Computational design provides the opportunity to integrate all planning disciplines and stakeholders of wood architecture from the earliest planning stages and, by consequence, to span across the statutory design, fabrication, and construction phases. Aleksandra Anna Apolinarska of Gramazio Kohler Research at ETH Zürich, introduces research related to the Arch_Tec_Lab building’s roof structure, an industry transfer project in robotic fabrication of complex timber structures. In her contribution, she presents the specific design features, the non-standard concurrent development process and the unprecedented fabrication and assembly method, all of which showcase how innovative computational design and manufacturing processes not only change the logistics of timber construction but also can give rise to novel architectural solutions.

Project description

Introduction

The Arch_Tec_Lab building project (Figure 3.1) was launched at the Institute of Technology in Architecture (ITA) of ETH Zürich in 2009 as a multi-disciplinary endeavour to design the institute’s new laboratory and office building located on the Hönggerberg campus in Zurich. The building will house a state-of-the-art robotic laboratory, workshops, offices and studio spaces, and is conceived as a real scale demonstrator showcasing innovative approaches to architecture and construction in terms of parametric design, digital fabrication, sustainability, HVAC (heating, ventilation and air conditioning), MEP (mechanical, electrical and plumbing) and structural systems.

One of the key features of the project is the robotically fabricated timber roof, designed and developed by the Gramazio Kohler Research group at ETH Zürich in tight collaboration with the planning team of the building. The group stands at the forefront of research in robotic
fabrication in architecture, and their long-term investigation of robotic assembly of timber structures (Gramazio & Kohler, 2008) is crowned by the realisation of the full-scale construction project presented here (Gramazio, Kohler & Willmann, 2014).

**Roof design**

Covering a total area of 2,300 square metres, the free-form structure consists of nearly 50,000 unique timber elements, designed using bespoke algorithms and fabricated and assembled with robotic machinery (Figure 3.2). Hovering above a double-height open office space, 28 metres wide and 80 metres long, the whole roof rests upon 12 prominent steel columns, unobstructed by partition walls. The seemingly continuous, undulating surface consists in fact of 168 trusses, with a regular span of 14.7 metres and 1.15 metres width. Each truss is made of 23 layers of 50mm thick timber slats stacked together in an alternating manner. The layering logic is derived from a basic form of a truss consisting of continuous top and bottom chords with diagonal webs and is adapted according to the layering concept. For the chords to be continuous, the top and bottom slats are arranged into three-layer chain-like packages, as opposed to diagonal members which can be accommodated in one layer (Figure 3.3).

This topological configuration exhibits great flexibility and allows for ample variance of truss shapes. For example, the curvature of the top and bottom chord, segment lengths and the structural height can be adapted to fit local or global needs (Figure 3.4). The distribution of the diagonal webs and connection nodes within the truss can be adjusted to improve structural performance or to adapt to interfaces with other building parts. For instance, the node distances can be locally increased to allow for the oblong smoke exhaust shafts to pass through the roof. Also, due to the redundancy within the structure, individual elements may be left out to create a recess where needed.

The spatial density of the trusses enables seamless integration of the structure with various subsystems. On the outside, they form a continuous surface onto which weatherproofing layers can be directly installed, without the need of secondary boarding. This is a major benefit, as covering a double-curved surface with panels would require considerable effort. From the inside, the lower
chord layer creates a tectonically vivid ceiling with porosity favourable for interior acoustics, as well as space and support for subsystems like artificial lighting, sprinklers, electrical cable routes and other devices (Figure 3.2). Conversely, the structure is transparent enough for the daylight coming from the skylights to permeate through, which has been evaluated experimentally in scale model tests using an artificial sky dome (Adam, 2014).

Timber

In the context of growing awareness over the use of natural resources, it was one of the project’s objectives to use simple and possibly low-engineered timber products, such as solid structural timber of strength class C24. The choice fell on 50mm thick, two-layer glued softwood, with planks cut on a split-heart basis to guarantee higher form stability and to reduce the risk of fibre splitting due to nailing. For the sake of material efficiency, three different cross-section heights were used: 115mm, 140mm and 180mm. The material was produced in the form of 10-metre long finger-joined, untreated, planed slats, with a reduced moisture content of around 10%. Compared to simple solid structural wood, this assures fewer moisture-related shape changes like bending and warping, which is essential to keep all connections in a layered structure gap-free. Natural behaviours like shrinking and swelling of timber were carefully taken into account in the planning process. To accommodate the changes in the direction perpendicular to the grain (which accumulate across all the 23 layers), a 15mm gap was introduced between the trusses.

Joints

To achieve a fully automated manufacturing process, only connection techniques that could be fully automated were considered. One of them was gluing with one-component polyurethane adhesive, which cures by binding moisture contained in wood, and which is widely employed in the timber industry. It requires, however, a certain contact pressure which might be difficult to achieve and control when pressing on a skewed stack of slats.

A competitive technique was a mechanical connection using nails. One of its advantages is its ductile character: the nails deform and bend before the brittle failure of wood occurs, which means that the structural collapse is not abrupt and allows for smoother re-distribution of stresses. Compared to the glued option, however, it poses additional geometric challenges. Nails can cause a fibrous material such as timber to split along the grain, and preserving minimal intervals between nails and distances to the element’s edges is necessary to reduce this risk. As specified in the Swiss norms (SIA 265:2003), these distances depend on the Shank diameter of the nail and grain direction of wood. This can be interpreted as an elliptical zone around a nail’s centre which must be kept clear (Figure 3.5). For the nails with 3.4mm Shank diameter used in this project, this distance amounts to 34mm in the grain direction and 17mm in the direction perpendicular to the grain. As each nail connects two pieces of wood, it must not only take the positions of other nails in the layer below into account, but also the orientation of the ellipse according to the grain direction of each layer. The minimal distance to the element’s edge, 51mm and 20.4mm respectively, is also grain-dependant, which means that the permitted zone between two overlapping timber elements is eccentric to the axis lines of both elements. Moreover, the permitted zone varies depending on the actual geometry of each two overlapping slats and their relative position to each other. On top of that, the required number of nails (ranging between four and 20) is determined by structural calculations for each of the 94,380 connections individually (Figure 3.6).
Figure 3.5
Connection between two timber elements: a) permitted overlap areas and possible nail distribution. Increasing the overlap area is possible by b) extending slab ends or c) increasing the cross-section height.

Figure 3.6
Distribution of nails through all 23 layers, according to geometry constraints and nail numbers in each layer, results in a highly complex nail pattern.

Design and construction process

This multidisciplinary and highly experimental project required collaborative involvement from all parties and planners from a very early stage, including structural engineers, consultants for timber construction, fire safety, weatherproofing and day lighting, as well as potential industry partners. Going beyond the established statutory design phases, concept development, structural analysis and fabrication details were developed concurrently. To achieve this, from an architect's perspective, different types of input information needed to be linked and processed within one integrated design framework. Apart from the usual coordination between disciplines, it enforced an exchange of large amounts of data from different sources (for example structural analysis) and active negotiation of the tightly interrelated architectural, structural and fabrication parameters within one computational model in an iterative development process. In the absence of suitable off-the-shelf solutions, several bespoke pieces of software were written as add-ons to commercially available NURBS-based 3D-modelling and structural analysis software packages. One of the algorithms, for example, generated the geometrically intricate model of the structure, its volumetric representation and an abstracted data model for the structural analysis software and fabrication simulation. Another procedure automated the setup of structural calculations based on this data model. The results of the structural analysis (such as the number of nails needed for each connection) were further processed by the fabrication simulation algorithm which also generated the nailing pattern. An initial roof model, consisting of equally sized members with a cross-section of 50 x 100mm, proved to be far from fulfilling all structural and fabrication
requirements. To resolve this, the design was refined iteratively by locally modifying the geometry of individual elements (Figure 3.7). If excessive internal forces (buckling, shear or normal stresses) indicated the need for a larger cross-section of a certain element, or if the nail pattern failed to accommodate all the nails required in a joint (for instance due to an insufficient overlap area between two slats), the geometry of an individual element or a pair of elements was modified by extending slat ends or increasing their cross-section. After several iterations, as soon as all structural and fabrication issues were cleared, the design was immediately ready for production with no need for further post-processing, as all details, dimensions, calculations and manufacturing data had already been generated in the process (Figure 3.8).

Structural analysis and tests

As this kind of connection and structural arrangement is not explicitly described by regulations, and as there are no established calculation models for structural analysis of such a structure, the calculations needed to be validated by means of physical experiments. First, a series of specimens consisting of a single node made of three slats were tested in various geometrical configurations, including different angles between slats (0°, 45° and 90°) and different nail patterns (with uniform, asymmetric or eccentric distribution) (Figure 3.9a). The data received from the results was used to refine the calculation model that was employed in further design development, dimensioning and detailing. The final design was validated by load testing of 15 full-scale trusses as control samples (Figure 3.9b). At the same time, the trusses produced for the tests served as prototypes for the newly developed manufacturing process.
Integrating cutting-edge robotic fabrication methods with advanced computational design techniques opens up new opportunities for formal expression as well as construction methods (Gramazio, Kohler & Oesterle, 2010). In this project, the design concept and the construction process were developed simultaneously from the very beginning, which is a novel approach. The use of digitally controlled fabrication tools enabled the design of a structure of a high geometrical complexity, liberated from constraints of standardisation and repetition. Moreover, the fully automated robotic assembly (with no manual labour involved) facilitated the use of small elements and simple, generic and notch-free joints. Conversely, the bespoke digital fabrication setup was developed simultaneously with the design. Not only the layering logic of the trusses reflects the construction sequence and manufacturing constraints, but also the number of possible different slat sizes was derived from an optimum between maximal operational space of the facility, minimal time losses for material feeding during production, and, conversely, a minimal number of cross-sections approximating ideal dimensions from a structural point of view.

The fabrication setup, proactively developed by the contractor for this challenging project, consisted of a six-axis gantry robot with a mechanical wrist and exchangeable end-effectors, a sawing table, a tool changing rack and a repository of 10m-long timber slats in the three different sizes (Figure 3.10). The trusses were built layer by layer using the following steps: 1) First, the material is picked by the gripper and cut by an automatically adjustable saw at the defined length and angles. 2) Then, the piece is placed in the target position and fixed preliminarily with one nail at each end. This allows to precisely control and correct its position at each end. Subsequently, the remaining nails are shot. 3) In some cases, additional trimming is needed in situ after the slat is fixed. For this step, the gripper end-effector is exchanged for a circular saw. 4) Finally, before the next layer is built, every node is automatically documented and checked for deviations or errors by a photographic camera attached to the machine.

The fundamental feature of this manufacturing concept is that the fabrication of parts and assembly take place simultaneously. Each timber element is cut to size only shortly before being joined with the rest of the truss—hence reducing logistics to a minimum by avoiding the need of labelling the elements, as each piece is installed in the right place straight away.

Figure 3.10 (facing page)
Custom six-axis overhead gantry robot of ERNE AG Holzbau, featuring a translational axis with a mechanical wrist and three additional rotational axes to perform fully automated fabrication tasks within an effective workspace of 48 x 6.1 x 1.9m. The control software enabling the fabrication was developed by ROB Technologies AG (Arch_Tec_Lab, 2015).
Summary

The timber trusses were fabricated and brought on site in 2015. The Arch_Tec_Lab building was opened to students and researchers in summer 2016. But already before it was finished, the project demonstrated how integrating advanced computational design tools, material-aware detailing and fabrication-driven concept development can lead to novel design and construction methods.

As a pioneering endeavour, the project presented certain challenges and risks to planners and contractors, and ultimately the client (ETH Zürich). It required novel design tools, custom calculation models for structural analysis, validation by means of physical load tests, and bespoke and fully automated fabrication processes. The successful development and realisation of the project was only feasible by involvement and integration of all planning disciplines and stakeholders from the earliest stages and, by doing so, going beyond the statutory design and construction phases.

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References

Swiss norm SIA 265:2003 Timber Structures (SN 505265), Chapter 6.4.

Notes

3. Non-uniform rational basis spline.
4. Structural model and calculations as well as the interface with the structural analysis software set up and conducted by the civil engineering firm Dr. Lüchinger+Meyer Bauingenieure AG, Zurich.
5. Given that every connection is potentially a unique situation, no regular grid can efficiently distribute all of the 815,984 nails. ROB Technologies AG from Zurich developed a bespoke algorithmic method for generating the nail pattern.