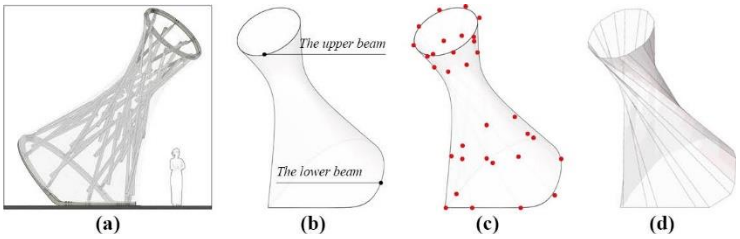

Figure 2. (a) Illustration of the position between the membrane and the wooden structure in the installation. (b) The form of the elastic fabric generated by kangaroo. (c) Control points of the wood structure for discretizing the knitting fabric. (d) Final discretizing approach of the fabric.

3.2. PATTERN DESIGN

To fulfill the formal and structural requirements, pattern types are designed for the knitting surface. In terms of form, the effect of increased transparency of the fabric from the bottom up is the most important part of the surface design. Within this aspect, the selection of pattern types should be contemplated first. Samples with different patterns were customized, which various in transparency. In contrast, the way of perforation effectively accentuated the transparency gradient. Consequently, the numbers of perforated needles are established as the independent variable for transparency variation. Ultimately, the design incorporated four types of patterns for the gradient portion of the knitting fabrics, which are half-cardigan, small-scale perforation, medium-scale perforation, and large-scale perforation.

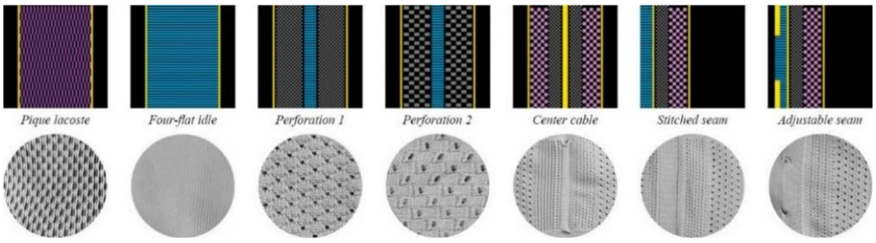

Figure 3. Samples of surface pattern types with corresponding BMP images

Besides, four additional surface pattern types were designed in the consideration of fabrication. A buffer area was set within the outline of the fabric as a reinforcement zone. For the reinforcement zone, a double-sided four-flat knitting technique, offering enhanced structural strength. The 16 fabric pieces were ultimately stitched together to form a tubular structure. An adjustable seam was supposed to be remained between two of the facets without stitching, making it possible to adjust for errors during fabrication. The other 15 seams were sewn using threads. Due to the distinction, the treatment of the edges of these 16 fabric pieces varied and were categorized into three types. Edge of the fabric on the sides of the adjustable seam were designated as type A and type B, while the remaining fabric pieces were designated as type C. Within type C, the reinforcement zones on both sides were evenly divided into 2 parts. The boundary zones were marked using a single-sided four-flat weaving technique as sewing guidelines. Simultaneously, the edges on one side of each fabric piece were offset outward by 50mm to provide space for interfacing with adjacent fabrics. The boundary between the expanded area and the original outline was also marked with a single-sided four-flat weaving technique. According to the design, the middle part of the expanded area served as the passage for cables. The pattern on one side of types A and B becomes a segmented four-flat idle, leaving space for cable to go through. Stitches were left at the edge of the hollow structure to maintain openness at both ends, ensuring non-coinciding.

3.3. ENCODING PROCESS

To integrate the digital model of design, encoding process was conducted within Rhino's Grasshopper. This research primarily focused on the construction of 2D fabrics, which required surface flattening post-segmentation. TT-Toolbox, a plugin in Grasshopper, was ultimately selected for surface flattening. During this process, it was ensured that the edges of the fabrics are of equal length. Based on the flattened surface, the minimum knitting unit of the fabric needed to be defined in a gridded manner. For the coordinate system of the grid, the corner point of the surface's bounding box served as the origin for the plane coordinate system. And the x and y axes in Rhino served as the two axes of the grid. Accurate sizing for each grid unit required subsequent experimental determination. In the initial coding phase, a rough initial value was set as the specification for the grid unit.

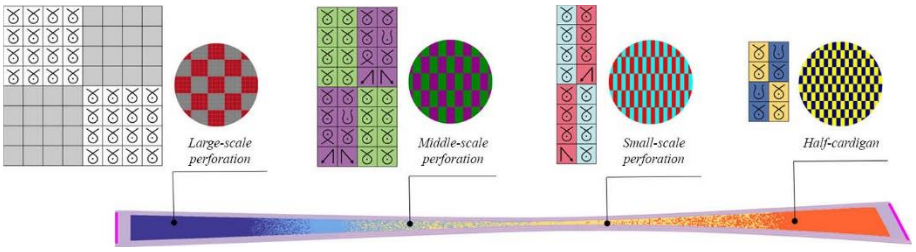

Figure 4. The multidimensional grading method for the fabrics used in the installation

Based on the design of surface types, the grids of patterns involving gradient structures needed to be defined. Upon investigation, the available machines for experimentation supported a maximum of 4 stitches for the loop. Consequently, this set an upper limit of 4 stitches for the largest perforated units in the current design. Adjustments could be made for the sizes of other perforated units within this constraint. The sole condition restricting these adjustments was that the starting and ending points of each perforated unit must not be crossed with empty stitches.

When multiple perforated units are superimposed, the number of holes is required to be reduced in a direction in order to even out the gradient, which makes randomness in the transition between two sizes of perforated units. This random variation needs to be done in an orderly manner in order to ensure that the end portion of one type of perforated pattern does not meet another type of perforated pattern, making it possible to complete the closure. To establish this order, the study applied the concept of modular grids. Within this modular grid, the smallest unit needed to accommodate both perforated and non-perforated stitches. In this design, the minimum unit for perforated units was set with a size of 1*4. To facilitate smooth connections between the minimum modules, they were defined as 2*8 grids. To enable larger modules to seamlessly connect with these minimum units, the larger modules were defined accordingly, with perforated units of 2*4 within this module and an overall grid size of 4*8. Similarly, the largest modules had perforated sizes of 4*4 and an overall grid size of 8*8.

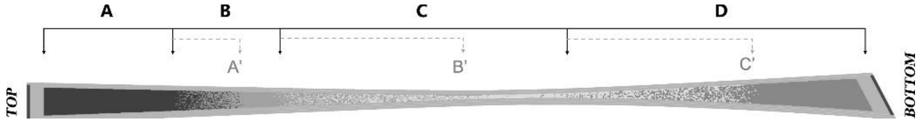

Figure 5. Distribution areas of the four surface types requiring transition

Regarding the correspondence between the grids and colors of BMP images, the positions requiring stitching for various grid specifications needed to be determined. The fabric was divided from bottom to top into four areas: part A, part B, part C, and part D. Additionally, partial regions A', B', and C' within B, C, and D respectively were designated as transition zones for A, B, and C areas. Therefore, the respective covered areas for these four patterns were calculated as follows.

S1 = S(A) +S(A')

S2 = S(B) - S(A') + S(B')

S3 = S(C) - S(B') + S(C')

S4 = S(D) - S(C')

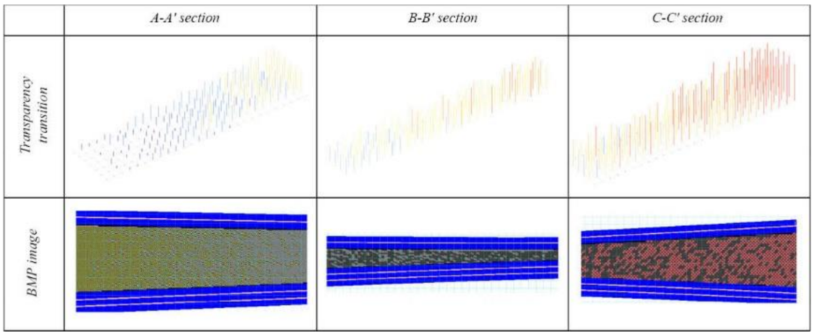

Figure 6. Changes in transparency in the transition region (indicated by different colors)

To ensure the perforated sections in each of the grid cells S1 to S4 to meet the non-perforated sections at the corners, uniformity in the relative positions of these two stitches was essential across the four sizes of grid units. Different colors were assigned to correspond to these respective areas. This approach facilitated the alignment of perforated sections from one size of perforated pattern with the non-perforated sections of another size of perforated pattern. Thus, at the micro-level of stitch operations, the transition zones guaranteed the feasibility of stitch placement. Simultaneously, at the macro-level, these transition zones achieved a uniform translucency gradient.

In addition to defining the stitches in the transitional zones, the color information for reinforcement areas, sewing threads, sleeves, and tuck stitches was also defined. Upon generating the first BMP image, a comparison was made between the actual fabric dimensions and digital model. This result of the comparison was used to calculate the specific regulation of the precise minimum unit grid size. Ultimately, 16 distinct BMP images are obtained, each comprising approximately 300,000 pixels and incorporating color information for 12 different stitches. Using the M1 Plus software, the color data was converted from the BMP images into knitting information.

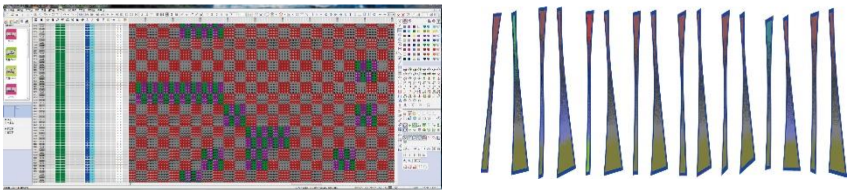

Figure 7. M1 Plus operation process and the 16 BMP images used

3.4. FABRICATION

After the completion of the encoding process, the production, sewing and assembly processes needed to be carried out. The estimated production time for each fabric panel was approximately 4 hours. During production, certain issues required attention. For instance, vigilant monitoring of the knitting fabric status was necessary to prevent excessive damage caused by machine. While minor damage could be remedied through manual hook, extensive damage rendered the fabric unusable.

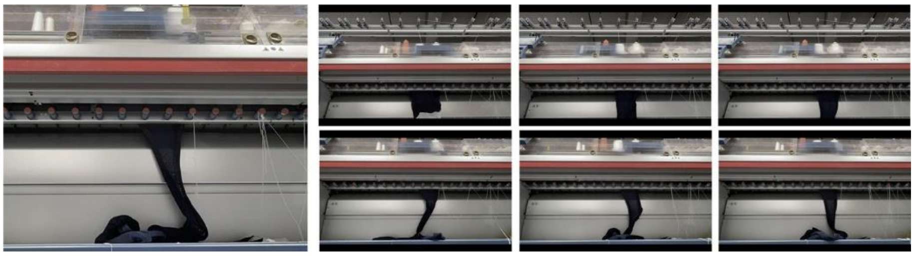

Figure 8. The process of fabrication with the STOLL machine

Following the completion of fabric facets, the stitching process commenced. Despite the consistent scaling applied to the 16 fabric panels, discrepancies between the physical fabric and the digital model arose due to variations in the encoded information. This inconsistency resulted in uneven edge lengths when adjacent knitting pieces were stitched together. To reduce the error, uniform sectional markers were delineated along the edges of the fabrics. This allowed for even error compensation during stitching, aligning the edges of adjacent sections. After sewing, cables were fastened at the upper and lower sleeves and the sewing areas to enhance the structural performance of the fabric.

Figure 9. Positioning, Suturing and Cordage Process

Additionally, the fabric needs to be mounted on the periphery of the wood structure, with the help of the top and bottom beams to provide surface tension for it. During assembly, sliding the fabric directly into the wooden structure poses a challenge due to the overall shape of the device, which is larger at the ends. Therefore, a segmented assembly method was used in the experiment. The wooden structure was divided into two parts. First, the fabric was completely secured to the upper beam and then hoisted together with it. Once the wood structure was assembled, the adjustable edge of the fabric was pulled down and installed onto the lower beam.

Figure 10. The assembly process of the fabric and the wooden structure

The final completed installation showcased the layered gradient transparency of the fabric, demonstrating a well-executed transition effect. This layered structure exhibited distinct expansion properties across the entire surface, thereby allowing controlled multidimensional grading of the knitted fabric.

Figure 11. Effect of the completed installation

4. Reflection

The study also identified issues encountered in the aforementioned experiments. Variations in knitting proportions due to different pixel image orientations and the lack of complete control over fabric structure scaling resulted in less smooth transparency transitions between different facets. Fortunately, we have now obtained the initial batch of data, allowing for future data prediction and assessment through methods such as machine learning. Additionally, existing research has demonstrated the feasibility of this approach.

5. Conclusion

The lightweight FGM enables smooth transitions in performance within a single manufacturing process, offering advantages such as reduced weight and structural flexibility. Leveraging these benefits, it finds wide applications in architectural contexts like facade structures and flexible partitions. The introduction of the STOLL flat knitting machine has facilitated fabric as a discrete construction method, allowing customized design and production of FGM through digital programming. However, a challenge arises in architectural-scale designs due to amplified performance differences, necessitating more hierarchical organizational structures for transition, resulting in complex and organic systems. Thus, orchestrating the overall organization of individual knitted units during the encoding process becomes pivotal.

Based on this challenge, the research proposes a modular-based architectural fabric encoding method suitable for continuous variations with diverse surface pattern types. It arranges fabric patterns at a macroscopic level while ensuring the interconnection of microscopic knitting. It serves as a reference for customized fabric performance design through three stages: pattern selection, grid overlay, and color definition. Developed on the Grasshopper platform and the STOLL machine, it bridges the digital design model and the encoding information by using BMP images. In the pattern selection stage, primary morphology and structure are considered as major requirements, defining the types and distribution of patterns within the outline. During grid overlay, establishing modularity between transitional patterns resolves the problem of orderly arrangement between different patterns in the FGM performance transition region. In the color definition stage, micro-level stitches within various grid units is considered. In this process, both the arrangement within a single grid unit and the junction between different patterns should be contemplated.

This method was validated in a pavilion project featuring gradient perforated fabrics in Tongji University. The experiment incorporated four patterns as surface types for the gradient section. Coding incorporated three grids of 2*8, 4*8, and 8*8, each housing three different-sized perforated units. The internal structure of these perforated grids was designed with perforated and non-perforated units. 12 color types were integrated into the BMP images, finally converted into knitting information using the M1 Plus software. Ultimately, after the stages of fabric production and sewing, the fabric was affixed to the wooden structure and displayed.

Through the exploration of knitted materials, this paper speculates on future paradigms for FGM for a lighter architecture, aspiring to offer new perspectives for digital fabrication.

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References

Aremu, A. O., Brennan-Craddock, J. P. J., Panesar, A., Ashcroft, I. A., Hague, R. J. M., Wildman, R. D., & Tuck, C. (2017). A voxel-based method of constructing and skinning conformal and functionally graded lattice structures suitable for additive manufacturing. Additive Manufacturing, 13, 1–13. https://doi.org/10.1016/j.addma.2016.10.006

Do, H., Tan, Y. Y., Ramos, N., Kiendl, J., & Weeger, O. (2020). Nonlinear isogeometric multiscale simulation for design and fabrication of functionally graded knitted textiles. Composites Part B: Engineering, 202, 108416. https://doi.org/10.1016/j.compositesb.2020.108416

Granberry, R., Eschen, K., Holschuh, B., & Abel, J. (2019). Functionally Graded Knitted Actuators with NiTi-Based Shape Memory Alloys for Topographically Self-Fitting Wearables. Advanced Materials Technologies, 4(11), 1900548. https://doi.org/10.1002/admt.201900548

Hascoet, J. Y., Muller, P., & Mognol, P. (2011). Manufacturing of Complex Parts with Continuous Functionally Graded Materials (FGM). https://doi.org/10.26153/TSW/15317

Liu, Y., Hua, H., & Li, B. (2022). Exploration and design of knitted composites for architectural application: The MeiTing project. Frontiers of Architectural Research, 11(4), 594–608. https://doi.org/10.1016/j.foar.2022.01.004

Liu, Y., Li, L., & Yuan, P. F. (2020). A Computational Approach for Knitting 3D Composites Preforms. In P. F. Yuan, Y. M. Xie, J. Yao, & C. Yan (Eds.), Proceedings of the 2019 DigitalFUTURES (pp. 232–246). Springer Singapore. https://doi.org/10.1007/978-981-13-8153-9_21

Loh, G. H., Pei, E., Harrison, D., & Monzón, M. D. (2018). An overview of functionally graded additive manufacturing. Additive Manufacturing, 23, 34–44. https://doi.org/10.1016/j.addma.2018.06.023

Mohan, J. M., Srikanth, D., & Kumar, K. P. (2017). STUDY AND APPROACH ON HYBRIDPOLYMER COMPOSITE MATERIALS WITH FGM. 3(6).

Naebe, M., & Shirvanimoghaddam, K. (2016). Functionally graded materials: A review of fabrication and properties. Applied Materials Today, 5, 223–245. https://doi.org/10.1016/j.apmt.2016.10.001

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

Sinke, Y., Thomsen, M. R., Tamke, M., & Seskas, M. (2023). Strategies for Encoding Multi-dimensional Grading of Architectural Knitted Membranes. In C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M. R. Thomsen, & J. Wurm (Eds.), Towards Radical Regeneration (pp. 528–542). Springer International Publishing. https://doi.org/10.1007/978-3-031-13249-0_42

Tamke, M., Sinke Baranovskaya, Y., Monteiro, F., Lienhard, J., La Magna, R., & Ramsgaard Thomsen, M. (2021). Computational knit – design and fabrication systems for textile structures with customised and graded CNC knitted fabrics. Architectural Engineering and Design Management, 17(3–4), 175–195. https://doi.org/10.1080/17452007.2020.1747386

Thomsen, M., Nicholas, P., Tamke, M., Gatz, S., & Sinke, Y. (2019). Predicting and steering performance in architectural materials. 485–494. https://doi.org/10.52842/conf.ecaade.2019.2.485