Spatial Timber Assembly

Robotically Fabricated Reciprocal Frame Wall

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Though highly robust and economical, traditional lamella and reciprocal structural systems cannot adapt to surfaces with complex double curvature; as the timber members are standardized with no variation. Recent research has explored the use of computation for design, structural optimization, and use of robotic systems for the automated fabrication of timber joints. The disconnection between fabrication and assembly makes the construction of non-uniform double-curved reciprocal frames challenging, due to the required precise placement of discrete members with compound angle butt joints. This project investigates the use of robotic fabrication to cut and assemble a timber reciprocal frame assembly. A computational model was created to generate the double-curved reciprocal frame geometry. Within this computational framework, joint analysis, fabrication, and assembly were monitored and adjusted to meet limiting factors. An industrial robot was implemented as a bridge between the computational model and the physical construction. This paper presents a number of novel computational and robotic fabrication techniques in designing, cutting, and positioning. These techniques were explored through the robotic fabrication and assembly of a demonstrator - a double-curved reciprocal frame wall.

Keywords: *Robotic Fabrication, Reciprocal Frame, Prototyping*

INTRODUCTION

History - Reciprocal Frame and the Lamella System

Reciprocal frame structures, also known as nexorades, consist of short linear structural elements, with nodes offset along the centerline vector of an adjacent member in the system, generating a mutually supporting structural network (Figure 3). As a result, each connection point only involves two structural members, making it easy to assemble. The construction of reciprocal structures can be traced back to medieval times, when timber shortage required efficient use of material. Although the reciprocal system lacks structural redundancy (Douthe et al. 2009), its high malleability and efficient use of material have attracted growing interests among architects and engineers. Using computation and digital fabrication tools, contemporary research aims to expand on the geometric adaptability of reciprocal frames. Reciprocal frames were notably documented in Leonardo da Vinci's sketches in 'Codex Atlanticus', where da Vinci explored various reciprocal patterns and uses (Thönnissen, 2015). In 1921, the lamella system was invented by German engineer Fredrick Zollinger (Zollinger, 1924), based on a similar set of rules to utilize short structural members for roof construction for houses, barns, hangers and other storage facilities, most of which follow symmetrical forms such as barrel vault and domes.

Previous Research in Reciprocal Frame Structures

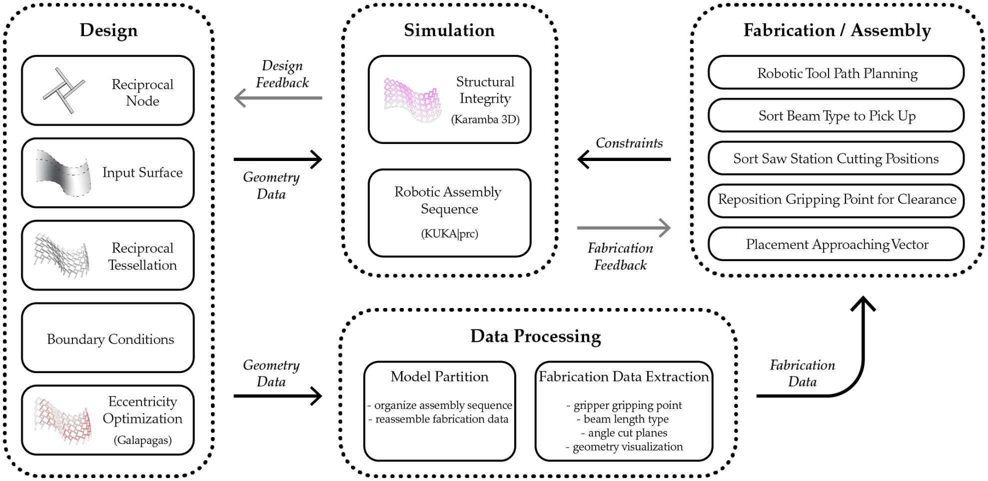
While most architectural applications of reciprocal frames are in simple symmetrical forms, the reciprocal frames built in the academic research settings are often non-uniform and cater towards cultivating students' hands on skills. Recent development on reciprocal frames was driven by the use of computation design methods from form-finding to digital fabrication. One of the most notable recent examples was the shell-nexorade pavilion by Romain Mesnil et al. (2018) from ThinkShell at the Laboratoire Navier, Ecole des Ponts ParisTech. Form-finding and robotic fabrication was used in this research. Their fabrication method employed a multi-robotic setup for milling the timber beams and panels. With 102 beams and 48 plywood panels, the pavilion was assembled on site without the use of robotics for positioning and fixing. On the other hand, research on spatial assembly has been conducted by Gramazio Kohler Research at the ETH Zürich (Eversmann et al. 2017; Kohlhammer et al. 2017; Parascho et al 2017; Adel et al. 2018). These research projects aimed to streamline the fabrication and assembly process to create large prefabricated modules from a series of discrete small pieces. This process preserves the element's identity information throughout fabrication and assembly, making building complex spatial structures less labour intensive. The use of structural reciprocity in their research was employed to resolve complex connections between small sized materials, which the robots were capable of processing.

Robotic Spatial Assembly of Reciprocal Timber Frames

The research presented here builds upon this recent research by integrating fabrication and robotic assembly, and extending the capabilities of fabrication and construction of doubly-curved reciprocal lattice structures. This paper discusses the processes involved in making a reciprocal lattice wall prototype. The overall workflow (Figure 1) outlines the four modules of the process: design, simulation, data processing and fabrication. The design module consists of geometry design, control and optimization; this module outputs geometry information for simulation and data processing. The simulation module takes input from both the design and the fabrication module constraints and provides output feedback for design adjustment and fabrication setup. The geometry data is processed to extract key information, such as gripping points and cut planes, and package the data for the fabrication procedure. The fabrication module translates the data into physical movement of the robotic arm; this process involves picking, cutting and placing material following a prescribed sequence. It is capable of making individual adjustments to accommodate fabrication needs for unusual beam geometries.

In the Method section, a computational approach is presented for the generation of non-uniform reciprocal frame structures for robotic fabrication. This novel geometric generation method is then coupled with structural simulation and geometric eccentricity analysis. In the Fabrication section, the robotic cell and tooling approach is presented. Through analysis of the computational model, fabrication tools and systems were designed to meet the limiting geometric factors presented in the Method section. We conclude by discussing the future potentials for the development of non-uniform construction of reciprocal frame systems.

Figure 1
The overall workflow of our spatial assembly of reciprocal lattice structure.



METHODS

This section contains a detailed description of the geometry development for surface subdivision for reciprocal frame generation. The focus was placed upon creating a simple quadrilateral reciprocal tessellated double-curved lattice with butt T-joints. In order for the structure to be buildable, the geometry was optimized to reduce eccentricity. This procedure ensured each connection point meets the minimum requirement for mechanical attachment. The reorganized geometry data was then simulated in a virtual environment to establish a collision free construction process.

Geometry Generation

Contemporary research (Thönnissen 2014, Mesnil et al. 2018, Apolinaskar 2018) utilizes mesh tessellation to generate reciprocal patterns, allowing other operations such as form-finding and structural optimization. The research method presented here, however, used UV division of NURBS surfaces, a more common method among architects. The final reciprocal lattice prototype employed a single direction quadrilateral reciprocal pattern which was created with the following steps (Figure 2):

1. A double-curved surface was created by lofting three curves with different curvature.
2. This input surface was then subdivided in U and V directions. The minimum spacing was based on fabrication requirements, in this case, the width of the gripper.
3. A reciprocal pattern was created through the rotation of UV grid segments around their respective midpoints, normal to the input surface. Each segment represented the centreline of an individual beam.
4. The beam dimensions for the demonstrator were approximately 44mm by 33mm.The four sides of a rectangular beam was created by offsetting four planes around its centre line. The ends of the beam were cut off by the side of two adjacent crossing beams. Therefore, the compound end plane of the beam was one of the side planes of the adjacent crossing beam. Using plane to plane intersection lines, a solid beam geometry was created by lofting the intersection lines on both ends of the beam.

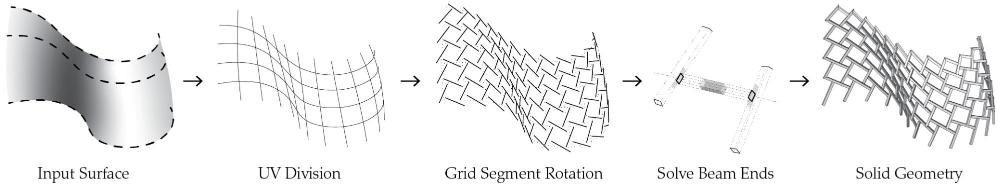


Figure 2
Reciprocal geometries were generated through tessellation of a double-curved surface.

Eccentricity Analysis

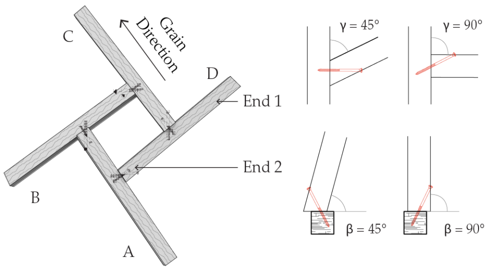


Figure 3
A reciprocal node where End 2 of D is supported by A, and End 2 of A is supported by B and so on (Baverel 2000). The logic repeats with End 1 supported by a member in another node. A minimum of two screws at each connection point was required for secure attachment. The zoomed in details illustrate the fastening technique we used in two scenarios, viewing from two different angles.

Eccentricity is defined as the distance between the axes of two attaching members (Mesnil et al, 2018). With the intention of using butt T-joints, a mechanical fastening method with wood screws was used in this research (Figure 3). A minimum of two screws at each connection point was required for secure attachment. This joining method required an adequate amount of contact area between the two joining beams. As the result of using a doubly-curved surface and a reciprocal-frame pattern, the eccentricity among beams would always be greater than zero. Therefore, the following steps were employed to minimize the eccentricity (Figure 4):

1. The collection of beams were divided into two groups of non intersecting beams. The positions of the two groups could be adjusted along each beam's surface normal vectors (refer to Geometry Generation) based on the average distance of the four connecting points at each beam. This method redistributed the eccentricity of a joint to other neighbouring joints.
2. The rotation of the beam (equivalent to the engagement length) could also control the eccentricity: the less the rotation, the less the eccentricity. As a result, the eccentricity could be reduced by locating an attractor point at the location of high eccentricity to reduce pattern rotations.
3. Lastly, the geometry of the input surface was another influencing factor. High curvature regions of the input surface typically results in high eccentricity. Adjustment was made to reduce surface curvature.

Genetic algorithm, Galapagos, was used to solve for the minimum eccentricity using the combination of the first two techniques to produce the final geometry for the demonstrator. A total of five genomes were used: the adjustment factors for the two groups of non-intersecting beams and the location of the attractor. 160 generations with a population of 50 each was computed, and the eccentricity was reduced from the original 40mm down to 28mm.

Simulation

Two simulations were conducted: one to evaluate the structural integrity of the reciprocal geometry, the other was the robotic path planning. Based on the simulation feedback, the design of input surface, robotic routine, and placement of geometry on the build platform were adjusted.

Figure 4
Steps were taken to reduce the eccentricity in order to create enough contact area at joints.

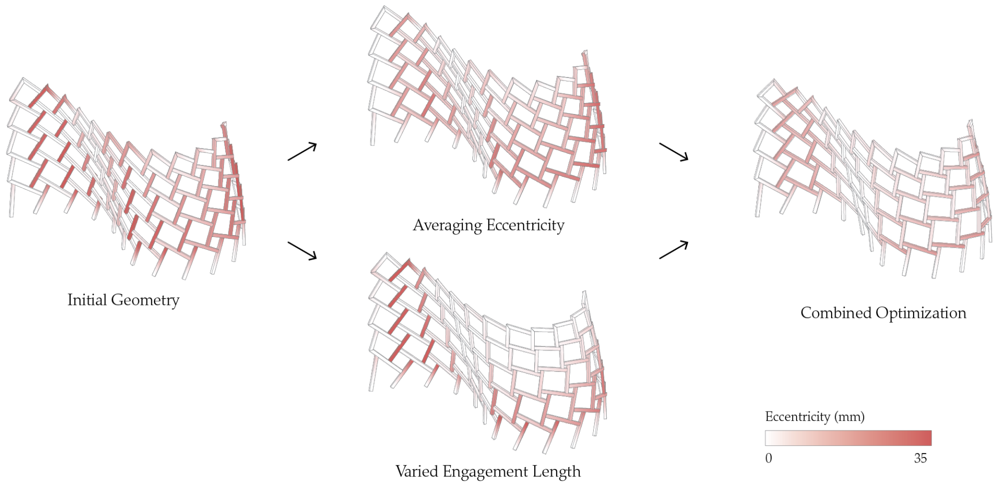
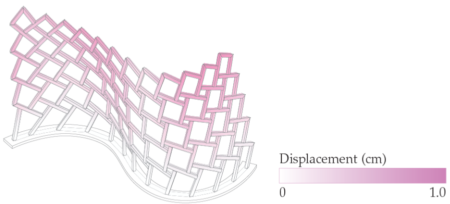


Figure 5
Structural simulation was done using Karamba 3D.



For the structural simulation, Karamba 3D plugin was used. Besides the gravity load, two point loads of 330N each were exerted on the two concave sides of the prototype lattice to simulate observers leaning against it. Wood material with Young's modulus of 1050 kN/sq.cm was used, while the base of the lattice was presumed to be fixed to the ground with rigid joints. The simulation indicated the prototype would have a maximum of displacement around 0.75cm at the top (Figure 5). The structural simulation provided feedback for design adjustment.

The fabrication and assembly processes were simulated within the Rhino Grasshopper environment using the KUKA|prc plugin, which writes KRL commands for robot controllers. The fabrication data, such as gripping point, beam length type, cut planes and sequence were extracted from the geometry model and packaged into individual beam units. The script simulated the robotic movement throughout while highlighting potential collisions; it evaluated the design of fabrication procedures. This feedback was used to improve the fabrication process. Mitigation for collisions include: repositioning structure on the build platform, shifting gripper gripping points, changing cutting positions, regripping between cutting and placing, adding or adjusting safe planes between steps, as well as adjusting placement approaching vectors. The final fabrication and assembly procedure singled out special scenarios such as short beams, special cut angles, etc. to apply above mentioned additional mitigation measures; approximately 36% of beams in the prototype required fabrication adjustment.

FABRICATION SYSTEM AND TOOLS

In order to construct the doubly curved reciprocal frame prototype, we designed and developed a robotic fabrication system capable of gripping, cutting compound angles, and positioning cut timber elements in the placement position. The quadrilateral reciprocal frame required a specific set of robotic routines to be defined for the fabrication procedure, this was achieved by developing integrated systems between multiple toolings through the main program logic controller to the Kuka controller via ethercat. The fabrication procedure calls upon this tooling for the robotic routine the material pickup, cutting and assembly of the reciprocal lattice wall.

Design of Robotic Cell Setup

The robotic cell was designed as a multifunctional robotic system for timber construction. The system was designed and implemented to process a variety of processed and unprocessed linear timber along with wood panels in various dimensions. The Kuka robotic arm was equipped with an automatic robotic tool changer, allowing a variety of tools to be controlled from the integrated system PLC for wood fabrication.

Robotic Cell Components, one industrial Kuka robotic arm mounted a linear axis 5m in length. The robotic cell featured two build platforms (one at 3m by 2m and the other at 1.5m by 2m), a Schunk pneumatic parallel gripper for material holding during the robotic routine, and a linear actuated saw station. The setup is depicted in (Figure 7) The entire cell was integrated into a safety PLC for operator control and safety. Robotic routines were stored in the system module (e.g. Saw activation/linear saw control/gripper control), these functions can be called directly from the generated robot code.

Robotic Cell Security, working within the robotic cell to allow for fast continuous construction, a specific set of security protocols were in place to minimize operating risk. The operator was protected at all times when the robot was running a routine behind a polycarbonate shield. The robotic controller was limited to a manual mode speed of 250mm/s, as the path planning was simulated in the KUKA|prc through a number of repetitive steps with variable positions for cutting and placement within the robotic fabrication loop. Due to these variable positions, the robot was limited to manual mode to mitigate robotic code simulation discrepancies.

Robotic Tooling Development

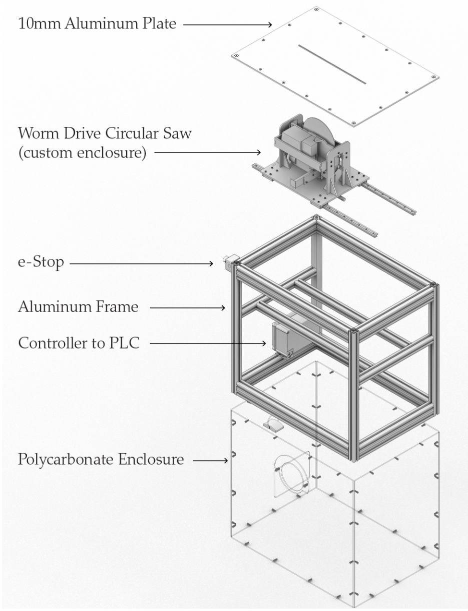
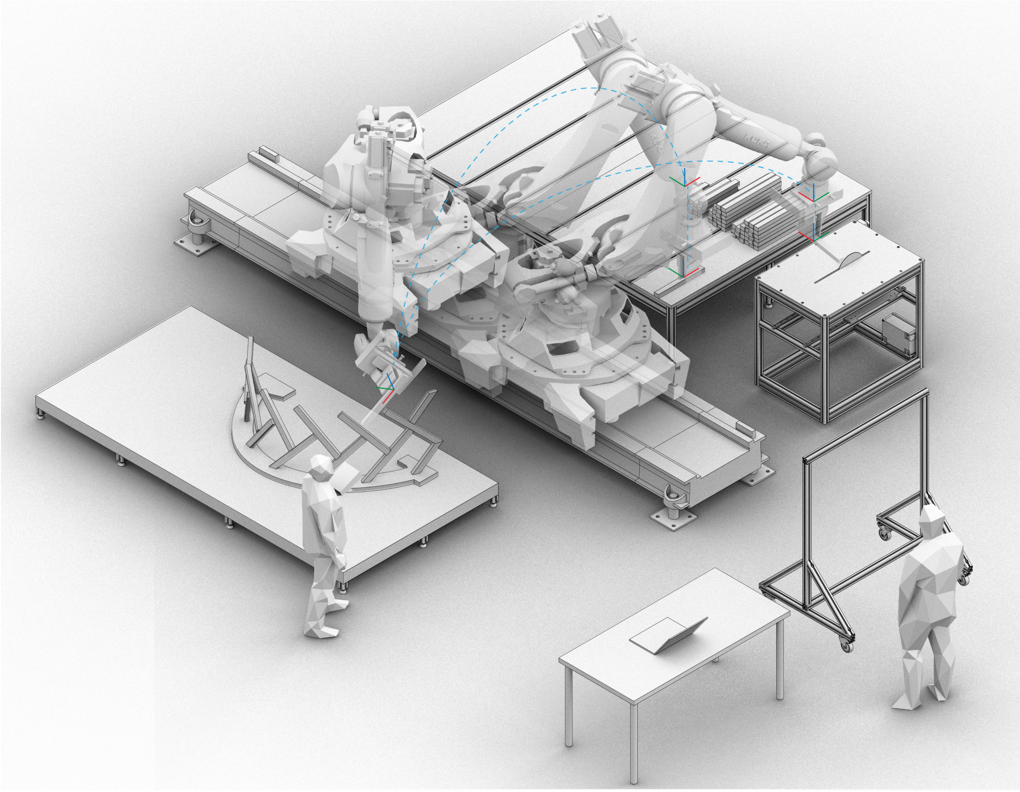


Figure 6
An exploded view of the saw assembly.

The generated geometric model allowed for constraint based analysis of the fabrication tooling. Development of gripping, cutting and placement was analyzed within the reciprocal frame computational model to re-inform the computational model for limiting factors, while generating specific requirements for the integrated robotic tooling. In order to precisely cut the compound angles within the reciprocal lattice structure, we developed a linear actuated saw integrated with the control PLC for calling from function within robot code. The saw (Figure 6) was constructed from a series of components (1) a worm drive saw with a 130mm blade mounted in a custom frame assembly, (2) a linear actuator with a speed of 41 mm/second, (3) control box for PLC integra-

Figure 7
Robotic Fabrication Cell: 1 platform for reciprocal frame construction, 1 sorting and pickup platform, linear actuated sawing station, KR150 R2700 with 5m linear axis, Schunk pneumatic parallel gripper, safety shield for robotic operator.



tion and saw control, (4) structural frame with polycarbonate enclosure. The saw traveled along linear rails via the actuator, allowing a cutting distance of 200mm with 76mm cutting height. The linear actuated saw was integrated through the security PLC and control PLC to allow for saw activation and linear activation from KRL robotic code. The functions defined within the Kuka controller module allowed for the linear travel time domain to be updated the length of cut in the cross sectional area of the beam.

Fabrication and Assembly Procedure

The fabrication loop comprised a series of primary steps which were augmented with subroutines dependent upon the beam analysis. The primary robotic fabrication loop consisted of material pickup (Figure 8a), material cutting (Figure 8b) and then positioning to final placement for fixing (Figure 8c). Within material pickup a sorting algorithm was run to generate a series of rough pre-cut lengths, these lengths were assigned to pick up locations on the material platform, allowing the robotic code to pick up the rough cut length based on the cut beam length. The beam was cut at both ends by orienting the compound cutting plane to the saw blade plane. Due to saw limitations, rough cut material was trimmed to desired length prior to the compound cut procedure. Therefore, each beam was cut twice at each

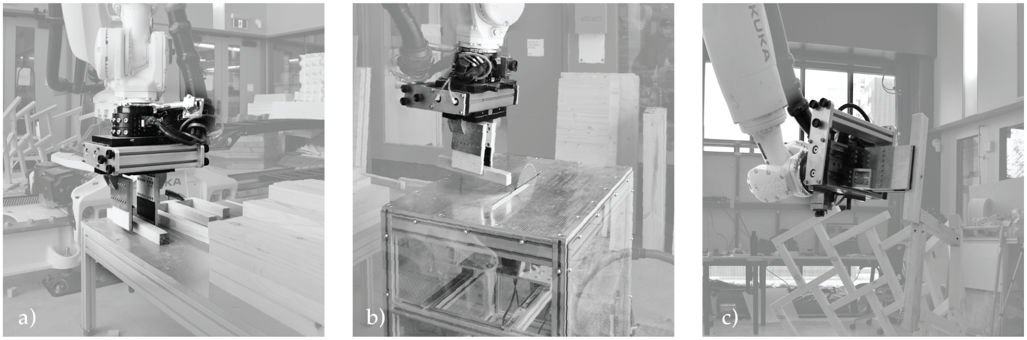


Figure 8
a) Robotic pick-up station, with four predefined rough beam lengths; b) Robotic cutting with linear actuated saw station; c) Placement of timber element for mechanical fastener securing.

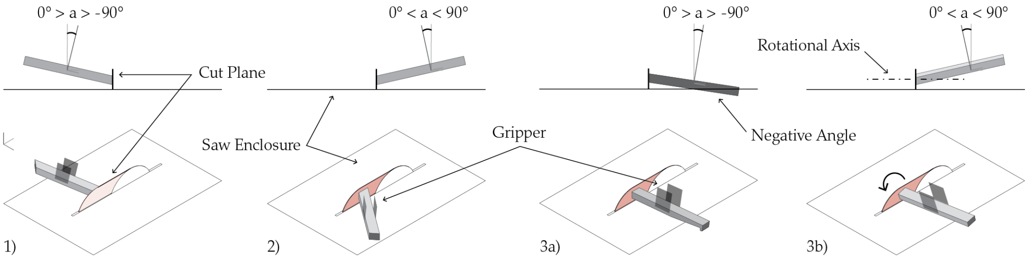


Figure 9
Cutting positions at the saw; the sequence of solutions was filtered until no collision was found.

end. Within our research all cutting angles could be resolved by filtering the beam planes through a set of subroutines for saw positioning (Figure 9):

1. All beam cut planes were first oriented to the left cut plane of the blade.
2. If the angle between the table saw surface and the subject beam was negative, meaning the beam would collide with the saw, the right cut plane of the blade would be used.
3. If the use of the right cut plane still resulted in a negative angle, the beam would be called out and rotated manually around the normal of the cut plane until the angle was no longer negative.

The final step for the robot arm was to position the cut beam for fixing. In order to avoid collisions and guarantee adequate amount of maneuverable space for the positioning, we concluded that the approaching vector to the final placement should be derived from the beam's end plane that would come in contact with the assembled elements. The technique was to allow the beam to reach the assembled beam at a diagonal angle, and adjust discrepancy in the assembled structure along its way.

While the beam was being held in place, it was manually attached to the two installed beams with wood screws. Holes were calculated and manually pre-drilled to avoid splitting the wood. The screw went in along the grains of the beam into the other which had wood grains crossing the screw's direction (Figure 3), allowing the screw threads to bite into the wood grain.

CONCLUSION AND DISCUSSION

The goal of our research was to encapsulate a computational design model which could re-inform the fabrication system through joint, timber and geometries limitations. The developed computational model allowed for the input of doubly curved surfaces to UV mapping subdivision. This has proven to be a robust analysis tool for evaluation of the capabilities of discrete linear timber elements to propagate the input surface parameters. The immediate feedback of the eccentricity analysis allowed the manipulation of the design surface to meet limiting factors of geometry due to higher degrees of curvature. Through the eccentricity genetic algorithm, adjustments were made to minimize the global level of eccentricity within the generated reciprocal lattice structure. The computational design tool performed the fabrication analysis of the timber elements to meet the minimum tolerance within the developed robotic system. The developed robotic fabrication tooling and system has proven to be highly capable in the ability to construct the doubly curved reciprocal lattice structure. Through the successful design and construction of the reciprocal lattice wall, these computational tools coupled with a timber robotic fabrication cell have demonstrated doubly curved reciprocal lattice structures are within the scope of production.

The future development of this research is to scale up the fabrication prototype beyond the reciprocal frame lattice wall. Self-supporting reciprocal frames, doubly curved envelopes and canopies are to be explored in the future. Larger geometries can be parsed into manageable components to be prefabricated for assembly on site. This component system had proven stable in the development of the prototype wall, as two modules were fabricated and later assembled as one due to robotic envelope constraints. The reciprocal structural system developed has demonstrated to be robust without full physical structural testing. Mechanical fasteners were placed by hand with only pre-drilling as a means to choose placement. The pre-calculation of mechanical fastener fixing angles and points would allow for the further optimization of the structural capacity of the reciprocal lattice node. Future research would expand the structural computational model while also providing fabrication data for the precise location and angle. The robotic fabrication system can be developed from the analysis of the optimal mechanical fastener angles from the computational structural model. Allowing for further development of the fabrication system to allow for greater precision and expediting the construction.

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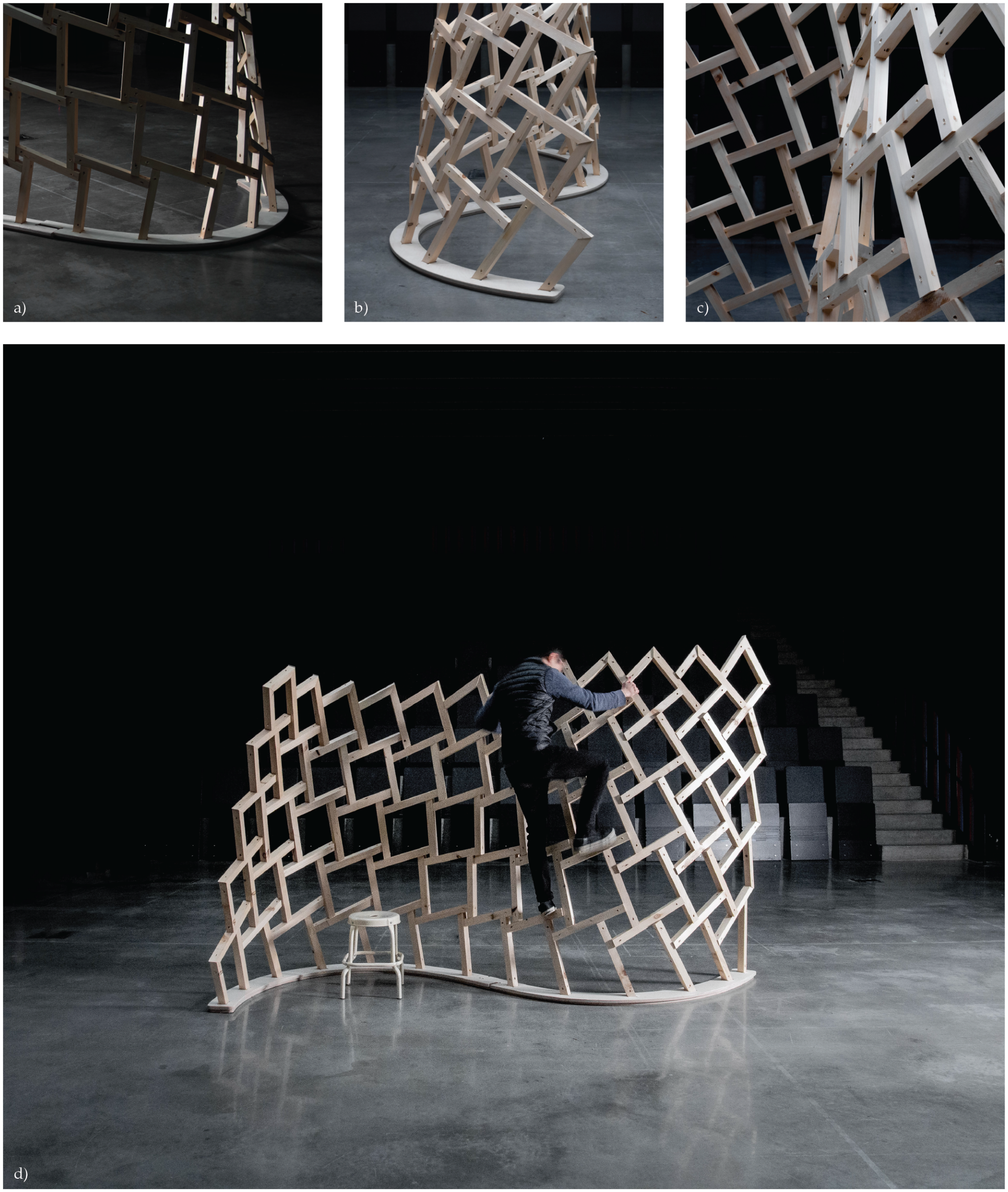

Figure 10
Module A of reciprocal wall B) Module B of reciprocal wall C) assembly of Module A and B D) overall assembly of reciprocal frame lattice wall.