Biomimetic Lightweight Timber Plate Shells: Computational Integration of Robotic Fabrication, Architectural Geometry and Structural Design

Oliver David Krieg, Tobias Schwinn, Achim Menges

Institute for Computational Design, University of Stuttgart

Jian-Min Li, Jan Knippers

Institute of Building Structures and Structural Design

Annette Schmitt, Volker Schwieger

Institute of Engineering Geodesy

Abstract. *The research presented in this paper pursues the development and construction of a robotically fabricated, lightweight timber plate system through a biologically informed, integrative computational design method. In the first part of the paper, the authors give an overview of their approach starting with the description of the biological role model and its technical abstraction, moving on to discuss the computational modelling approach that integrates relevant aspects of biomimetics, robotic fabrication and structural design. As part of the validation of the research, a full-scale, fully enclosed, insulated and waterproof building prototype has been developed and realized: The first building featuring a robotically fabricated primary structure made of beech plywood. Subsequently, the methods and results of a geodetic evaluation of the fabrication process are presented. Finally, as the close collaboration between architects, structural and geodetic engineers, and timber fabricators is integral to the process, the architectural and structural potentials of such integrative design processes are discussed.*

1 Introduction

New developments in computational design and digital fabrication currently lead to a rethinking of architectural design and delivery processes. In contrast to traditional, hierarchical, and form-driven design approaches, integrative strategies can activate discipline-specific knowledge in early design stages. In the case of the research presented in this paper, this includes the activation of reciprocal dependencies between architectural geometry, biomimetic engineering, structural design, robotic fabrication and geodetic evaluation (engineering geodesy being the scientific discipline concerned with surveying). Specifically, the authors introduce an innovative, biologically informed, computational design approach for the development and construction of a robotically fabricated lightweight timber plate structure (Fig. 1).

The timber construction industry is currently experiencing significant innovations in fabrication technology and structural applications. As a renewable resource and with its negative carbon footprint and low embodied energy (Kolb, 2008; Alcorn, 1996), wood undoubtedly plays a major role in the current development towards sustainable, carbon neutral construction. Additionally, from a life cycle analysis standpoint, the utilization of locally available building materials becomes crucial. Besides using local wood products, the project also investigates how innovative fabrication techniques, as part of an integrative computational design strategy, can lead to a rethinking of sustainability: Increasing structural performance and resource efficiency through a higher degree of shape variation in the building parts, while at the same time offering new spatial qualities and architectural potentials. The hypothesis is that by following biomimetic principles in form-finding and construction, a performative, structurally efficient, and geometrically intricate plate structure system can be developed, which, following the high-level biomimetic principle (Gruber & Jeronimidis, 2012) of functional integration, functions as a materially efficient load-bearing layer and building envelope at the same time.

Figure 1. Exterior (A) and interior (B) views of the finished prototype building.

The goal of the research project therefore is to investigate the architectural and structural potentials of an integrative design approach for timber plate structures, enabled by a close collaboration between architects, structural and geodetic engineers, and timber fabricators. Consequently, this method is evaluated through the design, fabrication, construction, and verification of a full-scale building prototype. Built for the Landesgartenschau Schwäbisch Gmünd, Germany, in 2014 and named the *Landesgartenschau Exhibition Hall*, the case study is a fully enclosed, insulated and waterproof building.

2 Computational Design Strategies for Plate Structures

2.1 Constructional Morphology of Plate Structures in Nature

A distinguishing feature of structural systems in nature is their geometric complexity. In contrast to engineering, living organisms are unconstrained by predefined structural typologies or aspects of calculability. Furthermore, geometric complexity forms the basis for material efficiency, which in turn is the prerequisite for survival. In other words, while in nature material and energy are more expensive than shape or geometry, in technology the opposite was true as of today (Vincent, 2009). Current developments in digital fabrication, however, ease many of the economic restrictions for varying the building components' shape. In particular, the kinematic freedom of robotic fabrication opens up the opportunity to introduce geometric complexity in construction systems for more efficient structures in architecture, a development that can be summarized as: more form, less material.

In this context, plate structures are of particular interest as they are a performative construction system made of individual, planar elements. Geometrically, they can be organized such that the individual plates constitute the primary load bearing structure, instead of the joints as in the case of grid shells (Bagger, 2010). However, previous research also showed that an integrative, performance driven computational design method is critical for the development of an efficient and adaptive plate structure system (La Magna et al. 2012; Schwinn et al., 2012). Plate structures can be found in many different biological systems, of which the sand dollar species of the class of sea urchins (*Echinoidea*) is most notable for its constructional morphology (Fig. 2a). The skeletal shell of a sand dollar is a modular system of polygonal plates composed of calcium carbonate and covered by a thin dermis and epidermis (Barnes 1982). On a microscopic level, the plates are joined by interlocking calcite protrusions (Fig. 2b) that can be seen as the biological equivalent to man-made finger joints. Through their topological rule of always joining three plates in one point, plate structures such as the sand dollar's skeleton transfer bending forces mainly through shear forces along the plate's edges.

By transferring biomimetic principles into a construction system, the material efficiency of geometrically differentiated building elements that is inherent in biology can be used for developing a new kind of construction system, which not only incorporates the connection principle within the building part, but also integrates fabrication constraints and material parameters. The research project therefore aims at the development of a modular, lightweight plate structure capable of adapting to free-form surfaces by making use of the extended design space, or Machinic Morphospace (Menges, 2012), for plate structures provided by robotic fabrication.

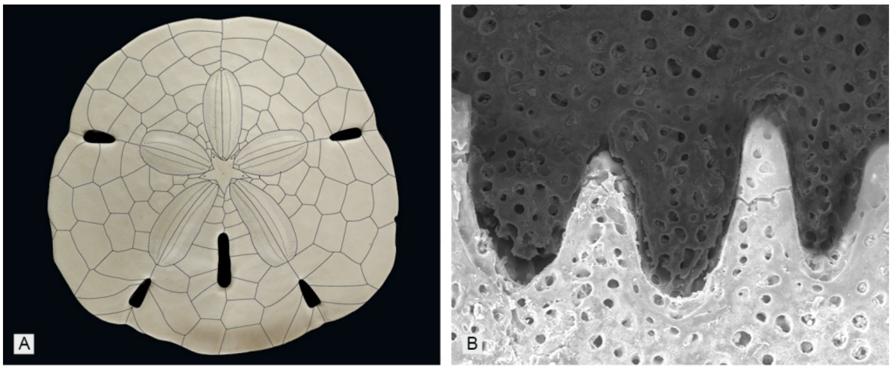

Figure 2. A: Top view of a sand dollar with highlighted topology (Gerber & Nebelsick, 2014). B: Microscopic view of a sand dollar's plate edge (Nebelsick & Grun, 2014).

2.2 Integrative Computational Design for Plate Structures in Architecture

In architecture, one of the prerequisites for developing an integrative design method for plate structures is solving the planar polygonal approximation of complex double-curved surfaces: not only in positive and negative Gaussian curvature regions, but also in regions close to the so-called parabolic line – the transition zone – where K=0. While this is a topic that is actively being researched in the fields of computer graphics (Cohen-Steiner et al., 2004; Zimmer et al., 2012) and architectural geometry (Manahl et al., 2012; Troche, 2008; Wang et al., 2008), a novel approach is being investigated as part of this research that synthesizes the principles of tangent plane intersection (TPI), the biomimetic principles of natural plate structures, and the rules and constraints of robotic fabrication in an agent-based modelling (ABM) approach. The promise of this approach is that (1) in addition to the numerical solution of the approximation problem, various sometimes conflicting objectives can be integrated into a design-fabrication feedback loop, where the various goals relating to fabrication, geometry, structure, and architecture can be described and negotiated in a behavioural model. (2) In contrast to the linear hierarchical model of the digital chain, which formalises a deterministic design process, in this approach the rules and constraints of digital fabrication are activated as design drivers resulting in a non-linear design process.

Tangent plane intersection (TPI) has a number of characteristics that make it applicable in the context of agent-based modelling for plate structures: first, all the intersection points of a tangent plane T_0 with its neighbouring planes lie in the plane of T_0 and can consequently represent the vertices of a planar polygon (Fig. 3); second, TPI produces valid results for double-curved geometry, i.e. synclastic and anticlastic surface regions, which is beneficial for the global stability of a structure, however with one caveat: TPI produces degenerate results in parabolic regions, where Gaussian curvature K approaches 0, requiring additional strategies: in this case the intersection points of three neighbouring planes usually lie far away from the input points, so that they have to be projected back and, consequently, will temporarily form non-planar polygons. Agents with non-planar polygons therefore follow a prioritized behaviour that leads them to minimize the non-planarity by numerically differentiating the measure for non-planarity, i.e. the out-of-plane distance, at that point, thus moving in a gradient descent towards areas of planarity; third, in order to determine which tangent plane intersects with which neighbouring plane the concept of a "neighbourhood" has to be established, which is implemented through the triangulation of the input point set. While the concept of the neighbourhood is integral to ABM where it is defined by distance/proximity, in the case of TPI, it is defined by topology, e.g. a Delaunay triangulation of the u,v-parameter space. Both definitions are consequently incorporated into the ABM approach for plate structures.

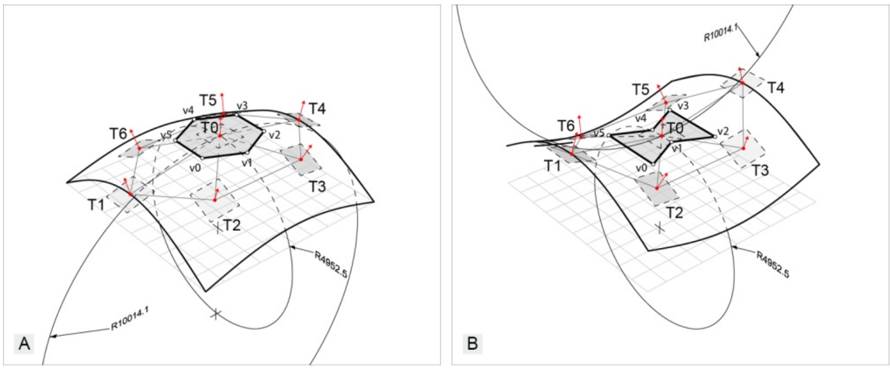

Figure 3. Tangent plane intersection for doubly curved surfaces. Oscillating circles indicate curvature (1/R), principle curvature directions and orientation. A. Synclastic, positive Gaussian curvature K > 0. B. Anticlastic, negative Gaussian curvature K < 0.

Agent-based systems are part of a rule-based computational modelling method whose premise is that through the calculation of the local interactions between individual entities (*autonomous agents*), which are based on pre-defined rule sets (*behaviours*), a global configuration emerges that meets higher-level goals. As such, ABM is an example of behaviour-based artificial intelligence (Brooks, 1986) and is used in a variety of fields ranging from finance to robotics to biology. The underlying models and the related behaviours of the individual agents are based on abstractions of the relevant application context. In the architectural context, ABM is often used for the simulation of pedestrian movements as in building evacuation or urban environments (Aschwanden, 2008), but also in design exploration (Snooks, 2013). In these cases, the agent models require the capacity for locomotion, which, introduced by Reynolds (1999) and borrowed from Braitenberg (1984), allows each agent to adjust position and orientation based on its local interactions with neighbouring agents and the environment. Recently, ABM has been introduced in the context of design integration, specifically focussing on fabrication requirements (Baharlou & Menges, 2013).

In the context of the presented research, the behaviours of the agents integrate the requirements of fabrication, biomimetic principles, and aesthetic criteria. Parameters of the model are divided into global parameters, such as number of plates and average plate size, and local parameters. Local parameters, which are the parameters that govern agent behaviour, are directly related to fabrication constraints such as available stock size, working envelope of the fabrication setup (Fig. 4). Theyare also based on the joint fabrication strategy, which determines the min-max ranges of the connection angles, and the min-max ranges for the edge lengths. Aesthetic criteria (symmetry within the plate, edge proportions) and biomimetic principles (heterogeneity of plate sizes, number of edges, and 3-plates rule) are controlled by the adaptive separation value between agents, the topology of the underlying mesh representation, and by responding to the local curvature at a the agent locations. All behaviours are defined such that the agent system is globally driven towards convergence.

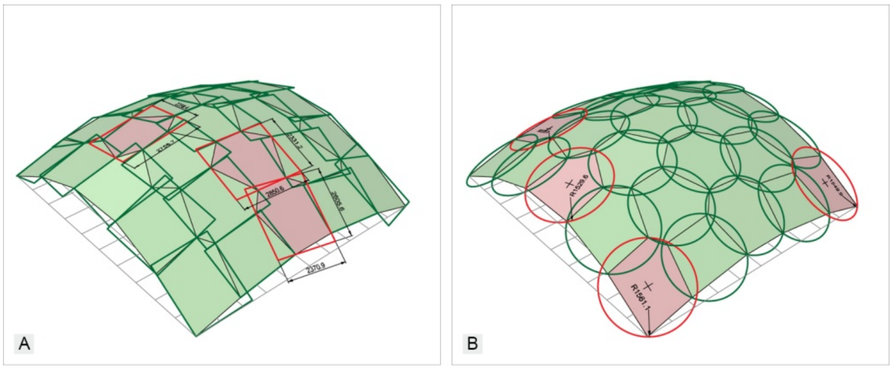

Figure 4. Global fabrication constraints are represented in the behavioural model and evaluated at runtime. (A) The minimal bounding rectangle evaluates the producibility in relation to the available stock material sheet size. (B) The circumcircle evaluates the plates in relation to the available fabrication workspace diameter.

3 Integrative Structural Design

3.1 Structural features

Segmented shell structures are common in nature but rare in building construction. At the academic level, a few segmented shells have been built out of panels from glass (Blandini 2005, Bagger 2010, Almegaard et al. 2007) or wood (La Magna et al. 2013), but with only limited use at larger scales. The main reason for this is the lack of applicable joint constructions satisfying conditions of sufficient structural load transfer and the restricted adaptability to various geometric and structural situations. Only a few studies on this subject can be found (Wester 1999, Veer et al. 2003), which either use adhesives for joining or apply combined mechanical/adhesive techniques.

Joints between prefabricated segments nearly always weaken shell structures as they disturb the continuity of their stiffness. Joints can also reduce the capacity to transfer bending moments or membrane forces. The structural capacity of joints not only impacts the overall load-bearing behaviour of the shell, but also determines the efficient arrangement of individual segments on a free-form surface.

The structure of the *Landesgartenschau Exhibition Hall* is designed as a segmented plate shell carrying loads mainly through membrane forces. It generates the global stability by its global double-curved shape and the binding strength in the connections between the segments. The *Exhibition Hall* is supposed to stand on site for at least five years and is therefore designed to meet the respective wind and snow load requirements.

Shell structures take out-of-plane loads by in-plane forces such that the out-of-plane bending and shears are minimized. Compared with lattice shells in which internal forces are mainly transferred through axial forces, plate shells transfer internal forces across edges not only through axial forces but also through in-plane shear forces (Fig. 5); the force flows could occur in either ways and their ratio is largely determined by the design of the joint and the joint patterns on the shell geometry. Observing the influence of the joint stiffness to the structural performance gives important clues about how to proceed with the structural design.

Like lattice shells with 6-valent triangular segments, plate shells with trivalent polyhedral segments are also kinematically stable (Wester 2002, La Magna et al. 2012) and connections with bending stiffness are thus not required. However, trivalent polyhedrons will become kinematically unstable if one of the three included angles of a vertex is close to 180 degrees. Additional bending stiffness in connections can effectively improve the structural performance of plate shells, especially in areas where included angles approach 180 degrees. Therefore, bending stiffness is still considered in the connection design of the Exhibition Hall.

Figure 5. Visualization of the forces inside the plate structure. The dominant in-plane shear forces are transferred through the plate's finger joints.

3.2 Structural Integration of Finger Joint Connections

Structurally designing a feasible connection, which provides sufficient strength and stiffness between the panels within a thickness of only 50mm, is an essential aspect of the joint development and was one of the key challenges of the project.

The objective that the connection could ultimately be applied to the building industry also means following the building code in the development process. The research therefore leads to a novel connection design for plate structures: by mimicking the skeletal configuration of sea urchins, finger joints are used in connections to resist the decisive in-plane shear forces, while the smaller axial forces and out-of-plane shear forces are taken by pairs of crossing screws (Fig. 6). The concept of crossing screws was first introduced by Blaß (2004).

The finger joints function similarly to step joint in traditional truss works. The thrust force will be taken by the contact surface and be transferred to the shear plane. Therefore, two failure criteria need to be examined: the shear capacity against the thrust and the compression capacity of the contact surface (Fig. 7).

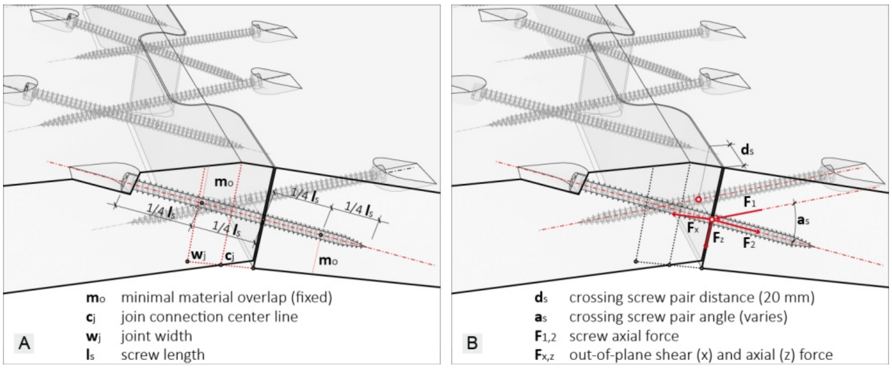

Figure 6. Visualization of the developed finger joint connection. Each finger joint includes a pair of parallel crossing screws, which intersect from the side view at the connection point between two plates. The crossing screws function as a small truss structure embedded in the plywood. Out-of plane shear F_x and axial force F_z are therefore taken by screw axial force F_1 and F_2.

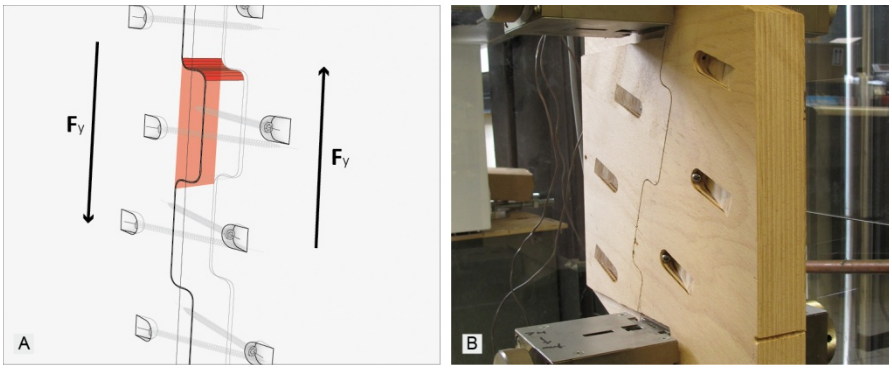

Figure 7. A: The in-plane shear force F_y is taken by the contact surface and transferred to the shear plane. B: The compression capacity of the contact surface and the shear capacity of the shear plane are evaluated through physical tests.

The axial forces and the out-of-plane shear forces are taken by the crossing screws, which lie in parallel planes, normal to the plate edge, with distance d_s to each other; the screws are intersecting with each other with a specific included angle in the side view (Fig. 6). Since the in-plane shear forces are taken by the finger joints, the analysis of the internal forces of screw joints can be reduced to a two dimensional force diagram problem; a simplified model is adapted here, in which the crossing screws are treated as a truss structure embedded in the plywood. The axial force and the out-of-plane shear force that are derived in the global structural model are taken as external forces of this truss structure.

3.3 Global Structural Analysis

From a structural point of view, an adequate model for structural analysis needs to be developed and fully integrated in the design process. Therefore, an automated sequence has to be developed to generate structural models from trivalent polyhedrons. In this way, the design process is directly linked to the structural analysis and the configuration of connections can easily be varied for finding an optimal solution (Fig. 8).

The structural performance of plate structures is largely determined by the connections between the plates. A proper simulation of the forces inside the connections is therefore an important aspect of the structural design. In the developed structural model the stiffness in connections is simulated by spring elements: Every connection consisting of a finger joint and a pair of crossing screws is simulated by four spring elements which act on two specific nodes situated at the two opposite plates in the finite element model (Fig. 8, right). Three springs are used for simulating the axial resistance; the in-plane shear resistance and the out-of-plane shear resistance respectively, while the fourth spring is used for simulating the bending resistance. Each spring is assigned with a specific direction of action as in Figure (8).

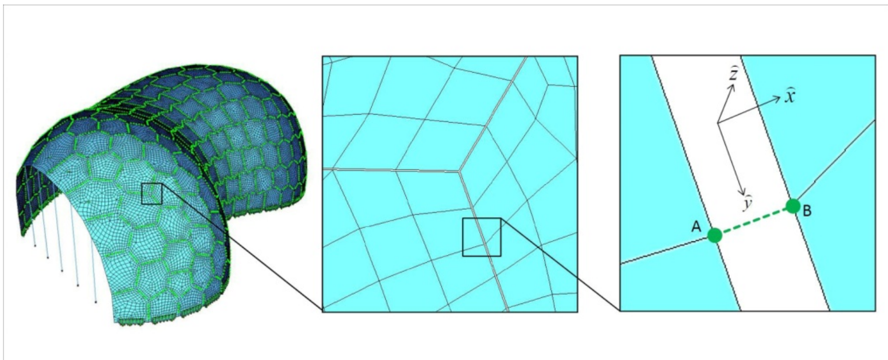

Figure 8. left: The global FE model of the pavilion. right: Spring elements are acting on two nodes, A and B, situated at the two opposite sides of neighbouring panels. Axes x, y, and z are the directions of the axial force , the in-plane shear, and the out-of plane shear respectively. Axis y is also the axis of bending resistance.

The spring coefficients are determined as follows: The axial resistance of a single screw is physically tested with various tilting angles in the plywood, and with these test values the spring coefficients for the axial resistance and the out-of-plane shear resistance can be determined by the simplified truss model. The spring coefficient for the in-plane resistance is determined by a simplified step joint model while the spring coefficient for the bending resistance is directly determined by the four-point-bending test of a real size joint.

4 Robotic Fabrication

4.1 Robotically Fabricated Finger Joints for Plate Structures

Through the extended kinematic range of robotic fabrication, complex connections become feasible and open up the possibility to integrate biomimetic principles at a deeper hierarchical level. Robotically fabricated finger joints had been developed in previous research for specific construction techniques (Schwinn et al. 2012, Krieg & Menges 2013). As in the previous research, the joint connection is developed with regards to the specific robotic fabrication setup and material parameters; in this research, construction and assembly constraints play an additional major role. As discussed above, an important driver in the plate structure system's development is the potential applicability in the building industry and therefore, in keeping with the resource efficiency of living organisms, the efficient and economic use of material. While this is achieved globally through an optimal distribution of the individual plate segments, and locally through the structural performance of the plate connections, the joint is also designed to keep production times short (Fig. 9), and to facilitate straightforward assembly (Fig. 10).

Figure 9. A: Robotic fabrication setup for milling a plywood plate. B: Close-up of the milling process.

The finger joint's parameters are subsequently integrated into the digital design and fabrication workflow. Based on the topology analysis of the plate structure surface model, the various tool paths for the finger joint fabrication can be automatically generated for each individual plate edge based on custom CAM strategies on three different levels. Besides milling the plate's boundary and the finger joints, the robotic fabrication process also ensures the precise localization of the crossing screws. While the joint width is a preset parameter to allow the space for the crossing screws and match requirements of the building code, other parameters such as the crossing screw angles, lengths and numbers, as well as the finger joint assembly vector are a function of the varying edge-specific, local geometric parameters such as angles between plates or plate edge length. This parametric process ensures a consistent connection performance while staying inside the machine's morphospace.

Figure 10. A: Assembly of a structural plywood plate. B: The plates are fixed and held in place through the crossing screws.

4.2 Strategic Use of Robotic Fabrication

The specific setup that defined many of the fabrication parameters consisted of a KUKA industrial robot arm with a 12KW spindle as an effector mounted on the robot flange, an additional revolute external axis used as a turntable, and an automatic tool changer. These components were preconfigured in a mobile robotic cell that was installed in the timber fabricator's workshop for the duration of the plate fabrication. The plates' formatting process consisted of two main fabrication steps: first, the plate stock material was cut with oversize from beech plywood boards on a Hundegger SPM machine, so as to minimize cut-off; second, the plates were mounted on the turntable in the milling cell, where milling of the finger joints down to the nominal joint dimensions could be accomplished. Both, the machining code for robotic fabrication as well as the code for pre-formatting the plates on the CNC-machine could be automatically generated from the digital plate information model.

Different cycle strategies were implemented in order to automate not only the precise trimming of each plate's boundary, but also construction details where necessary. For example, pockets and holes for the crossing screws are calculated for their optimal material overlap and screw angle in order to make the subsequent assembly on site easier. Pre-drilling is essential in the robotic fabrication process since the low material thickness does not allow for tolerances in the screw positions.

In this production process, robotic fabrication represents the crucial technology enabling the fabrication of the lightweight timber plate structure by solving the fabrication of the complex joints. However, other digital fabrication technologies such as CNC milling or waterjet-cutting, complemented robotic fabrication in order to form a coherent fabrication sequence. Not only the structural layer but also all other remaining layers of the building envelope required for insulation, waterproofing and cladding could be digitally fabricated.

5 Geodetic Evaluation

5.1 Evaluation of Fabrication Accuracy

Quality assurance, e.g. checking accuracy values, is an important task when developing new fabrication and construction processes. Thus a sample of 24 out of overall 243 plates was analysed. For the measurement the laser tracker API Radian™ is used together with an API IntelliProbe 360™, a hand-held probing instrument (Fig. 11). The laser tracker is a polar measuring system, measuring angles and distances and delivering point coordinates with an accuracy / root-mean-square error (RMS) of 50 µm in a distance of about 10 m. The high accuracy requirements are due to the fabrication that should be realized with 1 mm standard deviation, leading to a 10-times improved measurement RMS.

The 24 plates were measured with the help of an especially produced adapter for the API IntelliProbe 360™ to measure the plate's edges. Ten points on each finger joint element are measured. For a statement about the fabrication accuracy, the newly designed adapter for the IntelliProbe 360™ is tested with a reference metal work piece. The fabrication tolerance of that work piece is around 0.1 mm. One of the edges of this work piece is measured ten times. The medium RMS of these 3D-measurements is 0.24 mm.

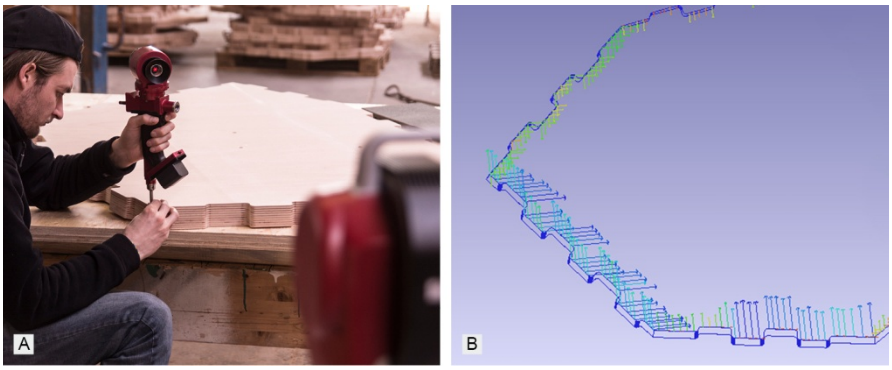

Figure 11. Measurement of the plate segments (A) and presentation of deviations in x and y direction (B).

The values in table 1 include the combined measurement and fabrication RMS as well as object properties and external influences on this object. The average 2D-RMS is given in Table 1 to 0.70 mm.

	x [mm]	y [mm]	2D [mm]	z [mm]
Accuracy (RMS)	0.48	0.51	0.70	0.74

Table 1 Accuracy (RMS) in each direction and 2D.

Wood is a natural material and its geometry can vary over time, based on its moisture content that results from changes in temperature or relative humidity. This is the reason why tolerances are generally defined for fixed temperature. Therefore, the measurements are repeated for four elements before transportation and before assembly defining three so-called *measurement epochs*: right after fabrication (epoch 1), two weeks later (epoch 2), and before assembly (epoch 3). The RMS of the comparison between the measured and the CAD model for the three epochs are shown in Table 1.

Number of Element	dx[mm]	dy[mm]	dz[mm]	3d[mm]
1 (Epoch 1)	0.37	0.64	0.51	0.90
1 (Epoch 2)	0.54	0.73	0.63	1.11
1 (Epoch 3)	0.59	0.66	1.21	1.50
2 (Epoch 1)	0.80	0.78	0.81	1.39
2 (Epoch 2)	0.67	0.85	0.99	1.46
2 (Epoch 3)	1.11	0.55	0.70	1.43
3 (Epoch 1)	0.54	0.52	0.57	0.94
3 (Epoch 2)	0.42	0.28	0.73	0.89
3 (Epoch 3)	0.49	0.29	0.75	0.94
4 (Epoch 1)	0.43	0.73	0.96	1.28
4 (Epoch 2)	0.55	0.71	1.16	1.46
4 (Epoch 3)	0.68	0.80	1.43	1.77

Table 2. RMS of Comparison between CAD model and measurements for four elements in three epochs.

Table (2) shows that the in-plane accuracy (RMS in X- and Y-direction) of a plate is between 0.28 mm and 1.11 mm. The values in the z-direction register the plywood’s tendency to buckle and dish over time and are not an effect of fabrication. However, due to the three-dimensional fabrication process the in-plane accuracy will be affected by these differences. The influence of non-specified external influences (differences in RMS between epochs) varies between 0.05 and 0.60 mm. A statistical test can be used to check if these variations are significant. A Gaussian distribution based test with a confidential interval of 95% is assumed. The test compares the averages of the deviations. It can be shown that no plate changes can be detected significantly.

5.2 Evaluation of Construction

After the Exhibition Hall's assembly, the building will be scanned by a laser scanner in at least two epochs to compare the result of the construction process with the CAD model and to detect any global and local deformations. The laser scanner is used for the deformation analysis, since it delivers a high resolution and a 1 to 2 mm accurate point cloud. For the scans the laser scanner Leica HDS7000 is used. It is planned to scan the pavilion from at least three different laser scanner positions. The different positions will be registered by reference targets, which make it possible to combine the different scans into one 3D model. This process also includes cleaning the point cloud from outliers.

To compare the different epochs of laser scanning, a point network is build up around the pavilion for registration and geo-referencing. The comparison of the epochs will be made by comparing the surfaces and edges of the elements.

5.3 Preliminary Conclusions on Accuracy in Robotic Fabrication

The evaluation of the fabrication process delivers a 2D-RMS of up to 0.70 mm. The average plate accuracy over the 24 elements is 0.48 mm for d*x*, and 0.51 mm for d*y*, which, in the context of timber manufacturing, is exceptionally low. However, measuring the average fabrication RMS proved to be not entirely straightforward since it is influenced by fabrication as wells as object properties and external influences. Slight dimensional changes in the material as well as rough surfaces due to the milling process might also have led to deteriorated deviations. An improvement may be reached by integrating the measurement process more deeply into the fabrication process and to design and implement a sensor-actuator control loop to correct for small fabrication deviations during the fabrication process.

6 Conclusion and Outlook

In order to be able to evaluate the dependencies and effects of material, fabrication, assembly, and building lifespan / occupation on timber plate structures and the role of robotic fabrication therein, a building prototype has been developed and realized as part of the presented research. The prototype building, which is open to the public since May 2014, is located at the *Landesgartenschau Schwäbisch Gmünd*, Germany. With a usable floor area of 125 m^2 and a shell surface area of 245 m^2, the insulated and waterproof building spans 10 m with a structural layer thickness of just 50 mm beech plywood. The automated machine code generation for all different 243 plates with 7356 joints was possible through an integrative computational design process (Fig. 12). Through the integration of an assembly order and specific assembly vectors for each plate, the construction process lasted only three weeks.

Figure 12. Photographs of the finished prototype building.

In addition to questions of accuracy, automation, or behavioural form finding, the research investigates a new concept of geometry in architecture: shape variation not as a formal feature, but a necessity for achieving structural performance. The building's global shape and the plates' differentiated arrangement enable the development of a material-efficient and lightweight construction system. While enclosing a volume of 605 m^3 the structural layer is only made of 12 m^3 of beech plywood. The plate structure development is also connected to the introduction of a new timber product. The Landesgartenschau Exhibition Hall is one of the first buildings to use beech plywood as the main structural building material. Relating to future foresting strategies, beech will become a more common timber product and also provides a higher structural performance than contemporary softwood timber constructions. The material's strength was essential in the development of both the joint geometry and the crossing screw connection.

Further improvement of the fabrication process with respect to accuracy and tolerances may be reached by integrating the geodetic measurement process completely into a sensor-actuator controlled fabrication process. By strategically using robotic fabrication and other numerically controlled machines throughout the fabrication process, the building prototype showed how robotic fabrication can become a valuable component in a fabricator's tool kit that not only integrates into existing fabrication technologies but, due to its flexibility, also opens up new applications. Given that the traditional discipline boundaries were effectively removed – architects controlling fabricators machinery – the project also demonstrates the viability of possible new alliances in the building industry and, potentially, new and more performative delivery models.

The prospect of this research is that through the integration of the various fields of biology, architecture, structural and geodetic engineering, in one coherent computational design approach, more intelligent contributions to the built environment can be made with respect to resource efficiency, structural material utilization, and architectural quality.

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Authors' address:

Oliver David Krieg (oliver.krieg@icd.uni-stuttgart.de)
Institute for Computational Design, University of Stuttgart
Keplerstrasse 11 – D 70174 Stuttgart, Germany.

Tobias Schwinn (tobias.schwinn@icd.uni-stuttgart.de)
Institute for Computational Design, University of Stuttgart
Keplerstrasse 11 – D 70174 Stuttgart, Germany.

Achim Menges (achim.menges@icd.uni-stuttgart.de
Institute for Computational Design, University of Stuttgart
Keplerstrasse 11 – D 70174 Stuttgart, Germany.

Jian-Min Li (j.li@itke.uni-stuttgart.de)
Institute of Building Structures and Structural Design, University of Stuttgart
Keplerstrasse 11 – D 70174 Stuttgart, Germany.

Jan Knippers (j.knippers@itke.uni-stuttgart.de)
Institute of Building Structures and Structural Design, University of Stuttgart
Keplerstrasse 11 – D 70174 Stuttgart, Germany.

Annette Schmitt (annette.schmitt@ingeo.uni-stuttgart.de)
Institute of Engineering Geodesy, University of Stuttgart
Geschwister-Scholl-Strasse 24D – D 70174 Stuttgart, Germany.

Volker Schwieger (volker.schwieger@ingeo.uni-stuttgart.de)
Institute of Engineering Geodesy, University of Stuttgart
Geschwister-Scholl-Strasse 24D – D 70174 Stuttgart, Germany.