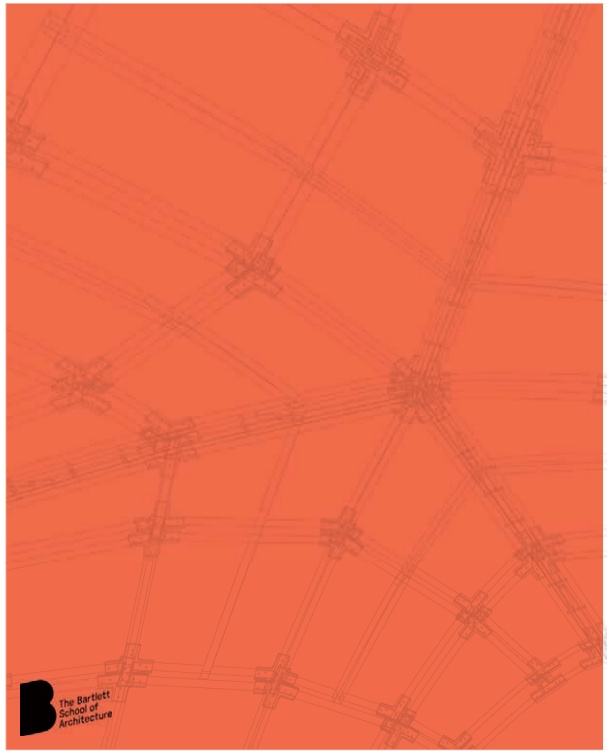


DESIGN FOR MANUFACTURE THESIS PORTFOLIO | 2021

BARC0060

MARCH candidate number: RGBR8 | student number : 18023281

Timber Double-curved Roof Structure: Design-to-Production Workflow

by Peter Buš

The Bartlett School of Architecture
University College London

My sincere gratitude goes to

Design and Fabrication Tutors:
Peter Scully | Marielena Papandreou | Vincent Huyghe |
Ben Spong | Arthur Prior | Samuel Turner-Baldwin

Structural Engineering Consultations:
Tim Lucas and Bedir Bekar (Term 4) | James Solly (Term 3)

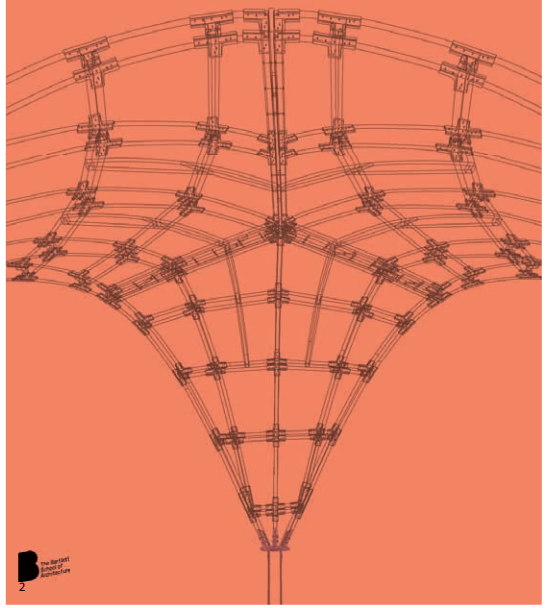


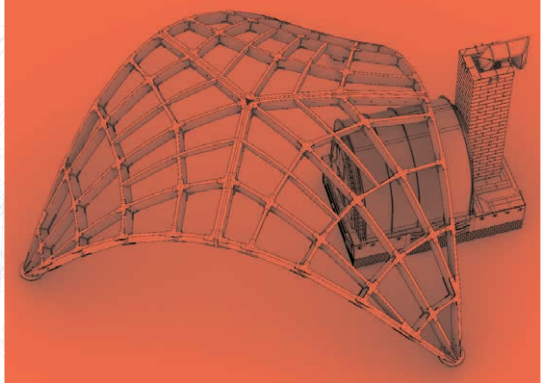
Table of Content

Research Scope and Research Questions 3
Design-to-Production: State-of-the-Art 4
Project Overview 5
Flimwell Park Site Introduction 6
Structure as a System: Design-to-Production Workflow Diagram 10
Form Finding Master Surface Process 11
Master Surface Analysis | Subsystems of the Structure 12
Subsystems of the Structure | Assembly Test Model 1:5 13
Structural Analysis 14
Structural Nodes Fabrication Process 16
Structural Nodes Fabrication Process - Test Iteration 1 18
Components Production and Assembly Tests 20
Assembly Sequence of the Structure 22
Evaluation and Outlook 23

Research Scope and Research Questions

This project builds upon a premise that complex double-curved geometries can be built out of simple, planar, and straight elements. If assembled, they create more complex and advanced double-curved geometries. As such, it is possible to simplify manufacturing, construction and assembly processes, as well as decrease the delivery time and cost. When operating with planar and simple components in the form of Kit-of-Parts there is an assumption that such components can be easily used by self-builders, not necessarily building experts. This can empower community-driven and participatory activities leading to a more sustainable and resilient engaged community.

This hypothesis is evaluated through the process of Design and Manufacture, supported by proposed advanced computational design-to-production workflow utilising digital fabrication technologies such as CNC machining and robotic milling. The design proposal is currently being evaluated in the scope of deliverability, operability and buildability.



How to proceed with the process of design and manufacturing towards simple planar components while preserving complexity and the notion of double-curved geometry?

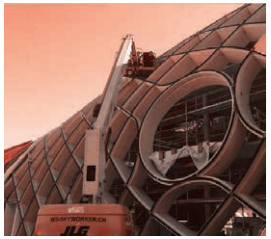
To what extent the complex structure can be assembled by unskilled self-builders and how does this influence the assembly process?

Design-to-Production: State-of-the-Art of Double Curved Timber Structures

The current Design-to-Production industrial practices incorporate digital fabrication technologies to address the production efficiency of the construction process while operating with complex geometries creating unique spatial scenarios with high precision. This has an impact on the overall process of construction delivery and assembly to be delivered easier and faster, often being digitally-driven, supported by advanced digital workflows for design, optimisation and fabrication. This requires agile design and modelling focus with wide solution space solving how parts fit together in detail from the very beginning of design (Scheuer 2021).

Presented examples consider these aspects of Design for Manufacture and Assembly-driven workflows (DfMA), leading to fabrication of building components for double-curved geometries. However, the scope of this thesis project is to test, observe, experiment with and learn from those aspects but from the perspective of a builder, not necessarily skilled, while operating with smaller-scale components or smaller sub-assemblies, convenient for hands-on operations, supporting community empowerment and participatory construction methods for an assembly.

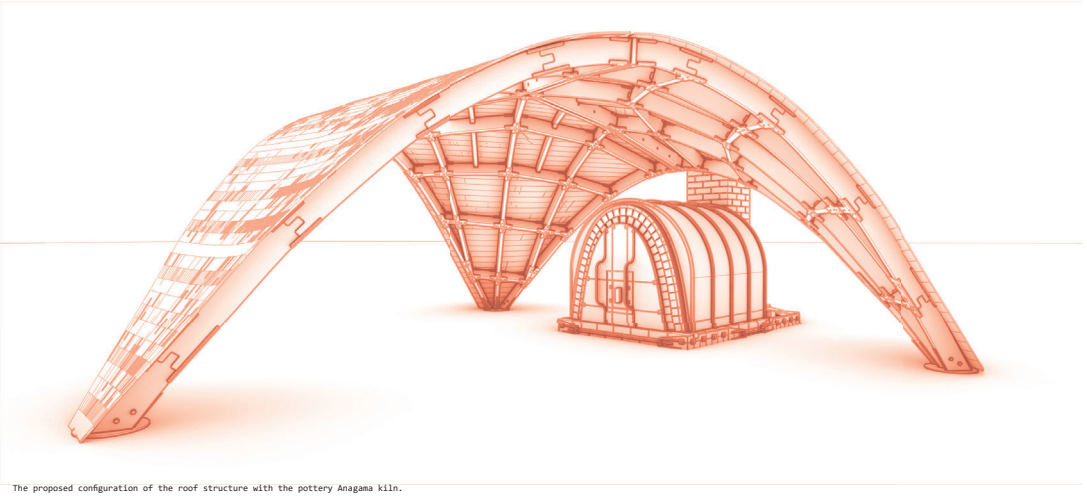
The Z-Plus Pavilion by Création Holz, Blumer Lehmann AG, Design-to-Production GmbH, and SJB Kempter Fitze. Photo: Design-to-Production GmbH
Accessed 12.11. 2021 [ONLINE]
<designtoproduction.com>



Fabian Scheuer | designtoproduction.com |
The City of Time | Omega and Swatch Headquarters | Designer Shigeru Ban
Timber contractor: Blumer-Lehmann
Biel, Switzerland, 2019
lecture by Fabian Scheuer, DfM BSA UCL, online
May 20, 2021

Cambridge Mosque | Marks Barfield Architects |
Timber Contractor Blumer-Lehmann |Timber Engineering SJB Kempter Fitze | Parametric Planning (Timber)
Design-to-Production designtoproduction.com | Cambridge, UK 2017
Accessed 12.11. 2021 [ONLINE]
<https://www.lehmann-gruppe.ch/en/holzbau.html>

Project Overview

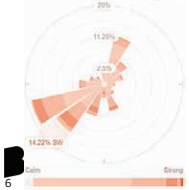


The proposed configuration of the roof structure with the pottery Anagama kiln.

Project Overview: Flimwell Park Site Introduction

Photo credit: Nivedita Sridhar

Scanned site. Image processing: Chia-Wei Yang



Wind rose
Annual (5 year average)
<https://wind.willyweather.co.uk/se/east-sussex/flimwell.html>

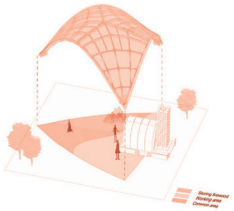
All Year Climate & Weather Averages in East Sussex High Temp: 22°C
Low Temp: 1°C
Mean Temp: 10°C
Precipitation: 69.5 mm
Humidity: 83%
Dew Point: 8°C
Wind: 7 mph
Pressure: 1015 mbar
Visibility: 15 km
<https://www.timeanddate.com/weather/@2650328/climate>

Project Overview

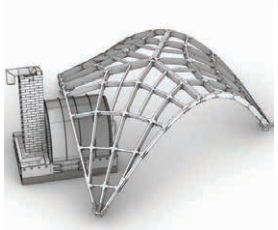
Our site is in the middle of the Flimwell Park Woodlands where there was a passion for firing ceramics as a community . Therefore the brief directed us to co-evolve the goal, design, discovery and outcome for a covered Anagama Kiln onsite at Flimwell. The kiln has been chosen as it is purposed architecture. It has observable and measurable performance criteria, whilst having a social utility and a clear aesthetic opportunity. The following project explores the Roof structure to be built to cover the Kiln.

Manufacturing and Deliverability go hand in hand. Within a sea of abstract project proposals, realising our Roof structure to be deliverable as an outcome is one of our major goals.

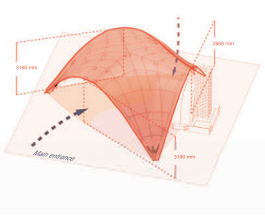
Text: Nivedita Sridhar



Functional analysis of the configuration.
Diagram credit: Yige Zhao



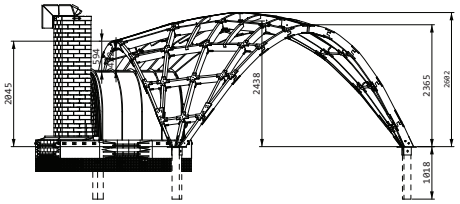
The proposed relationship between the kiln and the roof.



Access analysis
Diagram credit: Yige Zhao

Covered scenario

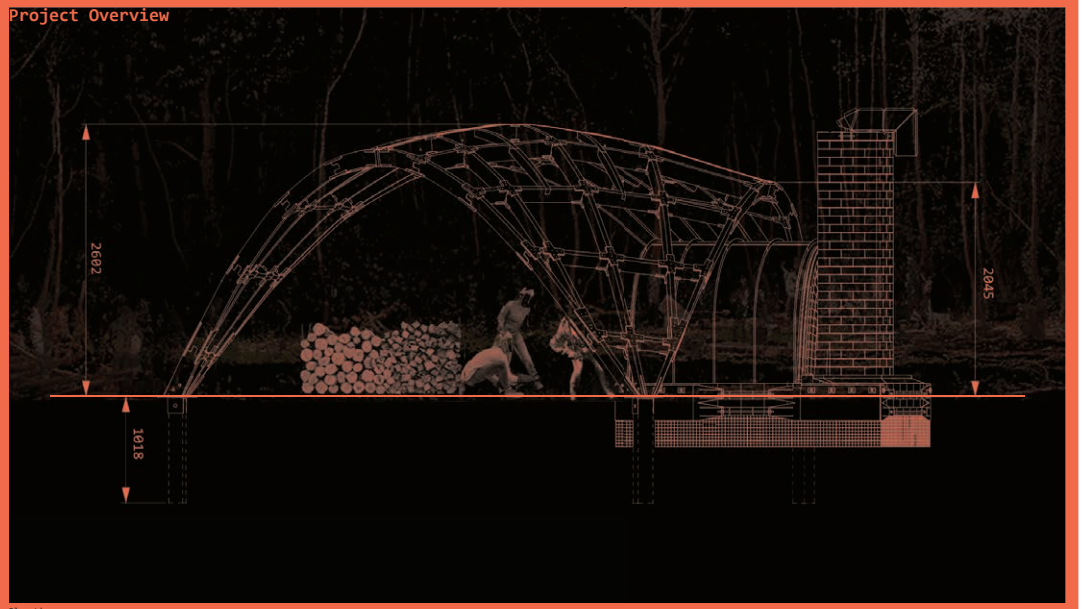
Project Overview



Front elevation with the kiln scale 1:50

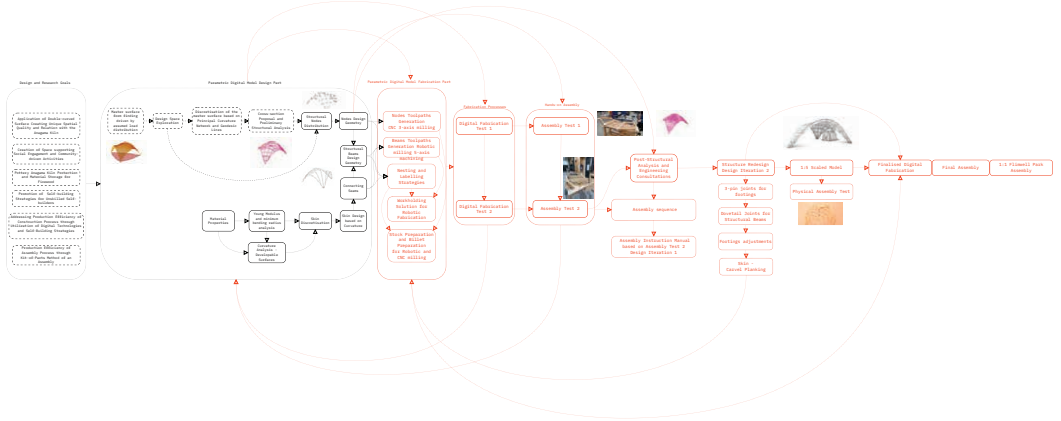
Configuration Proposal for roof and Anagama kiln at Flimwell Park site.
Original Image credits: Chenrui Chen

Site plan 1:50



Elevation

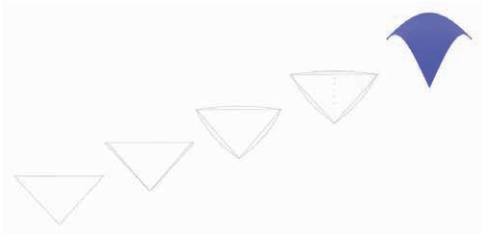
Structure as a System: Design-to-Production Workflow Diagram based on Project Aims



Form Finding Master Surface Process: Structural Loads-driven Shell Form Generation

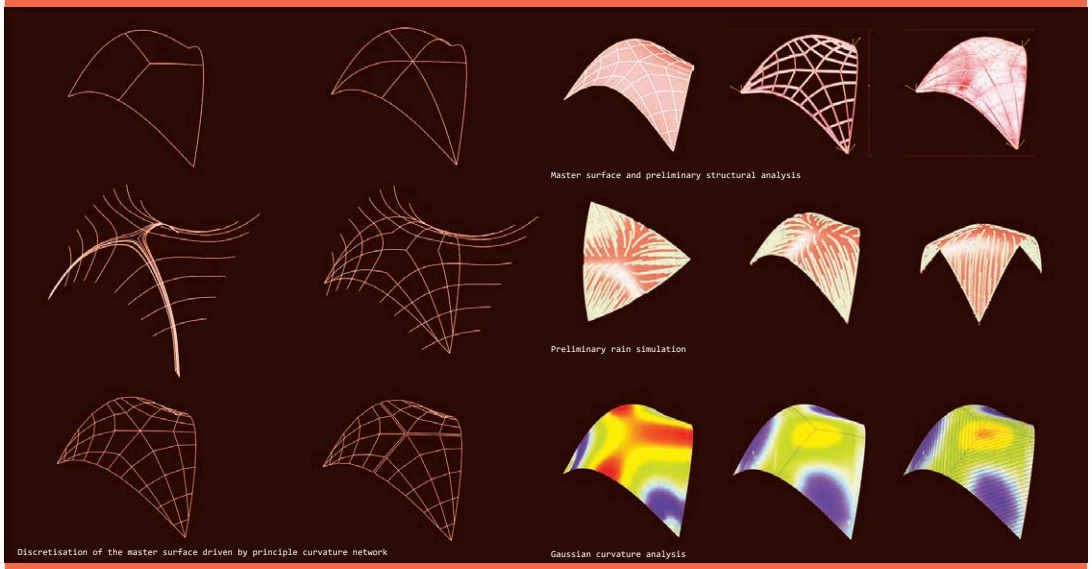
The shape is based on the 2D polygon. The process continues with bent edges, with moved vertices following parametrically defined distance.

The polygon is fed to physics simulation simulating loads affecting the mesh and generating a variety of catenary meshes with different deformation based on structural loads. The load is equally distributed across the surface.



Generated shape for the master surface defining the overall geometry of the roof structure. The shape is symmetrical in one direction, having one arch lower than two others. This intention follows the need to provide covering protection from side rain.

Design space exploration. Modifying the level of deformation, the user is allowed to generate a series of design options.



Discretisation of the master surface driven by principle curvature network

Master surface and preliminary structural analysis

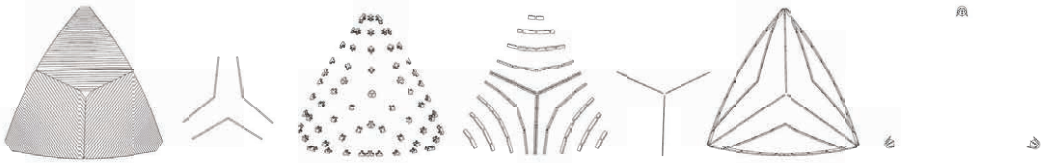
Preliminary rain simulation

Gaussian curvature analysis

Master Surface Analysis | Subsystems of the Structure

Discretisation of the master surface based on principle curvature network and geodesic lines. This defines the main geometrical distribution of all sub-components.
Discretisation algorithm: Yige Zhao
Image credit: Nivedita Sridhar

Dynamic rain simulation
Rain simulation algorithm: Chenrui Chen



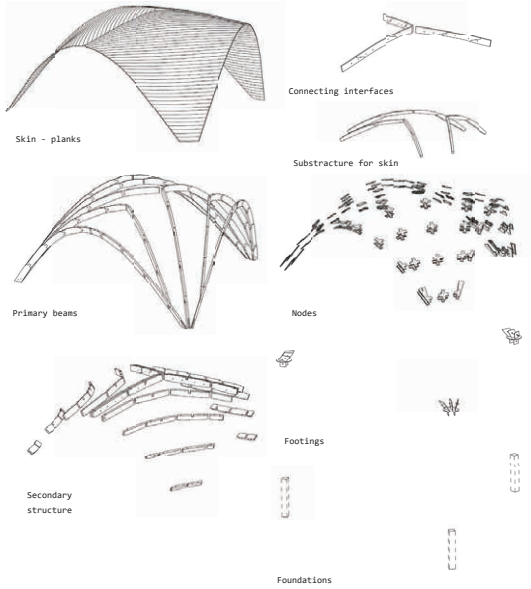
Skin - planks
Substracture for skin
Nodes
Secondary structure
Connecting interfaces
Primary beams
Footings

Plan view of particular subsystems of the roof structure

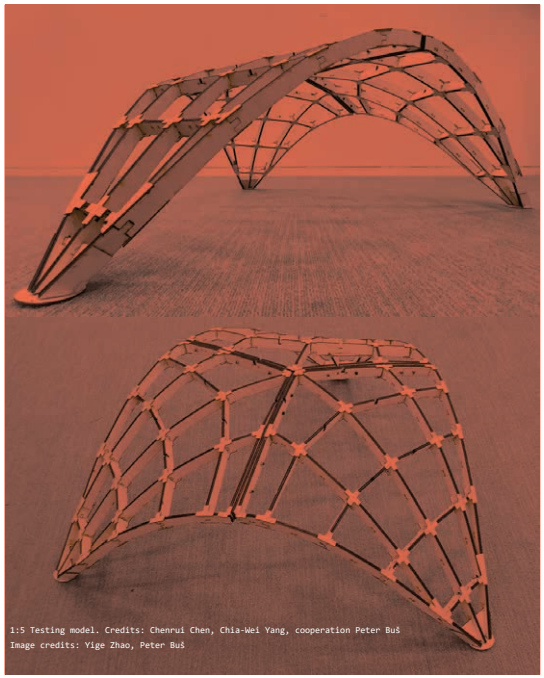
Assembly test model 1:5 with dovetail joints on the primary structure

1:5 Testing model. Credits: Chenrui Chen, Chia-Wei Yang, cooperation Peter Buš

Subsystems of the Structure | Assembly Test Model 1:5



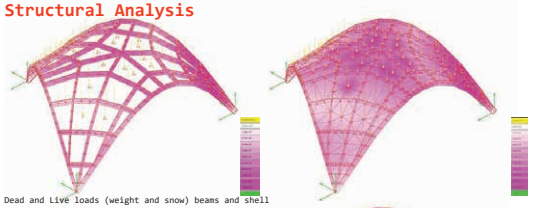
Skin - planks
Connecting interfaces
Substracture for skin
Primary beams
Nodes
Footings
Secondary structure
Foundations

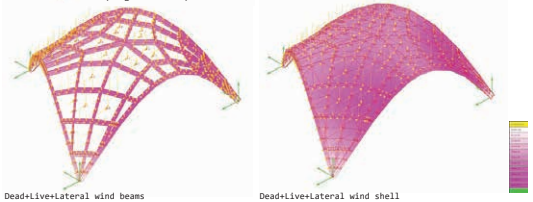


1:5 Testing model. Credits: Chenrui Chen, Chia-Wei Yang, cooperation Peter Buš
Image credits: Yige Zhao, Peter Buš

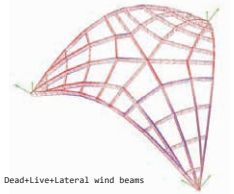
Structural Analysis

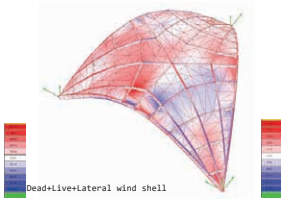
Structural material: Larch Wood
Cross section: beams 160 x 45 mm, shell 12 mm

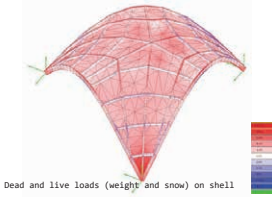

Dead and Live loads (weight and snow) beams and shell

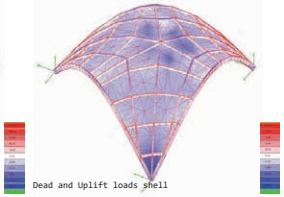

Dead+Live+Lateral wind beams

Dead+Live+Lateral wind shell


Dead+Live+Lateral wind beams


Dead+Live+Lateral wind shell


Dead and live loads (weight and snow) on shell


Dead and Uplift loads shell

Displacement

For the displacements investigation, the calculation considers safety factor 1.0 as this is a serviceability case of how the structure moves under load only.

The deflection limit is defined as H/350 for lateral deflections and H/250 for vertical deflections. The lateral wind value is 0.75 kN/cm2 for strengths calculation, alternatively 0.45 kN/cm2 for deflection investigation (displacement 0.735 cm for combined cases). However, in case the value of lateral wind is 0.8 kN/cm2, the displacment is 1.3 cm for combined load cases (Dead+Live+Lateral wind). For the type of structure, the deflection is still acceptable as this is a short term scenario.

Material physical properties of Larch Wood investigation: Nivedita Sridhar
Structural engineering tutors: Tim Lucas, Bedir Bekar (T4), James Solly (T3)

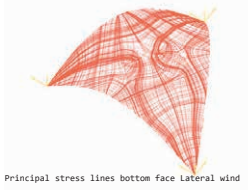
Load case scenarios (combinations)

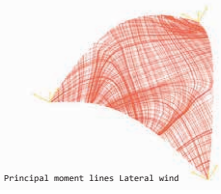
Dead+Live loads - beams utilisation (22 % compressive strength, 14 % tensile strength) | shell utilisation (8,2 % compressive strength, 2,0 % tensile strength)
Dead+Live+Lateral wind - beams utilisation (98 % both strengths) | shell utilisation (21,4 % compressive strength, 21,5 % tensile strength)
Dead+Uplift wind - beams utilisation (2,5 % compressive strength, 4 % tensile strength) | shell utilisation (1,7 % compressive strength, 1,2 % tensile strength)

For strength calculations:
Weight of finishes (strips) 0.6 kN/cm2, safety factor 1.35
Snow load 0.6 kN/cm2, safety factor 1.5
Uplift load 0.6 kN/cm2, safety factor 1.5
Lateral wind pressure load 0.45 - 0.75 kN/cm2, safety factor 1.5

Support conditions: fixed movements in all directions, 3 degrees of freedom for rotations

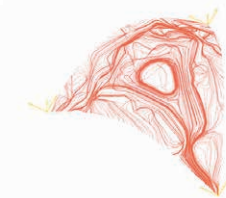
Load types
Weight+Gravity (dead loads)
Snow load (live load)
Uplift Wind Load (Vertical Wind)
Lateral Wind Load (side Load)

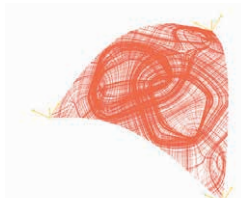

Principal stress lines bottom face Lateral wind

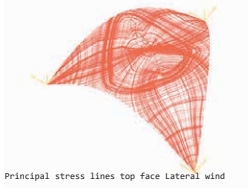

Principal moment lines Lateral wind

Principal stress top face Uplift load

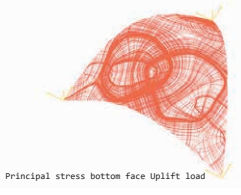
Principal stress lines middle part Lateral wind


Transverse Shear

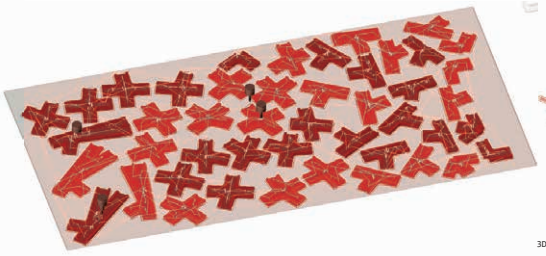

Principal stress middle part Uplift load

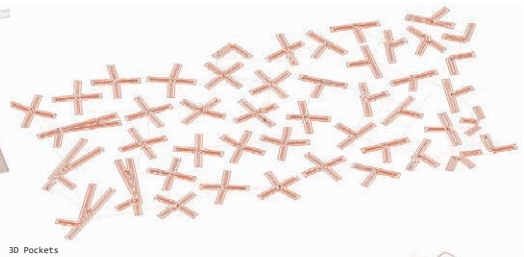

Principal stress lines top face Lateral wind

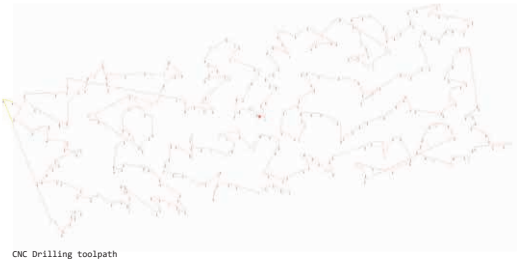
Force Flow Lateral Wind

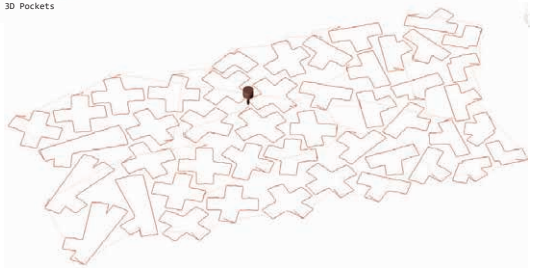

Principal stress bottom face Uplift load

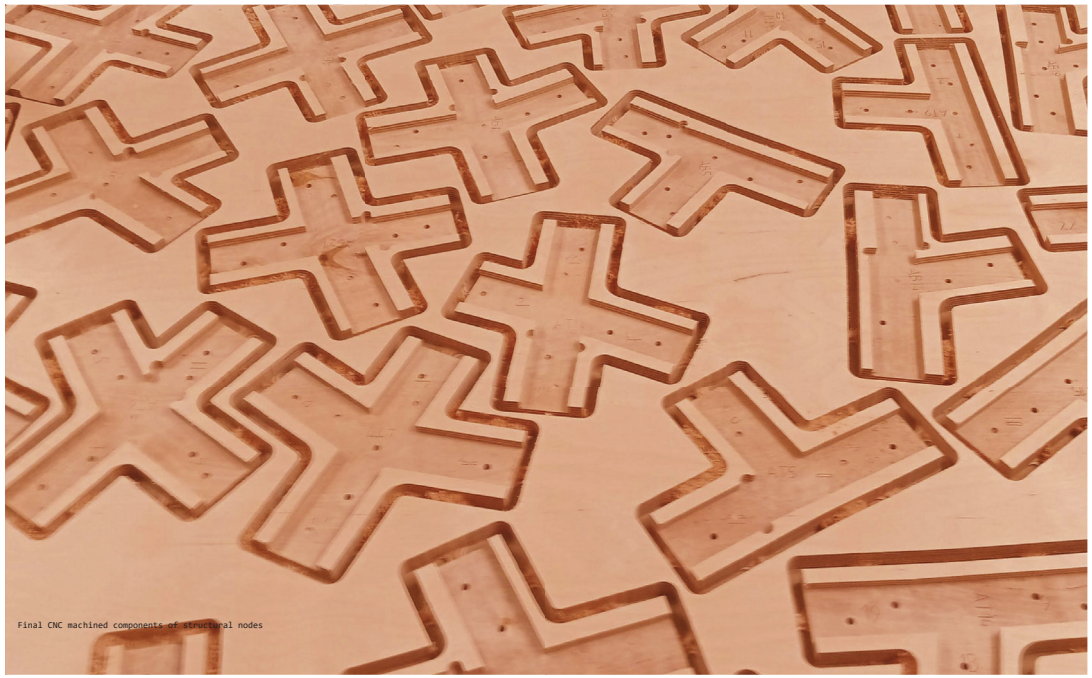
Structural Nodes Fabrication Process


Stock preparation with nested node components

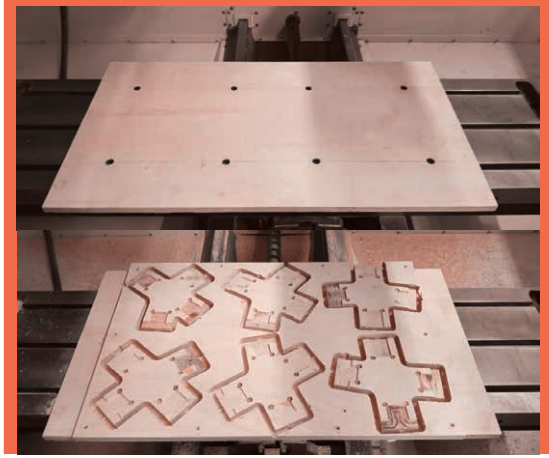

3D Pockets


CNC Drilling toolpath

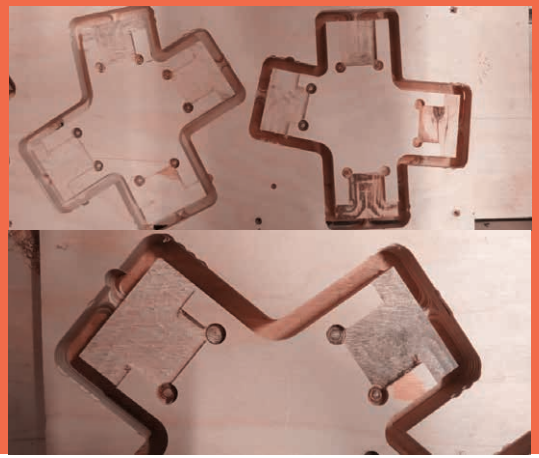

Contours with added tabs


Final CNC machined components of structural nodes

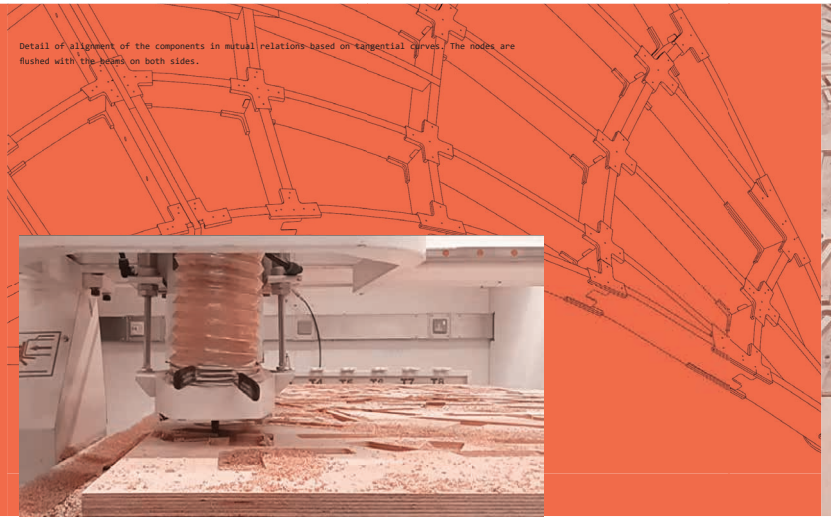
Structural Nodes Fabrication Process - Test Iteration 1



Workholding solution for HAAS CNC Machine. The 1st testing iteration. The fillets are removed with additional machined corners. The billet is screwd to the sacrificial piece. Material: Structural birch plywood 18 mm.



Detail of the countours with added triangular tabs.



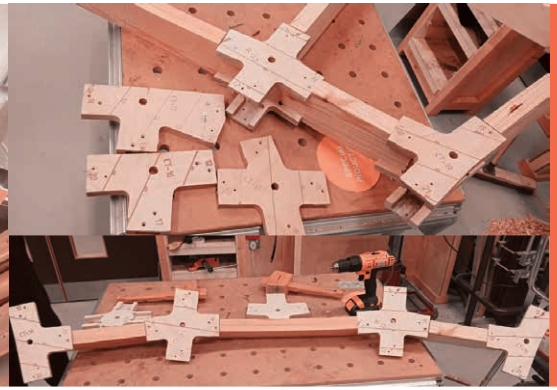
Detail of alignment of the components in mutual relations based on tangential curves. The nodes are flushed with the beams on both sides.

Large-bed CNC router Piranha machining a large plywood sheet to fabricate the final iteration of the structural components. The workholding is based on a vacuum bed.

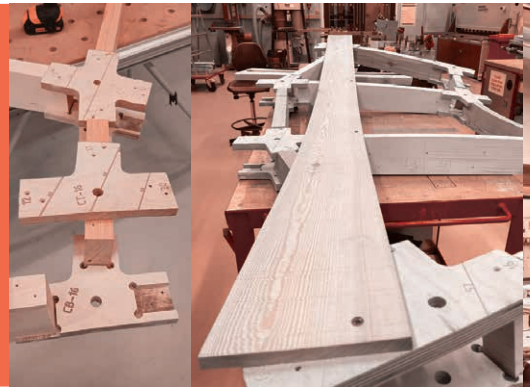
The final outcome of the machining process. The pieces need to be manually taken out of the sheet.

Components Production and Assembly Tests

Robotic production of primary and secondary beams.



Assembly test of selected quads of the structure.



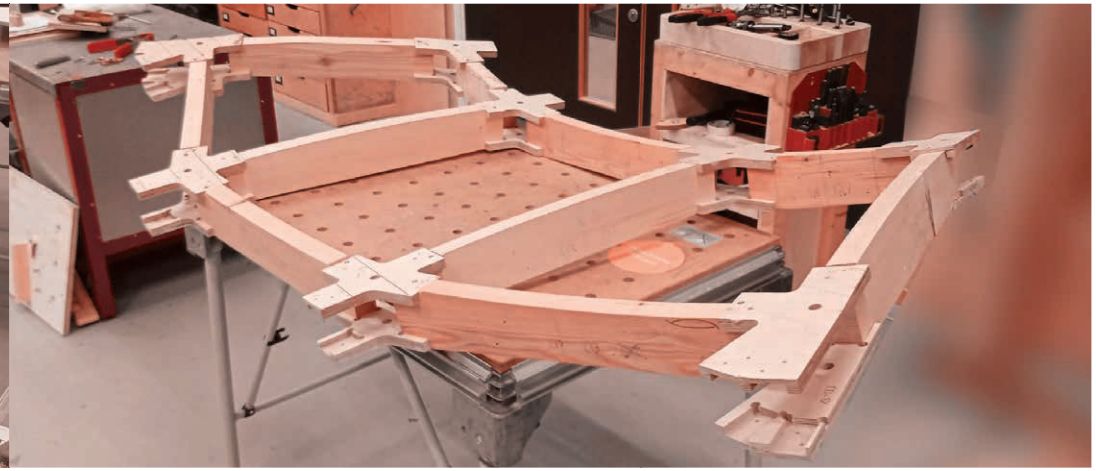
Detail of the node pockets with additional engraved information allowing an easy assembly.

Assembly test of 3 quads and qualitative weight evaluation.

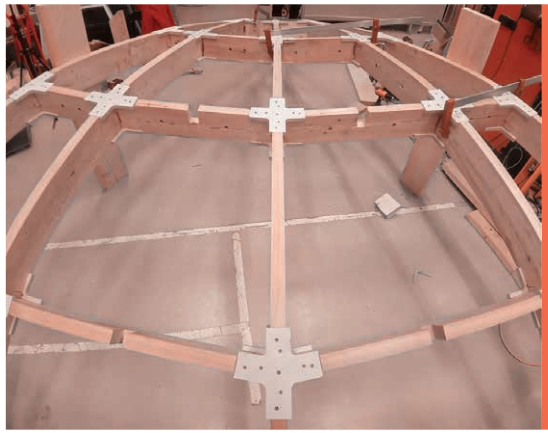
Joint test of the refined geometry of beams. The dovetail joint requires further attention.

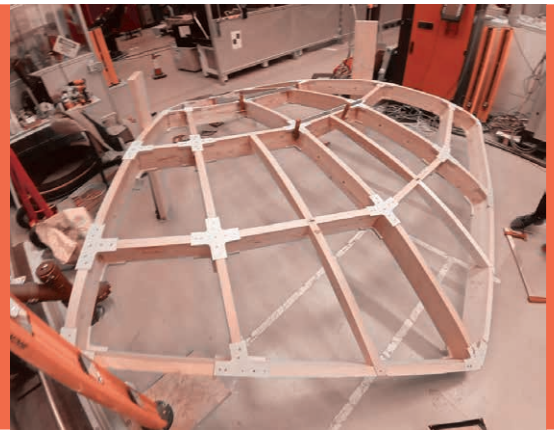
Photos credit: Nivedita Sridhar, Chenrui Chen, Peter Buš

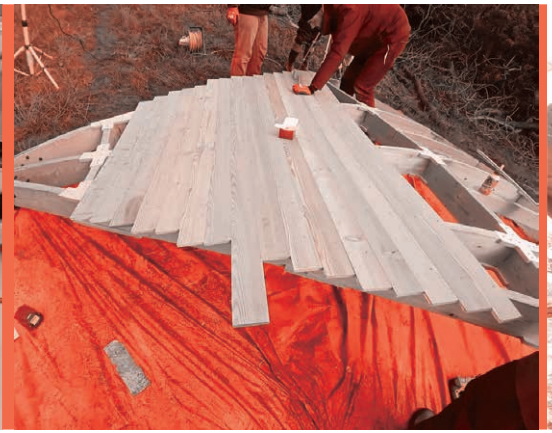
Test 1 3 Quads Asembly. The vertical primary beams are providing positions for the skin layer.



Test 2 3 Quads Asembly with sunk structural nodes with labels

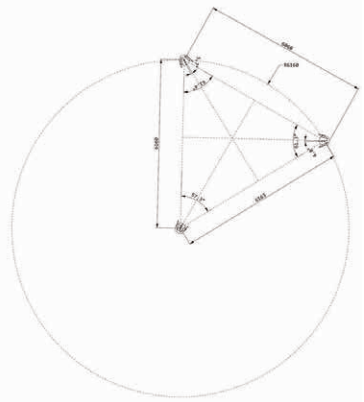




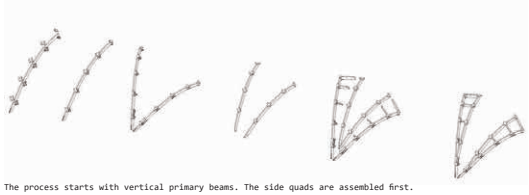


Assembly Sequence of the Structure

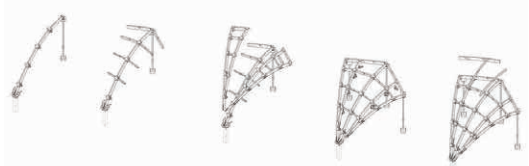
A series of tools needed for the assembly process.



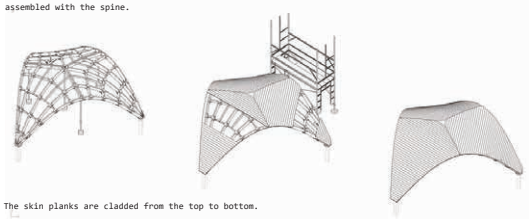
Position demarcation on the site based on a central pivot - one of the three corners.



The process starts with vertical primary beams. The side quads are assembled first.



The central “spine” has assembled secondary parts. The side quads are inserted into the footings and assembled with the spine.



The skin planks are cladded from the top to bottom.

Evaluation and Outlook

The project tested several computational design and digital fabrication strategies to achieve planarity and simplicity of the components for the assembly, following the criteria of deliverability and buildability while being aesthetically acceptable. For the time being, two assembly tests have been conducted before the final production of the components for beams. It has been observed that the assembled structure is stiff and can accommodate the proposed design scenario. However, it is critical to consider large-scale assembly and unknown conditions on the site at the production stage, including space for tolerances.

In addition, the second research question can be answered partially that the structure is buildable as it is, as observed during the sub-assembly of the selected parts of the structure conducted off-site. The proposed Kit-of-parts method allows straightforward participatory construction, however, this needs to be further tested onsite considering unpredictable site conditions and a larger scale notion of the assembly. The proposed assembly sequence needs to be tested onsite with more participants.

The last production test of robotically milled beams revealed certain difficulties that need attention, such as big gaps between the assembled components or large tolerances between the assembled beams. This can be addressed in the tool path generation process.

In principle, the research question stated at the beginning can be positively answered, however, with the comment related to modelling strategy of the components, which, eventually are unique.
The design workflow addresses this uniqueness.

This project and its entire design and production workflow was an incredible source of new knowledge I acquired during this course, opening new directions in my design and research agenda related to participatory construction methods supported by digital fabrication technologies utilising advanced computational workflows.

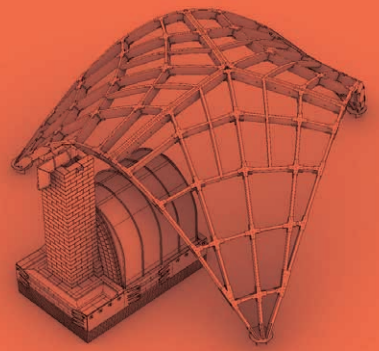
Image credit: Nivedita Sridhar, assembly test video available online < https://youtu.be/qqqFcQZWOFw >

DESIGN FOR MANUFACTURE THESIS PORTFOLIO | 2021

BARC0060

MARCH candidate number: RGBR8 | student number : 18023281

Timber Double-curved Roof Structure

Team Studio 2

Peter Bus
Nivedita Sridhar
Chenrui Chen
Yige Zhao
Chia-Wei Yang
Darwin Canga