

FULL SCALE PROTOTYPING

Logistic and construction challenges realising digitally designed timber prototypes

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Abstract. This paper reports on the final stage of a research project with the realization of a real scale prototype and ties an empirical finale to the project, which started as a fundamental research project three years ago. The scope of this research project was to explore new ways, how Non-Standard Architecture can be build with standard building elements using contemporary building processes and materials resource efficiently. Mass Customization and File to Factory, concepts where a continuous digital workflow is applied, were fundamental to our approach. Within this framework we developed generic parametric details and made them part of the whole process from the beginning of the design to the manufacturing. The present paper describes a strategy for the assembly of a large prototype, consisting of approximately 50 flat timber panels that are being assembled to a structure of the size of a small house. The paper focuses especially on the customized falsework, we designed for the construction of the prototype, which became a crucial part of the assembling process besides the assembly of the actual prototype.

Keywords. Digital fabrication and construction; precedence and prototypes; mass customization.

1. Introduction

As we can repeatedly observe in digital workflows, the integration of the digital model throughout the design process is not a problem but when the structure becomes physical the problems manifold. As many architects have

already experienced, we know how much manual work is required for (after) a digital production (Scheurer, 2009). We will address major issues, dealing with the physical assembly of a full-scale prototype (approx. 4 x 4 x 10 m) of a freeform structure assembled from flat cross laminated timber (CLT) panels. The falsework, which is required for the assembly, has to be as accurate as the structure itself. The job of this falsework is to secure each panel's position during the assembly process and must not allow movements in any direction.

In this paper we will discuss the experiences, we collected during the assembly process of the prototype with the focus on construction and logistic conditioned problems, which arise from the physical assembly of a prototype structure in building scale using a new gluing technique (Schimek et al., 2011), (Figure 1).

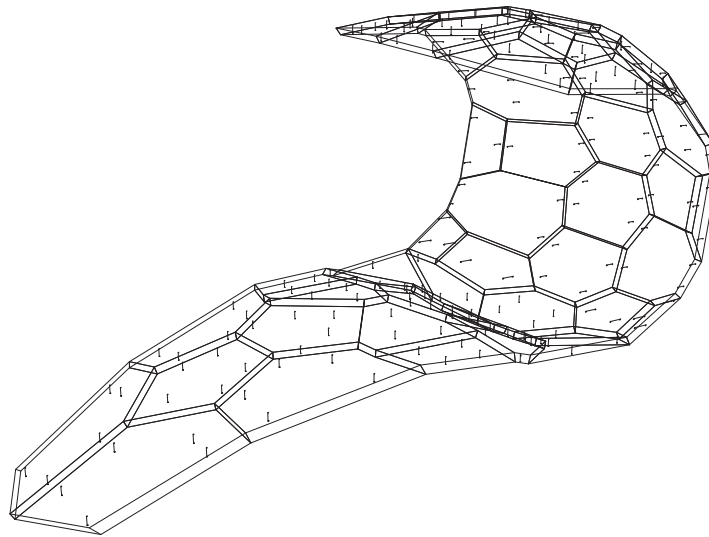


Figure 1. Prototype structure; Wireframe model of the panels. (IAM, 2012)

According to the concept of mass customization, we experienced a very smooth workflow through the whole production process of the parts with a five-axis router, but from our experience as architects we know, that the precision of digitally machined parts cannot be maintained throughout the whole construction process, especially when it comes to manual assembly. It seemed to be interesting to what extent we can perform a precise assembly

using rather heavy parts. At the preparation of the panels for the assembly process, we tried to exclude potential error sources. Complications we expected predominantly from the logistic handling of the falsework and the panels of the prototype structure. How would we secure a fluid assembly process avoiding the single parts from blocking each other and respectively create enough free space for the tools.

To discretize the freeform design of the prototype we developed a customized algorithm (Manahl, 2012). Consequently helpful was an accurate 3D-model in RHINOCERUS, where we could simulate almost every possible geometrical situation, that could occur with the assembly, (Calderon et al., 2011).

After eliminating most difficulties in the digital realm, we met with the craftsmen to discuss our theoretical approach. We incorporated their advices in our considerations before we started the assembly. Questions that are covered in this paper involve:

- How does the falsework fit the needs of positioning and securing the parts of the final prototype structure during the gluing process?
- Does the assembly strategy, e.g. the assembly order of the panels work in terms of the malleability of the structure.
- How can imprecisions, arising from the relatively large number of unique parts be addressed?
- How does the installation of the connectors work without interfering with the falsework?
- How can we avoid at the manual assembly (gluing) of the panels, that imprecision is reproduced through the structure with each part being added (error burst).

We were not able to draw upon experiences of former structures – for the time being no such self-supported timber structure exists. But looking at the sheeting of complex concrete structures, we can observe similar construction methodologies. At the Rolex Learning Centre in Lausanne by SANAA (Figure 2), Design-to-production, a Swiss based company, that provides services in realizing non-standard architecture, developed a specific formwork



Figure 2. Left: Wooden boxes on standard scaffold. Right: General View. (DPD, 2008)

solution for the large, double curved concrete slab. The curved surface was built, using standard steel scaffolding components, with some 1,500 individual wooden boxes. Like in our project, DPD had to deal with the same problem statement: How to keep construction elements in a defined and secured position (DPD, 2008).

2. Structural analysis

The structural calculation was performed on the FE-software ABAQUS. Load cases covered self-weight and wind blowing longitudinal to the structure. The structure is symmetrical to the centre line. The calculation led to a total number of connectors of approximately 300 (Pfaller, 2012). As foundation for the temporary prototype structure served a steel frame that was simply laid out on a gravel bed (Figure 3).

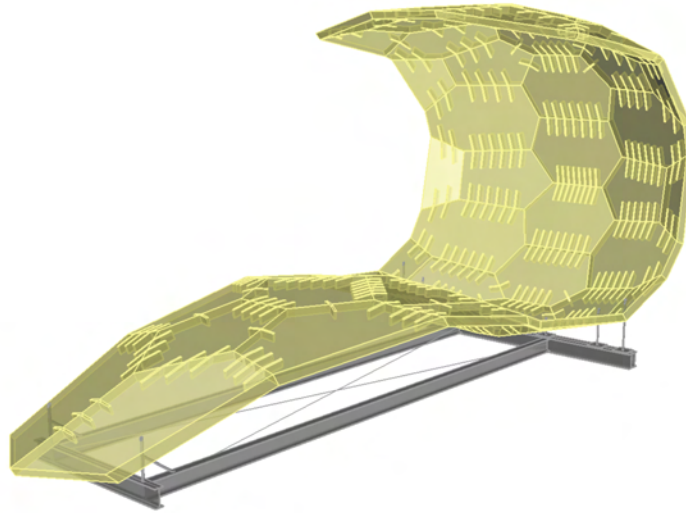


Figure 3. Prototype with connectors mounted on the steel frame (IAM, 2012).

3. Falsework

The major requirement for the falsework was to build a structure, which is capable of supporting the single panels point wise during the whole assembly process. The falsework also had to secure the position of the panels. Therefore the profile of the supporting elements had to be quite strong in order to be stiff enough. We decided to use single columns with a footprint of 100 x 100 mm based on the calculation of the structural engineers. The falsework columns were mounted on a grid of horizontal beams of the same dimension. The required precision of the falsework columns must not be different from the supported panels one.

In order to minimize an error burst through manual imperfections we decided to split the prototype for the final assembly on site into three modules A, B and C (Figure 4).

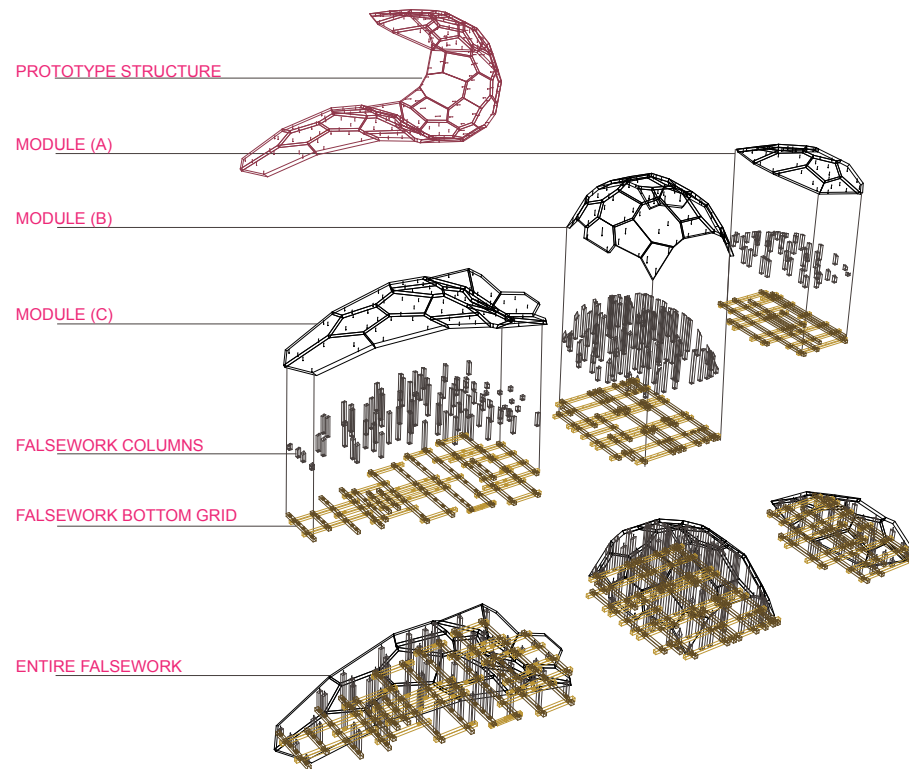


Figure 4. Topology of the assembly (IAM, 2012).

The panels of the prototype were temporarily fixed to the falsework columns by customized steel bolts and heavy screws. With the insertion of the bolts, the panels were aligned to the right position. For the alignment and as mounting fixture for the falsework columns, we inserted two boreholes in diagonal order in the bottom of each column. The differently angled column topsides also received a centred borehole to hold the steel bolts.

Both, the vertical falsework columns and the laying grid were milled on a 5-axis router using a saw blade for the customized angles and a standard drill for the boreholes and slots.

After the milling process we had 275 parts in total, 191 upright columns and 84 horizontal beams that all looked quite similar (Figure 4,5). Thus the labelling of the parts was crucial for the logistic handling of the parts. The

labels indicated, together with two diagonal arranged bores, the alignment of the columns with the underlying grid (Figure 5).



Figure 5. Left: close up of falsework. Right: Labelled falsework columns. (IAM, 2012)

4. Digital precision vs. manual imprecision

Using a five-axis router we experienced that the precision of the digitally fabricated parts were very satisfying, both, of the falsework parts and the panels for the prototype structure itself. The slots for the connectors could be produced within the required range of tolerance, which required a maximum gap width of 0,3 mm between the connector and the panel's slot. Working with such precision is certainly not common in the carpentry business on site and can only be achieved under factory conditions (Schimek et al., 2011).

The very smooth digital workflow at the fabrication of the parts proofed the qualification of a digital work chain, not a single plan was printed for the production and we directly provided Rhino's geometry to the workshop, where the code for the router was created. This reduced possible errors at the interface between the design and production. Using an integrated digital 3D-model, potential imperfections and errors could be identified in a very early stage.

We knew that this precise mode of operation could not be continued in the consequent manual assembly process. As mentioned before, we split the prototype into three modules (A, B and C). In a first stage we assembled the three modules separately in the workshop from the digitally fabricated falsework parts, then mounted the panels on top of it. Under factory condition we got much better results than we could expect on the building site. In a second stage we brought the modules to the assembly site and joined the modules on the prepared steel frame. This turned out to be the right decision

since both, the pre-assembly of the modules and the following installation on site worked properly.

Unlike the digital process including the fabrication of the parts, where no paper drawings were required, the following manual assembly, which we performed in two steps (module assembly and final assembly) required the full physical information transfer with section, elevation, perspective drawings and a physical model in order to communicate the desired result to the craftsmen (Figure 6).

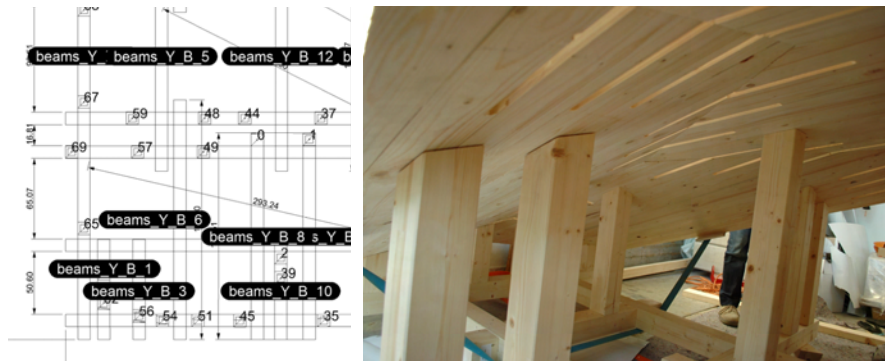


Figure 6. Left: clipping of working drawing falsework module (B). Right: Panels mounted on falsework module (C), view from underneath (IAM, 2012)

After all the craftsmen mainly used our 1:20 cardboard model of the complex surface, which communicated the freeform in a much better way.

5. Assembly strategy

The automotive industry has replaced the production methodology of singular craft in the twenties of the last century through the assembly line and some eighty years later through modular production, whereas the production of architecture still relies on the singular craft method, when it comes to complex buildings. In modular production sub-contractors built large chunks of a vehicle. At the end of the chain an original equipment manufacturer (OEM) finally puts together all the sub-assemblies to one piece. Sub-assemblies can be built simultaneously and the quality control of the single modules is much better. That makes the method of modular production very

efficient, both, in terms of quality and cost. Additionally it reduces the error rate due to the fact that joining just a few pre-assemblies to the final assembly on site is less “dangerous” than putting together the whole piece from scratch (Kieran, Timberlake, 2004).

Working in building scale, using pre-assemblies also means to be aware of the scale of the single modules since there is a limitation of size when being transported on public roads.

Therefore the sub-division of the prototype into three modules was strongly driven by these constraints. Without this limitation we would have assembled the whole prototype in one piece in the workshop.

A new gluing system, which was developed together with the structural engineers, used hard wood connectors that were inserted in the digitally fabricated slots. To meet the requirements of the one-component-polyurethane glue, which we used for the joints, the geometry of the slots had to be very accurate, leaving a maximum width gap of 0,3 mm between the hard wood connector and the slot. Consequently we had to angle the flanks of the slots conically. In doing so, we secured a very tight fit of the connector when it was inserted. A closer description of this process can be found in a former publication, (Schimek et al., 2011).

5.1. MODULE ASSEMBLY (WORKSHOP)

As pointed out before, we did not use any drawings for the digital fabrication. Ten again, the manual assembly required not only extensive plan work but also a physical representation of the final structure to communicate the design to the carpenter.

After checking the workshop’s floor for evenness, we started to lay out the first layer of the falsework. The horizontal grid of 100 x 100 mm wood trusses was assembled right on the floor, separately for the three modules A, B and C. We assumed, that we would have to use a laser positioning system to adjust the following vertical columns of the falsework and in the cooperation with the carpenter, the craftsmen confirmed our pre-assumption, that the precision of the digital production could not be maintained in the hand-craft. But the fact, that softwood is a quite flexible material, it turned out to be no problem using a slight force to position the parts. After fixing the panels to the falsework the connectors were glued in.

Nevertheless producing the parts with such precision was not wasted time, since we needed the precision for the connection slots anyhow. Before the modules left the workshop for the building site, we decided to join module A and B in the workshop.

5.2. FINAL ASSEMBLY (ON SITE)

The assembly of the 2 modules (A/B + C) on the site was equally successful. They were shipped from the workshop by a flatbed truck and fixed on the prepared steel frame structure that was equipped with a console to align the modules. Once correctly aligned, the connectors were glued in, (DIBt, 2011). The gap of the resulting joint was minimal and there was no further treatment necessary on the joint edge of the modules, other than some grinding to remove excrescent glue (Figure 7). After a week we removed the steel mounting jig, that supported the cantilever (Figure 8).



Figure 7. Left: Joint between Modules (A, B). Right: Module C. (IAM, 2012)



Figure 8. Left: Module (A, B) being moved in place. Right: Final assembly. (IAM, 2012)

6. Conclusion

Surprisingly little adaptations had to be made during the assembly phase because of an accurate digital 3D-model from which we could benefit by simulating various scenarios. “Everything that does not work virtually, will not work physical as well”, we can state for many stage of the whole assembly process.

Timber is an animated material that can indeed be machined with a large variety of tools. Depending on the quality of timber and the complexity of the desired geometry of the processed parts, we will get highly accurate pre-assembled parts.

The effective operation of a digital work chain using the file-to-factory principle can be considered as successfully established in the production of complex shapes in architecture and the concept also worked in this specific research project.

For this type of wood connection we were strongly dependent on the climate conditions because of the range of the processing temperature of the glue and the humidity, which must not exceed 12% wood moisture.

Overall we can say, that the chosen method of construction is highly efficient, although it requires specific conditions on the building site, which cannot always be established. The biggest problems are the atmospheric conditions, which prevail at the building site during the construction phase. Since humidity changes the volume of wood, we were dependent on dry weather for the assembly on the building site. This is, of course, not predictable and hence requires a high degree of indoor prefabrication. On the other hand, softwood is a quite forgivable and flexible material, which allows, to a certain degree, to overcome imprecisions by pressing the parts into the right form and position.

7. Future work

Future work will investigate on how the workflow of the different stages of the assembly can be standardized for commercial use in building construction and how we can become more independent from atmospheric conditions.

Acknowledgements

This research project was performed at the Institute of Architecture and Media of the University of Technology, Graz by Thomas Bogensperger, Emmanuel Ruffo Calderon, Heimo Schimek, Milena Stavric, Markus Manahl and Christoph Pfaller with Albert Wilsche and Urs Hirschberg as project leaders.

This project is supported by the Austrian Science Fund (FWF) under the grant L695.

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