Multi-Story Timber-Only Structures design coupling Graphic Statics with Robotic Fabrication

A case study of DigitalFUTURES 2024 Timber Pavilion

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Abstract. Conventional multi-story timber buildings often adopt a grid layout with uniformly aligned columns across floors, simplifying design and construction but limiting spatial flexibility and adaptability. To overcome these constraints, this research proposes a novel timber-only frame structure system that enables vertical column disalignment across floors. This approach enhances adaptability to diverse spatial requirements and allows for varied floor layouts. The proposed design method integrates graphic statics with robotic construction technology. Graphic statics is used to optimize global structural efficiency and define timber joint configurations, while robotic fabrication addresses the customization needs of joints for complex structural layouts. The process begins with a predefined multi-story spatial volume, where variations between upper and lower floors introduce column misalignments managed through this design approach. To validate the method, a 9.4-meter-high, three-story timber-only tower was constructed to validate the feasibility of the workflow from form-finding, structural analysis, joint design to robotic fabrication. The system can significantly improve the spatial flexibility and structural efficiency, paving the way for innovative applications of timber-only frame structures in modern multi-story construction.

Keywords. Multi-story Timber Building, Timber-only structure, Vector-based Graphic Statics, timber-to-timber joint, Robotic fabrication, Structural optimization

1. Introduction

Timber, as a renewable material with carbon storage benefits, plays a key role in combating climate change and advancing sustainability in the building industry. With the increasing demand for eco-friendly construction, timber structures are gaining attention, especially in multi-story buildings. Currently, most such buildings use grid-based layouts with vertically aligned columns, simplifying design but limiting spatial

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flexibility. Vertical misalignment for flexible layouts often requires a transition layer, which involves complex load transfer calculations and specialized techniques to ensure stability. While methods for steel and concrete transition layer are quite common in practices, timber solutions remain underexplored(Tattari, 2022). This study proposes a timber-only structure system that can accommodate the structural transition requirements in multi-story timber structures, by coupling graphic statics with robotic fabrication methods.

2. Background

2.1. TIMBER-ONLY STRUCTURES

Over the past two decades, Timber-only structures have seen significant advancements, as they eliminate the need for custom metal connectors, further reducing carbon emissions compared to traditional timber structures(Fink et al., 2019). Innovations in modular prefabrication and rapid assembly of timber-to-timber joints have improved construction efficiency while reducing waste and environmental impact(Eversmann et al., 2017). Additionally, digital technologies have transformed timber-only construction from traditional uses into diverse modern structural applications (*Tamedia New Office Building - Shigeru Ban*, n.d.; *University of Kansas School of Architecture and Design*, n.d.)

2.2. GRAPHIC STATICS-BASED STRUCTURAL DESIGN

Graphic statics is a well-established technique used to design structures that are in static equilibrium. It employs two interrelated diagrams: the form diagram, which represents the geometric shape of the structure, and the force diagram, which illustrates the distribution of forces within it. These diagrams are reciprocal, meaning changes in one directly affect the other. (Maxwell, 1864). Recent developments in three-dimensional graphic statics theory and practice have opened new possibilities for designing and optimizing complex 3D structures. One notable development is the vector-based approach, which represents structural equilibrium through closed loops of force vectors, intuitively depicting the force balance relationships at nodes in the force diagram. This method is particularly suited for designing complex spatial network structures (D'Acunto et al., 2019).

In practical applications, vector-based graphic statics is utilized in lightweight trusses and timber structures(Beghini et al., 2013; Rasneur et al., 2024). Its capacity for real-time interaction and dynamic adjustment provides significant freedom in the early stages of design, enabling efficient exploration and optimization of structural layouts (Rasneur et al., 2024).

2.3. ROBOTIC TIMBER CONSTRUCTION

Advancements in digital and robotic fabrication technologies have providing flexible and efficient solutions for complex timber-only structures. Use robotic fabrication technology to process irregular log branches and build free-form surfaces and spatial structures composed of three branched joints (Chai et al., 2024). The integration of computational design and robotic fabrication streamlines workflows from design to construction, enabling the full-process automated construction of tree-trunk-based mutual structural timber-to-timber joints (Geno et al., 2022).

2.4. INTEGRATION OF VECTOR-BASED GRAPHIC STATICS WITH ROBOTIC TIMBER FABRICATION

This research develops and validates workflows for designing, analyzing, and constructing multi-story timber-only structures, addressing column misalignment and complex joint challenges. By integrating vector-based graphic statics (VGS) with robotic fabrication, a 9.4-meter, three-story timber-only tower was constructed to validate the workflow, showcasing enhanced spatial flexibility and structural efficiency (Figure 1). The scope of research for this project includes:

- Structural Design with VGS: Using VGS to optimize form, load distribution, and stability, addressing column misalignment while balancing flexibility and performance.
- Multi-Member Intersecting Timber-to-timber Joints: Developing a mortise-and-tenon inspired joint system, accommodating multi-member intersecting at a single node.
- Design-to-fabrication Integration: Bridging design and fabrication through robotic technologies for precise and efficient joint fabrication.

Figure1. DigitalFUTURES 2024 Timber Pavilion

3. Methods

3.1. SOFTWARE AND HARDWARE SETUPS

Geometric modeling and robotic programming are performed in Rhinoceros 3D and Grasshopper, a parametric design platform. The VGS plugin in Grasshopper automates 3D form and force diagram generation based on vector-based graphic statics(D'Acunto et al., 2019). VGS enables designers to create 3D equilibrium structures and adjust force or form diagrams in real time.

The fabrication process utilizes a KUKA KR2700 robot arm equipped with a spindle for precise joint milling. The tool path is designed and simulated using the FURobot, which is a node-based robotic programming tool specifically designed for architects and designers (Lu et al., 2020).

3.2. STRUCTURAL DESIGN

3.2.1. Design Concept

Inspired by the Yingxian Wooden Pagoda, the world's tallest and oldest timber-only structure from the Liao Dynasty, this projects features a three-story timber pavilion. The pagoda's stability through centuries of earthquakes and conflicts provides as a model for modern timber design. The strategic placement of hidden layers between exposed layers is crucial for ensuring stability (Liang, 1985). The hidden layer, ingeniously designed as dual-ring hollow structures with diagonal braces forming spatial trusses, substantially enhances the structural integrity.

This project's three-story structure features vertically stacked cubic spaces with scaling and twisting transformations, disrupting vertical column alignment as shown in Figure 2. To address this misalignment, a "three exposed, two hidden layers" system is proposed, with the exposed layers serving as functional spaces and the hidden layers facilitating structural transitions.

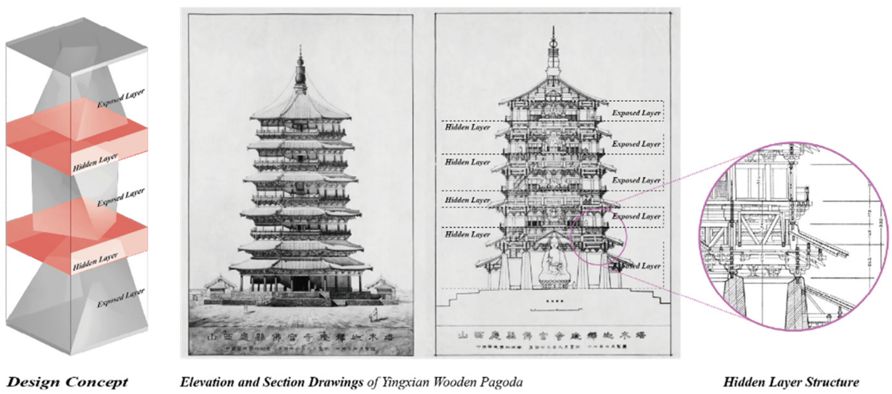

Figure 2. The design concept is inspired by the exposed and hidden layers in Yingxian wooden pagoda

3.2.2. Structural Design Based on Vector Graphic Statics (VGS)

VGS is employed to analyze and optimize the structure, enhancing its efficiency and stability by optimizing the force distribution and material utilization. The design process is divided into the following four steps:

- Initial Load Path Definition: The form-finding process begins with the development of a statically determinate structural system with the Load Path Network Method (LPNM) (Enrique & Schwartz, 2017). Figure 3-Section I describes the boundary condition, detailing its constraints and external forces. Different structural designs can be generated by connecting predefined load points and supports according to LPNM rules. Static loads proportional to each floor's surface area are evenly distributed across the nodes of generated spatial frame.

- VGS-based Equilibrium Analysis: Figure 3- Section II illustrates how VGS verifies structural equilibrium while generating form diagrams (spatial configurations of members) and force diagrams (magnitudes and directions of internal forces). These diagrams visually represent load flows, enabling the evaluation of the structure intuitively.

- VGS-based Structural Optimization: The optimization process aims to balance force distributions within the structure. By making interactive adjustments to the form and force diagrams, force concentrations in critical members can be effectively avoided. The optimization strategies include: (a) Adjusting node positions to increase the load path efficiency; (b) Manipulating the force diagram to reduce the forces in specific members;. (c) Reconfiguring connectivity if the first two strategies fail to achieve the desired outcome.

- Cross-Section Dimensioning: Internal forces from the VGS were used to define the cross-sectional dimensions of structural members. Exposed layers use square-sectioned spruce glulam, while hidden layers employ raw logs of varying diameters. Figure 3-Section III illustrates that the optimization result has the spruce glulam components optimized to four sizes: 140×140 mm, 120×120 mm, 100×100 mm, and 80×80 mm, and the log diameters to three ranges: 120–130 mm, 100–110 mm, and 80–90 mm.

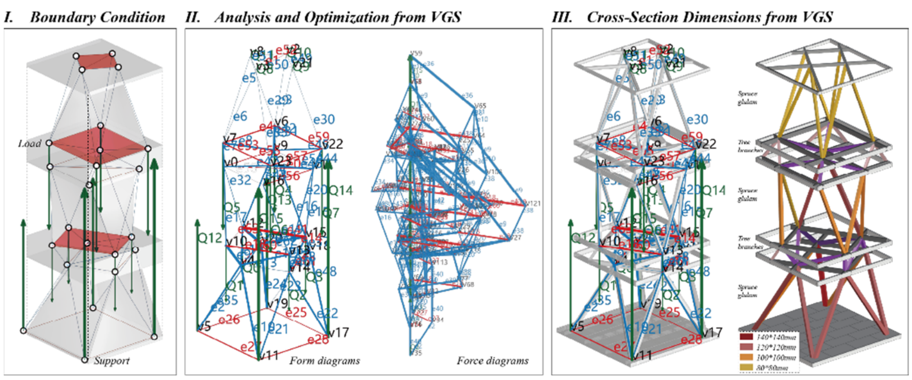

Figure 3. Structural design and analysis based on VGS

3.3. DEVELOPMENT OF TIMBER-TO-TIMBER JOINTS

3.3.1. Joint inspiration

Figure 4 highlights the traditional tenon joint, which is the inspiration for the timber-to-timber joints in this project. In this joint, transverse beams intersect using half-tenons, and the inward offset of the beams at the joint creates four grooves. The vertical columns are notched with cross-shaped slots, forming four tenons. These four grooves are designed to accommodate the four tenons, restricting their movement and creating a stable, interlocking system.

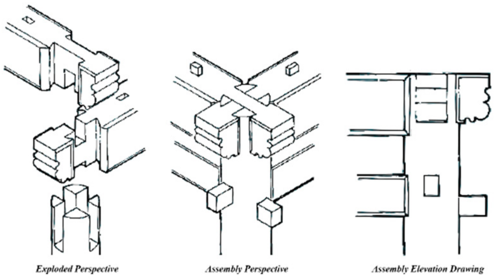

Figure 4. Traditional tenon joint

3.3.2. Joint Computation

The joint design in this study is based on computational rules rather than a fixed geometric form, enabling flexibility for varying member counts and intersection angles. Figure 5 illustrates key steps for joint computation:

- Define Horizontal Division Plane: A horizontal plane is first established at the centre of the beam, dividing the joint into upper and lower sides. Vertical members terminate at this plane, ensuring that there are no interferences between columns in the upper and lower regions.
- Compute Tenon for Columns: The columns are notched with cross-shaped slots, forming tenons as in traditional tenon joint. These tenons are designed to seamlessly fit into beam mortises during vertical assembly, preventing movement in directions other than the assembly axis.
- Solve the Collision between columns: the collision between columns is addressed through properly planning the assembly sequence. Tensile members are installed first, and their geometry is calculated to accommodate subsequent compressive members. Compressive members are then installed to press down and lock the tensile members into place, creating a stable and secure configuration. VGS provides the required magnitude and direction of internal forces for each member
- Compute Mortises for Beams: The beam mortises are defined according to the intersection areas between the tenons and beams. Beams are carved by inward offsetting the effective contact areas, also seen in traditional tenon joint.

The computational logic of the joints adheres to the design principles of traditional tenon joints, yet it can accommodate all the beam-column joints in this project, regardless of the number of members and the angles involved.

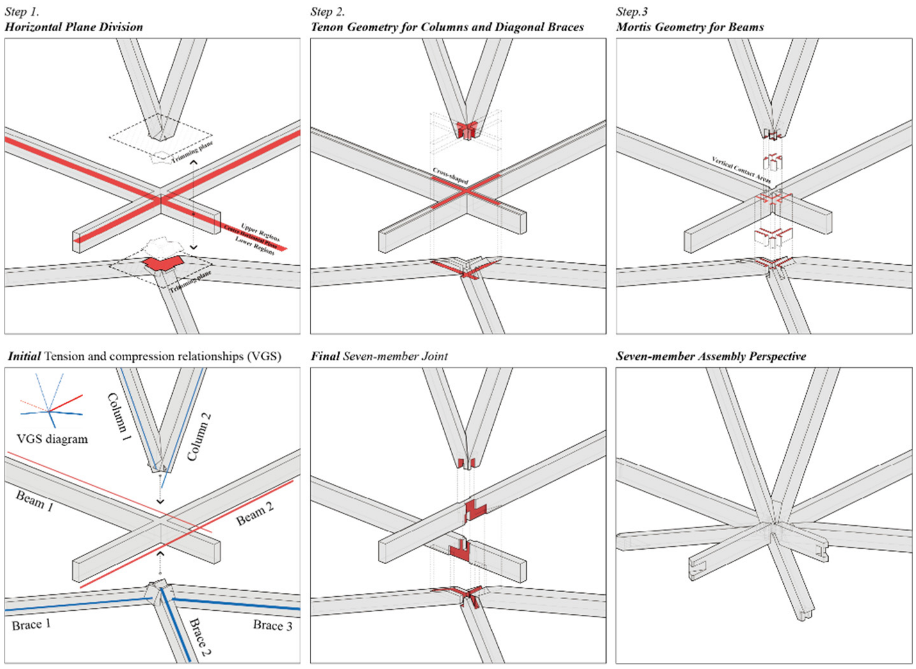

Figure 5. Multi-member intersection joint computational design process

3.4. ROBOTIC FABRICATION

Consistent design logic across beam-column joints ensures uniform robotic machining paths for all components, whether raw logs or glulam. Figure 6 illustrates the toolpath generation and internal corners processing involved in the machining workflow. The geometries of the proposed joints are all referenced to the beam division plane. As a result, during the machining process, the cutting tools only need to operate in directions that are either perpendicular or parallel to the beam plane.

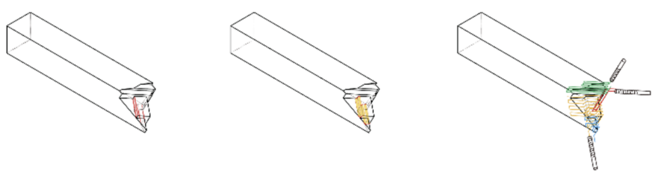

Figure 6. Toolpaths generation and inside corner processing

The generation of robotic tool path also takes into consideration some other parameters such as milling tool diameter, safe entry and exit planes. The tool paths can be simulated with FURobot, generating instructions for the robot to execute. Figure 7 illustrates the robotic fabrication process for both glulam components and logs. During robotic machining, each end of each column was completed in 5–10 minutes.

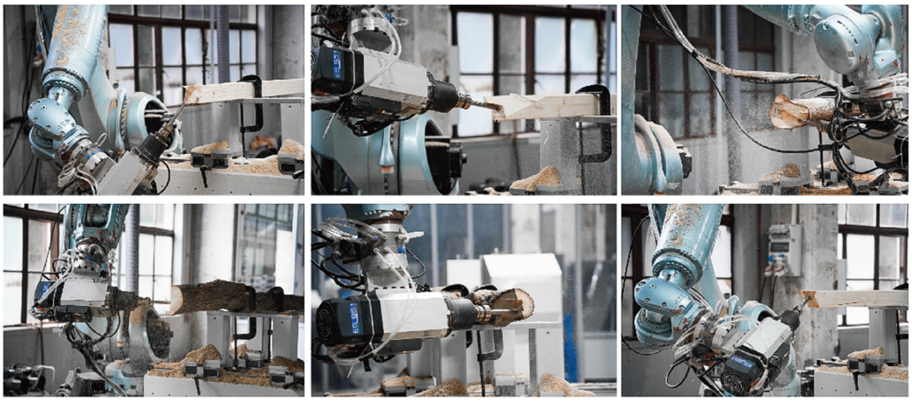

Figure 7. Robotic fabrication

4. Results

After machining, the components were transported to the site for assembly (Figure 8). Thanks to the precision of robotic machining, the entire assembly—including the installation and dismantling of five layers of scaffolding—was completed within two days.

Figure 8. Composition of the timber tower, including 22 diagonal braces, 22 supporting columns, and 48 beam components

The resulting structure is a 9.4-meter-tall, three-story timber tower, as shown in Figure 9. The structure is composed of 44 columns and 48 beam components, with the columns divided into 22 diagonal braces in the hidden layers and 22 supporting columns in the exposed layers. The coupling of graphic statics and robotic fabrication allows for the creation of structure in equilibrium without relying on nails or other metallic fasteners. The introduction of "hidden layers" effectively resolves column misalignment across different floors, enhancing both structural flexibility and adaptability.

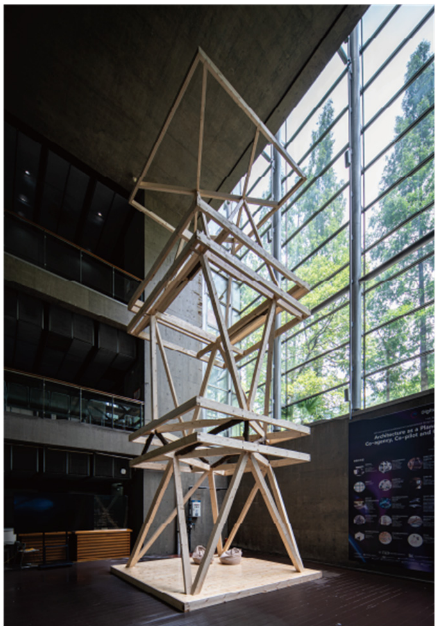

Figure 9. A 9.4-meter timber-only frame structure tower

5. Conclusion

This study presents a design and construction method for multi-story timber-only frame structures, addressing column misalignment challenges caused by flexible layouts. By integrating graphic statics with robotic fabrication, the approach provides a comprehensive solution for efficient timber-only structure, including structural design, joint computation, and robotic construction. The method was validated through the construction of a 9.4-meter-high timber tower structure, highlighting the spatial flexibility and structural efficiency of complex timber-only structure.

Future research will investigate the performance of the joint system and its application in highly flexible multi-story timber systems, laying the groundwork for scalable and adaptable timber-only structures in contemporary architectural practices.

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