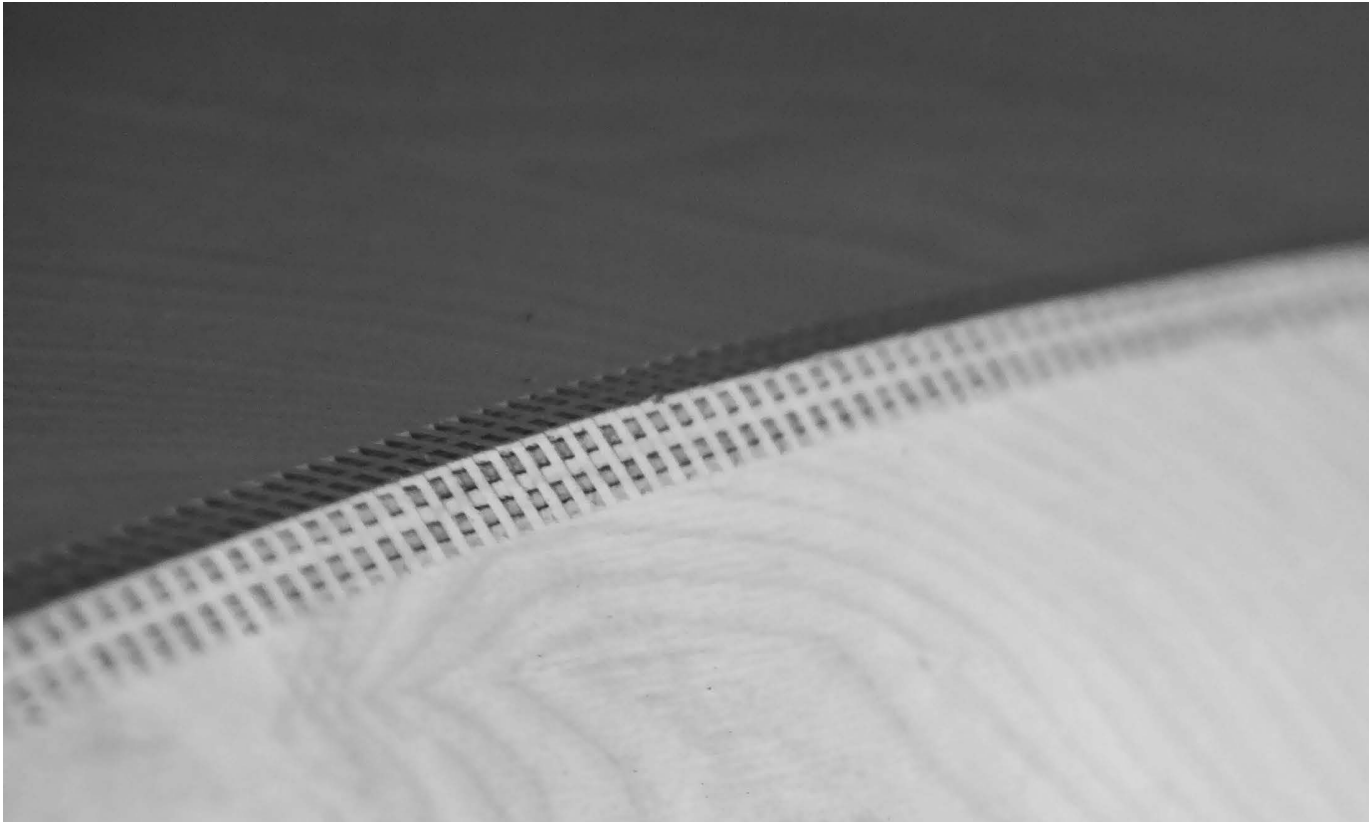


POTENTIALS OF ROBOTIC FABRICATION IN WOOD CONSTRUCTION:

ELASTICALLY BENT TIMBER SHEETS WITH
ROBOTICALLY FABRICATED FINGER JOINTS

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1 Curved finger joints – Elastically bent plywood plates connected by robotically fabricated finger joints

ABSTRACT

The paper presents current research into architectural potentials of robotic fabrication in wood construction based on elastically bent timber sheets with robotically fabricated finger joints. Current developments in computational design and digital fabrication propose an integrative design approach contrary to classical, hierarchical architectural design processes. Architecture related fields, such as material science, engineering and fabrication have been seen as separate disciplines in a linear design process since the Industrialization era. However, current research in computational design reveals the potentials of their integration and interconnection for the development of material-oriented and performance-based architectural design.

In the first part, the paper discusses the potentials of robotic fabrication based on its extended design space. The robot's high degree of kinematic freedom opens up the possibility of developing complex and highly performative mono-material connections for wood plate structures. In the second part, the integration of material behavior is presented. Through the development of robotically fabricated, curved finger joints, that interlock elastically bent plywood sheets, a bending-active construction system is being developed (Figure 1, Figure 2). In the third part, the system's architectural application and related constructional performance is discussed.

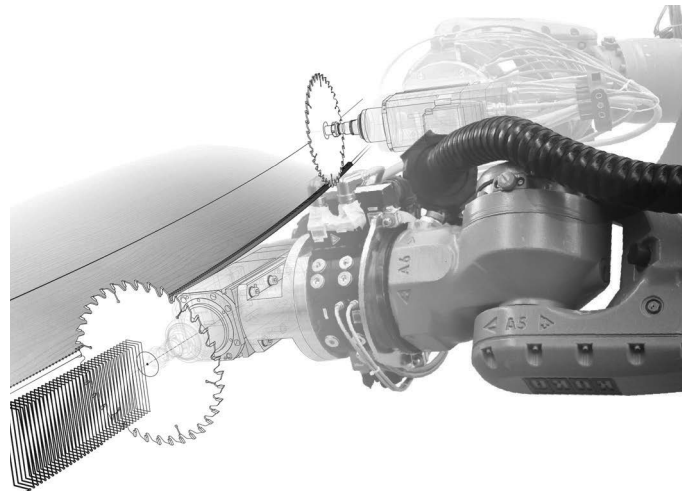
INTRODUCTION

Wood is a widely available and renewable resource in temperate climate zones. Over the last decades, it has again received increasing attention as a construction and building material (Kabelitz-Ciré 2012). In addition to its positive carbon footprint (Kolb 2008) and very low embodied energy (Alcorn 1996) both the efficiency and flexibility of robotic fabrication techniques in timber construction promise to improve the material's already outstanding ecological and economical performance. Due to wood's long history in building construction and architecture, as well as its predominance during the preindustrial era, it registers advances in production techniques particularly well (Schindler 2009). Historically, wood was characterized by manual and laborious fabrication processes, in addition to limited material supply. In reciprocal relation to the slow, yet geometrically highly complex fabrication methods, these circumstances led to a refined development of performative and efficient construction techniques (Graubner 1992, Schwinn et al. 2012). In contrast, industrialized manufacturing processes required mass produced, standardized elements. While the production speed was considerably increased in the industrialization process, the related mechanic automation led to simplified connection elements at the expense of a loss of efficiency and performance.

New developments in computational design as well as in digital fabrication are currently leading to a rethinking of architectural design processes. Related fields, such as material science, engineering and fabrication were separated and detached from each other during the industrialization (Kieran and Timberlake 2004). On the other hand, the present development opens up the opportunity to interweave and interconnect these disciplines efficiently through computational design methods (Harris et al. 2004). In addition, current research in the field of digital fabrication in architecture is characterized by a shift from process specific machinery designed for a certain task toward more generic fabrication equipments such as industrial robots. The development of adaptive fabrication methods promises new insight into how the extended kinematic range of robotic fabrication and its range of application can be used in order to develop novel ways in timber construction and ultimately architectural design. The increased potential in the morphological differentiation of building elements in relation to the machine constraints can be described as a machinic morphospace in reference to theoretical morphospaces in biology. This methodology allows conceptualizing the design space of theoretically possible fabrication methods given the parameters of a specific machine configuration (Menges 2012a).

ROBOTICALLY FABRICATED WOOD CONSTRUCTIONS

Recent research projects have shown the potential of developing robotically fabricated wood construction systems in an architectural context (Krieg et al. 2012; Schwinn et al. 2012). The experience gained from these studies also shows that an integrative



2 Robotic fabrication – Fabrication process for manufacturing curved finger joints. The plate element's outline and finger joint geometry is cut with a rotary blade in two different steps

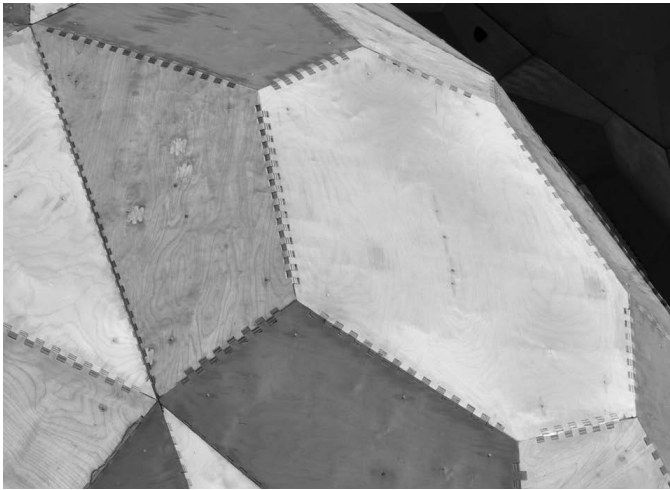
design process is necessary, which is diametrically opposed to well-established form-oriented design methods, and is instead an open, undetermined and explorative process (Menges 2012b). The following chapters present an integrative approach to architectural design with a special focus on how robotically fabricated mono-material connections can act as a design driver for elastically bent plywood plate morphologies.

FINGER JOINTED PLATE STRUCTURES

Finger Joints are traditional wood connections whose geometric complexity and fabrication effort led to a significantly reduced range of applications during Industrialization. Their performance lies in the possibility to connect planar elements in a specific angle without the need for an additional fastener. These inherently force and form-fitting connections exhibit a high structural capacity to withstand normal and in particular shear forces (Krieg et al. 2011). Through previous research projects, a new robotic fabrication method based on seven-axes robotic production was developed. It enables the efficient fabrication of differentiated finger joints that connect timber plates at varying angles (Figure 3). This fabrication method led to the opportunity to develop highly adaptive construction systems based on plywood plate structures. Additionally, the principle of interlocking two sheets of plywood on the basis of a highly adaptive fabrication method invites further investigation, enhancing the connection's inherent information by incorporating material performance, such as elastic bending, in both the fabrication and assembly processes.

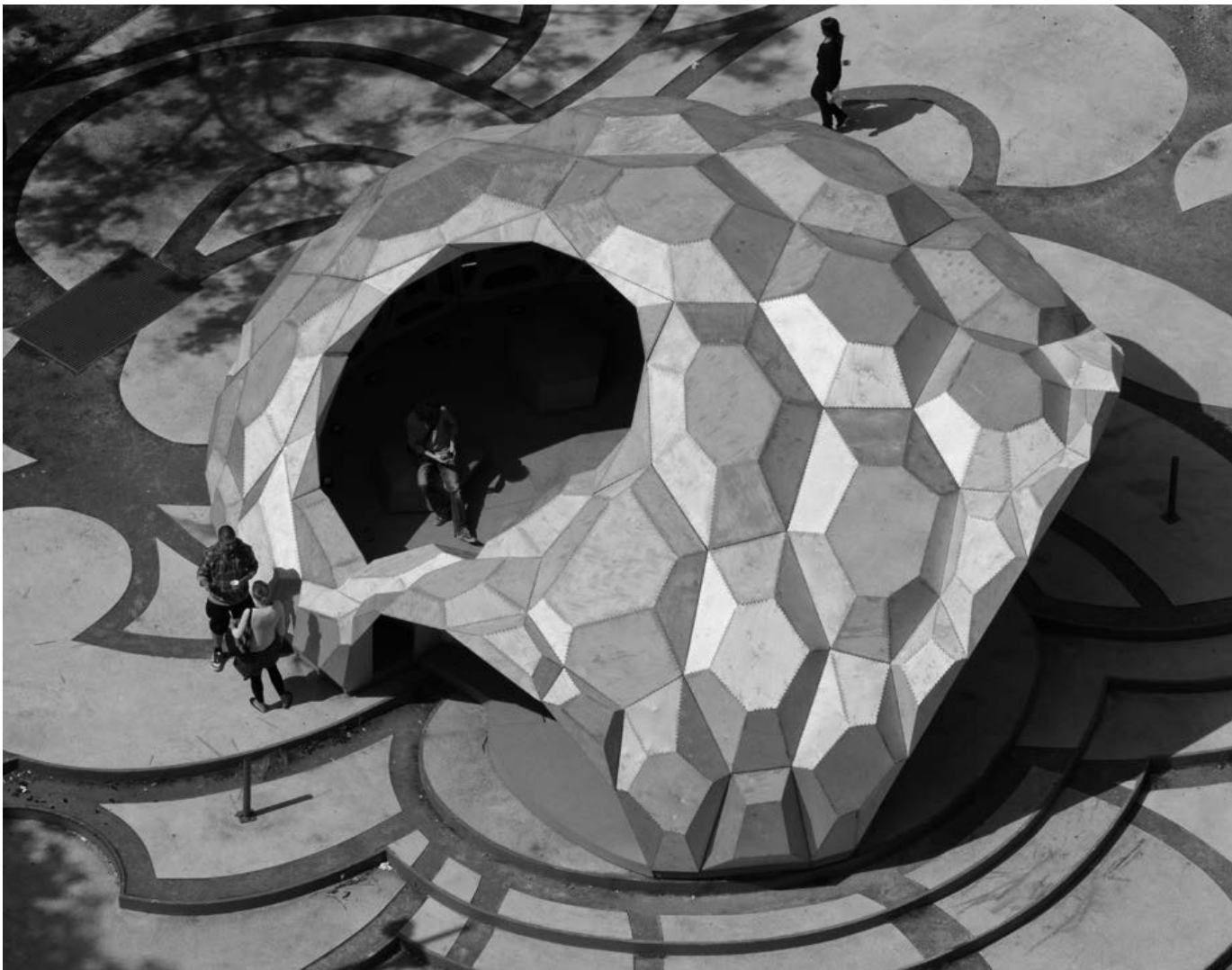
DEVELOPMENT OF ELASTICALLY BENT, FINGER JOINTED WOOD PLATE MORPHOLOGIES

Although elastic bending still poses a challenge to the computational design process due to the complex reciprocal relation of force, form and fabrication parameters, it enables a much more



3a ICD/ITKE Research Pavilion 2011 – Close-up view of the finger joints

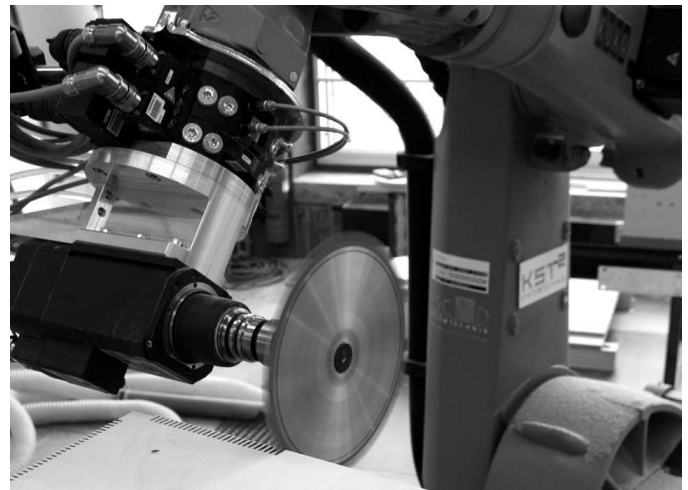
effective use of the available material. Wood's material characteristics can be used to elastically bend initially flat sheets of plywood during assembly. This method allows for a much more material-oriented design approach, a higher geometric differentiation and even the integration of structurally bending-active elements into the construction system. However, due to the technical difficulties in assembly and construction, there are only a few cases of elastically bent construction systems (Menges 2009). Current research projects, however, show the potentials of integrating material behavior in computational design processes (Fleischmann 2011; Menges et al. 2011; Menges 2011; Menges 2012c). The premise of this research is a newly developed fabrication technique that enables the production of finger joints along a curved edge of an initially flat plywood sheet. Consequently, the finger joint's specific geometry requires elastic bending of the corresponding elements during assembly. Differentiation in the connection's curvature thus de-



3b ICD/ITKE Research Pavilion 2011 – Aerial view of the pavilion



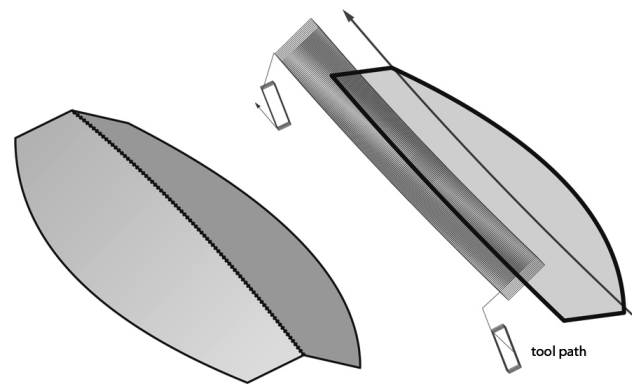
4a Finger Joint Fabrication – Curved finger joints connecting two plates



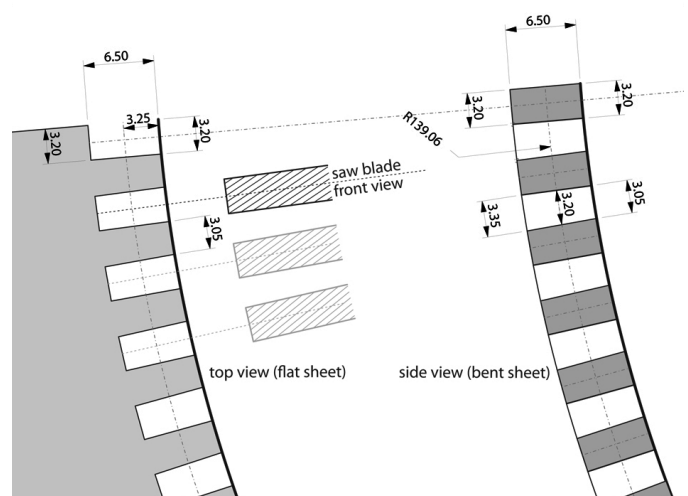
4b Finger Joint Fabrication – Fabrication setup for a six axes industrial robot

finishes the element's bending geometry. Additionally, the finger joint assembly method automatically interlocks both elements and ensures a form and force fitting connection (Figure 4a). In contrast to the mentioned examples of elastic bending, the newly developed process integrates prefabrication to ensure high precision.

While the basic connecting principle of the finger joint still resembles the classical connection, two major advancements were necessary during this research. On the one hand, the joint's initial geometric parameters, such as its width, make it unfit for curved connections. Since elastic bending causes the plate and therefore the plate's edge to be curved, the joints can only serve as a polygonized, close approximation of the actual geometry. If this approximation is too inaccurate, the assembly sequence will be compromised. The newly developed fabrication technique, however, allows the joint's width to be adapted to the new requirements. In consequence, the element's bending radius, and thus its final geometry after assembly, stand in direct relation to the joint geometry. This flexibility required different fabrication tools to be analyzed and used for development, such as saw blades for small-scale prototypes and side milling cutters for larger scales. Since these tools have different cutting vectors in relation to the tool axis, a modified fabrication process had to be developed (Figure 4b). Here, both processing steps can be executed with the same tool as long as the element's curved outline exhibits a radius that can be cut with saw blades. On the other hand, the joint's overall geometry is in direct relation to both the element's bending geometry as well as the adjacent element's angle. Since this information needs to be transferred to the fabrication process of the flat building element, there is a significant importance placed on the computational process prior to the machine code generation. The computational model needs to analyze both the already bent and assembled state of the building element as well as the flat, unrolled state. While the fabrication data is generated in reference to the flat sheet, the geometric



5a Digital Model – In relation to the bent and assembled geometry, the fabrication tool path is generated on the flat sheet



5b Digital Model – The joint geometry of a bent sheet of plywood (right) fits into the corresponding joints on its adjacent plate (left)



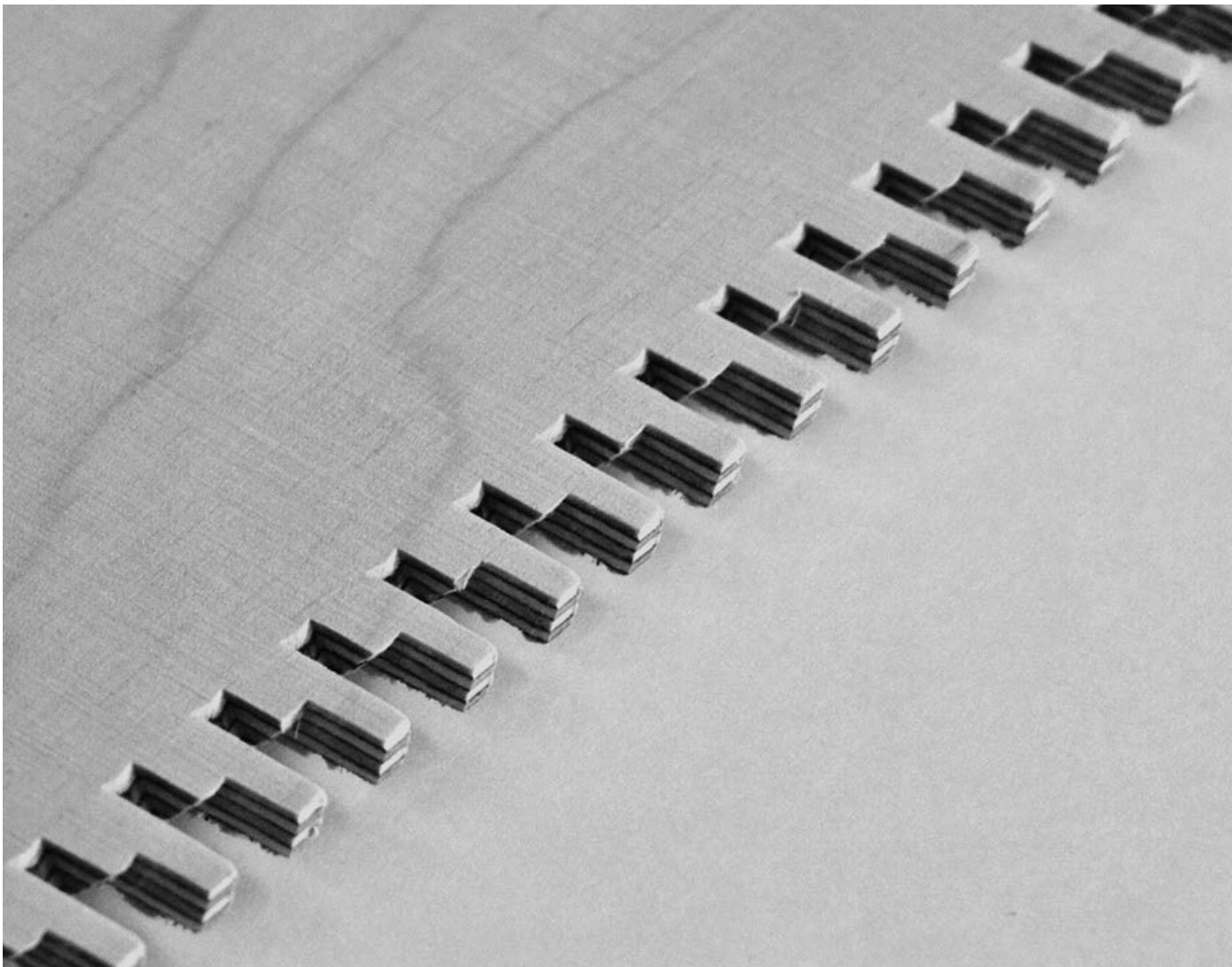
6b Multidimensional Connection – Close-up of an assembled prototype

information is evaluated on the bent sheet (Figure 5). Therefore, the computational model needs to contain both the bent geometry and the flat geometry, through which it is able to compute and reverse the geometric and fabrication parameters for assembly.

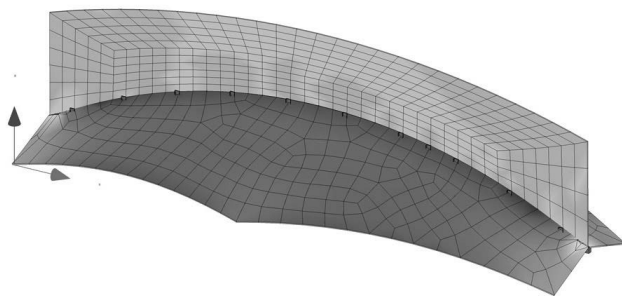
The joint geometry generation is a generic process adaptable to connecting more than two plates. While it is normally set up as one slit followed by a finger extrusion when connecting to just one other plate, the connection of three plates introduces a second finger extrusion after each slit. In this case, the extrusions' geometries alternate to connect to the first and second plate (Figure 6).

STRUCTURAL ADVANTAGES AND ARCHITECTURAL APPLICATIONS

Parallel to the development of the fabrication tool, the question of how the possible geometric differentiation of both the joint and the plate element geometry could lead to the development



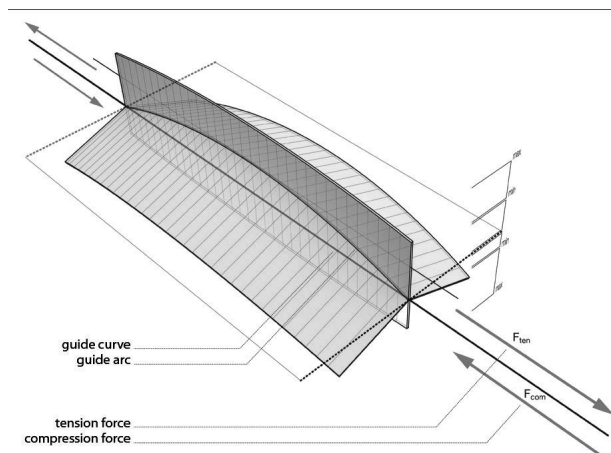
6a Multidimensional Connection – Close-up of finger joints for connecting to two adjacent plates



7a Structural Performance – FE analysis of the assembly process. The calculated residual stress is later used in load-bearing tests

of a structurally and architecturally performative material system was addressed. While earlier research projects showed the potential of using biomimetics to filter the wide range of possible morphological differentiation within building elements (Krieg et al. 2012; Schwinn et al. 2012), this research focused primarily on structural potentials and limitations of the developed construction principle. Bending active structures are curved beam or surface structures that base their geometry on the elastic deformation of their initially straight or planar elements (Lienhard et al. 2011). In these structures residual stress caused by elastic deformation is used to act against external load-bearing forces, while another advantage also lies in their geometrical stiffness due to the induced curvature. Finite element analyses showed that through the interlocking finger joint connection between two elastically bent plates, the residual stress caused a lower deformation under compression load (Figure 7a). The deformation can be reduced up to 5 per cent compared to the same geometry without residual stress; however, it is in direct relation to the amount of bending and therefore the plate element's bent and flat geometry. While the first aspect is limited by the material's maximum bending radius, the latter is also limited by the fabrication parameters and constraints.

The structural analysis proved that elastically bent plate elements not only extend the possible morphological differentiation within finger jointed plate structures but also enhance their structural performance, especially in relation to a modular construction system. Due to the fact that the analyzed residual stress can only be used to withstand compression forces along the main direction of the connection, another element is necessary to absorb tension forces through a maximum spatial division of the module's cross section (Figure 7b). Therefore, a third plate element acting as a tension lamella was introduced. On a local level, the cross-sectional length and width of all three plate elements inside a module func-

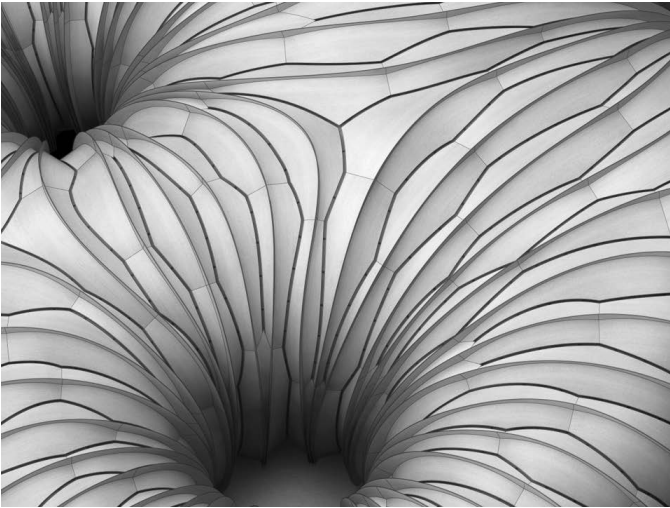


7b Structural Performance – The lamella on top of a module can attract tension forces, while the remaining two plates absorb compression

tion as parameters, able to react to system-internal and external forces. On a global level, the modular arrangement follows different biomimetic principles. In the longitudinal direction, the modules have to exhibit a continuous arrangement similar to lamella structures in nature, following the main load-bearing directions in order to carry the tension forces. On the other hand, their transverse alignment follows cellular arrangement principles in order to maximize the distance between module connections (Figure 8a). The resulting construction system was tested in different prototypical situations to analyze its architectural applications (Figure 8b). The modular arrangement principles and their geometric differentiation reveal distinct characteristics and a novel tectonic repertoire for architectural articulation. Prototypical situations were developed and analyzed during the research, such as open and closed, or exposed and introverted settings.

CONCLUSION

The presented research shows the potentials of robotically fabricated, modular, lightweight timber constructions, which are capable of adapting to internal constraints and external influences through their inherent ability of morphological differentiation. As these performative capacities are only achievable through an integrated computational design process, the research is expected to raise awareness of the paradigm shift in architecture from a hierarchical process to an integrated design without a separation of material and structure, and thus the importance of possibilities for fabrication methods and material behavior in architectural design. The developed fabrication method as well as the integration of elastic bending and structural performance promises new insight into the possibilities of integrating material performance into the design, assembly and fabrication process. The research shows that integrative computational design processes can lead to intelligent construction



8a Architectural Prototype – Close-up of a prototypical arrangement showing the differentiated module geometries as well as their longitudinal alignment

systems with far less material and energy input than traditional solutions. However, as fabrication and connection intelligence is in direct relation to the material's performative capacities and their proper application, more research on the effective use of the robot's morphospace as well as material behavior is of great importance. Additionally, the resulting possibilities in novel architectural articulations require further investigations.

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8b Architectural Prototype – Front view of a prototypical architectural situation

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