Engineering Design Tropisms

Utilization of a Bamboo-Resin Joint for Voxelized Network Geometries

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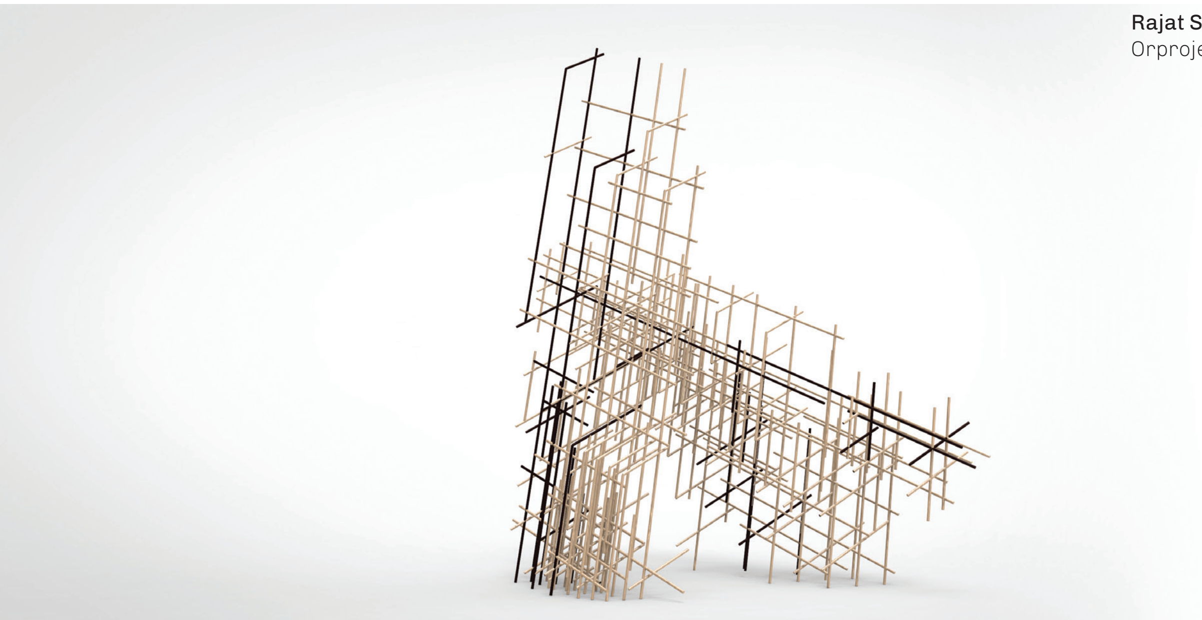

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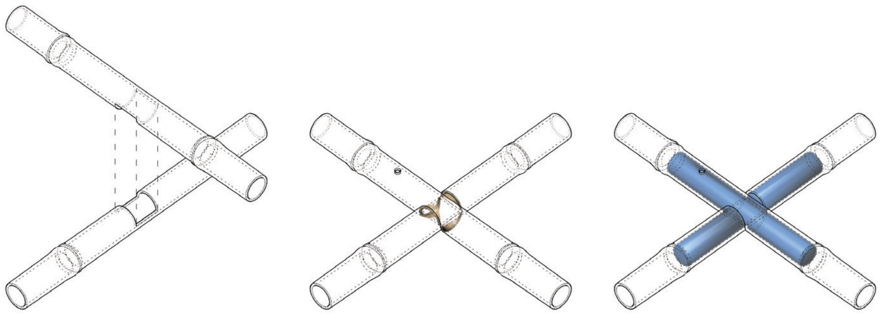
1 Voxelized bamboo cloud

ABSTRACT

We propose the combination of the traditional construction material bamboo with a novel epoxy-resin joint. The joint forms a bending-resisting connection that eliminates the need for diagonal members. This allows its utilization along rectangular grids as was tested with the design of a prototype structure that occupies a voxelized space. The design process used an agent-based simulation to mediate between design intent, site, and structural considerations. The prototype was constructed through the robotic milling of the components and forms a successful application of the joints and design methodology.



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2 A: Bamboo segments with notches.
B: Gap sealed and hole drilled.
C: Resin cast into the X-shaped hollow chamber.

INTRODUCTION

We propose the utilization of a moment-resisting resin joint for bamboo tubes in the construction of voxelized network geometries. The joint is a further development of a previously developed method (Gheorghe and Vierlinger 2016) that utilizes the hollow chambers found in bamboo material. We propose the notching of two crossing bamboo members halfway in order to intersect. The interior chambers of each member now combine at the crossing point into one larger chamber in an X-shaped form. After closing the edges with a malleable sealant, chambers are filled with epoxy resin. The bamboo becomes a lost shuttering for the resin that now connects the two members as a moment-resisting joint.

Due to the moment-resisting property of the connection, the bamboo elements can be assembled without the need for diagonal members. It is therefore possible to utilize the bamboo elements as edges within a skewed rectangular and possibly irregular grid.

In order to test the possibilities of the proposed joint, an installation constrained to a voxel grid was designed as a case study (Figure 1). We utilized a combination of agent-based systems, voxelized geometries, and structural analysis in Karamba as primary computational design tools.

We tested the following design process to utilize the joint for the voxel-based path network:

- Design of a target geometry as surfaces or meshes
- Structural analysis of the target geometry in order to define areas of increased stress
- Voxelization of the target geometry, with a higher subdivision in areas of increased stress
- Setup of the agent-driven simulation, definition of the agent behaviors and vector field
- Simulation of shortest paths across the network to test the structure for disconnected parts

We further tested the following construction process for the manufacturing of the resulting geometries:

- Measuring and sorting of bamboo material
- Assignment of measured pieces to the required geometry
- Generation of robot cutting schedules
- Robotic cutting of the bamboo and notches
- Assembly of the members with temporary attachments and sealing of the joints
- Casting of the resin nodes
- Removal of the temporary attachments

The proposed methods were tested on a 1:1 prototype, which was designed and built within a week.

RELATED WORK

Bamboo-Resin Construction

Bamboo is a construction material with a long history. However, common joints for the material are based on ties, or on timber or steel connectors (Minke 2016). We are proposing the utilization of a cast resin joint instead.

Computational Strategies

Our research builds upon previous research on agent-based simulations (Reynolds 1987; Andrasek 2012; Snooks 2013; Stuart-Smith 2014; Sugihara 2014); however, our interest does not lie in emergent swarm behaviors, but in utilizing the agents to define space and structure of heightened importance.

In order to devise an efficient construction logic, we explored space voxelization methods, building up on previous developments in the field (Retsin and Jimenez Garcia 2016; Retsin, Jimenez Garcia, and Soler 2017; Sanchez 2016; Hymes and Klemmt 2018).

Structural simulations were carried out using the plugin Karamba in the Rhino Grasshopper environment (Preisinger and Heimrath 2014).

Previous research on shortest paths algorithms was used in the design development process (Cormen et al. 2001).

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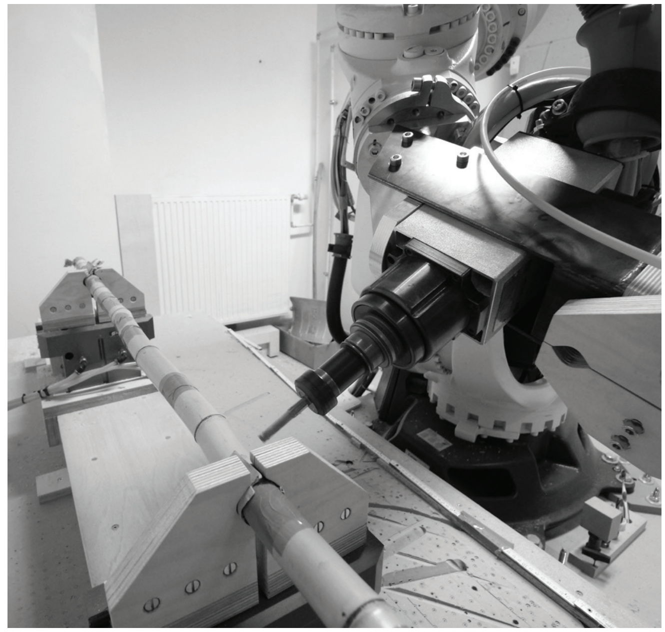

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BAMBOO RESIN JOINT

Bamboo is a readily and abundantly available material in many parts of the globe. Due to its structural build-up with hollow chambers and in-between stiffeners, the raw material itself has very high structural abilities. Bamboo is a traditional material with a long history in handcraft and architectural applications. It is commonly used in construction work as building material, and for scaffolding or support structures. Beyond its structural capacities, bamboo is also lightweight, easy to cut, and simple to connect (Minke 2016).

Commonly used bamboo joints are string-tied connections, or joints made from other materials such as timber or steel, but for this research we followed a different approach. In previous explorations, we tested a resin joint by cutting multiple bamboo sticks, joining them, and filling the resulting chamber with polymer concrete. Polymer concrete uses resin instead of cement as a binder, and demonstrates a high adherence to wood products and bamboo (Schober et al. 2016). Advantages of this technique are the creation of bending stiff nodes, as polymer concrete also has tensile abilities. Furthermore, it is malleable, not as brittle as traditional concrete, and does not shrink during curing, making it an ideal connector for a geometrically unique framework (Schober et al. 2014) (Figure 3).

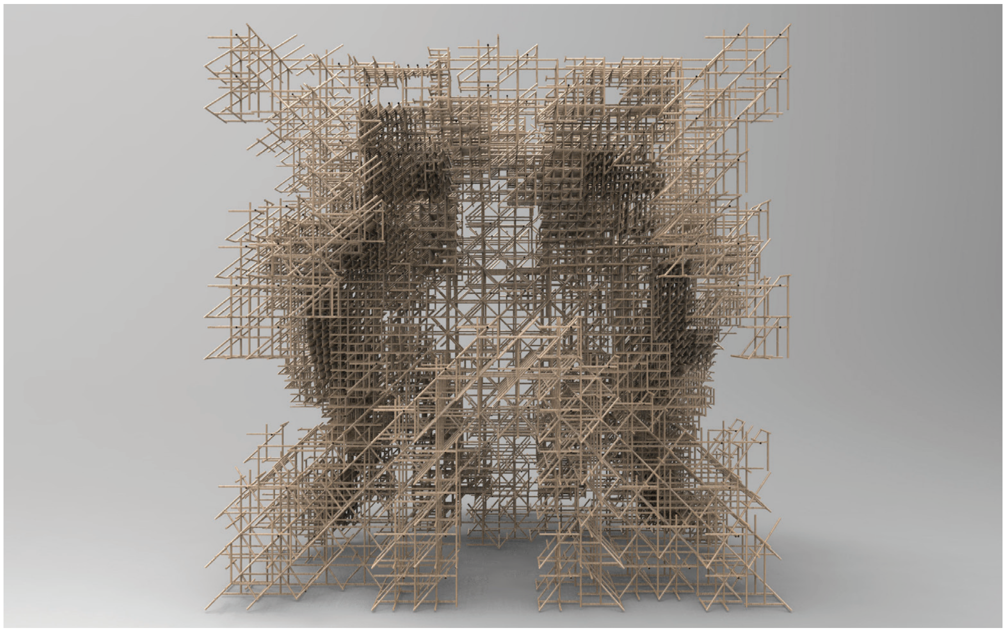
We explored a joint of two intersecting bamboo sections that are both notched halfway in order to fit into each other. The two chambers of the segments then connect in an X-shaped geometry. The edge of the notched joint is sealed with a malleable sealant, and liquid resin is filled into the connected chambers via a hole. After the setting of the resin, the sealant can be removed and the resin forms the moment-resisting joint (Figure 2).

ALGORITHMIC DESIGN PROCESS

An agent-based simulation was utilized as the tool to translate the initial design surface into a cloud of bamboo members that are placed along the edges of the distorted grid. The design starts with the intuitive conception of an initial guide surface, modelled as a 3D mesh object, which was subsequently voxelized, forming the grid for proliferation of bamboo.

While the agents move in space, following the guide surface, they activate the voxel edges that are closest to them. Different forces direct the agents in their movement that steer them towards areas of high importance according to the architectural requirements of the installation. The structural requirements of the guide surface were evaluated via a stress analysis using Karamba software. A stress map was then projected onto the guide surface, highlighting areas in need of increased support and causing the agents to concentrate in these zones.

The moment-resisting property of the joint allows for its use without diagonal members in the structure. Accordingly, it can be proliferated across a number of quadrilateral grids. For the prototype, the positioning of its structure was therefore constrained to a rhombic grid of 400 x 230 x 325 mm, with angles of 82 degrees between XY-axes and 68 degrees between XZ-axes. The grid edges in the Y-direction were offset downwards by 100 mm in order for every joint



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3 Resin joint

4 Robotic setup

5 Design exploration

to connect only two pieces of material.

A further refinement for structural reasons saw a densification of the voxel grid in areas of high stress, with voxels being subdivided multiple times according to a utilization analysis. This caused the agents to not only occupy areas of increased stress more intensely, but also to generate a denser structure in those areas.

Although unlikely, it is possible that the agent-based simulation generates a structure with disconnected parts. To avoid this possibility, in a final step the connectivity across the generated network was tested via a shortest path algorithm between different nodes of the structure. Those paths were visually reinforced to highlight the connectivity across the installation (Figure 5).

PROTOTYPE CONSTRUCTION

As a natural material, bamboo exhibits a large degree of irregularity in its geometry, with its diameter varying across segments as well as within a segment. In order to achieve a tight fit for the joints it was therefore necessary to measure, sort, and mark the material after delivery. The average diameter of the segments was 37.5 mm.

A KUKA KR120 R2500 robot was used to trim the bamboo segments to their required length and to cut the required notches. The generation of the cutting schedules was computationally automated based on the final outcome of the agent-based simulation. In this process, the varying diameters of the bamboo segments getting connected were taken into account, so that notch width and depth of every cut corresponds to the diameter of the connecting piece.

The robotic setup utilized two 2-finger grippers that were placed adjacent to the robot on an adjustable horizontal sliding track to hold the work piece. The robot itself was equipped with a custom end-effector combining a milling spindle with a further 2-finger gripper on top.

During the cutting process, the gripper of the robot first adjusted the location of the grippers on the horizontal track to suit the required length of the segment to be cut. Next, the labeled work piece was manually inserted into the two grippers on the horizontal track. The grippers then closed to secure the work piece, with the spindle of the robot trimming the segment to its length and cutting out the required notches. Due to the fact that all connecting notches are placed within the structures' offset XY- and XZ-planes, the majority of bamboo segments to be machined hold two sets of notch orientations. Those notches are locally defined, individual 3-axis pocket cuts. The combination of those cuts per bamboo segment sum up globally into one 5-axis machining operation. In case the robot cannot reach one or more notches in one milling operation—for example, due to the difference of notch orientations—the work piece is getting reoriented along its longitudinal axis by the help of the gripper integrated in the robot's end-effector. Therefore, the robot gripped the work piece, the two grippers on the horizontal track released it, the robot repositioned the part, the two grippers on the track closed again, and the robot released it. After the orientation of the work piece was adjusted, the remaining notches were machined. The finished segment was then released and manually removed from the setup. Due to the self-contained process of operations done entirely by the robot (trimming ends, cutting notches A, reorienting, cutting notches B, etc.) a minimum deviation between the digital planning and the physical fabrication was maintained (Figure 4).

For the assembly, the joints were temporarily held in position with tape and their gaps sealed with clay. The casting of the joints was carried out along the planes of the voxel grid by first assembling the separate XZ-planes lying down horizontally. After the setting of the resin in the XZ-planes, those planes were placed in their vertical positions and the members in the Y-direction were added. The 2-component resin was then inserted via a hole that was placed in the chamber. At the XY-joints the holes were placed centrally, while for the Y-joints they were positioned in the chamber offset above from the actual intersection of the two bamboo pieces.

The average volume of each chamber contained about 45 ml of resin. The percentages used for the resin mixture were 96% resin, 3% hardener, and 1% catalyst. After the curing, the temporary tape was removed. The additional bamboo members to highlight the shortest path connectivity were added subsequently (Figure 6).

EVALUATION

Resin Joint

The proposed resin joint proved successful as a moment-resisting connection. Although the design of the joint in principle is very simple, it took several iterations to develop a methodology of manufacturing the joints efficiently.

One difficulty was the leaking of the uncured resin from the edges of the notches. Clay was used as the sealant, with other materials proving less successful.

The casting of the resin needed to avoid larger air pockets in the center of the hollow chamber. This required a careful insertion of the material.

The structural plugin Karamba has been used to evaluate the design options and densify the structure where needed. In addition to virtual testing, physical structural testing of the resin joints themselves would be a required next step to assess the capability of this construction method.

Construction Process

The construction by layers along the voxel grid was efficient, as each layer could be manufactured horizontally. The layers required additional scaffolding while being cross-connected to their neighbors.

A difficulty occurs if joints are positioned closely together, so that one chamber intersects two adjacent members.

CONCLUSIONS AND FUTURE WORK

The design intent was to combine a well-known, traditional material with a state-of-the-art robotic fabrication technology. The research aims to identify potentials for future full-scale construction.

The proposed construction technique, the resin joint as well as the design process, functioned very well at the scale of the abstract prototype. The structure could be assembled relatively fast and was very cost effective compared to steel or timber joints. We are therefore hoping to test its possibilities at a larger architectural scale and with the functional and practical requirements of a building. Further explorations could include the structural testing of the joint, investigating the possibilities of using a bio-plastic for the casting of the joints, and the construction of other geometries with the joint such as shell structures.

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6 Bamboo prototype

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IMAGE CREDITS

All images by the authors.

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