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SEWING TIMBER PANELS

An innovative digitally supported joint system for self-supported timber plate structures

HEIMO SCHIMEK, EMMANUEL RUFFO CALDERON DOMINGUEZ, ALBERT WILTSCHE AND MARKUS MANAHL
University of Technology, Graz, Austria
schimek@tugraz.at

Abstract. This paper focuses on the joint system of flat panels as parts of a freeform building. This topic is a key area of the ongoing founded research project, in which we investigate nonstandard shapes, realised with standard building materials, namely cross-laminated timber (CLT). We use different discretisation algorithms to overlay arbitrary freeform surfaces with ornaments consisting of polygonal flat panels. We investigate a series of ornaments and their discretisation results on different surfaces. In this paper, we will present and discuss a new timber-to-timber joint system that we developed exclusively for this project. We discuss the results of the load tests that we performed recently and we take a look at the construction dependent requirements of the joint system concerning the tolerances and the geometry and also, how these constraints inform the digital process. As we will discuss throughout the paper, in earlier publications we described the form finding process and the geometrical guidelines for the discretisation of a desired freeform building using ornamental flat patterns. This paper moves one step further as the digital becomes physical and it is closely related to building construction and the computational design outset.

Keywords. Digital fabrication technology; computational algorithmic design; building construction; freeform optimisation; CLT joint system.

1. Introduction

Since the invention of numeric controlled machine tools, it has been evident that digital technology expands new methodologies for designing and controlling fabrication processes. Digital technology challenges architects, engineers and allied professionals to extend the limits of feasibility in the design and building industry into higher level of complexities. In our approach, we take advantage of the concepts of "File to factory" and mass customisation technologies, which are based on the idea of mass production that support the digital fabrication of individual components. Thus, the design and fabrication process is fully integrated using parametric strategies (Schimek et al. 2010). Parametric design strategies open up new realms for the integration of building construction issues into the design process at an early design stage and foster an economical scenario for generating nonstandard self-structures.

The use of discretisation strategies in the process for approximating freeform shapes is not new, many attempts have been performed with different kinds of construction strategies and materials, mainly steel and glass but there are just a few examples of freeform structures using solid wood panels like cross-laminated timber (CLT). At the present, there is no existing building with a self-supporting structure employing a timber-to-timber joint system that is also capable of transferring tension loads. The Laboratory for Timber Constructions IBOIS, in Lausanne, has published some interesting results of their research work. Buri and Weinand (2010) has been specialising in folding plate structures using cross-glued timber. In one of the institute's research projects developed by Buri and Weinand, named *Origami – Folded Plate Structures,* he investigated the performance of regular Origami folded plate structures using thin timber panels. A built version of the prototype structure failed due to under-dimensioned joints that could not provide the required rigidity (Buri and Weinand 2010). Research on structures with stronger CLT panels has been considered but, for the time being, there is no published work concerning this issue.

2. Surface and ornament

Published related investigations to the panelisation problem have showcased the possibilities of the top-down approach, where a freeform shape is first generated and then approximated with polygonal flat ornaments, which, according to these publications are produced on a slow track speed. On the other way round, our system allows a live fast track speed opportunity to generate and integrate the aesthetical and physical construction negotiations between the ornament and the overall building shape (Calderon and Hirschberg 2011). In earlier publications (Calderon et al. 2011), we have introduced different Gaussian surfaces and have found out different important relationships between the building shape and the ornamental structure. In particular here, we discuss a large-scale prototype that we are building on the year 2012 (Figure 1).

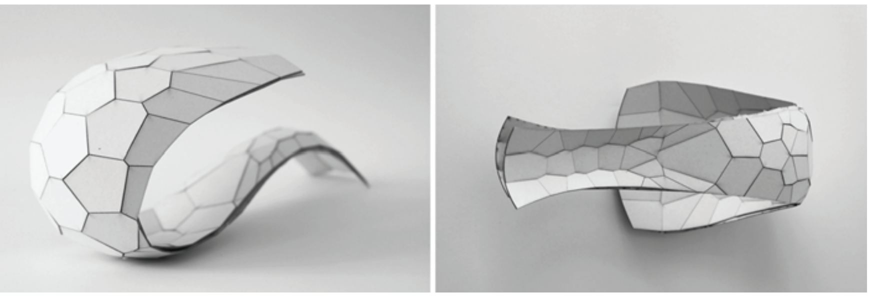

Figure 1. Large full-scale prototype envelope with a pattern mainly consisting of pentagons, hexagons and heptagons.

The surface of this prototype describes positive and negative Gaussian curvatures and it was a great example to explore the possible negotiations of the design ornament and the shape building, its structural capacities and its feasibility for fabrication, assembling and construction.

We designed two different strategies for generating patterns on double curved surfaces. Certainly, in the full-scale prototype we are constraint by the following design criteria: the size of the panels, the number of panels – a maximum of fifty panels are considered-, the topology of the panels – since we intent to use mainly pentagons, heptagons and octagons – and the thickness of the panels. Thus, the examples presented here are intended to envelop a slightly symmetrical parametric shape with a differentiated pattern over the surface.

However, the ornament should also follow, at least, two-fold construction criteria; the grain direction of the timber panels, the geometry of the connector (called Kerto-S, an engineered material, with high mechanical load capacity) and, subsequently, the continuity of the grain direction – distributed by the CLT structures – over the polygonal panels that eventually hold the overall components as a self-supporting structure. Thus ornaments and structure play an important role in relation to the building shape to construct.

As designers, we believe that both the FEM analysis and the loading tests were crucial to understand the possibilities of plate ornaments applied to non-standard buildings, but else, in order to integrate this novel knowledge into the algorithmic design, we identify the necessity to embed the potential that design and engineering aim to combine.

3. Joint system

"Joints are the key to harmonious structures. The challenge for the designer is to produce joints which early communicate their function – the job they are actually doing – and to do this in an efficient and elegant way" (Addis 1994). Joints have significant influence on the structural characteristics; therefore, the consistency of an architectural structural detail over the structure, as a whole, is crucial for the aesthetical appearance of a building with an exposed structure (Calderon et al. 2011).

In order to negotiate the aesthetics of the ornamental design on a self-supported structure, we know that FEM feedbacks constrain our designs in a two-fold way. The first is that flat panels on a surface should communicate tension forces throughout the whole surface using linear paths without breaking continuity (Figure 2).

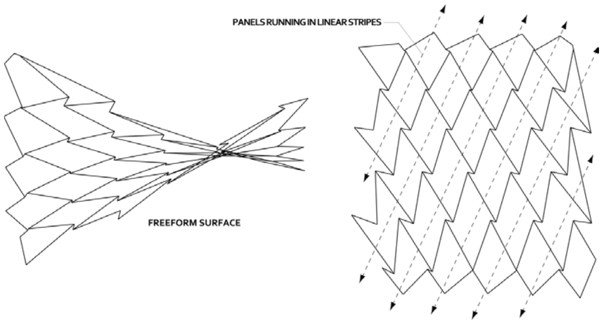

Figure 2. Double curved surface with linear discretisation.
Left: Perspective view. Right: Top view with indication of linear paths.

Caused by the anisotropic material behaviour of timber, a second issue arises, namely deviations between the grain direction of the outer layer of the CLT-panels and the Kerto-cleats have to be avoided as far as possible. Tensile stresses perpendicular to the grain in the panels should be as small as possible (Figure 3).

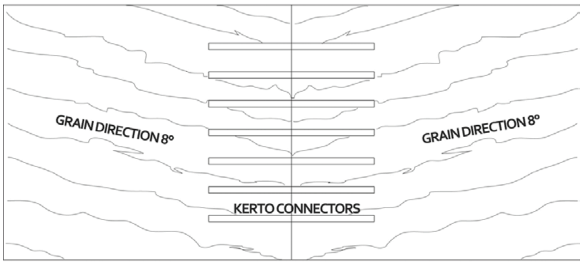

Figure 3. Diagram showing connector orientation and
grain direction with a deviation of 8°.

In Section 4, we will discuss different results of the bend tests concerning this issue, besides to this, we also provide general conclusions about the load-bearing behaviour of the joints.

3.1. INVENTION OF A NEW TIMBER TO TIMBER JOINT SYSTEM

In this research project this is the first time that a self-supported CLT-structure is built with a glued timber-to-timber guaranteeing tensile strength joint system. The building material we are using is CLT, which has an excellent reputation as a sustainable and regenerative material and CLT boards can be easily machined with a large variety of robotic tools including CNC milling machines. Since these structures are intended to be self-supporting i.e. carrying all loads without any additional structural supports, the joints between CLT boards become structural, which eventually transfer positive and negative axial forces, lateral forces and bending moments. The panels are connected with parallel laminated veneer cleats made of Kerto.

At the present, there are no built examples that use such joints for CLT structures (Schickhofer et al. 2010). Consequently, this paper proposes a new joint: the "sewed" joint, whose stitch pattern is similar in appearance to the stitches of a seam (Schimek et al. 2010). Since these joints will be exposed on the exterior of the building envelope, they will have a dominant influence on the appearance of the structure. Thus, being able to control the relationships and the distribution of the connectors is not only a question of load transferring between the panels but also a creative and intuitive process carried out by the architect.

3.2. ABOUT GLUEING, JOINT GEOMETRY AND TOLERANCES

Up to now, we have tested six different connector configurations with seven mock-ups for each configuration. The geometry for the glue joint had to be very accurate in order to meet the requirements of a one component-polyurethane glue, which belongs to the group of reactive adhesives. The glue is approved by the German Institute for Building Technique (DIBt), requires a wood moisture between 8 and 12% and a bonding pressure of 0,6 – 1.0 N/mm^2 with a maximum width gap of 0.3 mm between the Kerto-cleat and the slot (DIBt, 2011). Consequently, we had to angle the slots conically. In doing so, we are securing a very tight fit of the connector when it is inserted (Figure 4).

Figure 4. Gluing process: KERTO-S cleats are being inserted into conical slots.

Aside to this, we tested a two component cast resin, which is much more tolerant in terms of the width of the gap that can be up to 4 mm. The latter is a very important feature concerning the CNC-milling tolerance. But due to the relatively low viscosity of the product we had two major problems handling the material: since it was running away, what wasted almost 50% of the very expensive glue and, eventually, this also soiled the panels.

The gluing process for the test configurations was very revealing since we empirically could collect information about the effectiveness of the assembling process. Considering the workflow at the building site we decided to use the one component glue accepting tighter tolerances of the geometry.

3.3. MILLING

The first series of panels for the load tests were milled on a 6-axis industrial robot machine, which results did not fully satisfy, due to vibrations of the milling head – when it had to cantilever widely in order to reach the backside of the work piece – that eventually resulted in uneven flanks of the slots (Figure 5).

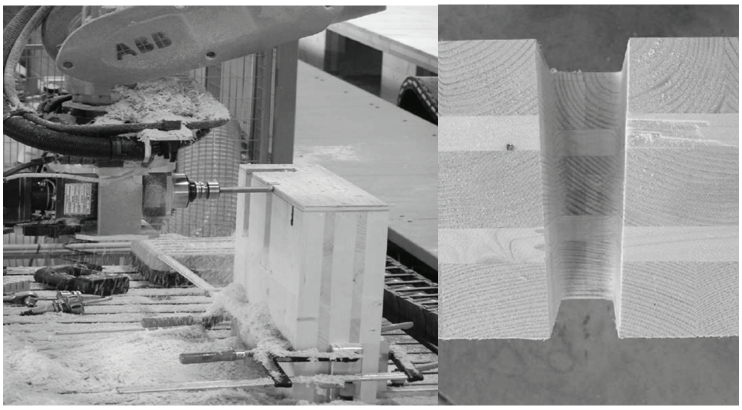

Figure 5. Left: Milling with 6-axis robot arm. Right: conical slot.

Consequently, we switched to a five-axis router, which led to feasible results, demonstrating that the slots could be produced within the required range. Working with such precision is not common in the carpentry business on site and can only be achieved under factory conditions. Once we could fulfil the accuracy – pre-defined by the specifications of the glue manufacturer – we started to glue our test series.

4. Load tests

4.1. CONFIGURATIONS

A first series of load tests of 30 samples with four different configurations were performed on early 2011 in order to test the shear resistance of the connection. In particular, we were looking at the parameters of the connector geometry, the used adhesive and its application, the position of the connector and the slide-in direction. The characteristic value concerning the shear forces of the Kerto-cleat was reached. We could observe both a collapse of timber and a collapse of the glue.

The purpose of the second test series was to verify the bending strength of the connection with configurations that might be used for the prototype structure, in other words, the load bearing behaviour of mitred butt joints, the load bearing behaviour of a non-grain-parallel glued Kerto connector and the impact of the insertion direction. In this second test series, we tested six different configurations with seven samples each.

4.2. LOAD TESTS FINDINGS – OPTIMISATION

As a conclusion of the load tests, the average utilisation can be specified with some 65–70% of the panels own specific load utilisation, which is very promising for our project's prototype. The estimated size of the connectors (Kerto-S) was proved to be right dimensioned. This was verified by tension and bending load tests on single connector ribs. In both cases, the expected forces were reached. No significant differences have been evidenced inserting the connector's top-down versus bottom-up.

Five criteria define and constrain the aesthetical appearance of our innovative joints: size, geometry, position, orientation and quantity of connectors (Calderon et al. 2011). Following the results of the load tests on mock-ups two of the criteria, size and geometry, have been empirically assigned. First, the engineers delivered the FEM stress analysis of the shape designed by the architect. The model used in their analysis is an ideal model i.e. the orthotropic characteristics of the timber material is not taken into account but the mechanical parameters of the material are estimated. The orientation of stress components suggests the required grain direction of the relevant member. The range of section moments defines the number of connectors to be inserted. This early stage FEM stress analysis represents a "calculated estimation" that conducts the design interventions concerning the connector position, distribution and orientation.

The geometry and grain direction is already pre-defined in the digital 3D-model, which establishes the connector direction. Then, the number of the connectors is calculated, based on the value of the applied loads on the edge to be examined. Then, the new geometry of the connected neighbouring panels is generated. Technically speaking, to calculate the discretisation of the surface, the thickening of the panels and the connector geometry of all neighbouring panels, we use an add-on for Rhinoceros that is programmed in C++ performed in Grasshopper using a C# component. In other words, we designed a parametrically controlled system capable of discretising a freeform surface, generating the panel geometry, the grain-connector direction, the connector's geometry and calculating the number of connectors based on the loading values. Consequently, we use this method – which work on a live and fast track speed – to investigate different ornaments on the same shape and negotiate both structural and aesthetical features of the joint patterns, which are dependent on the FEM pre-calculation in order to define an overall design from the outset (Figure 6).

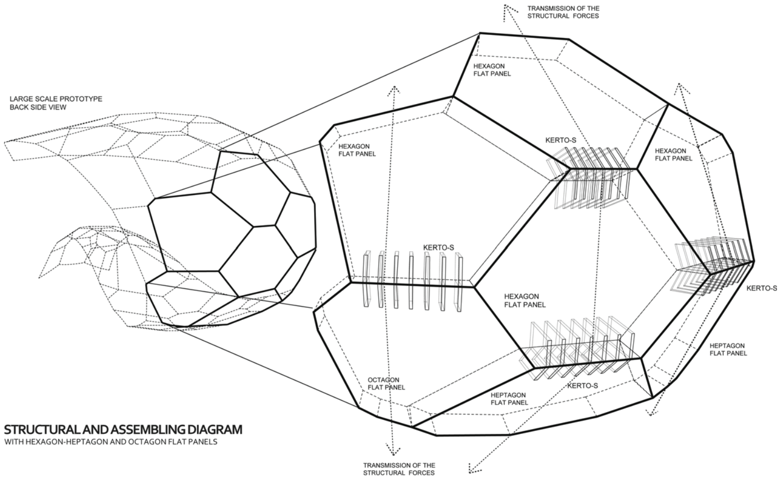

Figure 6. Load-time diagram of test configuration V300ANU-9.

In Section 3, we discussed the relationship of the grain direction of the panel's outer layers and the orientation of the connectors (Kerto-S), which should be close to the grain direction angle. Besides the other configurations, we tested one with a grain deviation in relation to the connector orientation. We did this because in earlier considerations – based on studies of the load behaviour of CLT – we assumed that the alignment of the connectors with the panel's grain direction would have to follow the same angle (Schimek et al. 2010). The test results of this configuration demonstrated a decline of the load capacity that was not too significant in relation to the average capacity and the curvature of the prototype (Figure 6).

5. Assembly

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. "One would not believe how much manual work is required for digital production", Scheurer (2009) states in an interview. By saying so, we are considering major issues, with the physical assembling of the full-scale prototype, at the required falsework level, which has to be as accurate as the structure itself. The job of the falsework is to secure each panel's position during the assembly process and must not allow inaccuracies in any direction. We know the latter is difficult to achieve, therefore, we consider a strategy of a flexible falsework construction that moves with the building process. Consequently, we have to permanently re-check the position of each panel during the assembly process, preferably with a 3D coordinate measuring laser system in order to be able to compare the coordinates with the digital model.

6. Outlook

We are currently working on a strategy for assembling a large prototype, consisting of approximately 50 panels that are being assembled to a structure of 10 × 4 × 4 m. We anticipate that the falsework supporting the structure during the construction will become a critical part of the assembling process. Consequently, the falsework has to be designed in the same digital model and digitally pre-fabricated with the same precision as the prototype structure. Following the cyclical design and fabrication process of the project, the digital process for optimising the joint system will certainly benefit from the information we collect during the physical assembly of the prototype and thus, integrate both digital and physical negotiations and constraints in one single embedded system.

Acknowledgments

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