Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Design to construction workflow of a robotic fabricated double-curved strained grid-shell structure

Mingzhe WANG, Kai PANG, Sihan WANG*, Lichao CHEN*

*China Academy of Art
352 Xiangshan Village, Xihu District, Hangzhou, Zhejiang Province, China
wangsihan@caa.edu.cn
0106038@caa.edu.cn

Abstract

In this paper, we present a digital design to fabrication process of a double-curved reciprocal structure made of small manipulable timber elements. The objective is to empower inexperienced people to construct free form timber structures. As a consequence, the entire process was generated by customized computer scripts from the upstream design of the structure to the downstream robotic milling of every piece of timber members with the instruction of their installations. We present a prototype from this system as a grid shell in the form of a reciprocal structure inspired by traditional Chinese mullioned windows. This is followed by a detailed introduction of the auto generation producing the geometry of each timber element with precise position and data of the assembly notches as well as the solutions for robotic fabrication. In the end, we conclude the result and discuss its application with future works.

Keywords: reciprocal structure, small timber elements, workflow, timber construction,digital design, robotic fabrication

1. Introduction

Digital design and fabrication have been explored with various types of materials in an increasing trend. These digital techniques bring novel solutions to architectural questions (Burry and Burry [1]). In the past 20 years, robotic fabrication has already became an important subsidiary subject under digital fabrication（Gramazio and Kohler [2]）. It has been utilized in constructions progressively, for example: the DFAB House [3] as well as the Sequential Roof of the ITA Building at the ETH Zürich [4]. These timber projects were empowered by the advances in geometric processing and CAM data interfaces to achieve novelties and complexities in forms (Adelzadeh et al. [5]). They demonstrate the potentials of robotic fabrication in constructing timber structures with various methods.

Our research of timber robotic fabrication is focused on nexorades which is also known as reciprocal structures or multi-reciprocal grids. They are structures consisting of rigid members that supported each other at both ends [6-9]. Compared with the overall spans of the structures, each structural member is relatively short which contributes to the flexibility in terms of constructing free form geometries such as double curved surfaces (Araullo [10]). They are easy to assemble as they avoid the construction of complex connection details and can be built using short members. In this case, their application can be traced back to medieval architecture, such as in the Villard de Honnecourt and the sketches of Leonardo da Vinci in the Codex Atlantic (Bowie [11]). Recent examples include "Plate Pavilion", designed by architect Chun Qing Li, engineer Ramboll, and Geometric consultant Evolute, and the timber connection at ETH Zurich (Kohlhammer et al. [12]). Robotic fabrication of reciprocal structures has been vastly studied, a number of these projects present the complexities in the designs of the structures with structural analysis as well as construction processes .

This research presents the automation of digital design to fabrication workflow to produce timber reciprocal structures. It focuses on enabling the inexperienced people to fabricate free form timber constructions such as double curved grid shells. It provides the ease of assembly and disassembling which can also be accomplished only by manpower in virtually any construction site. Under this circumstance, fabrication of such forms will no longer depend on expertise and heavy machinery.

2. Work Flow

The structural design and robotic fabrication process are integrated in a computational workflow as presented in Figure 1. Such a workflow directly transform the digital models of surfaces to reciprocal grid structure with robotic fabrication codes of all the members and their assembly sequences. Firstly, the designer sets a surface as an input geometry which will be subdivided into a grid as a guide line for the generation of the structure. Secondly, all the structural members and joints in the structure will be generated according to the guide line. This is followed by the the structural analysis for the adjustment of geometry. Thirdly, the robotic milling tool path of each member will be calculated to create the machine code. Finally, the assembly sequence with the instruction will be present to the designer.

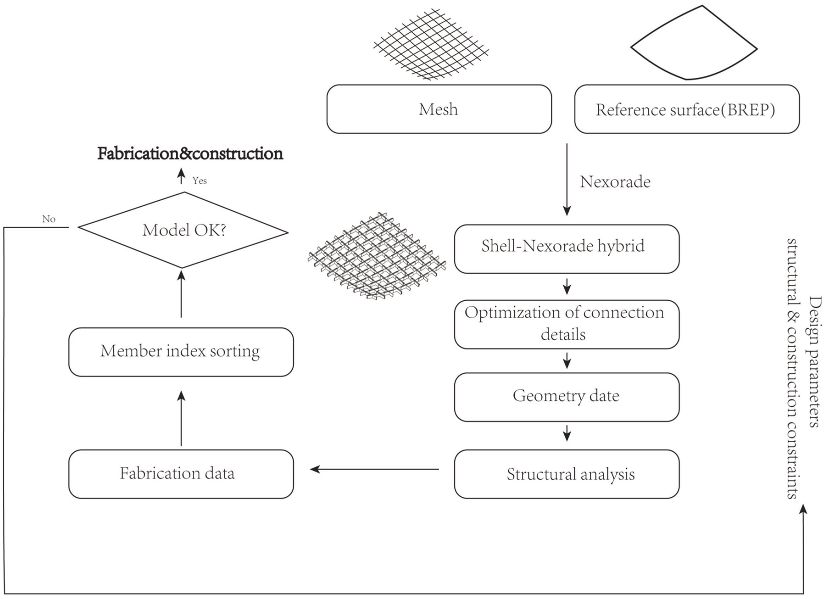

Figure 1: The flow chat of automated digital design to fabrication workflow.

3. Structural Design

The structure principle comes from traditional Chinese mullioned windows in which each joint has three vertical trusses and one horizontal truss. In this scenario, the entire structure can be made of relative small trusses compared with having single truss on each direction. Meanwhile, the load along vertical direction is supported with more structure members and the wind load is sustained with sufficient numbers of horizontal trusses.

In this paper, we introduce a double curved reciprocal structure as a variation of traditional Chinese mullioned windows. The structure is a grid made of rectangle cells with the dimension of 3580mm X 3064mm (Figure 2a) in its plan view. It contains nine vertical lines and ten horizon lines. Each vertical and horizontal line on the grid is made of a series of repeatedly single and double boards as shown in Figure 2b. The dimension of these boards is 15mm X 100mm X 600mm. These boards have holes on both ends so that they can be mounted into an united truss (Figure 2c). Under this principle, each cross joint on the grid consists single and double boards on different directions. The connection slots among boards are reversed on each direction so that the entire structure can be reciprocal supported Figure 2d.

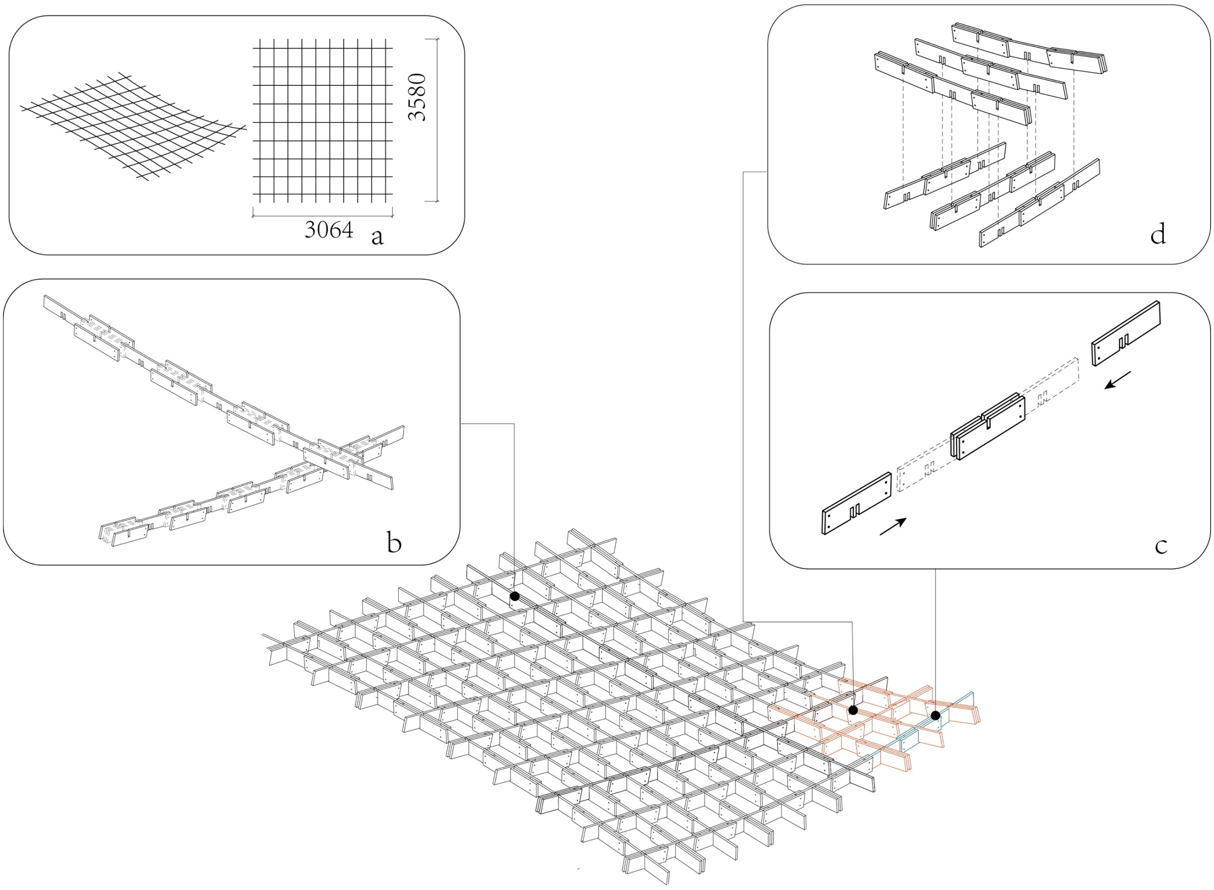

Figure 2: Design of the reciprocal structure: (a) overall dimension of the structure, (b) logistic of single and double boards connection, (c) holes for mounting neighbour boards, (d) notches for connecting cross joints.

3.1. Auto generation of the reciprocal structure

The digital model of our reciprocal structure was generated in the Rhinoceros-Grasshopper interface. Once a double curved surface was upload, it would be subdivided into a grid in its plan view. The node on the surface grid were extracted to transform the interpolated curves into poly lines. Subsequently, we found the middle points of these poly lines and connect them in sequence as the guide lines for each truss member. Each guide line was extended 35mm on both ends to create intersections with neighbour boards for the eventual connection. These extended guide lines were then distinguished into odd and even based on their sequence numbers along each direction. The odd guide lines were offset 15mm on both sides for the creation of double boards on one direction. For the other direction, even guide lines were offset. A rectangle cross section was added to one of the ends of each guide line to be swept into a board. The orientation of these rectangles were further examined to insure the long sides following the vertical direction. In this scenario, the digital model of the reciprocal structure with accurate positions and dimensions of all the board members would be set.

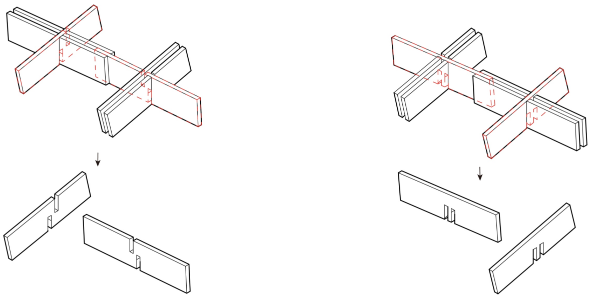

Figure 3: Notches arrangements: (a) notches on different sides, (b) notches on the same side.

In the following step, our script calculated the geometries of notches and holes for the assembly base on the intersections among all boards. As introduced in structural design section, each cross joint of boards connection had two boards on one direction and one board on the other. In this case, there must be two notches on the single board to be slotted with the twin boards. Once these two notches were on two different sides on the board (Figure 3a), the robot arm must mill from both sides which might inflict conflict with the clamping system that holds the board. To overcome this fabrication challenge, the two notches on the single board were set on the same side as shown in Figure 3b. In this circumstance, we set the notches on twin boards all pointing the down side while those on single boards pointing up for the ease of robotic milling.

We calculated the geometries of two intersections between the twin boards and the single board firstly. Then, two planes parallel to the world XY plane were drawn based on the volumetric centers of these intersections. These planes split the intersections into upper and bottom parts. By calculating the differences of twin boards with bottom parts and single boards with upper parts, we could get the designated geometries (Figure 4a). For generating the holes to bolt the neighbour boards together, we calculated the intersections of the projections along the perpendicular directions of these neighbour boards. Then we found the area centers of these intersections. By moving the area centers up and down along Z axis, the center positions of two holes could be confirmed(Figure 4b).

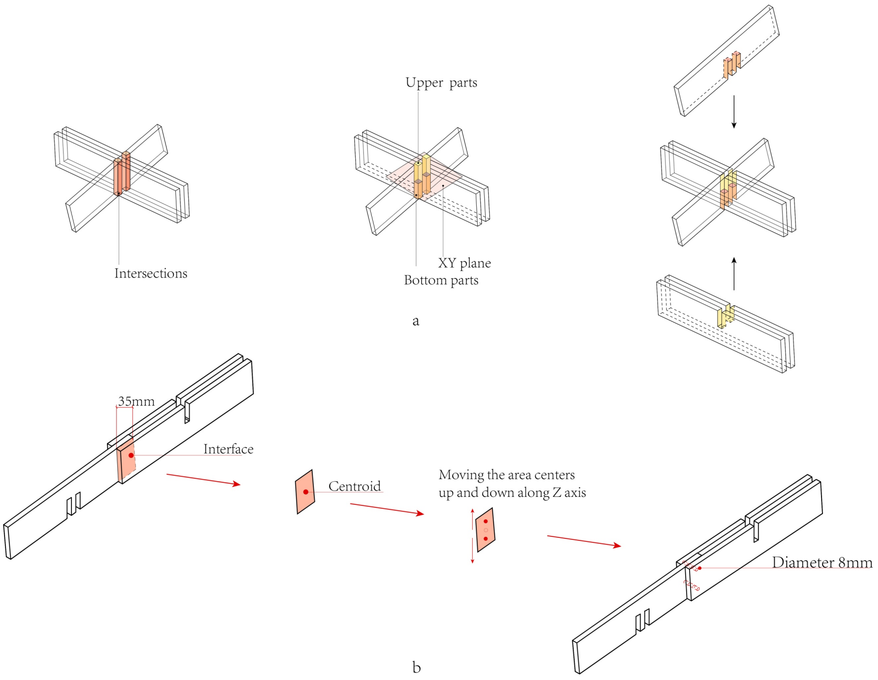

Figure 4: Generations of notches and holes.

We ran a structural analysis to gain a general concept of the structural performance of this reciprocal grid. The analysis was executed via millepede. We extracted the guide lines introduced in the first paragraph of this section as the simulation model. Three supports were added in the same manner of the final installation. The material property was set as 10 GPa in modulus of elasticity, 0.3 in Poisson ratio and 450 kg/m³ in density. There was a tiny displacement less than 0.1 mm detected through the analysis as the result shown in Figure 5.

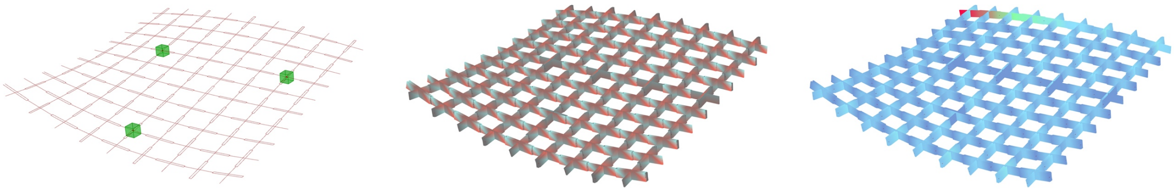

Figure 5: Structural analysis. From left: simulation model, stress distribution, displacement.

3.2. Generation of milling tool paths

For the ease of generating the robotic milling tool paths, we firstly oriented all boards from their original positions in the space frame to the same coordinate. To ensure all notches facing the same direction, we identified the volumetric centers of all boards as the volumetric centers must be on the different sides to the notches. Once the geometric models of boards were in the correct positions and orientations, the tool paths were generated in the sequence A to R from drilling holes to milling notches as presented in Figure x. There were maximum eight holes to be drilled on each board among which EFGH were for giving the slotting tolerance in assembly (Figure 6). The drilling positions and angles were decided by the center lines of the holes. As for the notches millings, the paths were following the edge on one side of the board while the angle of drill was determined by the relative positions of the two edges on both sides of the boards.

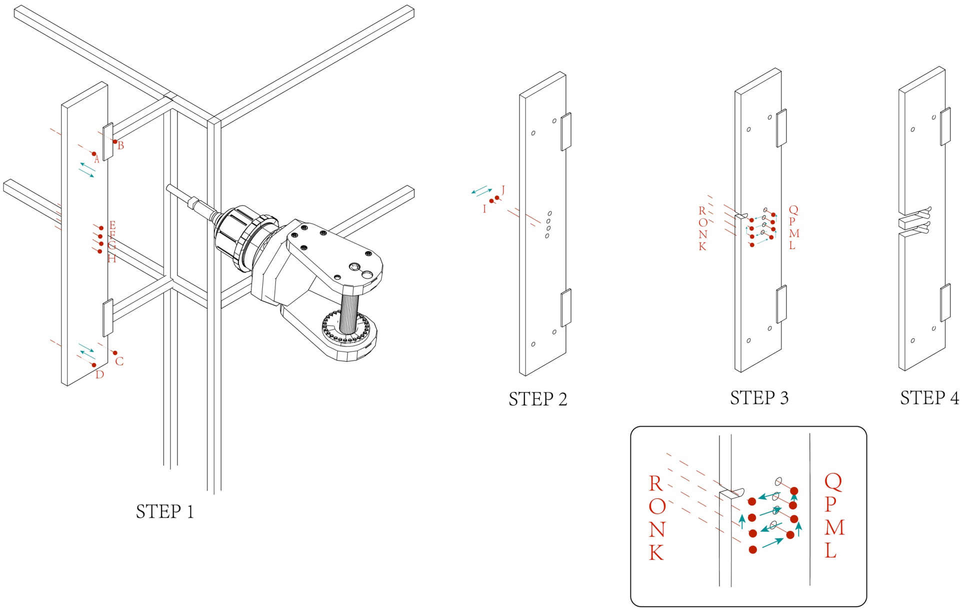

Figure 6: Tool path generation for drilling and milling processes.

4.Fabrication

4.1.Robotic setup

Our fabrication workcell consisted a KUKA KR 210 R2700 robotic arm attached with a 9kw electric spindle with a maximum speed of 24000rpm. The clamping system was built up with an aluminium frame with two clamps extended 200mm out of the frame to avoid the collides with the robotic arm in the angled milling process. The clamps held the boards perpendicular to floor which offered the flexibility for the robot movement. The distance between these two clamps was set as 400mm which successfully stabilize the boards during milling and enabled all fabrication proceeded within this range（Figure 7）.

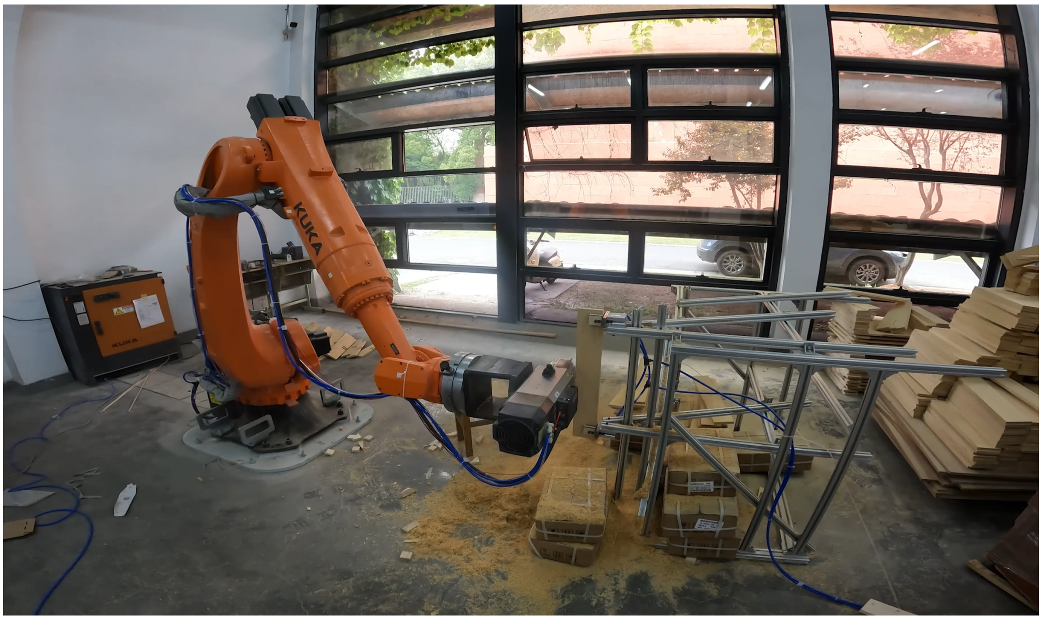

Figure 7: Setup of the fabrication system.

4.2.Milling tests

Ahead of the fabrication of final artifact, we ran multiple milling tests to calibrate the milling parameters according to the material, pine boards. As the designated pine boards were relative thin with thicknesses of 15mm, we decided to mill them through in single movement other than subtract material in progressive layers. In this case, the setup of spindle rotary speed and spindle movement velocity were crucial. Therefore, the objective of this experiment was to acquire a suitable rotary speed and movement velocity combination in conformity with the geometrical accuracy and flatness of the cuts. Through the experiment, we gained the conclusion that with higher rotary speed and lower movement velocity (Table 1), the cuts were more accurate and flatter. Another observation was with lower rotary speed less than 17400rpm and higher movement velocity more than 10mm/s, the clamping system tended to vibrate. In this scenario, the final fabrication parameters were set as 18600rpm for rotary speed and 10mm for movement velocity. While the spindle was free travelling, the movement velocity was given to 500mm/s for efficiency.

Spindle movement velocity Spindle rotary speed	1mm/s	2mm/s	6mm/s	10mm/s
12600rpm				
15000rpm				
16200rpm				
17400rpm				
18600rpm				

Table 1: Milling experiments in various combinations of spindle movement velocities and rotary speed.

4.3.Adjustment of the tool path

Through fabrication, we found that the outer layer of pine on the edge tended to be peeled off while the drill finishing the cuts (Figure 8a). To overcome this material challenge, we added a pre-cut procedure that milled the final target point along the tool path in advance to cut off the outer layer ensuring a clean finish (Figure 8b). In terms of the R angle issue, we shifted the corner nodes 2.8mm out along the outside angle bisectors (Figure 8c). In the milling process, the tool path should be offset inwards with the radius of the drill to ensure the edge surfaces were at the correct position. However, the drill might remove more material with higher rotary speed, which enlarged the dimensions of the slots. In our setup, the tool path was offset 3.75mm inwards as the drill radius was 4mm under the rotary speed of 18600rpm to ensure the accurate dimension of the notches.

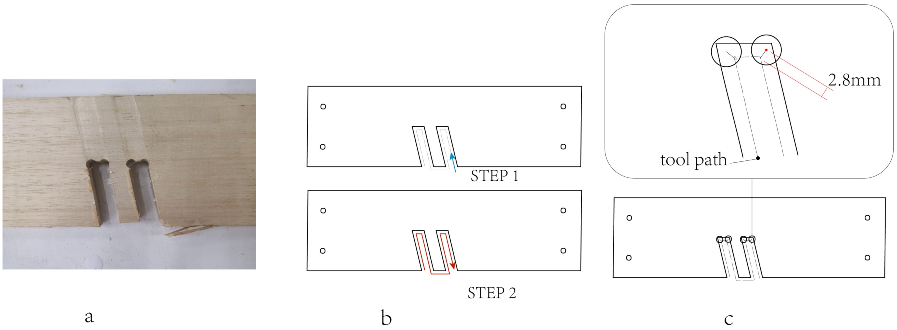

Figure 8: Adjustment of the tool path: (a) peels at finishing cuts, (b) tool path of the pre-cut, (c) solutions to resolve R angle issues.

5. Results

There were 270 boards in total produced within 15 hours. Despite the material loading time, each structural member took 116s to be fabricated in average. The assembly of the structure were executed by two inexperienced students utilizing a rubber hammer and an electric wrench. They followed the instruction generated by the computational script which demonstrated the positions, orientations and directions of all boards that could also be sorted by their indexes. The assembly process took place with boards milling simultaneously. While a row in the number of thirty of boards were milled, they were sent to be assembled. We built up the cross joints firstly, then mounted them with each other with screws and nuts. Once a row was finished, it was connected to the previous row in the following step. The entire construction process was accomplished within 5 hours, namely assembly of each row took roughly half an hour to be finished (Figure 9). The installation was smooth that all the notches and holes were in accurate positions. After the installation test, the structure was disassembled into two parts, transported to the set and reassembled for exhibition. No obvious displacement was detected through the whole process.

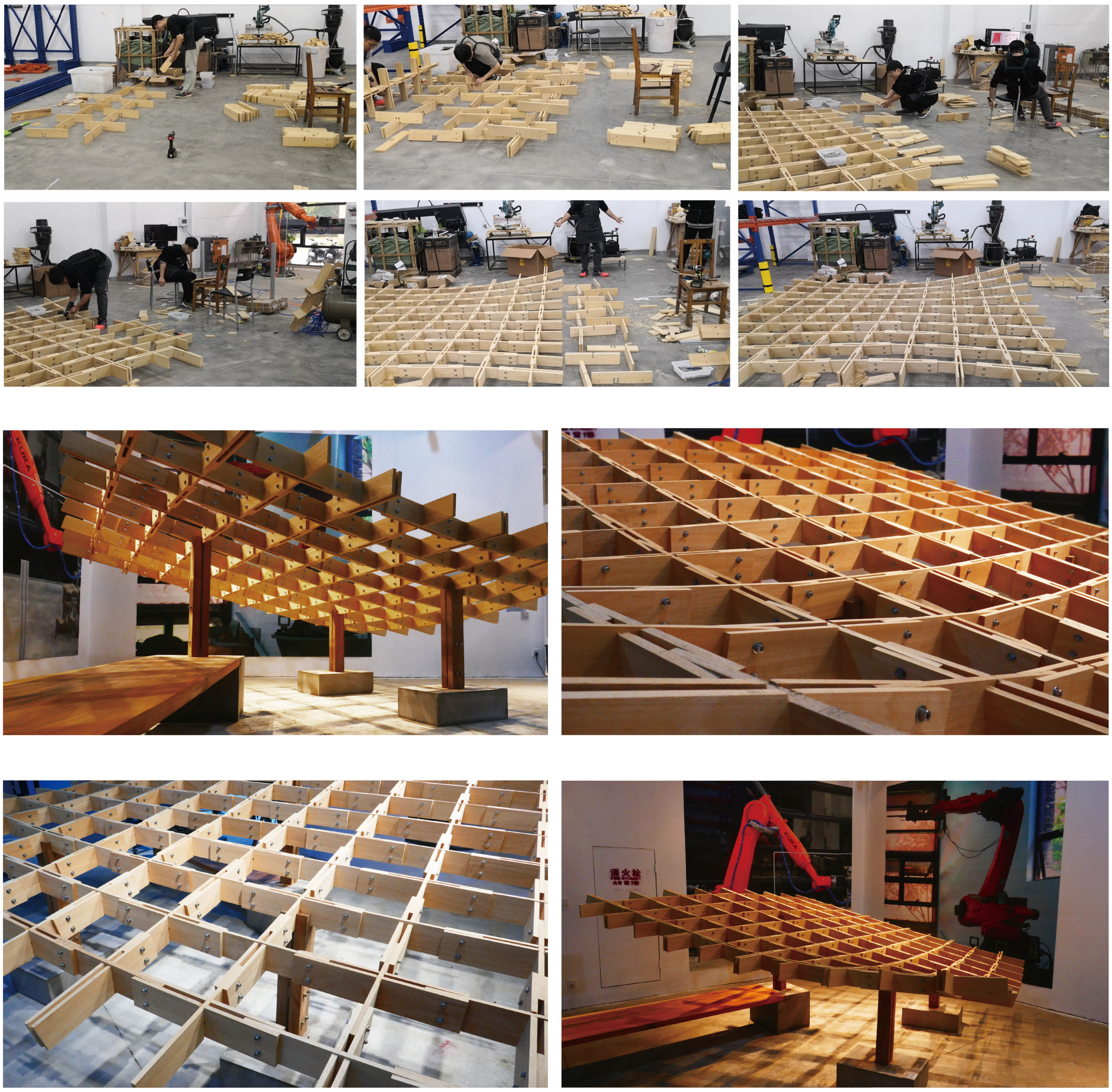

Figure 9: Installation and final outcome of the reciprocal structure.

6. Conclusion and future works

This paper demonstrates a digital design to fabrication workflow for the production of a double-curved timber reciprocal grid. There are three main advantages of this system. First, the design to fabrication process is fully automated which offers an ease for designers and construction workers to produce timber structures in free form geometries. This workflow has been tested by inexperienced students as workers that there is virtually no issues from fabrication of the boards to installation. Second, it utilizes small timber members to construct structures in a relatively large span. The overall volume of all timber boards is 0.182 m^3 which can be transformed to a grid shell with an over 10 m^2 surface area. Third, it offers the flexibility on crowded constructed sites as the structural members are manipulable and the installation does not require heavy machinery. Nonetheless, the curvature of the structure is limited by the clamping system that larger curvature requires larger robotic milling angles which may cause the collides between the robotic arm and the clamping frame. The structure has not been tested in a larger architectural scale neither. To respond, our future works will focus on improving the clamping system to enlarge the curvature limitation, expanding the achievable scale and exploring more structural forms than shells.

References

[1] M.Burry and J.Burry, *The New Mathematics of Architecture*, Thames and Hudson,2010.

[2] F.Gramazio and M. Kohler, *The Robotic Touch: How Robots Change Architecture*, Zurich,2015.

[3] A. Thoma, A. Adel, H. Matthias, W. Thomas, G. Fabio, and K. Matthias, "Robotic fabrication of bespoke timber frame modules", *Robotic Fabrication in Architecture, Art and Design 2018,* pp.447–458, 2018.

[4] A. A. Apolinarska, R. Bärtschi, R. Furrer, F. Gramazio, and M. Kohler, "Mastering the'Sequential Roof' - Computational Methods for Integrating Design, Structural Analysis, and Robotic Fabrication," *Advances in Architectural Geometry 2016,* pp. 240–258, 2016.

[5] A. Adelzadeh,H. Karimian-Aliabadi,K. Ahlund and C. Robeller, "ReciprocalShell A hybrid timber system for robotically-fabricated lightweight shell structures." *The 41st Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2023),* vol. 1, Graz, pp.651-660,2023

[6] G. Brown, "Three dimensional structures",United Kingdom, Patent GB2235479B, 1989.

[7] J. P. Rizzuto, "New Shell And Spatial Structures: Extended Abstracts, Notched Mutually Supported Element (MSE) Circuits In Space Structures", Proceedings of IASSAPCS Symposium on New Olympics, Beijing University of Technology, Beijing, China, 2006.

[8] O. Baverel, "A review of woven structures with focus on reciprocal systems -Nexorades", *International Journal of Space Structures,* vol. 26, no. 44, pp.281-288 , 2011.

[9] J. C. Chilton, B. S. Choo and O. Popovich,"Reciprocal frames – Past, present and future". *International Conference on Lightweight Structures in Civil Engineering* , pp.26-29, 1995.

[10] R. Araullo,"3D Growth Morphology - Tectonics of Custom Shapes in Reciprocal Systems", T*he 23rd CAADRIA Conference,* vol. 1, pp.307-361,2018

[11] T. Bowie, *The sketchbook of Villard de Honnecourt,* London,1959

[12] T. Kohlhammer, A. Apolinarska, F. Gramazio, and M. Kohler,"Design and structural analysis of complex timber structures with glued T-joint connections for robotic assembly. "*International Journal of Space Structures,* vol. 32, no. 3-4, pp. 199-215, 2017.