LIMB: Inventory-Constrained Design Method for Application of Natural Tree Bifurcations as Heavy Timber Joinery

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ABSTRACT

LIMB is a project recently started at Taubman College at the University of Michigan to explore the potential use of natural tree bifurcations as a new joinery method in heavy timber construction.

This research studied the natural occurrence of branch bifurcations in different wood species to develop practical concepts for design and fabrication of timber joinery in a single bifurcated wood form which would replace traditional mortise and tenon or steel connections.

Through the design and fabrication of a full-scale reticulated dome, this research showed how organic variations in tree limb bifurcation bring about valuable and sustainable opportunities for generative architectural design of heavy timber construction.

Toward this goal, a hybrid physical/computational workflow was developed to study the application of these organic elements through the integration of computational design modelling and 5-axis digital fabrication. The computational workflow used the inventory of harvested tree crotches to inform the geometry of the dome to reduce material use and routing time; moreover, the workflow evaluated the structural performance of the dome geometry using finite element analysis under self-weight and environmental loads and provided performance and fabrication feedbacks which informed the design process.

This computational workflow was then integrated in a genetic-based form exploration process where variations in design parameters were studied through visual and quantified fabrication and structural feedback, and the final geometry was chosen based on visual aesthetics and fabrication constraints.

This fabrication and inventory-aware process was a proof of concept for practical application of tree branch bifurcation for full-scale construction. Beyond the reduction of waste and added value, this research explored opportunities for more organic and sustainable design and construction of heavy timber joinery in the industry.

1 INTRODUCTION

Historic precedents for the use of tree crotches in wood structures can be found in both 17th-century framing for naval vessels, as well as joinery in timber barn construction.[1] Presumably, this technique

Figure 1: Bent and bifurcated elements taken from natural tree sections, from l'Encyclopédie méthodique Marin.[1]

offered angular joints without complex mortise and tenon details. Additionally, this could achieve a degree of moment resistance that exceeded other joining techniques. These are demonstrated in Figure 1, which shows examples of the described use of natural tree bifurcations. In these cases, the wood grain naturally follows the shape of the piece.

More recently, Claus Mattheck at the Karlsruhe Institute of Technology carried out extensive physical testing of the behavior and strength of natural forked tree sections.[2] In his work, he also provided guidelines for the selection and defect detection in these pieces in nature. More extensive research was carried out on structural and fracture capacity of tree bifurcations in hazel (Corylus avellane) by Seray Özden et al.[3] This research studied the toughening mechanism of the tree forks through destructive fracture tests to study the fracture capacity of the interlocking wood grain that produces the critical join between branches at the apex of a hazel fork. Gareth Buckley et al.[4] studied the effect of the angle of inclination on the morphology and strength of bifurcations in hazel trees. The bifurcations were subjected to rupture tests until they failed, and the results show that, as the angle of inclination increased from 0 to 90 degrees, the rising branches became more elliptical in the vertical plane, theoretically increasing the bifurcation's bending strength in this plane. The diameter ratio was also found to be a significant factor in determining bifurcation yield strength in the samples tested.

This research studies the potentials of using tree bifurcations to take advantage of structural benefits of a joint with a single piece of wood that purposely grew under natural forces for bifurcation in nature. The structural connection is moved away from where the vertical and horizontal members come together to develop a more strongly constructed joint. Beyond the reduction of waste and added value, this project has the following architectural opportunities:

- Overall architectural effect relates to the natural occurrence of branch bifurcations and their formal implications in exposed structures such as roof trusses.
- A reusable system made from locally sourced materials that is environmentally conscious in its life cycle and transportable for future uses.
- The development of new ways of connecting linear timber elements beyond the "crotch" where universal scarf connections are revisited using digital fabrication.
- A structural system that is scalable to utilize many parts of a tree, from major tree bifurcations at the base suitable for large pavilions, to smaller bifurcations adaptable to furniture.

Recent researchers and designers have tried to use locally sourced trees directly in fabrication without the need for extensive processing. This included unprocessed tree bifurcations as truss elements or round timber as columns and structural elements.[5]

This research was developed based on a syntactical approach to design. The interest was not in unique form generation based on unique parts, something that is very well explored in the realm of digital fabrication, but rather constructing a reusable language of bifurcated joinery. This research elaborates on the natural occurrence of tree bifurcation as a tectonic element using contemporary digital practices to propose new timber construction systems.

We designed a digital fabrication workflow that extracted standardized milled parts from an inventory of salvaged material. The cataloging of recurring angles and other physical properties inherent to different species of trees allowed for further development of the structural possibilities of this system, which can be applied to nearly any type of tree bifurcation. This then allows for various combinations within the language of bifurcated timber joinery seen in Figure 2. Some of these combinations include:

1. Spatially optimized parametric branching nested structure for occupiable space.
2. Spatially optimized parametric hexagonal organic dome with multi angular facets.
3. Three-way triangulated columnar structure.
4. Two-way triangulated frame reminiscent of the traditional timber framing.

The goal of the work presented here was to make use of these naturally forked tree sections as joining elements in architectural structural systems. In this effort, we focus on the design and fabrication of a reticulated dome structure. The raw tree crotches were cut to size and milled to final form and dimensions in a 5-axis CNC router. The design intent was to produce standardized nodal elements that can be joined easily to connective strut elements. By using the CNC router, exact final angular and linear dimensions can be precisely attained.

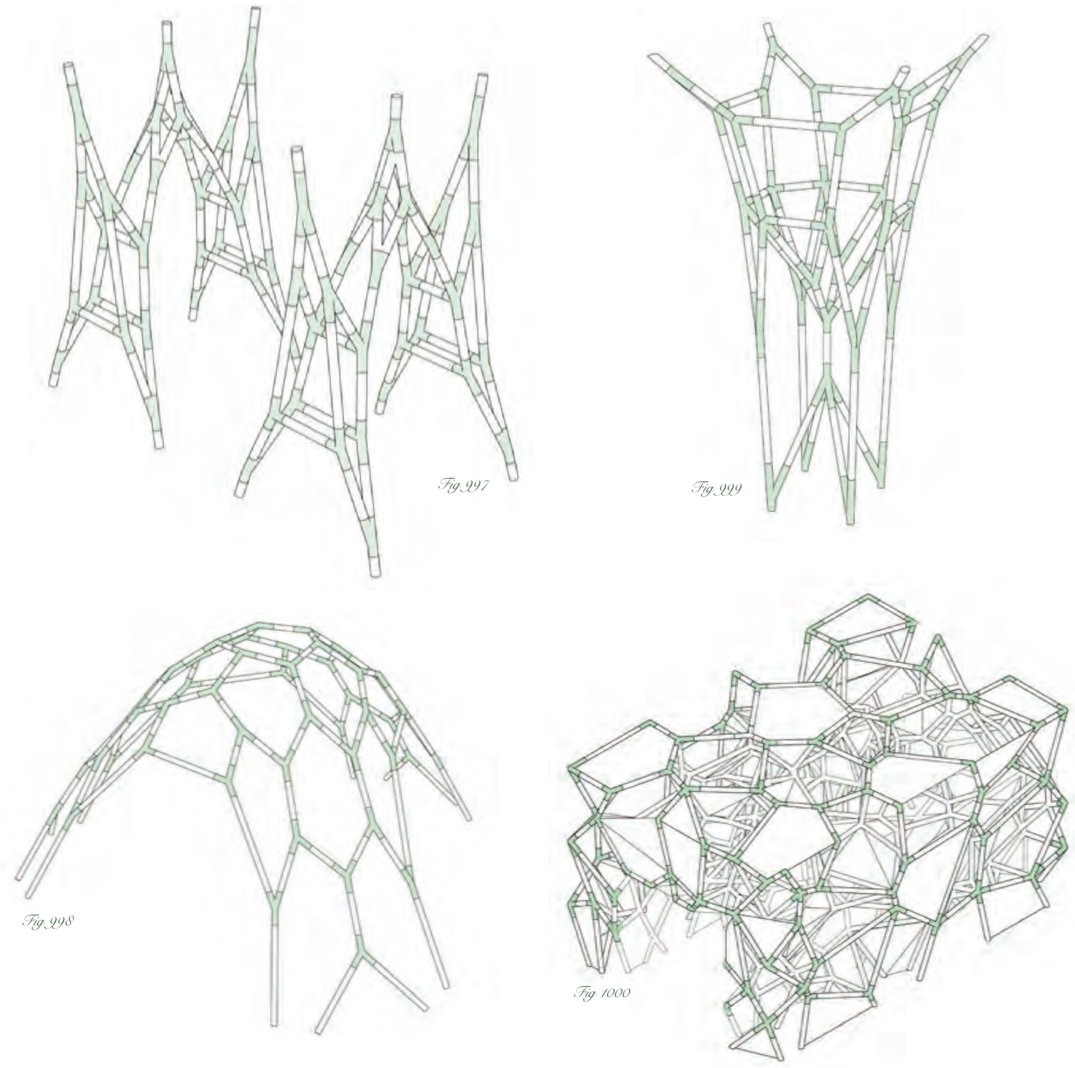

Figure 2: Different structural typologies proposed using tree bifurcation joinery.

2 DESIGN PROCESS

Natural forces in trees develop adaptive growth through the process of thigmomorphogenesis, which develops organic variations in size, shape, and fiber composition of tree bifurcations. This organic variation in tree crotches requires a specific design process that accommodates the uniqueness and variation of bifurcation geometry while also imposing a certain level of standardization for production.

Toward this goal, a computational workflow was developed to study the application of these organic elements through integration of computational design modelling and 5-axis digital fabrication. Through physical studies of the crotch geometries, key descriptive parameters of these limbs (e.g., dimensions and angular measures) were extracted as a data inventory which was then used in a computational process to determine the best fit of these crotches as structural joints.

The placement was determined through a novel two-step dynamic inventory-constrained form-finding process. This process imposed the available crotch geometries into the design geometry though iterative variation of local geometry to minimize the geometric discrepancies. As a fabrication aware process in this method, global geometry responded to organic crotch geometries in a bottom-up process that first informs the location of appropriate tree crotch in the design geometry and then iteratively minimizes the discrepancies of each crotch and its corresponding joint in the design geometry, leading to reduction in routing time and material use. This process transformed the design geometry into an organic shape which responds best to the available inventory of crotches. This method was implemented in Python, used dynamic relaxation formulation for minimization of discrepancies, and is compatible with different visual programming software. The process is scalable and adaptable for different design and structural typologies.

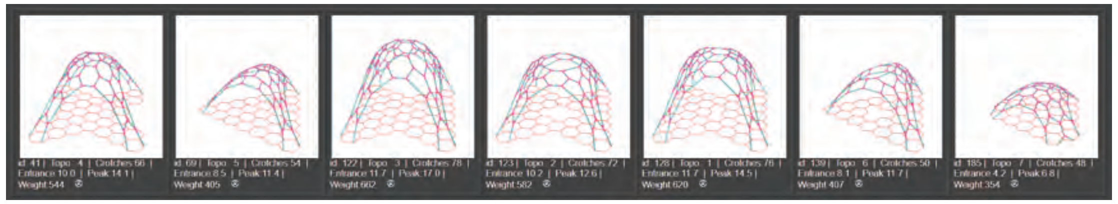

Figure 3: Different dome typologies the parametric model can explore.

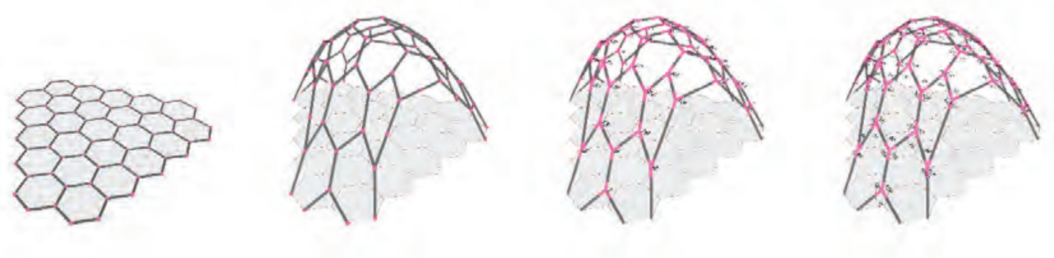

Figure 4: Catenary-based form-finding process.

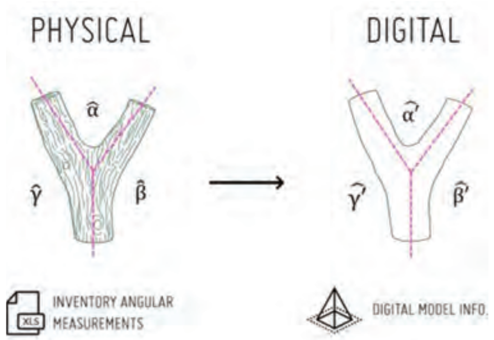

Figure 5: Physical/digital measurements.

3 RETICULATED SHELL

Reticulated shell was the first full-scale prototype designed using the proposed method. The design process of the reticulated shell executes the following steps in the generation of the design solution:

1. Selection of a base topology grid.
2. Relaxation of the grid to find an optimal compression shell geometry.
3. Assignment of the crotches from the inventory to the shell joints.
4. Minimization of the difference between the assigned crotch angles and the corresponding dome joint geometry.
5. Analysis of the shell under gravity and snow loading.
6. Genetic-based form exploration process to find the final design solution.
7. Export of performance metrics, fabrication information, and images.

3.1 Selection of a Base Topology Grid

Because tree crotches generally join three members, a hexagonal grid was chosen for the shell mesh. Also, for this initial study, it was desirable to limit the total number of joints and members to reduce fabrication time. With this specification, the grid topologies were limited in overall size and complexity. A parametric model can develop different grid topologies which control the number of joints, and some contain a central oculus that further reduces the number of joints and members. Figure 3 shows the seven topologies included in the form-finding process.

3.2 Catenary-Based Form-Finding of the Compression-Only Dome

The next step was to use the Grasshopper plugin Kangaroo[6] to apply an upward force to find a compression-controlled shell and solve the equilibrium state using dynamic relaxation. The force level (rest/length ratio) which drives the height extension is taken as a variable, and spring tensions are set over three ranges of the surface: the supporting legs, the edges, and the central portion. This will influence the final curvature in the different regions. The examples in Figure 4 show the form-fining process.

3.3 Assignment of the Crotches and Sorting the Inventory Data

Once the idealistic compression-only dome geometry was generated, the digital crotches are generated at every joint of the dome and the three angles between the limbs of each crotch are measured (fig. 5). In order to assign a crotch from the inventory to the closest joint in the digital model, we first had to sort the inventory data based on the angular measures. A natural way to sort the inventory was to define the controlling angles based on the morphology of each crotch. For the sake of clarity, we set up series of naming rules that determined that in each tree crotch, the biggest limb would be called the trunk, and the two other limbs were called branches. Three angles and diameter of each limb defined the overall geometry of the crotch. The angle between branches was the smallest of the three angles and called the bifurcation angle. We sorted the inventory data based on the bifurcation angle, and we set up the digital crotches vertically on their trunk limb. Then we assigned inventory items to the joints in the dome geometry based on the smallest sum of the difference between three angles as formulated as square root of sum of square as below:

Calculating Angle Differences to Determine the Closest Joint for Each Crotch in the Inventory

$$\sqrt{d_{ij}=(\alpha-\alpha')^2+(\beta-\beta')^2+(\delta-\delta')^2}$$

$$\forall\, i \in \{1 \ldots n\}$$

$$\forall\, j \in \{1 \ldots m\}$$

d_{ij} = SRSS of angles' difference of inventory crotch number i and digital dome joint number j
n = number of inventory elements
m = number of joint elements in the digital model

3.4 Minimization of Angular Differences

Once all of the joints in the digital model were assigned the corresponding crotch from the inventory, we formulated the minimization process to iteratively and simultaneously minimize the discrepancies between all of the tree angles of each joint and its assigned crotch. This process was developed based on defining angular constraints between each of the two limbs of the digital joints and constraining them within a given angular tolerance from the corresponding angle of the assigned crotch. Based on this method, the theoretical model had a number of constraints equal to three times the number of joints in the model. To solve this constrained model, we had to systematically and simultaneously change the joints angles in the digital model to minimize the discrepancies. This was done using the dynamic relaxation method to find the overall equilibrium of the geometry by solving the coupled constrained model iteratively. This process minimally changed the local geometry of the idealistic compression-only dome to incorporate the inventory data in the model and minimize the discrepancy of the digital node and the assigned crotch geometry for each joint in the model. In effect, this process ultimately reduces the milling time and material use and evolves the optimal compression-only geometry to a more organic shape which responds to the inventory (fig. 6).

3.5 Analysis of the Shell Under Gravity and Snow Load

Once the final geometry of the dome was defined, this geometry was analyzed to evaluate the structural performance of the dome under self-weight and snow load. Two basic categories of data were collected for the shell: geometric parameters and structural parameters. The main geometric values included: clear height of the side arches, center maximum height, number of joints and members, longest and shortest members, defining crotch angles, and base topology type. Since the member sections and wood density were preset, the overall weight was also calculated.

The shell was considered homogeneous, and the connections of members were considered fixed connections. Hardwood material properties were assigned to the members, and the dome was supported using pinned supports. The dome was analyzed under self-weight and 30 psf projected snow load using linear first order structural analysis using Karamba (structural analysis plugin for Grasshopper).[7] Values recorded from the analysis included maximum axial force, moment, and deflection, as well as utilization factors of members under axial and bi-flexural forces (fig. 7).

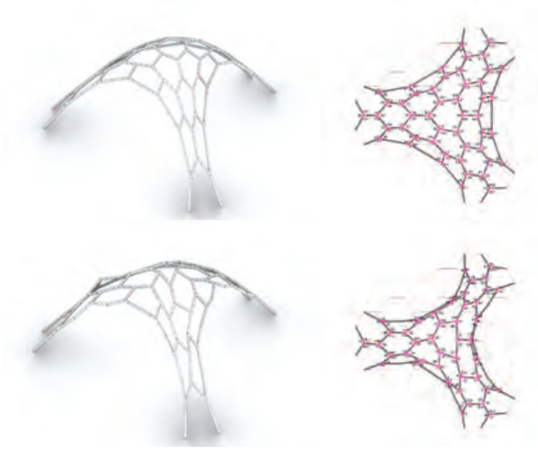

Figure 6: Iterative process of minimizing angular differences.

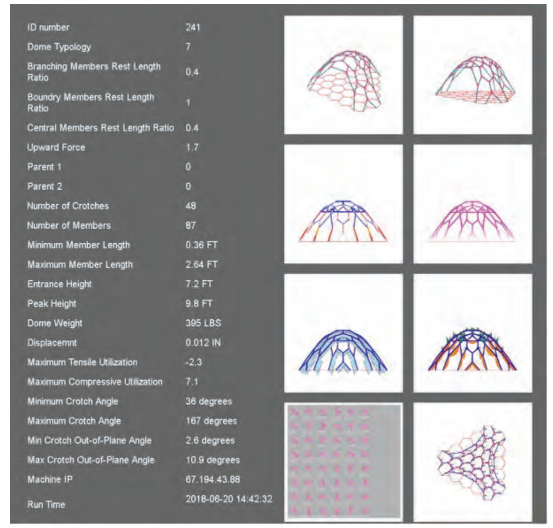

Figure 7: Generated data for each design solution.

3.6 Form Exploration Process Using ParaGen

In order to find the best dome geometry based on multiple design requirements, we used a form exploration process to study and explore the design space generated by the computational model. The generation of the solution space, along with the exploration to find the best solutions, was accomplished using ParaGen,[8] a design aid developed at the University of Michigan. Basically, the system couples some parametric form generation with simulation and analysis tools to generate and evaluate the entire design solution. The results are uploaded to a SQL server and can then be sorted and analyzed using SQL queries. Through visual and quantitative analysis of design solutions, the design space is narrowed down to find the best design solution based on visual aesthetics, performance metrics, and fabrication requirements (fig. 8). Then, all of the data on the final design solution is exported for the fabrication process.[9]

3.7 Export of Performance Metrics, Fabrication Information, and Images

The computational model provided a smooth data transfer for performance metrics and fabrication data. The performance metrics and geometric information were exported into data tables and DXF files. Additionally, the final joint geometry layout was exported to then be used in the development of fabrication data, including nesting and tool pathing (fig. 9).

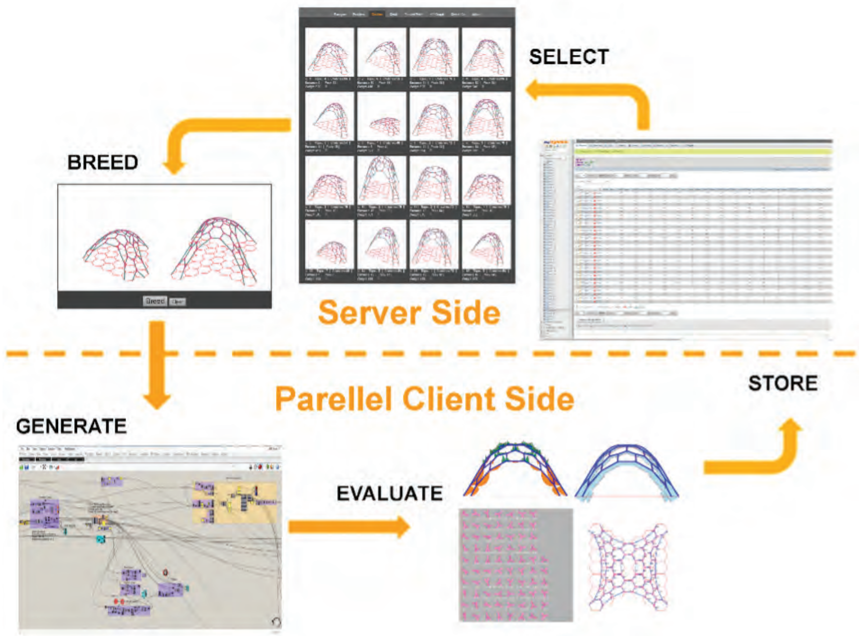

Figure 8: The ParaGen cycle showing the steps used to generate a range of solutions.

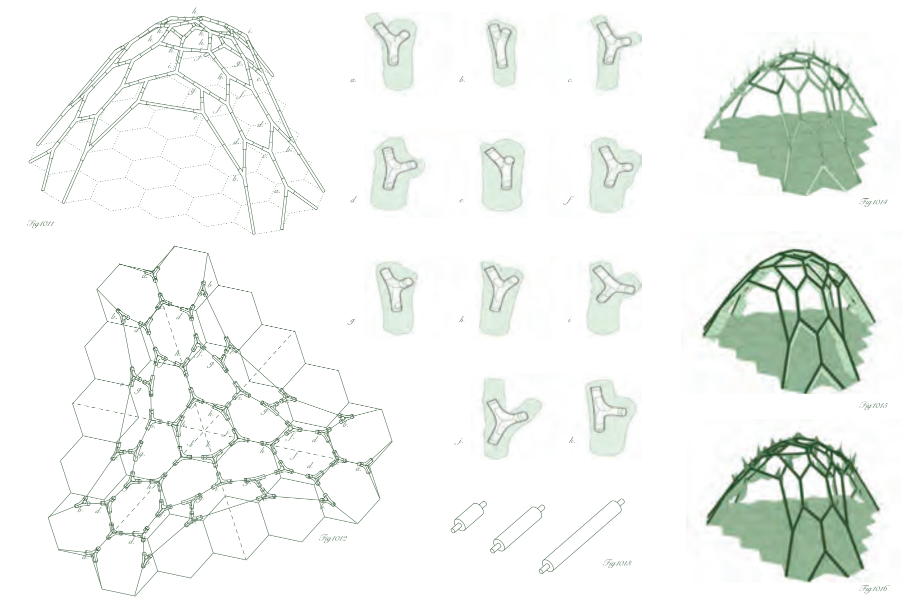

Figure 9: Exported fabrication and analysis data for the final design solution.

4 FABRICATION PROCESS

Through numerous scaled fabrication tests, different fabrication requirements and issues of working with organic tree crotches were resolved, and a fabrication workflow was developed to process the tree crotches into their final finished form. The developed workflow included: tree crotch acquisition; pre-processing, scanning tree crotches, and inventory generation; milling process, physical test, and post processing; straight member piece fabrication; pegged connection; and erection. These steps are further described below.

4.1 Tree Crotch Acquisition

Because of their size and disruptive grain pattern, tree crotches are oftentimes not harvested commercially, cannot be turned into mulch, and frequently end up being landfilled. Our ongoing workflow utilized discarded urban tree bifurcations from the City of Ann Arbor, Michigan. The team acquired 72 tree crotches from different wood yards near Ann Arbor.

4.2 Pre-Processing, Scanning Tree Crotches, and Inventory Generation

The crotches were visually inspected for defects and labeled. Then, their physical dimensions were measured. The length and diameter of each limb, as well as the angle between each limb of the crotch, were measured and tabulated in an inventory. This inventory was then used in a computational process to optimize the crotch assignment to dome joints (fig. 10). Then, each crotch was scanned using photogrammetry to generate a digital model of the crotch geometry for milling purposes.

Figure 10: Inventory measurements and data.

4.3 Milling Process, Physical Test, and Post Processing

Multiple 5-axis milling tests were conducted to develop an efficient fabrication process for this project. The desired finished geometry of each joinery was fit inside the corresponding scanned raw crotch geometry using 3D modeling and transformation in Rhinoceros 3D software (developed by Robert McNeel & Associates). Using Mastercam software (developed by CNC Software), milling toolpaths were generated for each piece and tested for the milling process (fig. 11).

All of the pieces were milled and sealed using a sealant to delay drying and cracking. The end of each limb of the crotch was milled to accommodate a peg connection to the linear connection member. Milled pieces were stored for assembly. Figure 12 shows a piece mounted in the milling jig at the conclusion of the 3D routing operation. Every piece went through this process, which took about two hours for each.

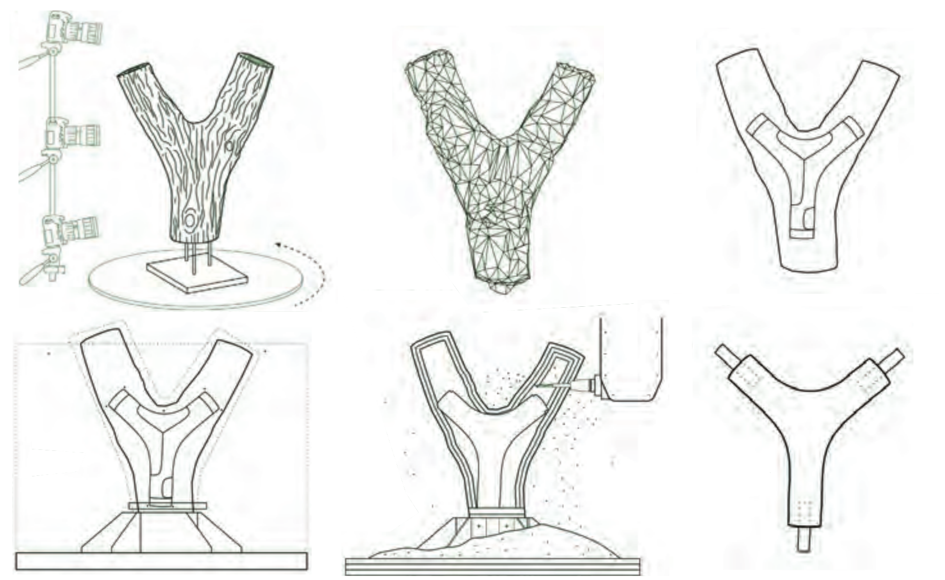

Figure 11: Scanning and milling process.

Figure 12: 5-axis milling process.

4.4 Straight Member Piece Fabrication

The straight strut elements between nodes were fabricated using 70 mm (2-3/4 inch) diameter billets. For these, rough turning maple blanks (commonly used to produce baseball bats) were used. These are knot-free pieces and should have a strength comparable to select mixed maple (NDS allowable compressive stress of 6000 kPa [875 psi]).

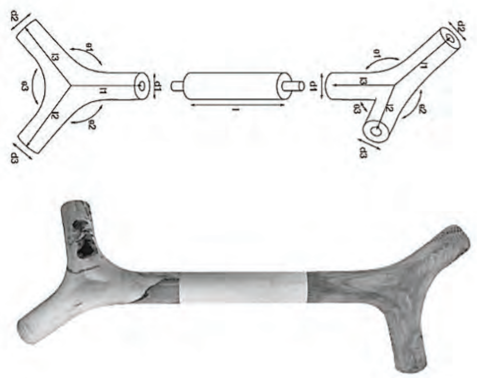

Figure 13: Pegged connection design.

4.5 Pegged Connections

The connecting element between the crotch node wand the straight struts was a simple 25 mm (1 inch) wood dowel used as a peg. In the original design, the intention was to glue the peg in place with casein (wood) glue (fig. 13).

The joint was tested in this form in flexure and was found to develop the full tensile strength of the dowel, which was 276 Nm (204 ft-lbs). However, because the prototype needed to be disassembled, the pegs were fixed in place with screws rather than glue, which reduced the flexure capacity to about 100 Nm (73 ft-lbs). The allowable compressive capacity would still be based on the net section and was about 20 kN (4500 lbs).

4.6 Erection Process

The erection process was easily accomplished with temporary bracing of the nodes. Due to a time limit to produce the prototype, only one-third of the designed dome was fabricated and erected. Although the erection of the shell took less than one day, the production of the joints through the process described above proceeded at a rate of about two per day. In the prototype, because disassembly was necessary, the pegged joints were screwed and not glued, which compromised the strength. This resulted is some joint slippage during erection (fig. 14).

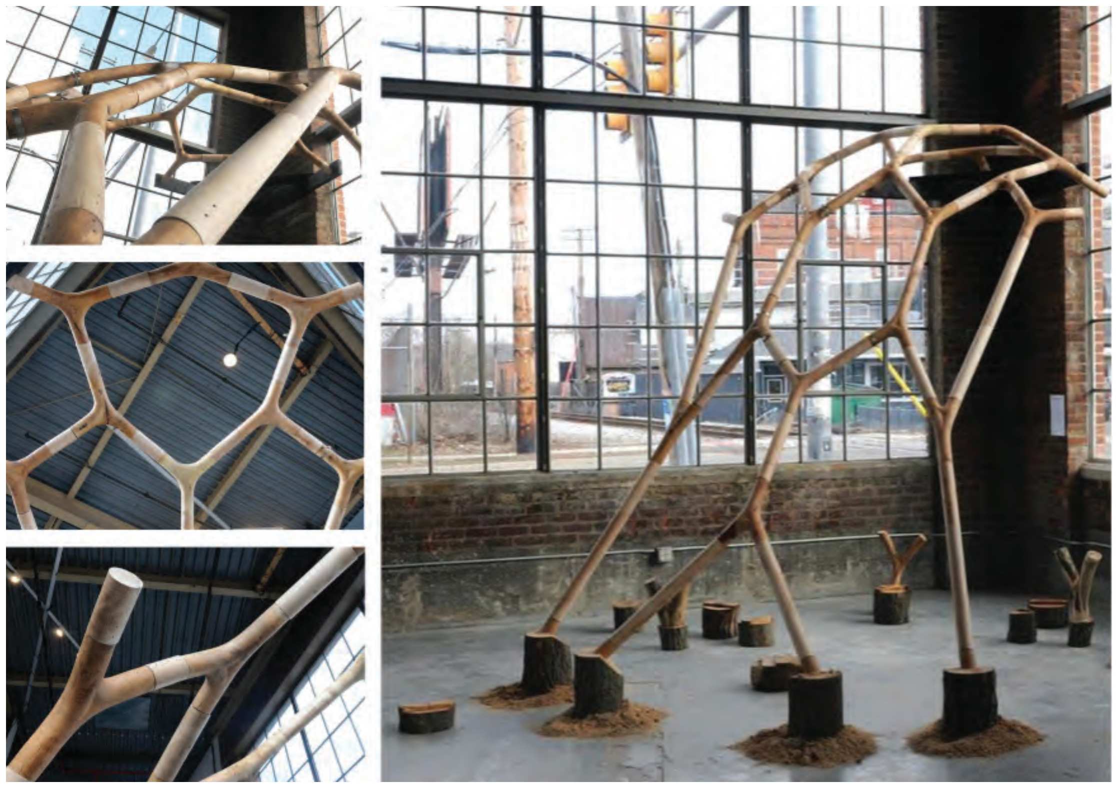

Figure 14: Details of the dome assembly.

5 CONCLUSION AND FUTURE WORK

The concept of repurposing the waste product of tree crotches did succeed, and a section of a dome was fabricated. The computational workflow proposed in this research effectively addressed the issues in form finding and inventory assignment, while also providing performance feedback and necessary fabrication data, which is directly used for the fabrication process; this workflow can be easily adapted to respond to different structural typologies. The design exploration process with ParaGen helped the team to study and analyze the design space toward choosing the most desirable solution based on aesthetics, performance metrics, budget, and fabrication requirements.

The full-scale prototype erection process was successfully done in a day. Problems encountered include the time required to scan and mill each piece. Also, the grading of the wood was a concern. One approach would be to pre-shape pieces with a band saw, thus exposing potential defects in the wood, reducing milling time, and expediting drying. After a few weeks standing in the dry indoor environment, some cracking of the crotch pieces was also observed. As a means of crack prevention, tests are currently being run using polyethylene glycol (PEG) injection under pressure. Also, kiln drying techniques using controlled pressure, temperature, and humidity to dry the lumber without cracking are being pursued.

Figure 15: The constructed prototype of one-third of the full dome.

ENDNOTES

1. Honoré-Sébastien Vial du Clairbois, *l'Encyclopédie méthodique Marin* (Paris, 1783).

2. Claus Mattheck, *Design in Nature: Learning from Trees* (Springer Science & Business Media, 1998).

3. Seray Özden, Duncan Slater, and Roland Ennos, "Fracture Properties of Green Wood Formed Within the Forks of Hazel (Corylus avellana L.)," *Trees* 31, no. 3 (2017): 903–17.

4. Gareth Buckley, Duncan Slater, and Roland Ennos, "Angle of Inclination Affects the Morphology and Strength of Bifurcations in Hazel (Corylus avellana L.)," *Arboricultural Journal* 37, no. 2 (2015): 99–112.

5. Zachary Mollica and Martin Self, "Tree Fork Truss: Geometric Strategies for Exploiting Inherent Material Form," in *Advances in Architectural Geometry* 2016, eds. Sigrid Adriaenssens, Fabio Gramazio, Matthias Kohler, Achim Menges, and Mark Pauly (vdf Hochschulverlag AG an der ETH Zürich, 2016): 138–53.

6. Gennaro Senatore and Daniel Piker, "Interactive Real-Time Physics: An Intuitive Approach to Form-Finding and Structural Analysis for Design and Education," *Computer-Aided Design* 61 (April 2015): 32–41.

7. Clemens Preisinger and Moritz Heimrath. "Karamba—A Toolkit for Parametric Structural Design," *Structural Engineering International* 24, no. 2 (2014): 217–21.

8. Peter von Buelow, "ParaGen: Performative Exploration of Generative Systems," *Journal of the International Association for Shell and Spatial Structures* 53, no. 4 (2012): 271–84.

9. Peter von Buelow, Omid Oliyan Torghabehi, Steven Mankouche, and Kasey Vliet, "Combining Parametric Form Generation and Design Exploration to Produce a Wooden Reticulated Shell Using Natural Tree Crotches" (2018).

ACKNOWLEDGMENTS

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