Textile Fabrication Techniques for Timber Shells

Elastic Bending of Custom-Laminated Veneer for Segmented Shell Construction Systems

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Abstract

Recent developments in the field of segmented timber shells have shown promising structural and constructional characteristics. Advancements in computational design and digital fabrication enable architects and engineers to handle the increased geometric complexity necessary for this new construction type, integrating fabrication constraints and structural feedback in one design model. The research presented in this paper builds on new findings from biological role models for the constructional morphology, connection type, and material distribution of segmented shells. Based on the transfer of these principles, a robotic fabrication technique was developed that enables the production of elastically bent, double-layered segments made from custom-laminated beech plywood, by transferring traditional textile connection methods to timber construction. The construction system was evaluated through the design, production, and assembly of a large demonstrator.

Keywords:
timber shell, segmented shell, elastic bending, textile fabrication, finger joint connection, robotic fabrication

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1. Introduction: Segmented Timber Shells

The transfer of biological principles of constructional morphology from natural organisms into technical applications has a long tradition in engineering. However, only recent developments in digital design and fabrication have unlocked the vast possibilities and opportunities of biomimetic design strategies for architecture and construction as the generation, communication, and fabrication of complex geometry becomes a crucial aspect of the design process (Kieran & Timberlake 2004). Simultaneously, these advancements have now driven architectural design research to seek for natural examples that are characterised by both their complex, hierarchical material distributions, and their high structural performance.

Often, morphological and process-specific role models in nature lie outside or between established categories and methods in building construction. In addition, their complex shapes necessitate a digital chain from design to fabrication. Especially in the field of lightweight timber construction, biological role models have helped to redefine building systems, design methodologies, and fabrication technologies. As shown in previous research by the authors (La Magna et al. 2013; Krieg et al. 2015), segmented shells exhibit promising structural characteristics as well as architectural articulations. However, they pose challenges to the fabrication and construction and therefore require innovative and integrative design methods.

The research presented in this paper is based on a new approach to segmented shells in architecture. It builds on existing role models and integrates newly discovered biomimetic principles as well as robotic textile fabrication techniques for thin timber shells. Common connections in timber construction are usually optimised for much thicker building elements, but can hardly be applied to thin layers of veneer. Instead, much more suitable solutions were found in textile manufacturing techniques, and the construction system presented in this paper was developed based on one of the oldest techniques for fastening and attaching objects: sewing. Although sewing is used in many different industries, the degree of automation is often far less than in other production processes. The reciprocity between the sewing machine's mechanics, the thread, and the sewn material mostly require sensitive manual labour and many fast corrections in the material or tool movement. Although contemporary sensing technology and machine control allow for the necessary adaptability, only few automated solutions have been developed to date. Still, the possibilities of industrial sewing machines in architecture are promising as they can go far beyond the connection of textiles.

Timber as a construction material offers notable advantages. Not only the ecological benefits such as its negative carbon footprint (Alcorn 1996), but also its strength to weight ratio as well as its high elasticity make wood an ideal material for lightweight building construction. Further, the advancement of digital fabrication in the timber industry and its ease of machinability provides great possibilities for innovative freeform structures. As a natural fibre composite it would

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seem counter-intuitive to use contemporary connection types that generally rely on subtractive fabrication that cut off and destroy the fibres and therefore weaken the material itself. In contrast, textile connections such as sewing provide the opportunity to connect timber elements while maintaining most of their fibrous material structure. Textile connection techniques have a long tradition in timber, e.g. in historical boat construction. They are often employed when geometrical flexibility is desired at the connection level, however they usually require predrilling of holes and large amounts of manual labour, making it less suitable for large scale applications. This can be avoided by employing modern robotic fabrication techniques in conjunction with an industrial sewing machine.

2. Biological Principles of Double-Layered Segmented Shell Structures

Previous research by the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE), in collaboration with the Department of Geosciences at the University of Tübingen in the field of segmented shells (La Magna et al. 2013; Krieg et al. 2015; Li & Knippers 2015) was characterised by a thorough investigation of biological role models as a basis for further structural and constructional developments. Exhibiting promising morphological features, the skeleton of echinoids was analysed to transfer functional and structural principles to the construction of segmented shells in architecture. As biological research advanced in the last years this previous work has been revisited and extended for a new type of lightweight timber construction.

Within the taxonomic phylum of Echinodermata, two species of the class Echinoidea (sea urchin) and the order Clypeasteroida (sand dollar) were identified as particularly promising for the transfer of morphological principles for the constructional morphology as well as procedural principles of growth and form-finding for an integrative design process. The biomimetic analysis of these species led to the further investigation of the following, already known, principles: (1) a double-layer skeleton, which forms in some species as so-called secondary growth and reinforces the test; (2) hierarchical material organisation and differentiation within the calcite stereom, which can be found in many biological structures (Gruber & Jeronimidis 2012); and (3) the principle of connecting segments with finger joints.

In an effort to thoroughly understand the constructional morphology, a number of previously unknown principles were also identified and integrated into this research project: (1) the differentiation of material composition for elastic or stiff material behaviour; (2) fibrous connections between segments in addition to the finger joints; (3) growth principles of plate addition and plate accretion (Raup 1968; Chakra & Stone 2011); and (4) morphological features such as internal supports and shell openings, which appear in most sand dollars and are most

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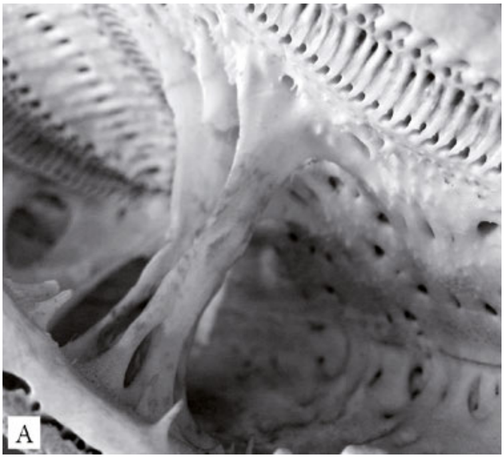

Figure 1a. Photograph of the interior of a Clypeaster Rosaceus with visible internal support structures connecting the top and bottom of the skeleton.

Figure 1b. The double-layered timber segments are most visible during the demonstrator's construction phase.

relevant in an architectural context. Although wood is a natural fibre composite with anisotropic material behaviour compared to the heterogeneous calcite with highly differentiated porosity, which makes up the skeleton of sea urchins, the analysed constructional principles can be transferred on an abstract level.

The basis of the system development was formed both by the abstraction of biological principles and the inspiration from the material. From the former a double layer construction similar to the secondary growth (Fig. 2a) in sand dollars was derived. The latter led to the choice of extremely thin and elastically bent plywood, which once bent and connected to neighbouring elements generates a stiff doubly-curved shell structure (Fig. 2b). In order to achieve sufficient interconnection between the two layers while allowing high geometric flexibility within the segment geometry, the general segment construction logic is based on three initially planar plywood strips with 3 mm to 6 mm thickness, which are bent around their longitudinal axis in order to connect on both ends with lap joints. These thin plywood strips are normally not suitable to bear significant bending moments, which is why forces are mostly transferred in form of in-plane shear forces and normal forces. This is also reflected in the joint layout. The shear forces and compression forces can be transferred between elements via finger joints. As an additional element, laces are used similar to the fibrous connection of sea urchins to withstand tensile forces.

The calcite plates of some sea urchin species are connected through fibrous elements (Fig. 3a), and it can be hypothesised that those play an important role in maintaining the shell stability during growth as well as for dynamic forces (Wester 2002). The possibility of the fibrous connections to adjust to continuously varying connection angles between the segments, and to adjust to tolerances during

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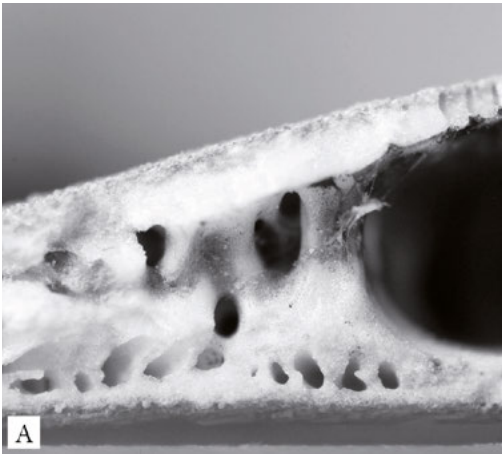

Figure 2a. Photograph of a cut Mellita 5-perforata with visible secondary growth inside the bottom layer. The exterior plate structure is supported by a second layer of calcite with small cavities in between.

Figure 2b. The principle constructional morphology of such structures is transferred into a segmented timber shell construction system with bent plywood strips.

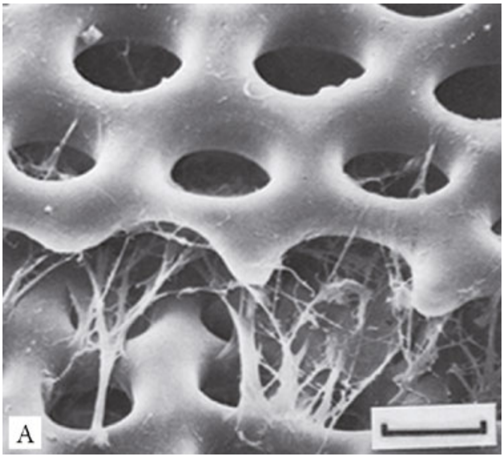

Figure 3a. Microscopic image of a joint between ambulacral plates, bound by collagen fibres, from a Diadema antillarum (scale bar 50 μm). From Telford (1985).

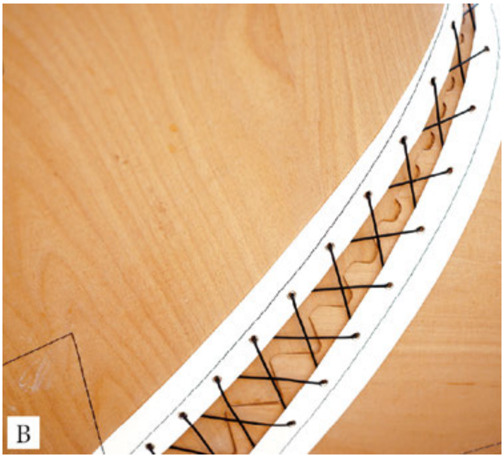

Figure 3b. A combination of finger joints and fibrous connection is used for the developed construction system.

assembly, can directly be compared to the biological role model, where the flexibility of the connections allows for the rearrangement and growth of the skeletal plates (Fig. 3b). In conclusion, the introduction of fibrous connections for thin plywood on multiple hierarchies turns out to be a very effective method for the robotic prefabrication of the segments as well as their on-site assembly.

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3. Implementation of Textile Robotic Fabrication Techniques

The transfer of forces via textile connectors is implemented on two different levels of hierarchy: On the segment level, robotic sewing of laminated veneer is introduced to connect each of the three elastically bent sheets of plywood into one double-layered segment (Fig. 4). In timber construction, multiple continuous connections are generally preferable to singular ones, as the local stress concentrations of the single joints are more critical to the fibrous nature of wood. This is one of the reasons why joining thin sheets of plywood is usually achieved by gluing. However, glued connections require planar configurations or complex form work to maintain the high pressures necessary to laminate veneer sheets. Each of the geometrically differentiated segments in this research project, however, necessitate the strips to be joined while in a deformed state, making a glued connection difficult and time-consuming to achieve. In addition, the pre-bending of the strips induces high stress concentrations at the ends of the lap joints, resulting in potential delamination. To prevent this effect robotic sewing of the laminate is introduced as a manufacturing technique (Fig. 4).

With a direct connection to the digital model an industrial robot is used to position each strip of a segment and guide it through an industrial sewing machine. To attain the required shape of each segment, the height and inclination of the two opposing planes where the strips are connected are indicated by the robot in a first step of the fabrication process. After the three strips are bent into place and glued to the lap joint, the segment is mounted onto the robot using an adjustable effector. The robot then guides the segment through a stationary industrial sewing machine. To avoid breakage of the needle, the plane of the segment's part that is currently sewn has to be orthogonal to the needle's axis. Furthermore, it has to be ensured that the segment is not moving during the stitching motion of the needle. For this purpose the sewing machine controller was integrated into the robot control. It receives signals for stitching commands and sends a signal back once a stitch is completed.

Common sewing processes in industry are designed for rather soft materials such as textiles. When sewing wood, the high resistance of the plywood requires an adjustment of this process. In order to generate the required force to penetrate the veneer strips, the setup of the industrial sewing machine was modified by increasing the machine's transmission to achieve a larger torsional moment and thus a higher penetration force. In order to enable the production of a wide range of segment sizes to create more freedom in the design space, a long arm sewing machine is used. Also, to prevent needle breakage and therefore ensure a continuous fabrication process while sewing comparably strong wood, the needle has to resist high axial forces and simultaneously exhibit a certain flexibility due to

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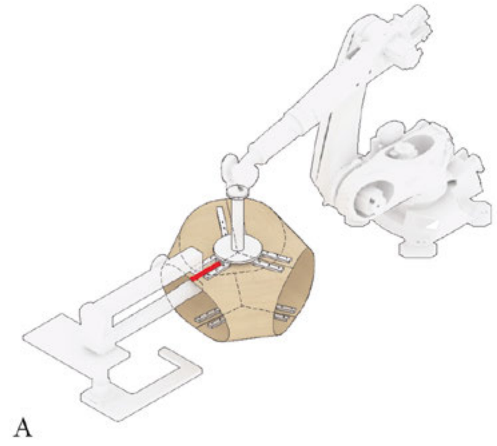

Figure 4a. Diagram of the robotic fabrication process. Equipped with an adaptable effector the robot holds a pre-assembled segment and guides it through the sewing machine.

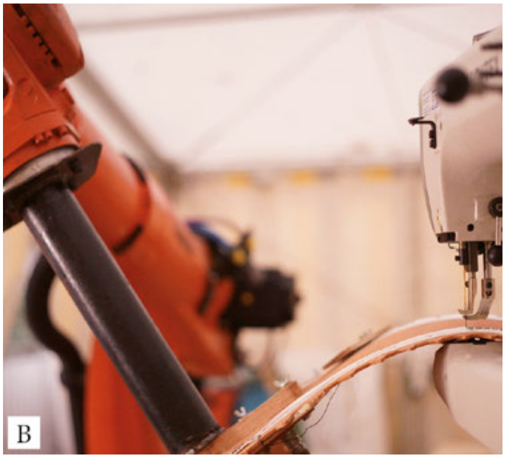

Figure 4b. Photograph of the process.

the deformation while puncturing the material. To achieve enough extrusion and therefore minimise the effect of abrasion or breakage of the thread, the needle tip was tested and evaluated. Thus, a titanium nitride coated needle was chosen, offering a greater hardness than standard needles and a better protection against wear and damages. In addition, a bonded polyamide thread is employed, which provides a very high breaking strength and abrasion resistance.

The robotic sewing technique offers the opportunity to directly integrate a second hierarchy of connection type. Sewing is further used to attach pre-cut, PVC-covered polyester fibre membrane strips along the finger-jointed edges of each segment (Fig. 5a). These allow to continuously transfer tensile forces between segments. They are joined using polyester-coated aramid ropes, whose density is adjusted to structural requirements. Traditional connections of membranes via laces typically require the folding of the membrane to create a keder rail, however in this case this would have been geometrically difficult to achieve. From preliminary finite element analysis estimations of the required tensile load bearing capacity of the joint are estimated. Afterwards, structural tests are performed on the connection to ensure that the membrane strips are still able to transfer those tensile forces between the elements with only a single membrane layer (Fig. 5b). The aluminium eyelets well known from membrane constructions are maintained. The laced connections between the segments allow the transfer of tensile forces and thus complement the finger joints. This connection type also has the benefit to be highly adaptable to varying geometric configurations and can ease the assembly by tensioning the laces gradually.

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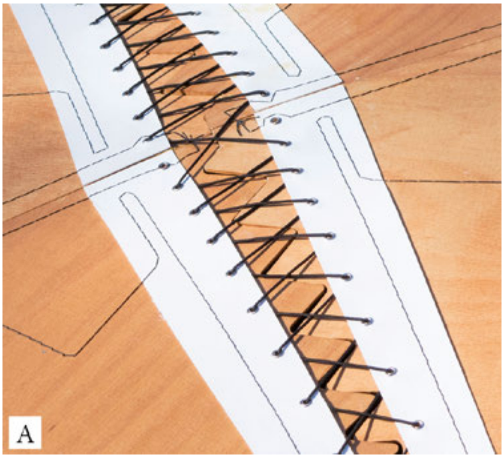

Figure 5a. Photograph of the membrane and lacing technique. The membrane strips are sewn onto the segments during robotic fabrication.

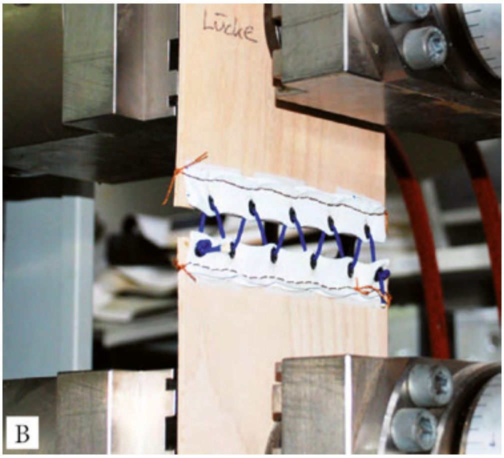

Figure 5b. Structural tests were performed for several lacing techniques.

4. Integrative Design and Hierarchy

The robotic fabrication setup in conjunction with the overall fabrication sequence is analysed for its possibilities and constraints, which are then implemented in the development process in order to determine the morphospace of possible segment shapes. For example, the element size is limited by the length of the arm of the sewing machine, and if elements become too distorted, collisions between element and robot arm are possible. This information is directly included in a computational design tool that implements the introduced principles all while staying within the solution space set by the material characteristics and fabrication constraints. It is using a form-finding process based on the biological role model of plate growth and plate addition. Compared to morphological principles, this process-based principle is abstracted for the design process in order to distribute segments over a user-defined area.

This integrative approach allows the design tool to act as an information model. It generates buildable solutions and is driven by structural and architectural requirements. It decides on the material orientation within each strip and exports fabrication information for lamination, CNC cutting, and robotic sewing. All data are automatically generated and exported into the respective file formats. This integrated digital process facilitates the production of 151 unique segments with their own differentiated material distribution, custom-fit finger-joints, and connection details (Fig. 6).

The biological role model is hierarchically organised, integrating functional aspects and constructional requirements at different levels. Similarly, the design

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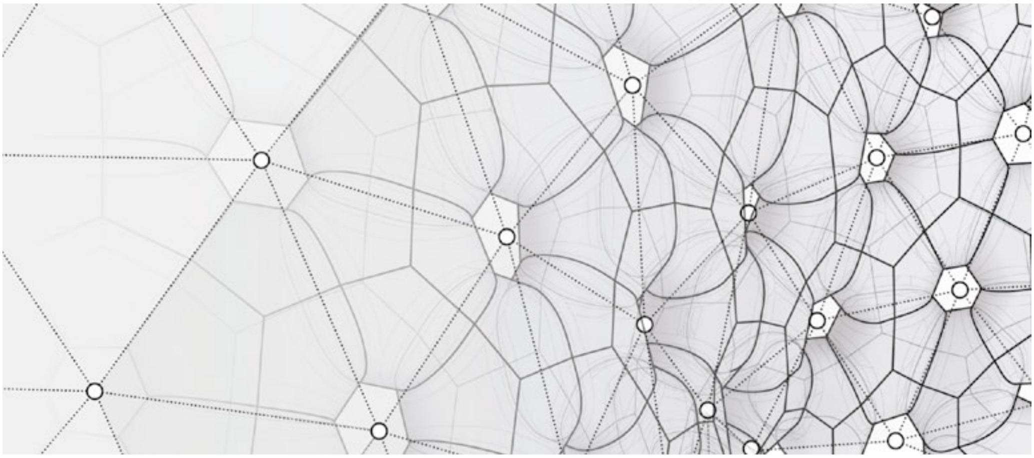

Figure 6. Visualisation of the geometric information in the computational design tool. A mesh forms the basis for all geometric operations that generate the final segment and membrane geometry.

tool also follows through all aspects of hierarchy from the fabrication of the finger joint to the assembly of the entire structure and integrates them in one global model. The developed construction system also allows for different morphological features similar to those from the biological role model. While the segments' arrangement is mostly characterised by openings in the shell, other types of segments form a closed arrangement. Similar to the internal supports of some species of the sea urchin, the shell can additionally form directional sub-structures that follow the material logic. In the case of the developed construction system, plywood strips bend outwards away from a segment and form a column. The structure is therefore not forced to end vertically on the ground but can cantilever horizontally above the ground while being supported by those column-like segments.

5. Material Differentiation and Form-Finding of Laminate Geometry

Generating doubly-curved structures from initially planar elements is of major interest in the field of architecture, as double curvature is highly beneficial to the structural behaviour, while the planarity of the elements facilitates fabrication. One possibility is to approximate doubly-curved surfaces with uniaxial elastic bending of initially planar strips (Lienhard 2011; La Magna 2016), creating the entire structure by bending it on a global level into shape. In this research project a different approach was chosen, whereby the elastic bending is used only at a segment, or local, level, thus creating complex geometries using initially planar strips. A

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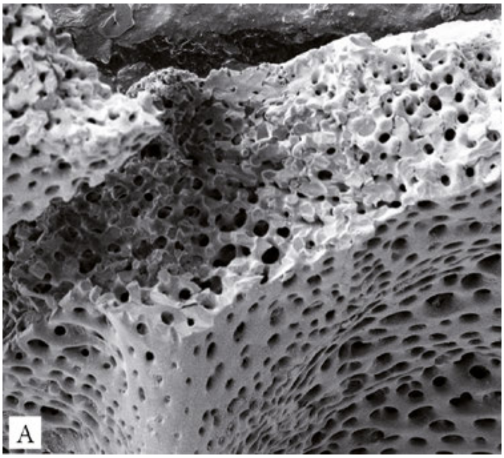

Figure 7a. Electron microscope image of a sand dollar's calcite structure with differentiated density (Image by Tobias Grun, 2015, from the Department of Geosciences, University of Tübingen).

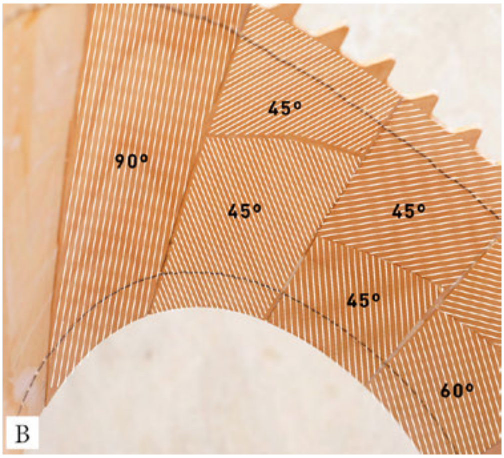

Figure 7b. Elastically bent plywood strip laminated with veneer layers facing in different directions.

major advantage is that the pre-bending forces are short-circuited inside the segment during fabrication and do not have to be maintained by an external device after assembly.

Biological structures often present a highly anisotropic material behaviour and characteristics that are locally adapted to comply with functional or structural requirements. In the sea urchin's case, the density of the stereom varies along the shell (Seilacher 1979) (Fig. 7a). This principle is transferred on an abstracted level, where local adaptation through a differentiated material stiffness is achieved by programming the material to comply with structural requirements. Although the role model's material has only few similarities to wood, it can be argued that the principle of material differentiation is transferred on a local level for each plywood strip. In both cases the material density is differentiated for functional requirements. In the case of wood veneer, the fibre direction is the main medium to control each strip's bending stiffness (Fig. 7b).

For the developed construction system, the shape for each segment results from the global shell layout, leading to continuously varying curvature along each strip. As the strips will be bent with an approximately constant bending moment, this results in the requirement of a gradually adapted stiffness distribution to achieve the desired 3-dimensional shape. The stiffness graduation is achieved by laminating discrete veneer strips on a base material of 3 mm beech plywood to locally reinforce and thereby stiffen the resulting laminate (Fig. 8a). For this purpose, a form-finding algorithm is developed, which allows to compute an approximate material layout as a consequence of the curvature distribution along each strip (Fig. 8b). This tool takes into consideration minimum bending radii,

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Figure 8a. Multiple plywood strips laminated with different veneer directions to influence their elastic bending behaviour.

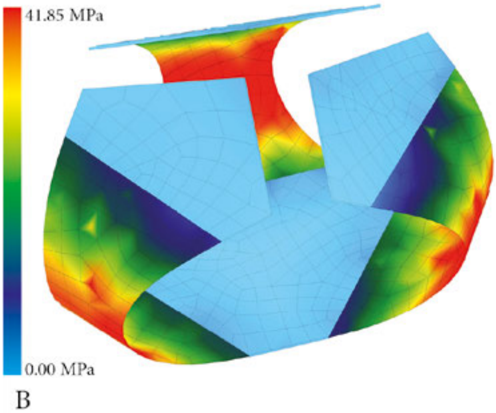

Figure 8b. Simulation of the bending behaviour with differentiated material make-up in finite element analysis.

veneer strip size and layer orientation to compute a material layout for the unrolled strip, which can then be laminated and cut into shape. During an evaluation period, physical tests and digital simulations were compared in order to identify the relationship between grain direction in laminated veneer and the resulting bending stiffness. However, it is important to note that the desired shape can only be approximated. The error results from the step-like differentiated stiffness (as a consequence of the additive fabrication process) and the time-dependent material behaviour (such as relaxation of the pre-bending stress), which was not considered for simulation. This ties back to the requirement of a flexible joint connection, which allows for tolerances and further justifies the choice of the textile connection system.

6. Form-Finding: Integration of Procedural Biological Principles

Several studies in biology have analysed the growth process of sea urchins independent from intents of transferring the underlying principles into engineering or architecture (Johnson et al. 2002; Ellers 1993). In general, several mechanisms can be distinguished, but mainly the plate addition originating from the apical disc and accretion of calcite material around each plate's edge are responsible for the growth and distribution of the sea urchin's skeletal plates. For a living organism it is especially effective, as these principles maintain structural integrity and stability of the shell during the entire growth process. The growth process can

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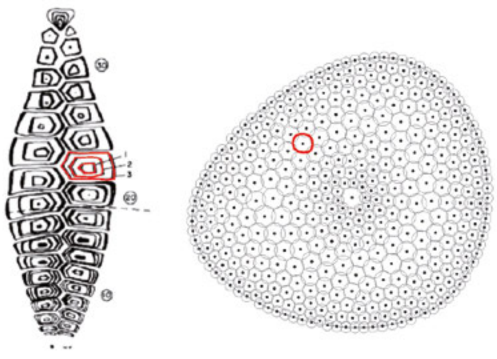
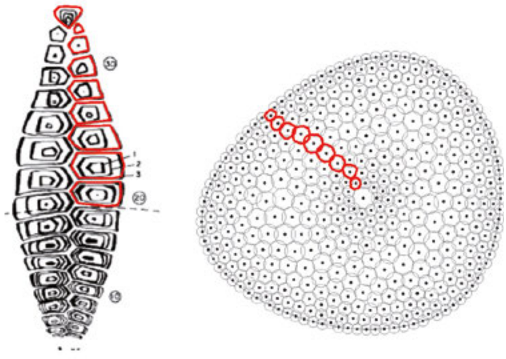


A

Figure 9a. Diagrammatic representation of plate accretion (left). A row of calcite plates is shown that grow in size while moving towards the middle. The principle of growth is abstracted in the computational design tool (right).



B

Figure 9b. The principle of plate addition (right) starting from the top (ambulacral plates) is also transferred to the computational design tool (right).

therefore be seen as a form-finding process that automatically respects certain geometrical and functional constraints. The principle of adding and growing segments – in the case of the research project over a pre-defined three-dimensional surface – can be transferred through a parametric circle packing approach (Zachos 2009). The geometric rules of distributing plates in a packed configuration resemble the attraction and repulsion between circles on a surface. While these circles represent segments, their radii determine the segments' sizes and keep them at distance from their neighbours. Once seeded at user-defined input areas, they grow until the surface is filled completely. In the case of the demonstrator, two opposing points were chosen at the base of the building. During the simulation the segments are seeded at those points and follow a user-defined design intent while growing and distributing over a specified area. This growth process leads to a similar segmented layout as the sea urchin's skeletal plates as segments that are further away from the starting points are usually larger. This geometric characteristic is also structurally advantageous as smaller segments lead to a higher density of interconnection and therefore to a higher structural stiffness at the base points.

A form-finding model based on procedural biological principles has several advantages for the design process. Similar to the sea urchin's growth the circle packing approach allows the control over areas where segments are seeded and hence the direction of growth. During the process segments can react to boundary conditions and follow pre-defined design intends. On a computational level, the resulting arrangement is translated into a mesh topology, which in turn forms the basis for the segment geometry. Architectural requirements are

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Figure 10. Photograph of the demonstrator. Once assembled, the robotically sewn segments act together as a rigid, double-layered shell.

mainly implemented through the pre-defined design surface on which the segments are distributed throughout the growth process, as well as the openings between segments.

7. Conclusion

The presented research is a collaborative project between biology, engineering, and architecture. It is based on a bottom-up research process in biomimetics and can be summarised by two main findings: On the one hand, biological role models cannot only be transferred for the constructional morphology, but also for the design process of segmented shells in timber construction. On the other hand, textile and fibrous connections for joining thin plywood strips are a valid technique and were evaluated on a large-scale prototype building. It can be concluded that the structural and architectural solution space for segmented shells was extended through the development of the described construction system within the context of computational design and construction.

The research was evaluated through the fabrication and construction of a prototype building. With 151 segments made from 3 to 6 mm thick beech plywood, the complete structure weighs 780 kg while covering an area of 85 m^2 and spanning 9.3 m. With a resulting material thickness/span ratio of 1/1000 on average, the building has a structural weight of 7.85 kg/m^2 shell. With this new kind of fibrous connection type no metal fasteners were needed for fabrication or assembly.

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As research in shells for timber construction progresses towards thinner materials, new connection types become necessary. Contemporary jointing techniques do not account for varying angles or exceptionally thin material and therefore need to be reconsidered. In addition, innovative form-finding processes allow for the exploration of lightweight and material-efficient architecture, but require a closed digital loop between design and fabrication. The developed construction system accounts for both the design process and new fabrication techniques while exhibiting the structural and architectural possibilities of lightweight segmented timber shells.

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