ABSTRACT

This paper presents the development of an integrative and adaptive robotic fabrication process for the production of wooden-based segmented shells of variable thickness. A material and construction process is presented whereby an industrial robot with a two-degree-of-freedom end effector acts as active formwork, positioning flexible strips of plywood so they can be assembled into a structurally performative configuration and then filled with a polyurethane expandable foam. The resulting material system is a structurally performative and doubly curved sandwich composite which performs well in bending.

This paper discusses the construction process and the material system, methods for structural analysis, an adaptive robotic fabrication process, as well as a computational design tool which integrates material constraints, robotic constraints, and structural performance. The resulting construction system expands the design possibilities for robotic fabrication in wood, particularly as a viable material system for implementation directly in an on-site condition.
INTRODUCTION

Wood construction advancements align with two paradigms of construction in architecture: the first one uses multi-layered, thick cross sections with a predictable behaviour to allow for precise detailing and fabrication; the second aims for thinner, lightweight constructions which are easy to shape on-site, where unpredictable behaviour due to anisotropy is mediated with procedural correcting logics and details for tolerance-handling.

With new advancements in robotic fabrication, in particular online control and sensor feedback, construction methods can adapt to unpredictable material behaviour instead of enforcing a strict plan of production in advance. Combining adaptive programming strategies with on-site conditions has potential to significantly expand the field of action for robotic fabrication in wood architecture, increasing the resulting design space of wooden material systems and opening up the possibility of in-situ production rather than prefabrication.

This research project aims to develop an integrative and adaptive fabrication process which enables in-situ production and assembly of wood-based segmented shells of variable thickness (Figure 1). During the construction process, the robot acts as an active forming agent, positioning thin sheets of plywood in space where they can be incrementally fastened to each other and the interior cavity subsequently filled with an expandable foam. This research includes the material construction system, methods for structural analysis and computational design, and an adaptive robotic fabrication and construction process. These methods are investigated and discussed through the production of a full-scale prototype in lab conditions. This combination of robotic fabrication and material-oriented design enables a novel construction technique with potential to advance wood-based architectural design.

MATERIAL AND CONSTRUCTION SYSTEM

The construction strategy is to achieve a lightweight doubly curved sandwich composite made of birch plywood strips and polyurethane expandable foam through an incremental bending, fastening, and forming process. Thus, the system needs to be performative in two different stages: first, as a bending-active plywood structure which can carry its own weight during assembly (Figure 2), and in its final state as a composite, filled with an expanded foam core. This construction process (Figure 3) takes advantage of the behaviour of thin plywood strips, starting as lightweight flat elements that can be sequentially bent and locked into highly curved geometries (Bechert et al. 2016; Brütting 2016).

2 First plywood assembled unit produced using robotic shaping for its fabrication.

3 The construction system uses a 6-axis robotic arm and a custom made end effector for the shaping process of the double-curved plywood assembly.
To achieve complex, double-curved geometries, the computational strategy discretizes a given surface into narrow, developable panels (Figure 4). Adjacent panels are connected with an undulating inner plywood band to provide stability during fabrication, thus eliminating the need of static moulds and minimizing the use of temporary scaffolding.

The outer faces and inner connecting layer of the sandwich composite are made of birch plywood. The plywood strips are joined by blind rivets made of aluminum to create a structurally performative unit. The core is filled in a subsequent step with polyurethane expandable foam. Four-point bending tests were conducted and evaluated to obtain the properties of the materials used and the overall behaviour of different sandwich configurations. Adding an expanded foam core significantly increases the stiffness and load bearing capacity of the wooden, bending-active construction. Depending on material selection, sandwich constructions present a better structural performance without significantly adding weight; increase thermal and acoustic insulation; and provide a surface finish and environmental resistance, all relevant factors for architectural design (Zenkert 1997).

The material system takes advantage of grain directionality of the plywood to enhance the curvature and strength of the sandwich surface. The faces are oriented with the grain parallel to their main curvature, while the inner bands are oriented with the grain at 90° to achieve smaller bending radii and maintain better control over the distance between the outer faces. Neighbouring panels are connected using blind rivets on overlapping flaps. The flexible joint design allows for fabrication tolerances during assembly because the position of the rivets can be adjusted.

**STRUCTURAL ANALYSIS**

The structural analysis provides the limits for the bending-active form finding process and the optimization of the sandwich height distribution performed as part of the computational design.

The stress due to pure bending is calculated using expression (1) below (Lienhard 2014; La Magna 2017). The shape and maximum stress of the inner bands can be approximated using the expressions (2) and (3) for an elastica with fixed supports (Wagner and Vella 2013).

The flexural stiffness of the sandwich mostly depends on the thickness and separation of the faces (Petras 1998; Steeves and Fleck 2004).

The flexural stress in the faces can be approximated using (4) where \( M \) is the out-of-plane bending moment, \( b \) is the width of the element, \( t \) is the thickness of the faces and \( c \) the height of the core (Gibson 1997). Hence, the distribution of the core height on a sandwich structure can be modified to reduce the stress in the faces by locally increasing the height of the sandwich.
In this project, an iterative process was developed to analyze the sandwich construction using the finite element analysis software SOFiSTiK. The height of the foam core is iteratively redistributed to achieve a maximum global deformation, using the stress distribution in the structure as a parameter (Figure 5). The height of each finite element is based on the following expression (5):

\[ h_{i+1} = \frac{\delta_{\text{max}}}{\delta_{\text{goal}}} \frac{\sigma_i}{\sigma_{\text{max}}} h_i \]  

**COMPUTATIONAL DESIGN**

The development of a computational design tool enabled design explorations to be informed by both the robotic fabrication constraints as well as the rather restrictive possibilities of actively bent plywood. An initial step in the research considered the possible morphologies which could satisfy both the condition of developability of the segments and reachability for the robot. From this set of feasible shell typologies, a double-curved cantilevering canopy was selected to explore the possibilities of this construction system for non-vaulted structures.

This initial design geometry is subjected to a form-finding process applying the dynamic relaxation method (DR) implemented in the physics engine Kangaroo Physics, embedded in the visual programming environment Grasshopper within Rhinoceros. The goal of this process is to find a form that satisfies the curvature limit of the plywood for an arbitrary set of curves. The resulting surface is then split by the curves which correspond to the edges of the panels. The panels are further rebuilt to ensure their developability. The top panels of the sandwich are added with variable distance to the bottom panels, matching the result of the sandwich height optimization. The overlapping flap joints are then populated along the longitudinal edges of the outer strips approximately every 200 mm.

The last step defines the distribution of the undulated inner bands which interconnect the outer faces and control the height of the core, respecting the curvature limits (Figure 6).

**FABRICATION PROCESS**

The fabrication process for the assembly of the shell follows a sequential logic, starting with the production of the base, where the faces of the sandwich unit attach. This provides a fixed support with different inclination for each panel. Next, the computationally generated outlines of the first...
The custom designed 2DOF end effector uses a linear drive to move the fork sideways and a stepper motor with gearbox for its rotation. These two movements allow it to handle the inner undulated bands, pushing them towards the faces while holding them with the supporting rollers.

Working prototype for 2DOF robotic end effector that shapes the plywood bands mounted on a 6-axis robotic arm.

The shaping process integrates the movements of a 6-axis robotic arm with the movements of the end effector through control trading, whereby the robot stops and allows the end effector’s motors to actuate. This end effector has a central fork with 2-DOF which moves laterally and rotates (Figures 7, 8), and is able to hold and twist the inner bands of plywood and push them towards the faces to achieve controlled three-point bending (Figure 9). When the faces and the inner bands are in contact, it is possible to drill through and connect them using blind rivets using a pneumatic gun (Figure 10). This assembly generates the self-supporting structure that is later filled with expandable foam to provide the combined stiffness.

After a unit is complete, sensing tools are used to digitize the built geometry to update the computational model. The results are integrated using ViveTrack, a Grasshopper plugin that allows for the use of HTC Vive controllers to digitize the edges of the panels (Figure 11). Each strip of the sandwich is designed and built based on the scanned geometry of the previous assembly to match the required tolerances of fabrication. This feedback is required to match the three-dimensional bent shape of the subsequent unit with those already built. One limitation is the accuracy and precision of this scanning tool, which will need to be verified in subsequent research.

CONSTRUCTION OF A DEMONSTRATION
A demonstration was built in laboratory conditions using a robotic arm Kuka KR-125. Because the robotic arm has a defined space to work where it can comfortably reach the panels and introduce the end effector to handle the inner plates, the fabrication strategy was to sequentially move the base of the structure, reorienting the working edge to fit within the comfortable limits of the robot.

This constraint could be removed in case of an on-site fabrication scenario where a robotic unit is mobile and can sequentially relocate itself to sequentially assemble strips.

RESULTS AND DISCUSSION
The potential of the developed integrative fabrication method was explored through a full-scale architectural demonstration. The demonstration enabled the testing of initial steps of fabrication and the chance to observe the amount of deviation resulting from unpredicted material behaviour.
An integrated approach using form-finding, structural analysis, panelization, and material and fabrication constraints was developed which facilitates the computational design and panelization of segmented sandwich shells. The developed tool performed satisfactorily on continuous surfaces which exhibit no topological singularities such as branching, merging or the presence of openings. A novel material system has been developed which is made of flexible strips of birch plywood, two outer bands serving as skin-layers and one inner band allowing a variation of thicknesses of the sandwich panel while also improving its shear resistance. A polyurethane expandable foam functions as the core. The sandwich panel enables the fabrication of double-curved, structurally performative shell typologies while only weighing 11 kg/m² for a thickness of 200 mm. The limitations for scalability of the proposed material system are in the strength of the riveted connections and the high prestress in the undulated bands.

A robotic fabrication process is introduced using a self-developed, custom end effector mounted on a 6-axis robotic arm. For the robotic control, the research development reached a partial integration of the automated movement of the robot and the end effector, allowing the operator of the robot to control the end effector actuation while observing the behaviour of the material. An implementation of sensor-based-robotic control would allow the full integration of the movements of the robotic arm and the actuation of the robotic end-effector. The implementation of a tracking device enabled the digitization of the built prototype to update the computational design of subsequent panels. The system used, namely HTC Vive controllers and ViveTrack, showed limited applicability outside of lab conditions due to its reduced area of work and the requirement of thorough calibration process.

The deviation from the digitally designed surface of the first built unit was up to 190 mm, mainly due to spring-back after releasing the assembly from the robotic arm. This result shows the need of an adaptive fabrication system which is able to react for those variations and reduce the fabrication tolerances to properly assemble the following neighboring units.

**CONCLUSION AND OUTLOOK**
This project demonstrates the possibilities of an integrative, adaptive approach to fabrication for segmented sandwich shells where the unpredictability of material behaviour is greater than the tolerance allowable for a predetermined design. The authors firmly believe that the further development of fabrication workflows which integrate...
the use of flexible materials and enable one to react on construction tolerances within the design phase is beneficial for the construction of double-curved, segmented sandwich shells in timber architecture. To integrate the developed methodology into larger-scale applications, the use of more performative and sustainable materials could be explored for the sandwich construction. Reducing the environmental impact and cost of a building sandwich unit and the further assessment of thermal and acoustic insulation were out of the scope of this study, but could be subject of further research.

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**REFERENCES**


**IMAGE CREDITS**

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