Robotic Sewing

A Textile Approach Towards the Computational Design and Fabrication of Lightweight Timber Shells

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1 Interior view of the ICD/ITKE Research Pavilion 2015-16. The finished large-scale prototype building serves as an architectural demonstrator for research into robotic sewing.

ABSTRACT

Unlike any other building material, timber has seen numerous innovations in design, manufacturing, and assembly processes in recent years. Currently available technology not only allows architects to freely shape building elements but also to define their micro- or macroscopic material make-up and therefore the material itself. At the same time, timber shells have become a focus of research in wood architecture by rethinking both construction typologies and material application. Their main advantage, however, also poses a challenge to its construction: As the shell is both the load-bearing structure as well as enclosure, its segmentation and the individual segment's connections become increasingly important. Their complex and often differentiated geometries do not allow for standardized timber joints, and with decreasing material thickness, conventional connection techniques become less feasible.

The research presented in this paper investigates textile strategies for the fabrication of ultra-lightweight timber shells in architecture. Specifically, a robotic sewing method is developed in conjunction with a computational design method for the development of a new construction system that was evaluated through a large-scale prototype building.

INTRODUCTION

The development of new building products such as Laminated Veneer Lumber (LVL) and Cross-Laminated Timber (CLT) not only enabled the use of planar elements but also drove timber construction towards a homogenization of wood properties for the sake of calculability. The unique and specific characteristics of wood, such as its anisotropy and elasticity—which both depend on grain direction—are leveled out through the cross-lamination of individual anisotropic layers. Whereas conventional timber construction relies on thick cross sections and metal fasteners for connections, the aim of this research is to construct very thin shells made from plywood by taking advantage of the specific material characteristics in the design and fabrication process and by using alternative connection strategies suited for very thin sheet material. Consequently, form-finding principles have to be established that incorporate materiality and fabrication possibilities.

New developments in digital fabrication, particularly in robotics, allow for the implementation of design principles such as heterogeneity, hierarchy, or anisotropy in architecture, which are characteristic principles found in nature (La Magna et al. 2013). Enabled by computational design strategies, the premise of these high-level principles is that, similar to biology, more geometric variability can lead to higher performance of the structure, given that its elements are individually adapted to specific requirements and less energy and material is required in their construction. Consequently, the research presented in this paper is to a large extent based on the abstraction and transfer of morphological principles from biology to the design and fabrication of thin shells in architecture.

The availability, analysis, and abstraction of relevant biological principles and the aspects related to structural analysis and simulation, both of which are discussed in Bechert et al. (2016), lie outside the scope of this paper. Rather, this paper focuses on the technical transfer of these principles and on its methods of implementation in the design and fabrication of thin shells; specifically, on the joint design and custom robotic fabrication approaches. Its main hypothesis is that the design and construction of very thin, geometrically differentiated timber shells requires alternative connection and fabrication methods and that, consequently, they can be built entirely without the need of traditional timber fasteners (Fig. 1).

CONTEXT AND RELATED WORK

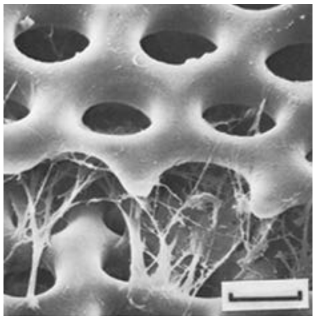
Thin Timber Shells

Continuous thin concrete shells have been a popular typology in architecture and engineering from the 1930s to the 1980s. However, they seem to have lost their appeal in recent decades due to the comparatively high effort necessary for their in-situ construction, which involves the manufacturing of complex formwork and extensive manual labor, even with today's high degree of automation. An alternative is the construction of thin timber shells made from segments, as demonstrated in previous work in the Landesgartenschau Exhibition Hall (Krieg et al. 2015) and the ICD/ITKE Research Pavilion 2011 (Menges and Schwinn 2012). However, the dimensional limitations of plywood, as well as the subsequent need for transportation, limits the size of the segments from which the shell is to be constructed. In addition, as the previous case studies have demonstrated, the planarity of the available timber sheet material leads to the requirement of elaborate planarization strategies in order to approximate complex double-curved surfaces while respecting fabrication constraints (Schwinn et al. 2014; Schwinn et al. 2013).

Another major challenge in the development of segmented shells is the design of the joints, as the stiffness continuity of the shell is interrupted (Li and Knippers 2015). Therefore, a particular focus of any design approach for segmented shells has to be the joint design. This has led to a considerable research effort directed towards the design and fabrication of so-called integrated joints (Krieg et al. 2015; Robeller and Weinand 2015). Contrary to conventional timber construction, the complexity of the joint is integrated into the element through elaborate digital fabrication techniques. However, this poses a problem for thin shells with a highly reduced material thickness. Not only can the geometric complexity of integral joints not be embedded within an element's edge below a certain material thickness, but building codes also regulate the required distance between metal fasteners like screws and the material surface. Both aspects limit the further reduction of shell thickness. Furthermore, although integrated connectors such as finger and dovetail joints are form- and force-fit connections, they are usually the result of subtractive fabrication processes such as CNC milling. In these processes, the continuity of the cellulose fibers in the wood is disrupted, potentially weakening the material, particularly where the main forces are transferred between building elements. These aspects have led to the search for alternative joining techniques for thin timber and to the investigation of a possible transfer of textile processing techniques into timber construction.

Textile Techniques

From a microscopic point of view, wood, like most biological constructions, can be considered a natural fiber composite exhibiting similar properties to man-made composites such as fiber-reinforced polymers (FRP). In both cases, the fiber direction in the lay-up determines the anisotropic material behavior. In the case of technical textiles, this allows users to design the material properties to meet structural or other requirements in a



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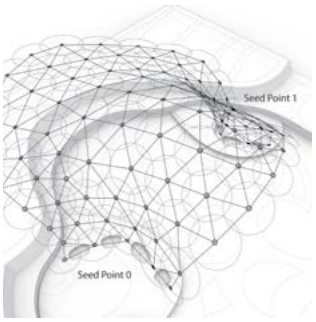

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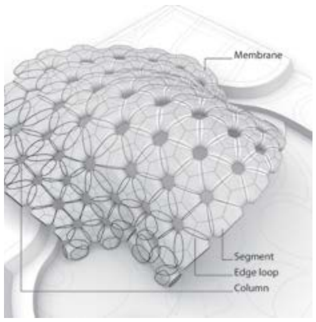

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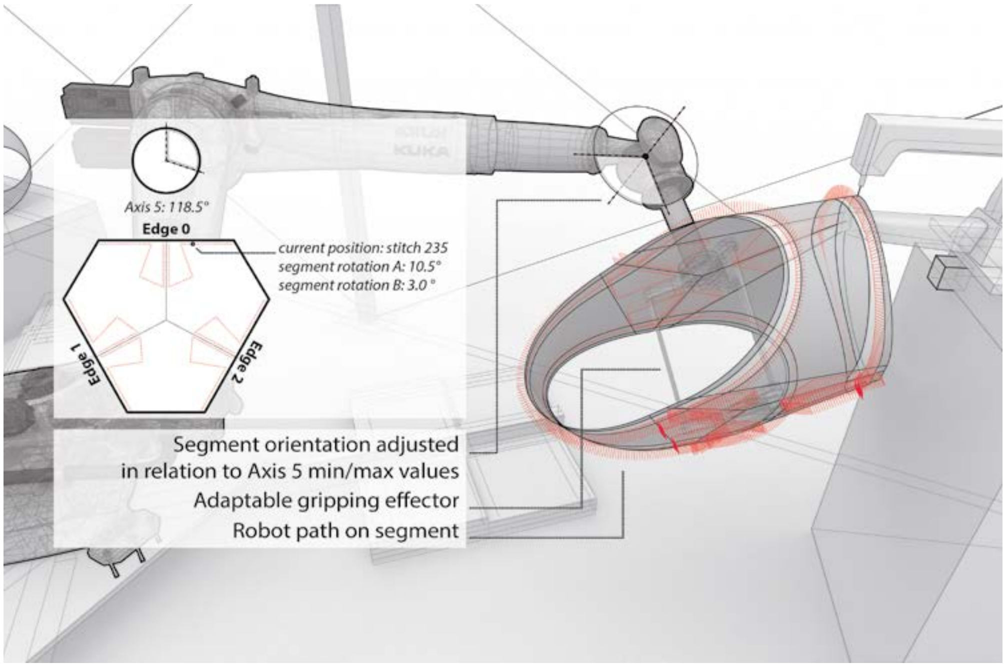
bottom-up manner. This is why FRPs play such a crucial role in automotive and aerospace industries, where a high stiffness-to-self-weight ratio is required. In the case of wood, however, the anisotropic material behavior is usually considered undesirable in the context of the building industry, leading to the development of plywood or fiberboards with mostly homogeneous characteristics.

The objective of this research is consequently to re-consider and re-interpret the material properties of wood in light of its textile nature. The field of technical textiles and in particular the field of fiber-reinforced polymers provides established methods for manipulating anisotropic sheet material with the potential of being transferred into an application in timber architecture. Sewing is identified as a particularly promising approach, where initially planar sheets are connected along their edges using thread, resulting in complex three-dimensional forms based on two-dimensional cut patterns. The goal is therefore to apply techniques such as patterning, sewing, lacing, and lamination to the fabrication of lightweight building components made from timber, and to exploit the material's elasticity during fabrication, resulting in self-supporting and stable structures.

The parallels between timber and textiles become more evident at material thicknesses much lower than those usually used in timber construction. Given the thickness of rotary sliced veneer of about 1 millimeter, the material can be manipulated like a textile. Furthermore, sewing has similar advantages in timber construction as it has in textiles, as many small connections are usually preferable to few large connectors (Herzog et al. 2003), which lead to force concentrations and possibly material failure. While textile approaches have previously been proposed by Weinand and Hudert (2010), as well as Fleischmann et al. (2012), they have mainly been limited to weaving and intersecting plywood strips.

Despite the possible benefits and advantages of sewing timber, examples seem extremely rare. The Couture armchair by Färg and Blanche (2015) is made with a stationary industrial grade sewing machine used to connect layers of plywood of approximately 4 mm each. The fabrication is restricted to two-dimensional sewing in the plane on a large table and the work piece is guided manually. However, it proves the viability to sew plywood using machines from the leather and upholstery industry and indicates the high quality of sewing that can be achieved. An industrial example of robotic sewing with applications mostly in the automotive industry is the 3D-Robot Sewing unit by KSL for the "application of decorative seams to automotive interiors" (Keilmann 2014). In general, however, sewing has mostly eluded automation, most likely due to the complications of simulating the complex behavior of textiles. It remains a process where human sensory capacity and manual dexterity cannot be easily replaced by mere robotic precision.

Yet, robotic sewing does provide the opportunity to sew three-dimensionally, unconstrained by any work plane, and with high precision. It opens up areas of application thatin turn would lie outside the range of human capacity. Using an industrial robot for



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2 A: Microscopic view of the collagenous fibers in the connections between plates (Telford 1985). B: Fibrous connection between segments in the built demonstrator.

3 A: The circles represent the particle system that originates from two seed points. B: The resulting mesh provides the basis for the subsequently added geometric parameters that define each segment shape and type.

4 Front view of the built demonstrator with the visible double-layered construction.

5 The robot guides the segment through a stationary sewing machine. Its orientation can be adjusted according to certain out-of-reach or collision criteria, which are mainly in relation to axis 5 and can therefore be solved by rotating the segment out around the needle's center point.

handling timber veneer through a stationary sewing machine was therefore investigated as a fabrication approach in this research project.

Biomimetics

In previous research, biology has been an extensive concept generator for the design of segmented shells (Grun et al. 2016). Biomimetics serves as a design strategy to analyze and transfer the mechanical behavior, constructional morphology, and functional properties of load-bearing systems from nature to technology. Different biological role models have been repeatedly used as concept generators for the design of thin shells. This includes the aforementioned timber shells, the ICD/ITKE Research Pavilion 2011 and the Landesgartenschau Exhibition Hall, but also the ICD/ITKE Research Pavilions 2012 (Reichert et al. 2014) and 2013–14 (Dörstelmann et al. 2014). In the latter two examples, the fibrous morphology of natural fiber composite shells of lobsters and flying beetles, which consist of chitin fibers in a protein matrix, was translated into extremely lightweight shell structures.

Research Objectives

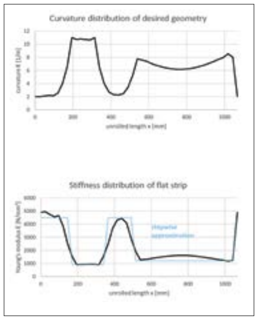
Based on the observations regarding the architectural and structural potential of segmented thin shell structures, the anatomy of wood, the textile approaches in lightweight constructions using FRP, as well as the opportunities provided by a biomimetic design approach, the objectives of the research within the scope of this paper are as follows:

1. Transferring textile processing methods from the field of technical textiles to digital fabrication and construction in architecture;
2. Utilizing the specific material characteristics of wood as drivers for the development of a construction system including multi-material joints;
3. Investigating alternative approaches to planarization for segmenting shell surfaces taking the bending elasticity of wood into account;
4. Synthesizing the design principles, material characteristics, and textile methods in an integrated computational design and robotic fabrication approach; and finally
5. Testing the above hypotheses through the construction of a full-scale architectural prototype.

METHODS

Biomimetic Design

Biological examples of segmented shells as they can be found in the regular and irregular sea urchins in the class of *Echinoidea* have been investigated and analyzed with a focus on the structural morphology of the shells on different levels of hierarchy, ranging from the microscopic level to the whole organism. In the context of this research, the most relevant novel principles that have been identified and translated into design principles for segmented shells include (1) the fibrous connections between the plates in the test (Fig. 2); (2) internal supports, which connect the upper and lower shell layers of irregular sea urchins (Fig. 4); (3) shell openings, which can be found in irregular sea urchins in the form of lunules; and (4) the growth principle of plate accretion and addition was transferred for the design process of the shell.



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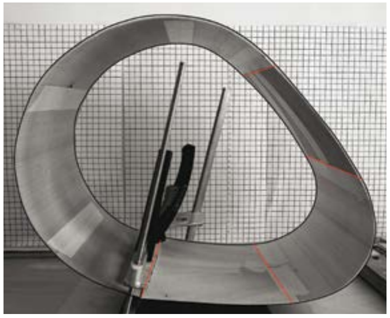

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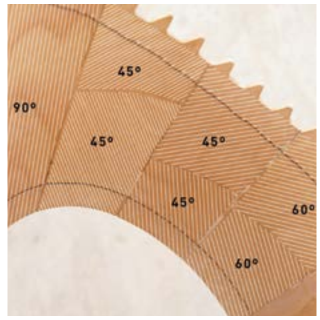

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The fibrous collagenous material acts as an additional connecting element, which can be observed in the joints between the plates of some sea urchins. It is hypothesized that it plays an important role in maintaining the shell integrity during growth as well as for dynamic forces throughout the sea urchin's life (Chakra and Stone 2011). This principle of a multi-material connection has been translated on the level of the connection between elements as well as on the level of connection of layers of veneer during lamination using robot sewing.

Computational Design and Simulation

An integrative computational design approach is essential in order to incorporate different requirements of fabrication, material characteristics, biological principles, architectural design intentions, structural analysis, and ultimately also constraints of time and budget. There are different computational strategies to control and evaluate interdependent parameters within a form-finding process. In this research project, the aforementioned procedural biomimetic principle of plate accretion and addition was used as a basis for the development of a design tool.

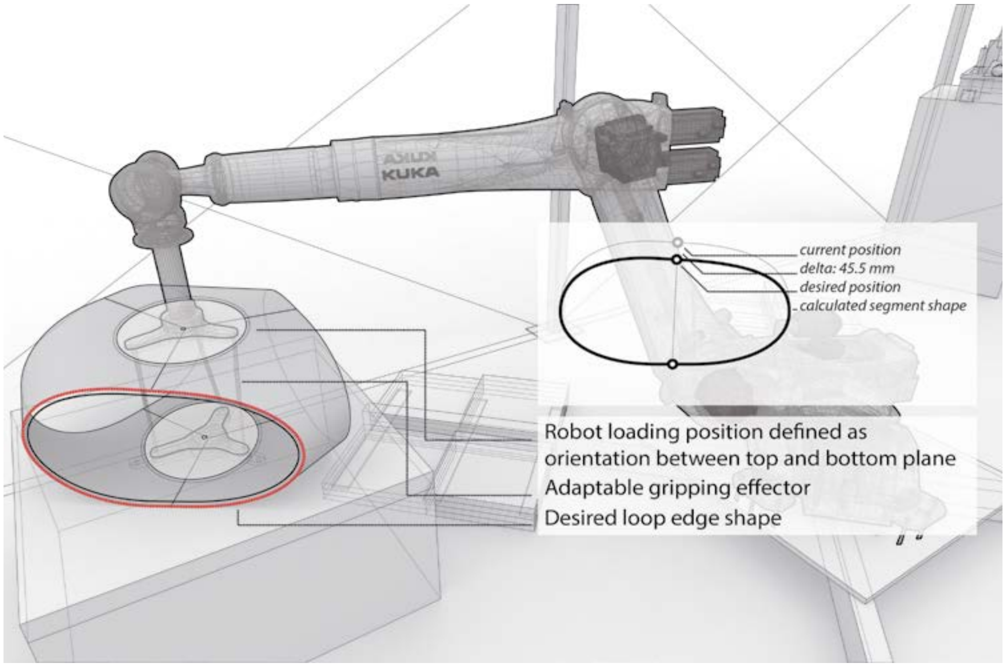
In a first step, the design of the spatial configuration of the shell structure—that is, its orientation on site, its span, and its support points—is defined parametrically as a design domain in the form of a non-uniform rational b-spline (NURBS) surface. In the subsequent step, the design domain is populated by a particle system originating at the supports, which represents the segment center points and implements the growing radii of the segments over time. The result is an evenly spaced arrangement of input points with tangent circles indicating the increasing radius of separation between segments away from the seeding origins. This process terminates as soon as the design domain is filled with input points and the kinetic energy of the system is minimized (Fig. 3A). The third step constitutes the generation of a topological relation between previously generated input points on the design domain using a Delaunay triangulation of the UV parameter space. The edges in the resulting mesh form the basis for the generation of the segment loops in the shell (Fig. 3B).

An initial challenge for the design of the loops' edge curves was the approximation of elastic curves of different radii that result from varying the material stiffness of the bent plywood. However, as the required stiffness can be calculated from the desired curvature radius, discretized stiffness values could be deduced from the digital model, resulting in a database of element-specific lamination instructions (Fig. 6). The resulting tri-looped segments each consist of three developable surface patches of varying curvature.

The digital model at this point not only captures the architectural design intent, and the material specifics of bending custom-laminated plywood, but also the constraints of fabrication resulting from the specific robotic fabrication setup. These are continuously monitored by simulating the robotic fabrication process within the digital design environment, which allows for checking for out of reach positions and collisions (Fig. 5). In order to arrive at a configuration that integrates these constraints, design iterations of the parametric model allowed us to locally adjust curvature of the design domain, the spacing and location of the input points for the segment generation, and control the curvature of the segments through the shape of their edge curves. Additionally, each design iteration has been analyzed structurally. The structural analysis has been informed by material tests described in Bechert et al. (2016). This informed model then forms the basis for the generation of the fabrication data: the lamination instructions, the generation of the finger joints along the edge loops where the segments are connected to each other, the NC-code necessary for their 3-axis milling, and finally the generation of the robot code based on the sewing lines (Fig. 5).

Textile Methods: Material Design

Similar to textile fabrication methods, the grain direction and lay-up of the laminate ultimately defines the material's characteristics. In order to approximate the required curvature along one of the elastically bent strips, their bending stiffness has to be programmed through an individualized lamination process (Tamke et al. 2012). The relation between varying grain directions and



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6 A: Digital prototyping through data-driven simulation. B: Physical prototyping allowed the deduction of a database of discretized stiffness values depending on the material lay-up.

7 A: An elastically bent strip shows areas with differently arranged veneer. B: A stack of laminated and CNC cut strips shows their diversity in veneer lay-up.

8 The robot is employed as a positioning aid in a first step in order to fix the three strips in their correct position. The upper part of the effector indicates the position in which the strips have to be attached.

layers of veneer, and the resulting bending stiffness was evaluated through physical bending tests with beech plywood (Fig. 6). These experiments also established the lower bound of curvature that the laminate would tolerate before failing. Summarizing, in areas of higher curvature, the material stiffness has to be low, resulting in low material thickness and the grain direction of the laminate running mostly perpendicular to the bending direction. Conversely, in areas of low curvature, a high stiffness is required, resulting in a material thickness of about twice as high and the predominant grain direction in the laminate running parallel to the bending direction.

Each strip is divided into 100-mm-wide areas of discretized stiffness and carries information on the number of veneer layers and their grain direction, depending on the required radius. The strips are then unrolled and nested on the bounding box of available beech veneer and plywood stock material. From here on, the production information is connected to a sheet of stock material that usually includes two to four individual strips. In order to guarantee a precise and efficient lamination process, the instructions are transferred to the stock material using a projector. Since the resulting laminates have locally differentiated material thickness, lamination is achieved through vacuum pressure. The individual strips are then cut out from the laminated sheet using a 3-Axis CNC cutting process. The finger joints along the looped edges are shaped to accommodate the varying angles between segments. As these range from coplanar to perpendicular, the finger joints vary in width and length (Fig. 7).

Textile Methods: Robotic Sewing

The robotic prefabrication process is developed not only to connect three elastically bent strips into a segment, but also to assist in their assembly beforehand. In this first step, the robot is used as a positioning aid in order to assemble the three strips in their correct elastically bent shapes. As there is otherwise no information on the relative position of the upper and lower base plane of the segment where all three strips meet, the robot positions its variable effector accordingly (Fig. 8). All three strips are then glued and connected to the effector, which in turn is fixed in its predefined position in order to stabilize the segment for sewing.

An industrial grade sewing machine is used as an external tool through which the robot then guides the segment (Fig. 9). It is integrated into the robot control and activated through a command in the robot code. When the sewing machine controller receives a command, it initiates a stitch and sends back a signal once the stitch is complete. This method ensures that there is no lateral movement of the segment while the needle is penetrating the material. Instead, the segment is only moved in between stitches. Even with the communication between robot control and sewing machine, one stitch only takes about 500 milliseconds. Sewing lines are predefined in the digital model based on the size of the segment and the robot effector position in order to ensure a distributed connection, and as a consequence, evenly distributed pressure between the strips. In order to accommodate minor differences between the simulated segment model and the actually bent segment, a path correction

9 Robotic sewing process. The robot guides the segment through an industrial sewing machine. Both machines communicate through a common control system. The stitches are placed 10 millimeters apart, and are also used to attach the white membrane strips onto the segment.

routine has been incorporated into the sewing process that allows the online control and adjustment of the robot position during fabrication.

As the robotic sewing ensures that the three strips are tightly connected while the glue is curing, even after the segment has been taken off the robot effector, it is also used to attach an additional membrane element along the segment edges, which allows the connection of neighboring segments through lacing. As a second hierarchy of textile connection, this conventional and well-proven membrane technique ensures easy accessibility during assembly.

On-Site Assembly

After varnishing the segments in order to protect the wood against moisture and to prevent fungi growth, the 151 pre-fabricated segments where assembled on site in 12 days. While the finger joints could be used as a positioning aid, the lacing technique allowed the gradual tightening of the connection between two segments during the assembly process, and thereby adjusted already connected segments when necessary. The overall structure not only showed a high flexibility but also enough rigidity to be built from the ground up without large-scale support, even during critical assembly phases (Fig. 10).

RESULTS

Each of the 151 segments is between 0.5 and 1.5 meters in diameter and has a material thickness between 3 and 6 mm. The extremely low thickness of the material required the development of the described textile connection approaches. Consequently, the entire shell has been constructed without the need for traditional timber fasteners. The structure ultimately weighs 780 kg while covering an area of 85 square meters and spanning 9.2 meters. With an average material thickness / span ratio of 1/1000, the building has a structural weight of 7.85 kg/m^2 shell.

The large-scale building prototype is not only a demonstrator for the developed construction system, but is also designed to incorporate surrounding site conditions. The pavilion opens up towards the campus area and provides a view towards the university buildings and the neighboring park. It provides shade and forms a point of attraction for an otherwise rarely used part of the campus (Fig. 11).

Similar to the biological role model, the structure not only functions as a pure shell, but allows for structural situations with higher bending moments through the introduction of columns (internal supports) as an integral part of the construction system. All forces are ultimately translated locally into membrane forces in the plywood segments, but globally, the system allows a transition from a shell system to a column and slab system. This offers entirely new architectural possibilities by expanding the catalogue of structural types and possibly constitutes one of the main contributions to the field of segmented shells. The synthesis of the many different and sometimes-conflicting design requirements allows for the exploration of a specific domain of the solution space that would not be accessible otherwise.

10 Assembly process of the demonstrator. The lacing connection's rigidity allowed the cantilevering of segments during the construction.

DISCUSSION AND OUTLOOK

Multi-material fibrous connections have proven to be a valuable technique for thin, segmented timer shells. Being exposed to rain and UV-light, delamination has been expected to be a major concern. However, the sewn connections within each segment have proven to prevent delamination even after the employed glue was heavily exposed to the weather. Instead, the pretension in the elements derived from elastic bending was lost faster than expected due to creeping of the wood. This was presumably due to the unusually wet spring and the repeated wetting and drying of the wood, resulting in the sagging of the structure in the mostly horizontal slab area of the shell. Although the construction system has not been developed as a weatherproof shell, the integration of membranes already hints at the possibility for integrating larger membrane elements, such as a secondary layer functioning as a constructive wood protection, which is expected to mitigate the creeping effect.

The described robotic fabrication process is based on a large-range industrial robot arm with the material attached to the robot flange and a stationary sewing machine. An alternative robotic sewing setup has been tested as part of the Robots in Architecture workshop, "Robotic sewing of timber veneer laminates," where two cooperating robots handle the work piece and guide it through an industrial sewing machine. Another alternative setup where the sewing machine is carried by the robot as an effector is currently under investigation. In each case, the robot's reach and the orientation of the sewing machine define the resulting design solution space. As the fabrication process gets more complex, adaptive robot control is being investigated through the integration of a sensor-based control loop. In order to achieve highly adaptive sewing techniques for thin and flexible materials, sensor input is essential to react to, or encourage and build upon the inherent material behavior during the fabrication process.

ACKNOWLEDGEMENTS

The work presented in this paper was partially funded by the German Research Foundation (DFG) as part of the Collaborative Research Centre TRR 141 "Biological Design and Integrative Structures." The project was also supported by GettyLab.

The authors would like to thank their fellow investigators from the Institute of Building Structures and Structural Design (ITKE)—Prof. Jan Knippers, Simon Bechert, and Daniel Sonntag—and the work group Paleontology of Invertebrates of the department of Geosciences at the University of Tübingen (IPPK)—Prof. Oliver Betz, Prof. Nebelsick, and Tobias Grun—as well as their colleagues Long Nguyen, Michael Preisack, and Lauren Vasey for additional support during design development.

The presented research was conducted at the intersection between research and teaching together with students of the ITECH MSc programme. The authors would like to express their gratitude towards the students Martin Alvarez, Jan Brütting, Sean Campbell, Mariia Chumak, Hojoong Chung, Joshua Few, Eliane Herter, Rebecca Jaroszewski, Ting-Chun Kao, Dongil Kim, Kuan-Ting Lai, Seojoo Lee, Riccardo Manitta, Erik Martinez, Artyom Maxim, Masih Imani Nia, Andres Obregon, Luigi Olivieri, Thu Nguyen Phuoc, Giuseppe Pultrone, Jasmin Sadegh, Jenny Shen,

11 Top view of the finished demonstrator. B: Interior view at night.

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Michael Sveiven, Julian Wengzinek, and Alexander Wolkow, who strongly contributed to the development of this work.

REFERENCES

Bechert, Simon, Jan Knippers, Oliver David Krieg, Achim Menges, Tobias Schwinn, and Daniel Sonntag. 2016. “Textile Fabrication Techniques for Timber Shells: Elastic bending of custom-laminated veneer for segmented shell construction systems.” In *Advances in Architectural Geometry 2016*. Zurich: AAG. Forthcoming publication.

Chakra, Maria Abou, and Jonathon Richard Stone. 2011. “Holotestoid: A Computational Model for Testing Hypotheses about Echinoid Skeleton Form and Growth.” *Journal of Theoretical Biology* 285 (1): 113–25. doi:10.1016/j.jtbi.2011.06.019.

Menges, Achim, and Moritz Dörstelmann. 2014. “Leichtbau BW Installation.” *Institute for Computational Design (ICD)*. http://icd.uni-stuttgart.de/?p=10992. Accessed May 4, 2016.

Dörstelmann, Moritz, Stefana Parascho, Marshall Prado, Achim Menges, and Jan Knippers. 2014. “Integrative Computational Design Methodologies for Modular Architectural Fiber Composite Morphologies.” In *ACADIA 14: Design Agency—Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by David Gerber, Alvin Huang, and Jose Sanchez. Los Angeles: ACADIA. 219–228.

Färg, Fredrik, and Emma Marga Blanche. 2015. “COUTURE Armchair.” Färg & Blanche. http://fargblanche.com/COUTURE-armchair-produced-by-B-D-BARCELONA-DESIGN. Accessed May 3, 2016.

Fleischmann, Moritz, Jan Knippers, Julian Lienhard, Achim Menges, and Simon Schleicher. 2012. “Material Behaviour: Embedding Physical Properties in Computational Design Processes.” *Architectural Design* 82 (2): 44–51.

Grun, Tobias B., Layla Koohi, Tobias Schwinn, Daniel Sonntag, Malte von Scheven, Manfred Bischoff, Jan Knippers, Achim Menges, and James H. Nebelsick. 2016. “The Skeleton of the Sand Dollar as a Biological Role Model for Segmented Shells in Building Construction: A Research Review.” In *Biological Design and Integrative Structures*. Berlin: Springer. Forthcoming publication.

Herzog, Thomas, Julius Natterer, Roland Schweitzer. 2003. *Holzbau Atlas*. Basel: Birkhäuser.

Keilmann, Robert, and Yongwu Chen. 2015. “Basic 3D-Robot Sewing Unit KL 500.” KSL. http://www.ksl-lorsch.de/en/products/automotive/composites/basic-3d-robot-sewing-unit-kl-500/. Accessed May 4, 2016.

Krieg, Oliver David, Tobias Schwinn, Achim Menges, Jian-Min Li, Jan Knippers, Annette Schmitt, and Volker Schwieger. 2015. “Biomimetic Lightweight Timber Plate Shells: Computational Integration of Robotic Fabrication, Architectural Geometry and Structural Design.” In *Advances in Architectural Geometry 2014*, edited by Philippe Block, Jan Knippers, Niloy J. Mitra, and Wenping Wang. Cham: Springer International Publishing. 109–125. doi:10.1007/978-3-319-11418-7_8.

La Magna, Riccardo, Markus Gabler, Steffen Reichert, Tobias Schwinn, Frédéric Waimer, Achim Menges, and Jan Knippers. 2013. “From Nature to Fabrication: Biomimetic Design Principles for the Production of Complex Spatial Structures.” *International Journal of Space Structures* 28 (1): 27–39. doi:10.1260/0266-3511.28.1.27.

Li, Jian-Min, and Jan Knippers. 2015. "Segmental Timber Plate Shell for the Landesgartenschau Exhibition Hall in Schwäbisch Gmünd—the Application of Finger Joints in Plate Structures." *International Journal of Space Structures* 30 (2): 123–139.

Menges, Achim, and Tobias Schwinn. 2012. "Manufacturing Reciprocities." *Architectural Design* 82 (2): 118–125. doi:10.1002/ad.1388.

Reichert, Steffen, Tobias Schwinn, Riccardo La Magna, Frédéric Waimer, Jan Knippers, and Achim Menges. 2014. "Fibrous Structures: An Integrative Approach to Design Computation, Simulation and Fabrication for Lightweight, Glass and Carbon Fibre Composite Structures in Architecture Based on Biomimetic Design Principles." *Computer-Aided Design* 52: 27–39. doi:10.1016/j.cad.2014.02.005.

Robeller, Christopher and Yves Weinand. 2015. "Interlocking Folded Plate—Integral Mechanical Attachment for Structural Wood Panels." *International Journal of Space Structures* 30 (2): 111–122.

Schwinn, Tobias, Oliver David Krieg, and Achim Menges. 2013. "Robotically Fabricated Wood Plate Morphologies." In *Rob | Arch 2012: Robotic Fabrication in Architecture, Art and Design*, edited by Sigrid Brell-Çokcan and Johannes Braumann. Vienna: Springer. 48–61. doi:10.1007/978-3-7091-1465-0_4.

Schwinn, Tobias, Oliver David Krieg, and Achim Menges. 2014. "Behavioral Strategies: Synthesizing Design Computation and Robotic Fabrication of Lightweight Timber Plate Structures." In *ACADIA 14: Design Agency—Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by David Gerber, Alvin Huang, and Jose Sanchez. Los Angeles: ACADIA. 177–188.

Smith, Andrew B. 2005. "Growth and Form in Echinoids: The Evolutionary Interplay of Plate Accretion and Plate Addition." In *Evolving Form and Function: Fossils and Development*, edited by Derek E. G. Briggs. New Haven, CT: Yale Peabody Museum. 181–195.

Tamke, Martin, Paul Nicholas, Mette Ramsgard Thomsen, Hauke Jungjohann, and Ivan Markov. 2012. "Graded Territories: Towards the Design, Specification and Simulation of Materially Graded Bending Active Structures." In *ACADIA 12: Synthetic Digital Ecologies—Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Jason Kelly Johnson, Mark Cabrinha, and Kyle Steinfeld. San Francisco: ACADIA. 79–86.

Telford, Malcolm. 1985. "Domes, Arches and Urchins: The Skeletal Architecture of Echinoids (Echinodermata)." *Zoomorphology* 105 (2): 114–124.

Vincent, Julian. 2009. "Biomimetic Patterns in Architectural Design." *Architectural Design* 79 (6): 74–81. doi:10.1002/ad.982.

Weinand, Yves, and Markus Hudert. 2010. "Timberfabric: Applying Textile Principles on a Building Scale." *Architectural Design* 80 (4): 102–107. doi:10.1002/ad.1113.

IMAGE CREDITS

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