Additive robotic fabrication of complex timber structures

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The research into robotic timber assembly serves as a breeding ground for assembly- and material-aware construction methods that provide new opportunities for architecture and construction. In his contribution, Volker Helm, of the Gramazio Kohler Research group at ETH Zürich, introduces the most recent investigations into innovative methods for robot-assisted assembly of complex timber structures. In cooperation with the Bern University of Applied Sciences and within the framework of the Swiss National Research Programme "Resource Wood" (NRP 66), material-specific and constructive aspects of timber assembly are combined in a continuous digital design and manufacturing process taking advantage of both the flexibility of robotic manipulation and its capacity for precise spatial positioning. The project points the way towards future construction processes that are no longer encapsulated in a static plan, but rather are described by a programmed set of adaptive rules.

Spatially assembled constructions

The current status of research in the area of digital fabrication of complex timber structures is limited mainly to the improvement in geometry and mechanical processing of components. This method involves high resource consumption because of material cutting procedures, like milling, as well as a high degree of manual labour. Especially in the case of a high geometric variability in construction, considerable costs must be taken into account.

Here, automatic assembly of generic timber components is an alternative that has been intensively investigated by the group of Gramazio Kohler Research at ETH Zürich and has already resulted in the first 1:1 construction prototypes, such as The Sequential Wall (Gramazio, Kohler & Oesterle, 2010). However, the two-dimensional stacking process considerably limits the
performance and range of applications and the degree of geometrical freedom in the assembly of the components. Consequently, the research has extended to spatially assembled constructions, opening up new approaches for automatic manufacturing of architectural structures at full building-scale (Figure 2.1 and Figure 2.2).

The precise spatial positioning of wooden components represents the possibility of an innovative industrial procedure with a high degree of building precision, which can be manufactured without additional formwork or supports. In this context, the main goal was to create new combinations of fast-drying adhesive and automated assembly procedures, focusing on a multi-layered truss system as exemplary case. This approach made it possible to leave behind the standardised processing of wood and to design and manufacture new types of construction systems in a continuous digital process. The potential of such an integrally automated approach is still largely unexplored.

This interdisciplinary research approach requires a rigorous investigation of the individual working steps. Therefore the goal of the following chapter is to depict the different development and production steps of a full-scale multi-layered truss system. The following areas are examined in detail: a) the constructive design system, b) fast-drying adhesives, c) automated fabrication and the consideration of the full scale prototype.

Constructive system

The fundamental element of the constructive system is the expanded node. Here, a node in general is defined as a unit of contiguous bar-ends connected at or near one point within the system (Figures 2.3 and 2.4). Regarding fabrication and assembly of nodes, the complexity increases with the number of bars meeting at one point. The proposed geometric expansion of the node reduces the complexity and allows a simple sequential joining process. This, in turn, creates a node with structural reciprocity, which has bending resistance (Figure 2.3) and shear resistance (Figure 2.4), even though in its static system all connections are pin-jointed (Kohhammer & Kotnik, 2011a).

Single layered structures with two-dimensional expanded nodes are well known, such as Reciprocal Frame Structures or the Zollinger-System. The flexural rigidity of these types is considerably low, as it depends on the cross-section of the bars (Kohhammer, 2013).

This research focuses on multi-layered systems with three-dimensional nodes, as they promise a wider range of application than single layered systems because of a much higher bending resistance. This arises from their truss-like bearing capacity in addition to the reciprocal node behaviour. The developed system consists of three structural layers: 1) an upper layer, 2) a lower layer, and 3) an intermediate layer (Figure 2.5). In the upper and the lower layer, bars form a surface structure with reciprocal nodes. The intermediate layer consists of diagonal bars linking both outer layers.
With respect to the vertical loads the structural behaviour of the system can be partitioned as follows (Figure 2.6).

1) Both outer layers act as a grid with reciprocal nodes. The grid has flexural rigidity, and thus the bars are under bending stress (Kohlhammer & Kotnik, 2011b).
2) The intermediate layer generates the structural behaviour of a truss grid, which induces normal forces in the bars.
The structural interest focuses on the interrelation of geometric parameters of the system and its static performance. The following parameters were defined as prime system parameters, as they are seen as characteristics of this structural system: First the node expansion, which mainly influences the bearing capacity of the outer layers. Second, the slenderness of the structure (ratio of height and span), which only impacts the static performance of the trusses formed by the intermediate layer.

Parameter studies with a structural analysis software showed that the bearing capacity is primarily dependent upon the slenderness, and secondarily upon the node expansion. The importance of the respective parameters increases in accordance with the resistance of the joints, thus node expansion is more essential in the case of joints with lower bearing capacity.

Connection technology

Gluing is the main connection technology for this construction system because it can be fully integrated into a robotic fabrication process. However, standard adhesives for timber construction require both a long hardening time and substantial pressure during gluing, which, in fact, would not correspond to speedy construction enabled by a robotic arm. In order to overcome this barrier, cooperation with Nolax AG was established. Nolax AG is currently developing a fast-setting 2K PUR-Polyurea adhesive, which allows custom application processes. This near real-time curing adhesive (Brandmair et al., 2011) for non-structural connections (or low-force connections) may be extrapolated to fulfill the requirements found in high-performance timber construction.

This assumption was validated through a first feasibility study (Zock et al., 2014). It comprised of a comprehensive digital analysis, as well as the fabrication and testing of physical connection prototypes focusing on stiffness properties, tolerances and processing. All prototypes were designed as longitudinal joints connecting to the end-grain since this is the most critical connection. Two strategies were pursued: a) glue-only connections with low-load carrying capacity, using minimal expense in the manufacturing (Figure 2.7), and b) rod-shaped/flat elements glued with high load carrying capacity, and increased expenses for the automation (Figure 2.8).

Based on the results of the physical tests, glue-only connections were sufficient for this project. Therefore, the production of the final demonstrator (see following section) used glue-only connections without perforation to join the timber members.

Digital workflow and integrated automation

The advantage in using digital information in the positioning of elements lies in the automated transmission and processing of data (Bachmann, 2005). With current timber construction techniques the digital process workflow typically ends with the manual fitting together of the
parts. As a consequence, necessary assembly information is transmitted in an analogue way and processed by the worker (Bachmann, 2009). In contrast, a seamless digital workflow is required to assemble complex timber structures from a large number of individual components (Figure 2.9).

Accordingly, in the developed prototypical automation process all relevant fabrication data is gathered from a 3D-CAD model and written in an xml-structured file by an export tool. This file contains identification, length, cutting angles and target position of each timber member as well as the overall assembly order. The timber is cut with a mitre saw (Figure 2.10) that can be digitally controlled by an electric angle adjustment and conveying system. Its integration enables the adjustment of elements in real time, and sequences the timber elements for the robotic assembly process. The subsequent positioning was carried out by an industrial robot equipped with a pneumatic gripper. For the fabrication of the prototype, an industrial robot arm (Figure 2.11) was used, which is mounted on a linear axis to enlarge its working area. Within this setup, the demonstration prototype could be produced in seven segments, featuring a span length and width of 5m.

To connect two timber components, the robotic arm releases them at their target position. The length of the timber elements is calculated to leave a small interspace at the nodes. This interspace is then filled with the glue. A neoprene gasket (Figure 2.12) prevents leakage, ensuring injection pressure and defining the tolerance range at the same time. The gasket used can cover a gap of 5.0mm and can be compressed to 3.5mm. The adhesive is still injected manually with an applicator gun (Figure 2.13) to acquire comprehensive experience of the processing. The machine process of gluing will be automated once it is fully defined in future work.

**Figure 2.9**
Diagram of the developed system components: left side, black or the digital design and fabrication workflow, and the functions which are currently under development; right side, blue or planned for the second phase of the project.
Gramazio Kohler Research, ETH Zürich.

**Figure 2.10**
Automated timber cutting using a CNC mitre saw to specific length and end cut angles.
Bern University of Applied Sciences.

**Figure 2.11**
Robotic positioning in space.
Bern University of Applied Sciences.
were calculated and the new target positioning is updated automatically. This referencing process reduced positioning errors to the required tolerance range which enabled the precise production of the final model.

Prototype of a multi-layered truss system

The last step in this project phase was the implementation and structural check of the multi-layered truss prototype. The structure featured a span of $5.0 \times 5.0\text{m}$. The slenderness as one of the primary system parameters was set to seven, which results in a maximum height of $0.7\text{m}$ in the centre. In relation to the distribution of the bending moment, the height decreases to $0.5\text{m}$ towards the supports (Figure 2.15). The upper layer is flat to facilitate the use of the structure, e.g. as a floor slab. The height variability results in a curved lower layer. For the prototype all bars had cross-sections of $70 \times 70\text{mm}$.

To analyse the ultimate load of the prototype, a series of digital tests with structural analysis software were conducted. The calculated ultimate load on the level of design is $5.7\text{kN}$ in addition to the dead loads. Resistances which refer to average values of tensile and shear tests of different qualities of spruce by EMPA (Eidgenössische Materialprüfungs- und Versuchsanstalt, 1955), result in an ultimate load of $14.2\text{kN}$ in addition to the dead loads. As the developed system is redundant, the structure is still able to bear loads after breaking the connection with the highest stress at ultimate load level, simulating a crack. After the failure of the first critical node (I) (Figure 2.15), the ultimate load of the structure decreases to 70%. After another failure at the second critical node (II), the remaining bearing capacity is 66%.

In order to understand the behaviour of a structure with glue-only connections, a first initial large-scale loading test was performed. During the test eight central nodes were vertically loaded with sand. Within this testing procedure, it was not possible to reach the point of failure. The test had to be stopped at a load level of $20\text{kN}$. One interpretation of this result could be the outstanding quality of the wood used for the prototype. Another explanation could be that the redundancy of the system implies an extraordinary bearing capacity due to changes in load distribution.

To finally test the structure to its maximal load, a test setup was implemented by using six hydraulic cylinders and a test rig (Figure 2.16). However, the second loading of the structure resulted in a much lower load of only $8.5\text{kN}$. It is possible that the high load during the first test already weakened some of the connections. The experience clearly shows that timber elements which have been previously highly loaded often fail in retesting at much lower loads compared to the first loading.

As a conclusion of the first physical test, the ultimate load is at least $350\%$ higher than the result of the calculation. Furthermore, the second test showed the same mode of collapse as in the digital simulations. This means that the consequence of the first connection failure does not include the total collapse of the structure, but a residual bearing capacity of about 70%. The second load test also confirmed the sequence of critical nodes as predicted from the computational simulations. For a detailed confirmation of the calculation model, a series of physical tests are necessary.
Future work

Our goal is to further advance the developed techniques and methods for robot-based timber construction. In addition to the further refinement of the experimental setup, including, for example, enhanced robotic control and automated design generation of construction scenarios, we will continue to explore the integration of material-driven feedback processes in the robot-based assembly. By so linking the formal, constructive and fabrication parameters, an optimisation of the entire generation process can be achieved. Here it becomes apparent that with a certain ‘critical mass’ of complexity, construction components with mutual dependencies, the use of digital design, and fabrication processes becomes not only meaningful but mandatory. Correspondingly, the computational design can no longer be encapsulated in a static plan. Rather it is described by a programmed set of rules which advantageously allow for seamless adaptations, throughout and even at very late stages of the design process. The intent is thus less a purely functional modus operandi of digital fabrication than a focus on equally assembly-driven and material-aware construction methods, fostering robotic timber assembly as a unique breeding ground to induce new opportunities in architecture (Gramazio, Kohler & Wüthrich, 2014).

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References


