PERFORMANCE AS A DESIGN DRIVER IN ROBOTIC TIMBER CONSTRUCTION

A case study on the Implications of Material Properties and Construction for an Additive Fabrication Process

SILVAN OESTERLE
ETH Zurich, Department of Architecture, Professorship for Architecture and Digital Fabrication, Prof. Gramazio & Prof. Kohler
oesterle@arch.ethz.ch

Abstract. In the research project presented in this paper we investigate the architectonic and constructive potential of additive digital fabrication in timber construction through robotic processes as well as the relation of functional requirements of an exterior wooden wall to design. Form finding through performance analysis is of great interest for architects. With advanced digital fabrication technologies at hand it is possible to produce articulate building elements. This can be exploited to analyze and transform performance criteria into architectural expression. We argue that functional requirements and formal characteristics are interdependent. To allow performance criteria drive the generative parameters of design, custom software tools need to be developed which impart physical aspects of building elements to digital design models.

Keywords: Digital fabrication: design performance; robotic construction; timber wall.

1. Introduction

Material and production processes that inform design have come to the interest of architects over recent years (Bonwetsch, 2007). But still the focus on geometry is at the core of today’s digital design representation within CAD software (Kilian, 2006). Geometry does not capture the complex relations between material properties, the constructive logic of building elements and the fabrication process. On a proto-architectural level geometry is coupled with
analytic feedback through the use of simulation software and physical modelling (Menges, 2008) which integrates performance criteria into architectural design concepts.

With building scale digital fabrication technologies available to the architect today it is possible to construct full scale physical prototypes during the design process within an acceptable time frame. In our research we investigate the possibilities of 1:1 scale analysis of such architectural prototypes and the consequences for the design process.

The paper shows that a close look at real world constraints (material, performance and construction) during the beginning of the design process allows turning constraints into a qualitative property of the result. This leads to simpler systems that integrate performance aspects into the design without relying on complex optimization methods which have to be applied afterwards.

2. The Sequential Wall

In this project we explore the design of load bearing, water proof timber walls which allow for insulation and are produced through an additive digital fabrication process.

We further present some of the results developed and produced during a one month student research course. The goal of the course was to develop a full scale wall prototype at the size of 4 meters width by 2.5 meters height and an approximate thickness of 30-60 centimetres suitable to work as the building envelope.

2.1 MATERIAL SPECIFICATIONS

Wood had been chosen as the preferred building material for the following reasons.

First, it is relatively inexpensive compared to other building materials suitable for outdoor application. Second, depending on the type of wood and how it is applied, it possesses great durability and strength compared to its weight. Third, it gives the flexibility to be processed into different shapes and lengths, which makes it an adjustable component. Fourth, it is sustainable; a construction material available on the local market and a resource growing again.

For the project presented here 40mm by 60mm spruce slats with a length of 5 meters have been used. Although the durability of spruce is lower than the one of hardwoods like oak or robinia (Schweizerische Normen-Vereinigung, 2007) it was suitable for the semester project because the relative softness of spruce allowed for fast cutting with a standard circular saw.
Besides the type of wood selected, constructive weather proofing plays an important role for the durability of wooden building elements (Schweizerische Normen-Vereinigung, 2007). These requirements led to the following guidelines which are part of constructive wood protection.

Facewood was not allowed to point into an upward direction due to its sensitivity regarding water absorption.

Areas where rain water could accumulate were to be avoided and an overall good drainage should be achieved. This provided protection against fungus infestation and fissuring.

Together material dimensions and material properties formed the first set of parameters driving the design process. They were directly related to the later on explained requirements derived from the building component and the fabrication process.

2.2 BUILDING COMPONENT SPECIFICATIONS

On the building component scale load bearing capacities had to be addressed and the wall prototypes needed to offer the possibility for additional insulation.

The insulation material chosen was cellulose flakes. It can be blown into the hollow core of the wall structure. To function as insulation the cellulose flakes needed to be protected from moisture and the wood structure had to provide a certain degree of air tightness.

These building component requirements form the second set of performance criteria.

2.3 FABRICATION PROCESS

As fabrication tool we applied a six-axis industrial robot equipped with a custom gripper (Fig. 1) for handling and placing the slats at the right position in space with a specified angle. The robot arm can operate a workspace of three by three by eight meters.

In addition we used a circular saw to cut the wood slats to length. Since every slat can vary from 15cm to 120 cm in length the robot was used to show the length of the slat for cutting. In this stage of the project the cutting procedure had been kept semi automatic as this process can be handed over to a standard industrial trimming machine.

The connections between the slats were made through nailing. The fabrication was a layer based additive stacking process which allows for closed structures. The resulting building components can either be kept as horizontal layered structures or be turned over by an angle of 90 degrees.
The stacking process and the nailed connections set some constraints. Together they formed the third set of design driving parameters, which namely are:

- A minimal required overlap of half the slat’s width between the slats of one layer to the slats of the next layer which allowed for a proper nailing connection.
- A maximum allowed cantilever of approximately 70cm for the overall structure during production in order to avoid sagging and deformation.
- A placement logic for the slats either predefined or through optimization, which prevented collisions between the gripper and the already built wall.

2.3 DESIGN PROCESS

The research course aimed to provide the students with hands on experience of digital fabrication and design. It started with an early on analysis of the before described material, building component and fabrication parameters.

2.3.1 Mockup and Analysis

A valuable tool for the development of first design sketches was model building (Fig. 2). It helped to understand the constructive requirements and revealed build-up logics which could not be preconceived in a 3D model representation. It facilitated to address constraints early in the design process and turn them into drivers of the design system development.
After several iterations and refinements the most evolved sketch models got built as 1:1 mock-ups for analysis of the performance requirements weather protection and the structural feasibility of the systems (Fig. 3). To address them the following two student projects used different approaches.

Project one (Fig. 4) tried to decouple the load bearing inside part of the wall from the outside part which provides stiffening. The ends of the slats protruding outwards form a sacrificial layer. Through alternating them from layer to layer they shield the bracing part of the wall from rain, similar to pine needles and drain the water away from the hollow core which will hold the insulation (Fig. 5, 6). Their facewood gets protected by always pointing downwards.

In this project the different performance requirements are addressed through different systems that complement and support each other.

![Figure 2. 1:10 Design system models.](image)

![Figure 3. 1:1 Connection analysis and insulation analysis mock-ups.](image)

![Figure 4. Full scale wall prototype, project one.](image)
Project two (Fig. 7) developed an integrative approach of structure, insulation and rain protection. The singular performance requirements are not addressed through different parts but are incorporated within one system.

The mock-up development of project two showed that some of the ideas from the 1:10 models could not be translated directly into 1:1 scale. For example the stiffness of the glue connection does not translate to the stiffness of the nailing connection. As a result the structure of the design system had to be adapted. The goal was the maximization of overlaps between the slats and the introduction of triangles for stiffening. This led to the rippled undulating surface on the outside (Fig. 8) which provides better connections between the outer slats and the bracing slat. On the inside the facewood was allowed to stick through (Fig. 8) the inner layer to give space to the nodal points and enhance the overlap between the layers. This decision led to stronger connections, a
thicker insulation core and a better aspect ratio of the bracing triangles.

Figure 7. Full scale wall prototype, project two.

Figure 8. Detail view of outside layer (left) and inner nodal points (right).

In both projects the analysis of the 1:1 mock-up allowed a full understanding of the design and a precise definition of the parameters at hand. The iterative refinement of the material system and its requirements led to a robust design model which balances the different performance aspects and transforms limiting factors into design expressions.

2.3.2 Tool development

In a next step the physical evolution of the design system got coupled with the translation into programming code.

The design and construction parameters derived from physical testing should inform the setup of the design system. But the tools available within standard CAD packages did not allow the control of performance and fabrication logics. Also the clumsiness of parametric modelling applications limited the rapid
development of variations and adaptations of the design. Therefore an integrated
toolset for design and production got set up. It consisted of two parts.

The first part was a predefined hierarchical grouping logic within the 3D
design package that corresponded to the production logic of stacking. The top
level group formed the whole wall and contained further sub groupings which
formed the production layers. These layer groups held the actual slat
components. In addition to geometric information, like size and position in
space, fabrication details were attached to the 3D slat objects. This information
constituted the basis for the second part of the design system.

The second part consisted of custom export functionality which latched
into the grouping hierarchy to extract the layer data and read out the additional
production data attached to the slat components. It directly generated the
machining code for the robot and checked the design for collisions between
slats and between the gripper and slats. The export offered the option to optimize
the sequence of placement if collisions were detected.

Together these two parts allowed for an immediate translation of design
data into production data and informed the 3D representation about the
fabrication process. The setup allowed testing the robustness of the design
systems developed by the students and generating a wide range of variants for
rapid 1:1 robotic prototyping and performance analysis (Fig. 9).

Figure 9. Material – analysis – coding – production loop.
4. Conclusions

The project demonstrates how digital fabrication can establish a loop between physical performance aspects and the development of a custom design system. The immediate fabrication of 1:1 prototypes and their successive analysis can inform the design from the first idea on. This gives the ability to turn parameters such as insulation, structure and water shielding into the drivers of a project. If the constructive logics of the final building element as well as the construction process itself are the resource for design parameter selection, downstream optimization becomes obsolete. This leads to straightforward design systems which help to control the overall complexity of a multi-element building component and ensure the feasibility of possible results.

Furthermore the experiment showed that material properties are closely related to construction and performance. Therefore this paper argues for the development of custom software tools which incorporate material aspects of building components because only the mastery of tools allows mastering and controlling the performance aspects of design.

Acknowledgements

The course was made possible through funding from “Haering Timber Engineering”. I would like to thank Ralph Bärtschi and Michael Lyrenmann for their invaluable support with the teaching project and the fabrication process; furthermore Tobias Bonwetsch for his advice and proofreading and Prof. Fabio Gramazio and Prof. Matthias Kohler for their trust in my work. Special thanks go to my hardworking and eager students. They were: Michael Bühler, David Dalsass, Simon Filler, Milena Isler, Roman Kallweit, Morten Krog, Ellen Leuenberger, Jonas Nauwelaertz de Agé, Jonathan Roider, Steffen Samberger, Chantal Thomet, Rafael Venetz, Nik Werenfels.

References
