

Integrated computational-robotic workflow for complex timber-only structures

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ABSTRACT

Traditional timber joinery has been largely replaced by metal connectors due to industrial standardization, compromising the material's inherent low-carbon benefits and recyclability. To address this, this paper proposes a joint-informed computational-robotic workflow for timber-only spatial frames. The approach integrates vector-based graphic statics (VGS), geometric computation, and robotic toolpath generation into a continuous process. As a proof-of-concept, the workflow is demonstrated through the construction of a full-scale, 9.4-m-tall timber tower. While mechanical joint properties were not quantified through laboratory testing, the prototype confirms the system's geometric adaptability and construction feasibility under self-weight. Results indicate that the workflow successfully enabled robotic fabrication of 20 unique spatial nodes, achieved a 74% reduction in embodied carbon compared to steel-jointed equivalents, and facilitated a rapid 10-h reassembly process. This paper establishes a reproducible framework for materially coherent construction, contributing to the advancement of circular building practices and automated timber fabrication.

1. Introduction

Timber construction has reemerged as a central topic in sustainable architecture and structural engineering. As global construction industries aim to reduce embodied carbon, timber has attracted growing attention due to its renewable nature and carbon sequestration capacity. However, despite the material's inherent sustainability, most contemporary timber structures still rely heavily on steel connectors and hybrid assemblies [1], which compromise both the environmental performance and recyclability of the system [2,3]. The development of efficient timber-to-timber joints has become a critical research focus for achieving sustainable and circular timber construction.

Traditional carpentry joints exhibit remarkable mechanical performance and cultural value [4]. Recent advancements in digital design and fabrication have reopened the possibility of reinterpreting traditional joinery through digital workflows [5,6]. This resurgence is further demonstrated in several landmark projects in contemporary timber construction, including the Tamedia Office Building [7], the Bjergsted Financial Park [8] and the new Swatch Headquarters [9]. While these

projects successfully demonstrate the viability of all-wood connections within modern engineering frameworks, their application has been largely confined to resolving planar configurations or low-degree geometric intersections, typically involving no more than four converging members. A critical challenge persists in realizing multi-member spatial intersections in pure timber, as evidenced by projects like the Aspen Art Museum [10] and Museum Historisches Oberamteistraße [11]—which ultimately rely on customized steel connectors to resolve these complex geometric conditions.

1.1. Research questions and objectives

The challenge of multi-member timber construction extends beyond mere geometric complexity; it resides in the inherent conflict between material grain orientation, structural load paths, and the physical constraints of assembly. Unlike steel or concrete, where intersections can be resolved through welding or casting, timber requires subtractive machining and interlocking logic that must respect the material's anisotropy. Current digital timber research often treats geometric

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modeling and structural performance as sequential tasks, leading to the necessity of metal reinforcements in complex spatial nodes.

To address these challenges, this paper explores a systematic approach to resolve and physically realize multi-member intersections. We hypothesize that by coupling the geometric generation of joints directly with structural load paths and assembly sequences, a repeatable construction process can be achieved for timber spatial grids. This study addresses three primary questions:

- (1) **Geometric Generation:** How can traditional mortise-and-tenon logic be generalized to accommodate complex multi-member intersections with variable spatial angles?
- (2) **Workflow Integration:** How can structural analysis, geometric fabrication constraints, and assembly logic be integrated into a continuous workflow?
- (3) **Feasibility Validation:** Can such a system be robotically fabricated and assembled at full scale to ensure structural integrity and circularity?

The primary objective is to develop and validate this integrated computational-robotic methodology through a full-scale case study (Fig. 1). By implementing the design-to-fabrication chain in a real-world scenario, this paper demonstrates the viability of high-complexity, pure-timber spatial structures that prioritize both structural performance and ease of assembly.



Fig. 1. Timber structure case study.

1.2. Contributions

While recent advancements in digital timber have expanded the possibilities of all-wood joinery, existing research often treats joint geometry, structural performance, and assembly sequence as fragmented domains. This study moves beyond the optimization of isolated joints toward a systemic, workflow-oriented approach. The primary contributions of this work are categorized as follows:

- (1) **Spatial Complexity:** Existing projects primarily resolve orthogonal or planar intersections. This paper establishes a generalized geometric system capable of resolving irregular, multi-member spatial intersections where up to eight members converge at variable angles within a single node.
- (2) **Force-Informed Assembly:** Previous digital joinery libraries often prioritize geometric variation over structural logic. This proposed method introduces a force-driven assembly sequence, where tension members are installed first and locked by compression members, ensuring the joint geometry is inherently structural.
- (3) **Integrated Digital Chain:** This paper establishes a continuous design-to-fabrication workflow that bridges the traditional gap between design modeling and fabrication planning. By co-generating joint geometries, structural load path, and robotic toolpaths within a single process, the framework ensures that complex timber structures are both machinable and assemblable without the need for manual adjustment.

1.3. Methodological overview

To address the challenges of multi-member timber connections, the proposed research implements a digital-to-physical workflow organized into three interlinked modules (Fig. 2):

- (1) **Computational Joint Development:** A new parametric joint system is introduced, derived from the traditional *Gutou* (hoop-head) tenon of Chinese timber carpentry [12]. The system generalizes the mortise-and-tenon logic into a computational framework that can accommodate up to eight intersecting members within a single node. The design logic incorporates both assembly sequence and fabrication constraints, ensuring that every generated geometry is inherently manufacturable.
- (2) **Joint-Informed Structural Design:** To correlate structural behavior with joint feasibility, the workflow employs Vector-based Graphic Statics (VGS) as a computational analysis tool. VGS represents internal forces as vector geometries, allowing real-time interaction between the form diagram (spatial configuration) and the force diagram (load equilibrium) [13]. Through this approach, the internal force directions are mapped directly to the assembly sequence of components—where tension members are installed first and mechanically blocked by compression members, forming a self-locking structural hierarchy.
- (3) **Fabrication and Assembly:** The computed joint geometries are translated into fabrication-ready instructions within a single parametric environment, ensuring continuity between geometric computation and robotic execution. Each mortise and tenon volume can be decomposed into machining primitives defined by perpendicular tool orientations, allowing all cutting operations to be executed using standard end-mills. During on-site construction, Augmented reality (AR) overlays are used to communicate this sequence to workers, showing the required orientation and installation direction for each member. The predefined assembly sequence—encoded in the joint geometry through insertion directions and interlocking surfaces—provides clear guidance for the assembly process.

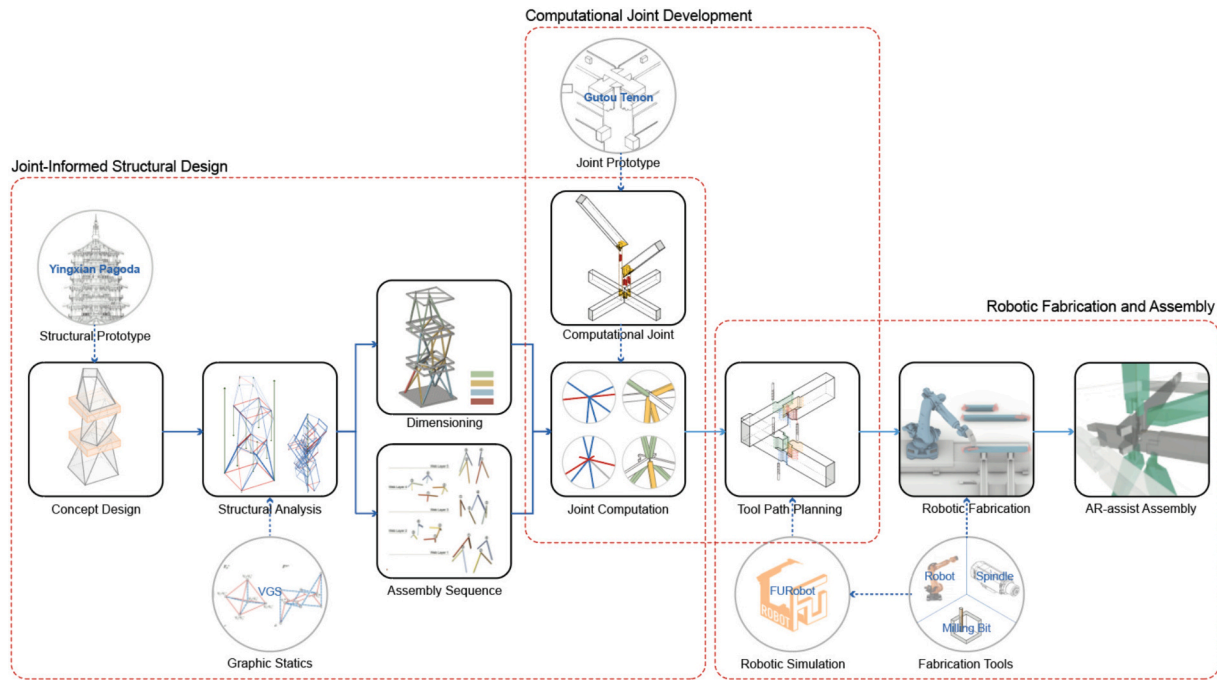


Fig. 2. Integrated workflow for case study.

1.4. Paper organization

The remainder of this paper is organized as follows. [Section 2](#) reviews current research on timber-to-timber connections and identifies the gaps that motivate an integrated joint-informed workflow. [Section 3](#) presents the proposed computational joint system, including its geometric logic, multi-member generalization, and its integration with fabrication constraints. [Section 4](#) introduces the case study context and outlines the structural, material and joint design of the full-scale prototype. [Section 5](#) details the implementation of the workflow, from parametric modeling to robotic milling and on-site assembly. [Section 6](#) reports the fabrication results, evaluates the performance of the prototype, and discusses broader implications and remaining limitations. [Section 7](#) concludes with the methodological contributions and outlines directions for future development.

2. Related work

Research on timber-to-timber connections has evolved significantly over the past decade, moving from the digital reproduction of traditional joints toward integrated design-fabrication workflows enabled by advanced computation and robotics. This section reviews the major trajectories that have shaped this development, concluded by identifying the missing links in current practices.

2.1. Geometric reinterpretation of timber joinery

Early research in digital reinterpretation of traditional joints focuses on geometric formalization of historical carpentry techniques, such as mortise-and-tenon joints, adapting them for CNC machining capabilities [14]. This led to the development of digital joint libraries and databases, which serve as repositories for standardized yet adjustable connection geometries [15]. Design tools and software plugins emerged to automate geometric reasoning, parameter management for custom timber joints [16,17]. These studies were characterized by geometry-centered experimentation, where the primary goal was to reproduce and catalogue joinery types digitally [18,19].

While advancements in digital design and fabrication have validated

the feasibility of digital, non-standard timber joints in timber construction, current research remains largely confined to assemblies of linear or planar components joined in repetitive patterns. Multi-member spatial intersections remain a significant challenge for all-wood connections due to the geometric, structural, and fabrication complexities. While some approaches attempt to address spatial complexity [20,21], they often introduce structural compromises or largely confined to orthogonal or regular grid-based configurations. This highlights a persistent gap in developing integrated, high-performance solutions for spatially irregular, multi-member timber joints.

2.2. Performance verification of interlocking timber systems

In parallel with geometric formalization, the performance verification of interlocking geometries has been rigorously investigated, ranging from theoretical carbon quantification [3] and specific seismic testing [22] to a broader integrated performance verification. This systemic approach has been validated through several emerging structural systems that serve as benchmarks, such as the segmented timber shell structure, which utilize highly complex, interlocking finger joints for assembly [23,24], and the folded plate structures, which are based on integrated through-tenon joints that are robotically milled and assembled [17]. Notably, a robust empirical foundation has been established for dovetail massive wood board elements, validating the structural capacity of interlocking geometries in multi-story construction, particularly concerning their optimization and behavior under out-of-plane bending [25,26]. Beyond structural mechanics, research has further demonstrated that interlocking geometry critically influences building physics, with experimental validations confirming its efficacy in air permeance, airborne sound insulation, and fire resistance [27,28,29]. These studies provide a robust foundation regarding the mechanical behavior and physical properties of interlocking timber connections, upon which this paper builds to extend validated joinery logic into complex spatial frameworks. While these studies verify performance after the joint geometry is defined, optimizing the synergy between geometry and performance remains a critical frontier.

2.3. Fabrication continuity in robotic timber construction

Building upon digital models, the field advanced with robotic joint fabrication, which introduces precision and flexibility in materializing complex geometries. The core of robotic joint fabrication is the precise milling of intricate joint geometries, most commonly using 6-axis industrial robotic arms equipped with milling spindles (milling bits, saws) as end-effectors [30,31]. While this capability shares functional similarities with established Computer Numerical Control (CNC) machinery—both achieving high levels of precision in subtractive processes [32,33], robots have also become active participants in the construction sequence, capable of handling, positioning, and assembling the elements into structural modules [34,35,36].

However, current workflows predominantly suffer from a lack of fabrication continuity. In conventional practice, joint geometries are finalized in a design environment and subsequently exported to external CAM software for toolpath definition [37]. Although integrated fabrication tools allow for robotic programming and kinematic simulation directly within the computational environment, the generation of machining trajectories often remains a manual or semi-automated task analogous to conventional CAM operations [38]. A fully continuous computational lineage—where joint geometry inherently dictates its own fabrication path—remains to be perfected.

3. Computational joint system

The proposed computational joint system constitutes the central element of the integrated workflow, enabling the geometric, structural, and fabrication coherence required for timber-only assemblies. It translates traditional carpentry principles into a parameterized, fabrication-aware digital model capable of accommodating multi-member intersections under realistic machining constraints.

3.1. Prototype and conceptual foundation

The system is derived from the traditional Chinese Gutou (hoop-head) tenon, in which horizontal beams lock and stabilize a vertical column through interlocking bearing surfaces [12,22]. Its underlying logic—where intersecting members occupy distinct volumetric zones around a central crossing—offers a scalable geometric framework that is conceptually extendable to more complex, multi-member spatial intersections, serving as an ideal foundation for computational reinterpretation (Fig. 3-a).

To generalize this logic for the computational workflow, the conventional column-beam-brace hierarchy of timber frames is simplified into two distinct categories based on a host-insert relationship between structural members (Fig. 3-b), defined as follows:

- **Beams:** Intersecting structural members analogous to the horizontal locking beams of the *Gutou* tenon, serving as the ‘host’ elements for connections.
- **Webs:** Obliquely oriented members that insert into the beams, acting simultaneously as the primary vertical load-bearing components and as bracing elements for lateral stability.

The intersection of two orthogonal beams defines a horizontal crossing plane. Together with the vertical normal axis perpendicular to this plane, a local Cartesian reference frame is established. This 3D frame subdivides the joint volume into eight distinct regions, or ‘octants’—four above and four below the crossing plane (Fig. 3-c). Each octant represents a potential insertion zone for a web member. This octant-based subdivision provides a rule-based structure for mapping the relationship between beams and webs, which allows up to eight web members to interlock around the beams at variable spatial angles.

3.2. Multi-member generalization

Implemented in Rhinoceros 8 and Grasshopper, a multi-member generalization algorithm was developed to resolve intersections involving both beams and webs, which generate geometrically valid, assemblable, and machinable solutions for each spatial intersection through a priority-based allocation process within the octant framework. The process is summarized in Fig. 4 and Fig. 5, which can be described in 4 main steps:

- (1) **Input and Preprocessing:** The joint generation process is initiated by importing three types of data derived from the structural model: member axes, cross-sectional dimensions, and the assembly sequence. The input members consist of a pair of beams—primary horizontal frame elements—and a variable number of webs—obliquely oriented members that insert into the beam intersection (Fig. 5-a). These inputs collectively establish the foundational parameters for each joint: member vectors define the spatial orientation of each component, cross-sectional dimensions determine the physical size and volume envelope,

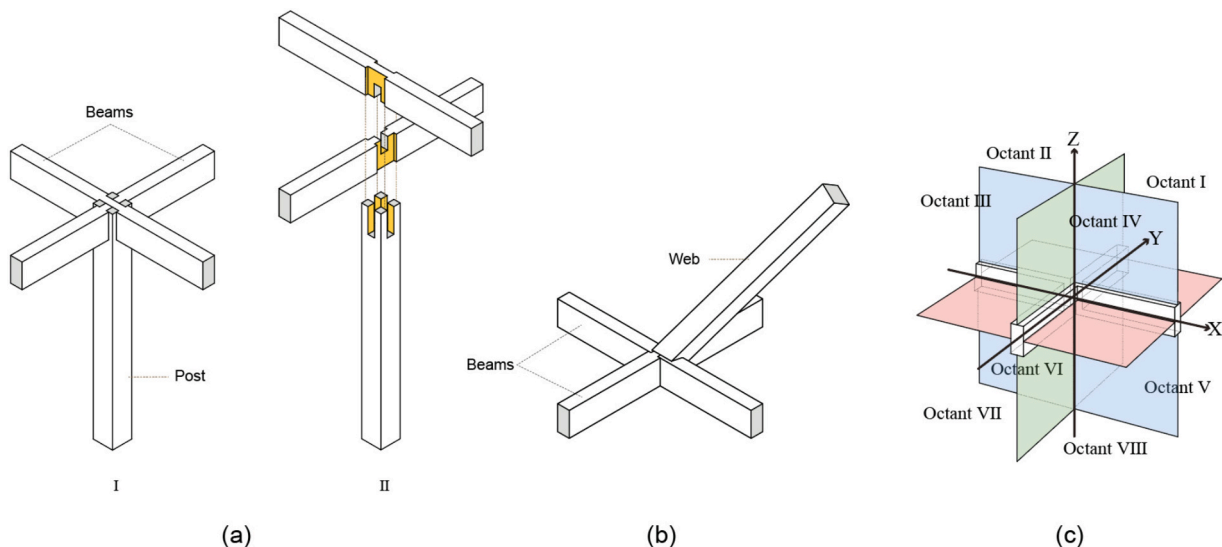


Fig. 3. Joint prototype and conceptual foundation: (a) Tradition Gutou tenon; (b) Potential reconfiguration; (c) Octants definition.

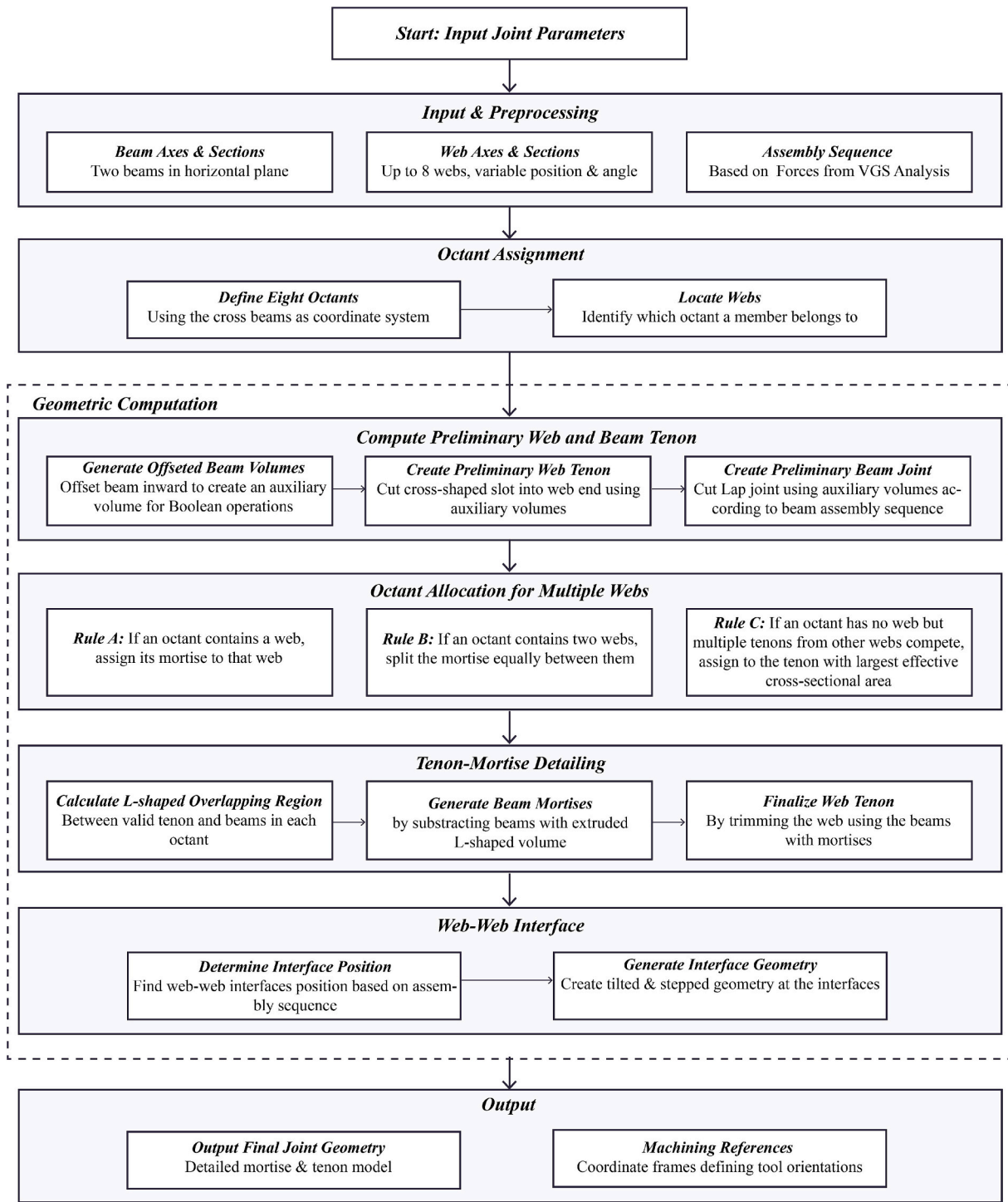


Fig. 4. Joint computation workflow.

- and the assembly sequence establishes the insertion hierarchy based on construction logic.
- (2) **Octant Assignment:** The intersection of the two crossing beams establishes a reference plane, which divides the surrounding space into eight octants. Each web member is assigned to a specific octant based on its spatial orientation (Fig. 5-b). Members located in octants I-IV do not clash geometrically with those in the opposing octants V-VII, as all web members terminate at the central beam plane. Within each octant I-IV or V-VII, the geometric intersections of multiple web members will be resolved sequentially.

- (3) **Geometric Computation:** The geometric computation stage resolves the spatial interactions between beams and multiple web members and synthesizes them into a valid, fabrication-ready mortise-tenon configuration. This process consists of three tightly coupled steps: preliminary tenon generation, octant-based allocation for multiple webs, tenon-mortise detailing, and web-web interface.

First, auxiliary beam volumes are generated by offsetting the beam solids inward by a predefined width. These auxiliary volumes serve as Boolean references that define clearance and insertion depth. Based on them, preliminary tenons are created at

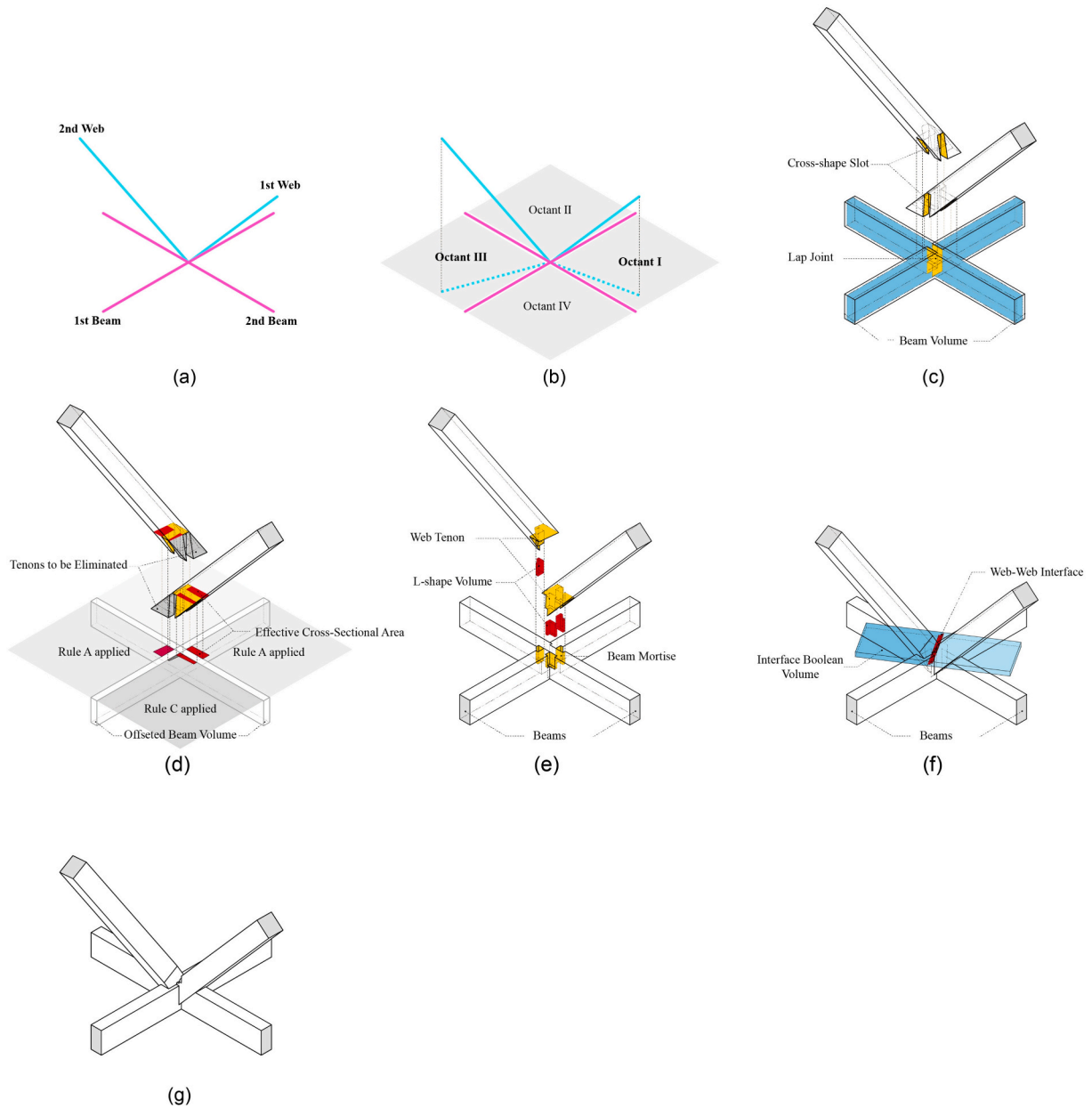


Fig. 5. Illustration of joint computation process.

the ends of web members, and provisional beam joints are formed between the crossing beams according to the predefined assembly sequence (Fig. 5-c). At this stage, the geometries are intentionally oversized and may still overlap.

Second, an octant-based allocation strategy is applied to resolve competition between multiple web members for the limited mortise space within the beams. Each beam-defined octant is evaluated independently using three deterministic rules (Fig. 5-d): (a) if an octant contains a single web, the mortise in that octant is assigned to that web; (b) if two webs occupy the same octant, the mortise volume is evenly subdivided between them, ensuring that each resulting tenon retains adequate material thickness to avoid structural compromise; (c) if no web is present in an octant but competing tenons extend into it, the mortise is assigned to the tenon with the largest effective cross-sectional area—implying that its corresponding web is spatially closest to this octant—to maximize the effective shear transfer interface. By prioritizing the retention of maximal tenon cross-

sections, this strategy ensures that the resulting nodes are not only free of geometric conflicts but are optimized for structural integrity under varying nodal densities.

Third, the final mortise-tenon geometries are generated by computing L-shaped overlapping regions between valid web tenons and the beam volumes (Fig. 5-e). These regions are subtracted from the beams to form mortises, and the corresponding web tenons are trimmed accordingly. The web is inserted perpendicular to the beam plane but designed to carry axial loads along its own inclined axis. This geometric disalignment, combined with steppe tenon geometries, creates a mechanical interlock that resists pull-out forces (Fig. 6-a). All cutting faces are constrained to planar or beam-orthogonal orientations to maintain consistent machining references for robotic milling.

Finally, web-web interfaces are introduced to encode the predefined assembly sequence (Fig. 5-e). Where web members intersect, a tilted and stepped interface is generated so that later-installed members mechanically block earlier ones (Fig. 6-b,c).

These interfaces remain compatible with planar machining operations and embed assembly logic directly into the joint geometry.

Through this staged computation, complex multi-member intersections are reduced to a set of non-overlapping, assembly-aware timber joints that are both structurally effective and fabrication-ready.

- (4) **Output:** The finalized joint model consists of mortise and tenon geometries (Fig. 5-g) together with fabrication-related metadata. For each joint, machining reference boxes are generated to define

for robotic path planning. This ensures that the fabrication model remains consistent with the computational generation logic, enabling automated translation from geometric synthesis to toolpath execution.

Algorithm 1. Octant-based spatial joint generation.

Input:
B: Beam Coordinate System
W: Set of Web members {*w*₁, ..., *w*_{*n*}} (up to 8)
*F*_{vgs}: Internal Forces from VGS analysis

Output:
*G*_{joint}: Final Joint Geometry (Brep)
*Ref*_{machining}: Tool orientation frames

1. Preprocessing & Sequencing
 For each web *w*_{*i*} in *W*:
 Calculate Force Magnitude *F*_{*i*}
 End For

Sort *W* into Assembly Sequence *S* based on *F*_{*i*} and geometric accessibility.
 Initialize Octants[1..8] based on Beam Coordinate System *B*.

2. Octant Assignment
For each web *w*_{*i*} in *W*:
 Identify vector direction *V*_{*i*} relative to *B*
 Assign *w*_{*i*} to corresponding Octants[*k*]
End For

3. Geometric Computation
 Initialize *G*_{joint} ← GeneratePreliminaryBeamJoint(*B*)
For *k* = 1 to 8 (**For each Octant**): *Count* ← Number of webs in Octants[*k*]
 // Apply Topological Rules (Deterministic)
 If *Count* == 1 then (Rule A)
 *w*_{target} ← The single web in Octants[*k*]
 GenerateStandardMortise(*w*_{target})

 Else If *Count* == 2 then (Rule B)
 Sort webs *w*_{*a*}, *w*_{*b*} in Octants[*k*]
 SplitMortiseSpace(*w*_{*a*}, *w*_{*b*}, ratio=0.5) // Equal split

 Else If *Count* == 0 and Neighboring Tenons Compete then (Rule C)
 *w*_{winner} ← Web with Max(Effective Cross-Sectional Area)
 Assign extended mortise space to *w*_{winner}
 End If
 End For

4. Detail Resolution (Tenon & Interface)
For each web *w*_{*i*} in Sequence *S*:
 // Tenon-Mortise Detailing
 *Vol*_{*L*} ← CalculateLShapedOverlap(*w*_{*i*}, *B*)
 *G*_{joint} ← *G*_{joint} - Extrude(*Vol*_{*L*}) // Boolean Difference

 // Web-Web Interface Generation
 If *w*_{*i*} intersects adjacent web *w*_{next} then:
 // 1. Tilt Operation (Based on Assembly Sequence)
 If Sequence(*w*_{*i*}) > Sequence(*w*_{next}) then:
 Set *w*_{later} = *w*_{*i*}
 Else:
 Set *w*_{later} = *w*_{next}
 End If
 Set *Plane*_{tilt} = AlignPlane(*w*_{later}.InsertionVector)
 // 2. Step Operation (Mechanical Blocking)
 Set *Surface*_{interface} = AddSteppedFeature(*Plane*_{tilt})
 Update *G*_{joint} = Trim(*G*_{joint}, *Surface*_{interface})
 End If
 End For

5. Return *G*_{joint}, *Ref*_{machining}

local tool orientations for robotic milling. All cutting faces are constrained to remain planar or orthogonal to the beam reference plane, allowing this plane to be used as the primary setup orientation during machining. The geometry and metadata are stored within Grasshopper environment and directly referenced

The workflow integrates structural reasoning, fabrication constraints, and assembly logic into a unified parametric process for joint generation. Structural coherence is maintained by embedding force-derived orientations from Vector-based Graphic Statics into joint geometry, while fabrication feasibility is ensured through planar and

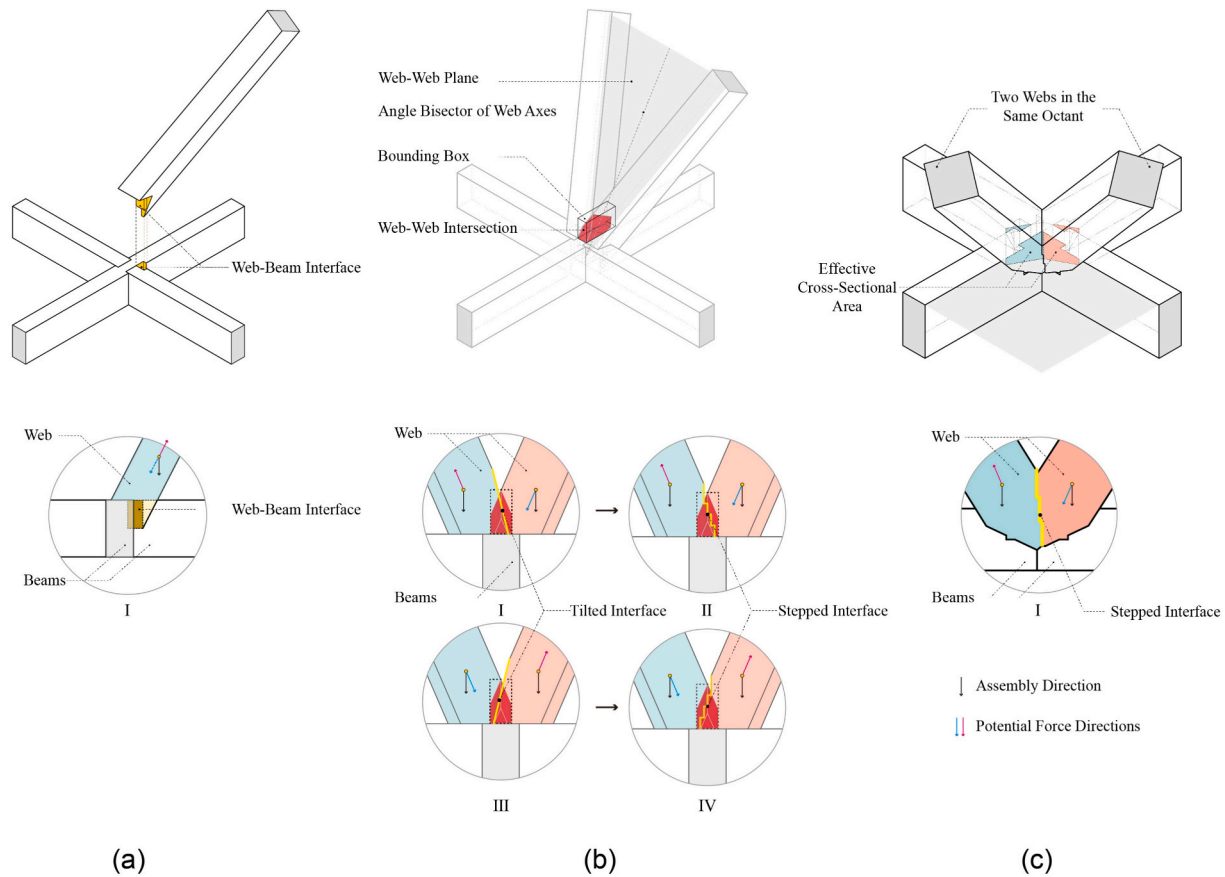


Fig. 6. Component interfaces design: (a) Interfaces between beam and web; (b) Tilt and stepped interfaces between webs in different octants; (c) Interfaces between two webs in the same octant (rule B applied).

orthogonal cutting constraints compatible with robotic milling. Assembly requirements are incorporated by encoding insertion order and geometric blocking directly within the joint model. All constraints are evaluated and resolved within a single computational environment, enabling consistent feedback between design intent and manufacturable output. As a result, joint geometries function simultaneously as analytical representations, fabrication models, and assembly instructions, establishing a continuous and coherent information framework from computation to construction.

4. Case study context and development

This section presents the development of a full-scale timber demonstrator as tangible proof-of-concept for the proposed workflow. The process, spanning architectural conception, structural analysis, and computational joint generation, is systematically articulated to illustrate the practical execution of the computational-robotic methodology.

4.1. Conceptual scenario and prototype definition

The conceptual framework of the tower draws inspiration from the Yingxian Wooden Pagoda—the world's oldest surviving all-timber high-rise structure. This historical precedent demonstrates how spatial continuity and hidden structural layers contribute to stability in timber-only systems. Adapting this principle to a contemporary context, the system envisions an architectural scenario characterized by flexible functional layouts and continuous, open floor plates. This programmatic flexibility inherently leads to vertical structural misalignments between adjacent levels. Consequently, “hidden layers” are designed to function as critical structural transfer zones, while simultaneously providing ideal spaces

for accommodating mechanical, electrical, and plumbing (MEP) systems (Fig. 7).

For the purpose of experimental construction and empirical study, a fundamental 3600 mm by 3600 mm spatial module was extracted from this broader architectural scenario to serve as the demonstrator. The resulting prototype was designed as a five-level structure composed of three visible floors and two hidden structural floors. Each visible floor possesses a clear height of 2700 mm, while the hidden layers measure 600 mm in height. Specifically, the enclosed internal areas from bottom to top are 9.0 m², 3.4 m², and 4.5 m², respectively. Although this footprint may appear compact, it demonstrably provides a fundamental and valid usable spatial volume for human occupation.

It is critical to emphasize that this full-scale demonstrator is not intended to serve as a fully resolved, standalone architectural design; consequently, this study deliberately excluded secondary architectural elements such as vertical circulation and building envelopes. Rather, its primary objective is to function as an extreme methodological stress-test for the proposed integrated design-fabrication method within a scalable, modular framework. Therefore, severe topological and geometric complexities were intentionally introduced to validate the robustness of the workflow far beyond standard orthogonal framing. The alternating configuration of visible and hidden layers produces a hierarchical load path, where strategic misalignments provide an ideal scenario for generating complex multi-member joints. Additionally, a dual-material configuration was utilized to evaluate the system's robustness under different material conditions. Spruce Glulam was used for the visible floors, providing standardized geometry; Camphor Logs were employed for the hidden floors, introducing natural irregularities and testing the system's tolerance for non-uniform geometries.

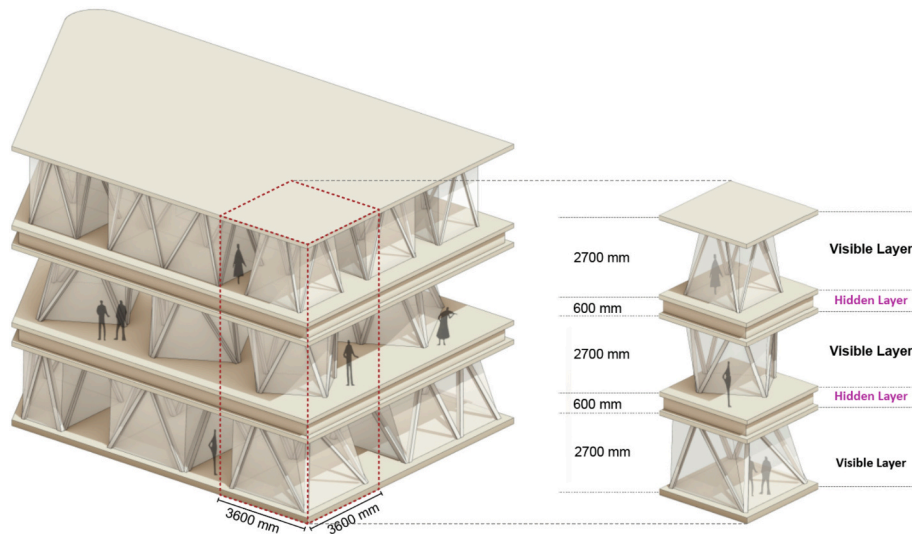


Fig. 7. Conceptual architectural scenario (left) and prototype definition (right).

4.2. VGS-based structural analysis

Our design strategy for joint integration is to align the internal forces of the components with the planned assembly sequence. Due to the limited stiffness typically offered by timber-to-timber connections, the timber-only framework is designed as a pin-jointed structure. This approach simplifies the design and fabrication of complex all-wood joints, as the structure ensures that the primary load transfer occurs through axial forces.

Building on this premise, we employed graphic statics for structural analysis. This method inherently treats the structure as pin-jointed and enables the simultaneous, intuitive manipulation of both the form diagram (representing spatial geometry) and the force diagram (representing internal force distribution) [39]. The analysis was conducted using the Grasshopper plugin VGS, which supports interactive real-time design between form and force diagrams within the parametric workflow [13].

The application of VGS in this workflow relies on the assumption of pin-jointed behavior, which simplifies the structural model to focus purely on axial forces. This assumption is mechanically justifiable for the

proposed spatial truss topologies, where triangulation ensures that load transfer is predominantly characterized by tension and compression rather than bending. Furthermore, in timber construction, interlocking joints often exhibit semi-rigid behavior with rotational slip, rendering them mechanically closer to hinges than to the perfectly rigid nodes assumed in continuous frame analysis. Therefore, while this assumption simplifies the model by neglecting secondary bending moments induced by joint fixity or eccentricities, it effectively captures the primary axial force flow required to drive the early-stage geometric generation and assembly logic of the joint system.

Building upon the predefined axial framework, boundary conditions and loads—primarily distributed floor loads—were subsequently applied to establish static equilibrium for structural analysis (Fig. 8-a). Through the VGS interface, the internal forces and their directional flow within each structural member were visually rendered, employing a color-coded scheme where tension is indicated in red, compression in blue, and external forces (loads and support reactions) in green (Fig. 8-b). The relative magnitude of internal forces within members was visually represented in the diagrams by line weight.

Building upon the results of the VGS analysis, the derived data was

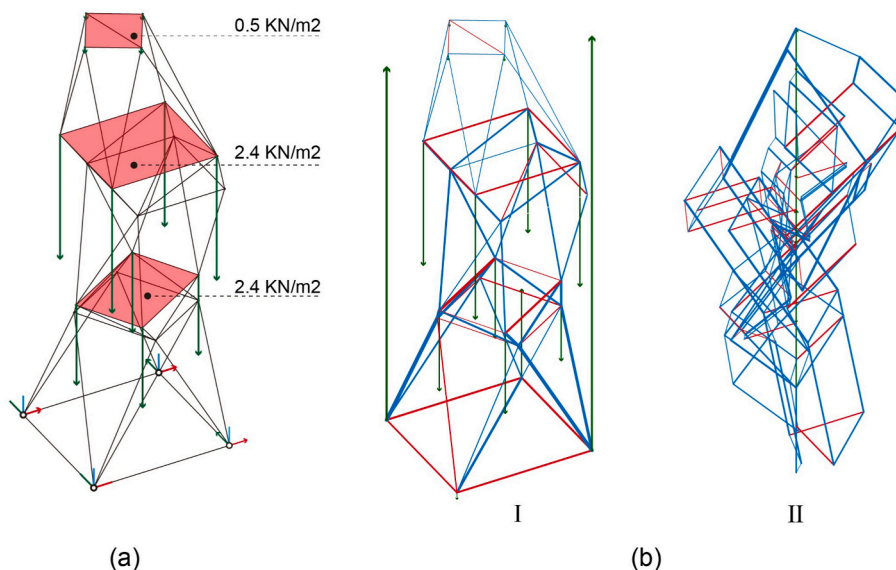


Fig. 8. Structural design of case study: (a) Boundary conditions for structural analysis; (b) VGS-based analysis: form diagram (I) and force diagram (II).

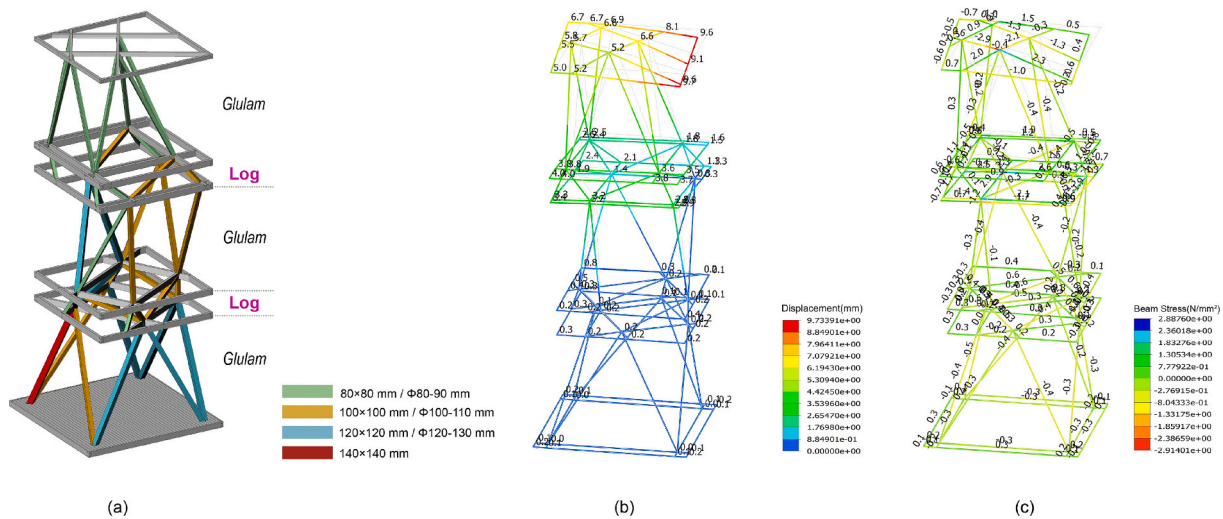


Fig. 9. Cross-sectional sizing and FEA validation: (a) Cross-sectional sizing model; (b) Structural displacement; (c) Stress distribution.

Table 1

Correlation between axial force ranges, member dimensions, and material selection of webs.

Index	Axial Force (KN)	Dimension (mm)	Material	Web Count
1	7.0	140 × 140	Glulam (Spruce)	1
2	[2.5, 7.0)	120 × 120 ø120–130	Glulam (Spruce) Log (Camphor Wood)	7 2
3	[1.0, 2.5)	100 × 100 ø100–110	Glulam (Spruce) Log (Camphor Wood)	6 12
4	(0, 1.0)	80 × 80 ø80–90	Glulam (Spruce) Log (Camphor Wood)	8 8

directly applied to two subsequent critical phases: the sizing of structural components and the planning of the global assembly sequence.

- (1) **Cross-sectional sizing** — Following the analysis of internal force distribution, a sizing strategy was formulated to correlate member cross-sections with the magnitude of axial forces in equilibrium. The strategy classified members into discrete categories—four standard sizes for square glulam sections and three diameter grades for solid timber logs (Fig. 9-a). The detailed sizing criteria, mapping force ranges to specific section dimensions, are shown below in Table 1:

Following the VGS-based form-finding, a Finite Element Analysis was subsequently conducted as a confirmatory verification step—rather than a predictive design tool—to validate the global performance of the design. All members except the continuous horizontal beams were modeled as pin-ended connections, consistent with the theoretical premise of graphic statics. The FEA results indicated a maximum structural displacement of 9.7 mm under the given loads (Fig. 9-b). Furthermore, the analysis revealed a maximum stress of only 2.9 MPa in the critical cantilever beams (Fig. 9-c). This corresponds to a stress ratio of approximately 0.25 (based on a conservative design bending strength of 12 MPa for Spruce Glulam), confirming that the structural elements operate well within the material's elastic limits with substantial safety margins.

- (2) **Assembly sequence planning**— The graphic statics analysis also provided the internal force direction (tension or compression) for each member. This information directly determined the

assembly sequence according to the principle of force-driven assembly: tensile members were installed first, followed by compressive members that mechanically lock them into position, with the order further refined by the magnitude of axial force. This ensured a direct correspondence between the joint's geometric design and the internal force flow.

The overall assembly sequence of this case followed a layered strategy, as illustrated in Fig. 10. Within each web layer, components were subdivided into multiple groups, organized according to the points of convergence at their upper junctions. The sequence of these groups was governed by the magnitude of internal forces at the lower convergence points, as indicated by circled numbers. Within each group, the installation order of individual components was determined by the magnitude and direction of forces at their upper convergence points, as indicated by the color coding of the members.

While demonstrated on a vertical tower, this force-driven assembly logic is topologically scalable to other discrete spatial typologies capable of being resolved via VGS, such as spatial trusses and vaulted frameworks. The proposed force-guided sequence relies on a pre-determined equilibrium state—typically governed by the permanent loads—to establish a consistent hierarchy of internal forces. To address scenarios involving complex variable loads, such as wind uplift or seismic reversal, which may theoretically alter force distribution during service life, the methodology advocates for a comprehensive multi-load case analysis to derive the most robust assembly sequence. For critical members subject to force reversal, supplementary mechanical fasteners, such as locking pins, could be integrated to ensure connection stability. In addition, the resulting stepped and tilted interlocking joints provide inherent mechanical resistance against shear forces in multiple directions, thereby contributing to structural integrity even when transient load cases cause internal forces to deviate from the assembly-driving static state.

The design of the timber framework outlined above gave rise to a notably high level of joinery complexity, which served as the core motivation for developing a computational joint-generation solution. This complexity is manifested in three key aspects:

- (1) the large and variable number of members intersecting at each joint, ranging from 3 to 7.
- (2) the variation in cross-sectional dimensions among these converging members; and
- (3) the requirement for each joint to be geometrically resolvable in accordance with the predetermined force-driven assembly sequence.

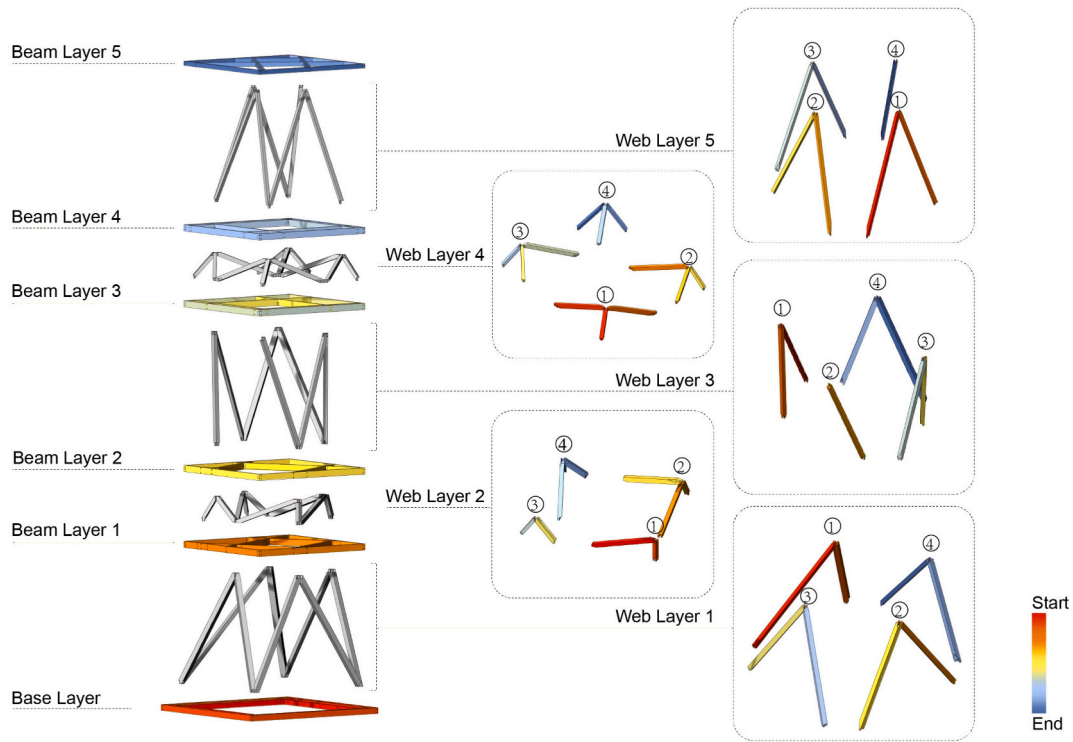


Fig. 10. Force-driven assembly sequence planning.

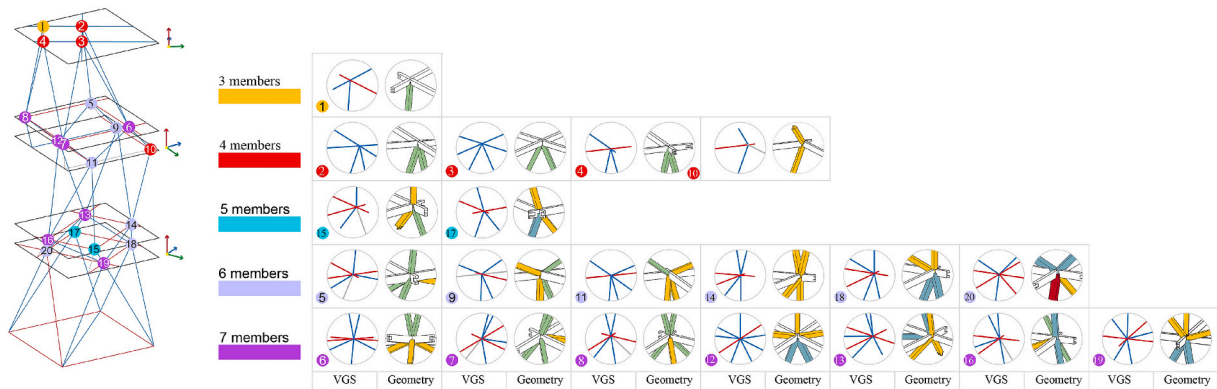


Fig. 11. Joint detailing of case study structure.

The following section details the development of a computational workflow specifically designed to address these challenges and generate the corresponding custom timber joinery.

4.3. Joint computation

This algorithm was employed to generate the 20 complex spatial nodes for the case study structure (Fig. 11). Based on the vector-based structural framework established in Section 3, the member axes, cross-sectional dimensions, and assembly sequence were imported as parametric inputs to the joint generation algorithm.

All Boolean and morphological operations were implemented within Grasshopper. As shown in Fig. 11, each node comprises a pair of intersecting beams and one to five web members, with varying internal force directions and cross-sectional dimensions across all nodes. The system successfully generated all unique joints, with each joint automatically adapting to its specific spatial configuration and assembly logic. Consequently, any changes in member position or cross-section can be

automatically accommodated by the algorithm, which regenerates the corresponding joint geometry and associated fabrication metadata accordingly.

5. Robotic fabrication and on-site assembly

This section describes the physical realization of the proposed joint-informed workflow through robotic fabrication and on-site assembly. Building on the computational joint system and parametric data flow introduced in previous sections, the fabrication and assembly processes were designed to execute the geometric and assembly logic encoded in the digital model.

5.1. Robotic fabrication setup

All timber members and joints were fabricated using a KUKA KR210 R2700 six-axis industrial robot equipped with a spindle-based milling end effector (Fig. 12). The robot was mounted on a linear rail, enabling

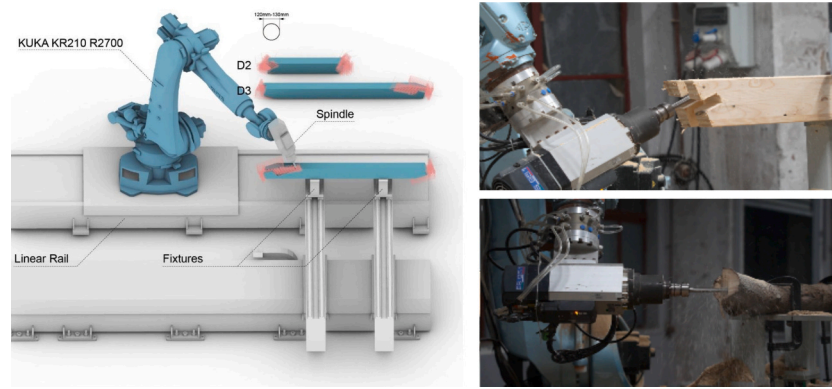


Fig. 12. Robotic fabrication setup illustrating (left) simulated milling toolpaths, and (right) robotic fabrication of glulam and log members.

access to both ends of each member within a single setup and allowing continuous machining without reorientation. Timber members were placed on two horizontally adjustable support rails, which could be repositioned to accommodate different member lengths. The fixtures on the rails also provided a consistent geometric reference for positioning. For standardized members, this setup allowed repeatable fabrication without the need for re-registration. For irregular log members, a localized scanning and positioning approach was employed to align physical geometry with the digital model, which follows the workflow previously reported in [40].

Robotic fabrication was implemented on the FURobot platform, which interfaces directly with the parametric model developed in Grasshopper [41]. This setup enabled the automatic translation of joint geometry, machining reference frames, and tool orientations into executable robotic toolpaths. The robot was controlled through KUKA Robot Language (KRL) commands streamed via a TCP/IP socket directly from Grasshopper, eliminating the need for intermediate file export or offline post-processing. Detailed implementation of the Grasshopper-KUKA communication framework was also documented in [40].

5.2. Tool path planning

As described in the preceding sections, toolpath planning was derived from the joint design logic. Here, a joint prototype comprising four web members is used to illustrate the toolpath planning method. Fig. 13 shows the geometry of each member together with its corresponding assembly sequence. For each joint, machining reference boxes were first extracted from the parametric joint model to define local coordinate frames and tool orientations. Toolpaths were then generated by iterating over the box volumes removed during Boolean operations in the joint modeling process. The resulting discrete tool paths were subsequently concatenated into continuous machining sequences for each member (Fig. 14). All generated toolpaths were verified through robotic simulation to detect potential collisions, reachability issues, and axis

singularities. After validation, the toolpaths were executed directly on the robotic system. This model-driven approach allowed toolpath generation to remain synchronized with geometric design. Although this approach does not provide the full optimization capabilities of mature CAM programming environments, it offers a transparent and tightly coupled link between the digital joint model and the machining strategy.

In evaluating the system's performance, a critical distinction must be drawn between robotic machining efficiency and overall production efficiency. As quantified later in Section 6.2, the robotic arm exhibits high efficiency in the actual subtractive manufacturing phase, rapidly executing complex toolpaths that would be time-consuming for manual carpentry. However, the total production cycle is currently constrained by auxiliary logistical processes, such as manual material handling, clamping, and referencing, which occupy a significant portion of the workflow. The primary contribution of this integrated system is seamless 'file-to-factory' data integration. By eliminating the labor-intensive CAM programming and jig setting typically required for non-standard geometries, the workflow ensures that the robot's high-speed execution capabilities are effectively applied to bespoke components without being bottlenecked by software preparation.

5.3. Assembly and reassembly

The on-site construction process followed the force-driven assembly sequence established during the structural analysis. To improve construction accuracy and efficiency, an Augmented Reality (AR) guidance system was employed on site (Fig. 15). Using Fologram plugin for Grasshopper [42], the digital model was precisely overlaid onto the physical environment in real time via a Microsoft HoloLens 2 device. This setup functioned as a real-time holographic template, allowing the team to verify the correct positioning and orientation of each component without traditional physical jigs. A team of four workers completed the full assembly over two consecutive days.

In addition to the initial construction, the structure's reversibility and

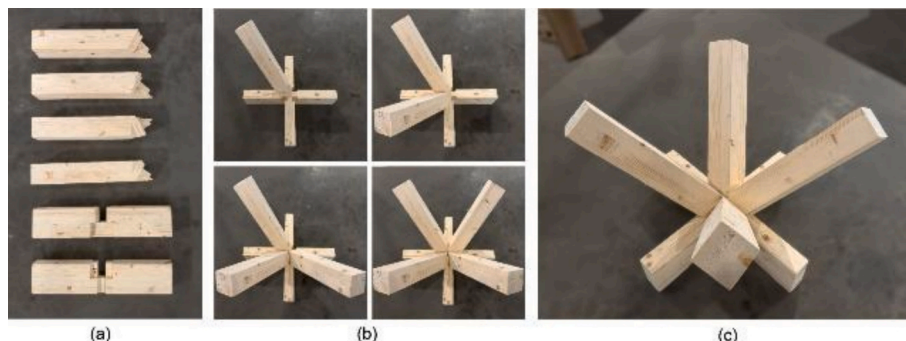


Fig. 13. Physical model of four-web joint prototype: (a) Individual members; (b) Assembly process; (c) Completed joint.

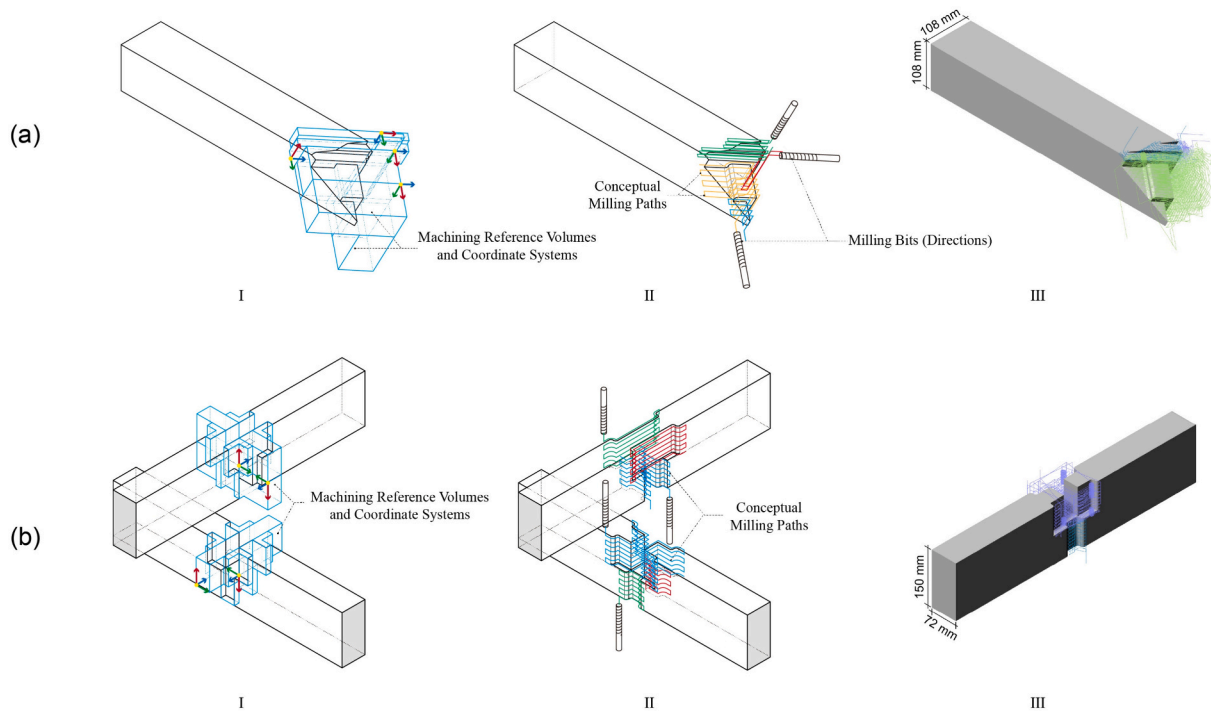


Fig. 14. Toolpath planning workflow for (a) web and (b) beam members: (I) Machining reference volumes extracted from joint design; (II) Conceptual definition of tool orientations and milling paths; (III) Executable robotic toolpaths.

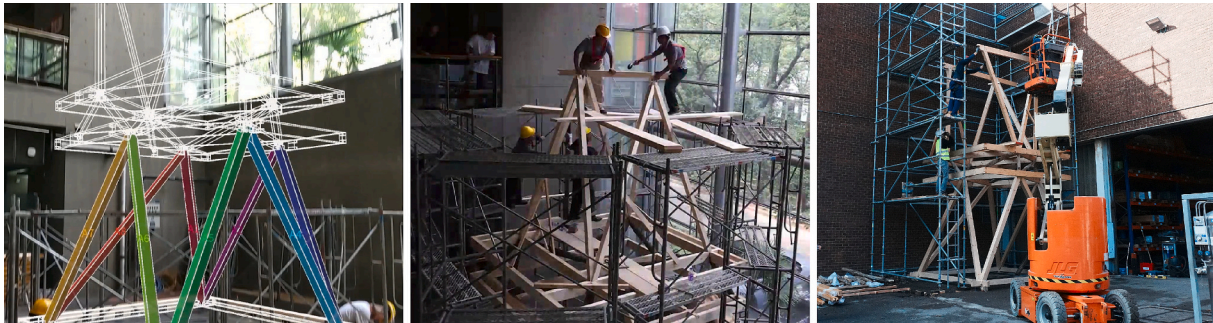


Fig. 15. On-site assembly: AR-assisted assembly (left); Shanghai installation (middle); Louvain-la-Neuve installation (right).

deployability were further validated through a complete reassembly process. Following a one-year exhibition in Shanghai, the pavilion was fully disassembled, packed, and shipped to Louvain-la-Neuve, Belgium. There, it was reassembled in just 10 h, demonstrating the system's capacity for repeated deconstruction and rapid redeployment without loss of structural or geometric integrity.

6. Results and evaluation

The realized outcome is a 9.4-m-tall, fastener-free timber tower structure (Fig. 16). This full-scale prototype implements the proposed computational joint system and applies it to the resolution of complex spatial intersections (Fig. 17). The assembly and subsequent reassembly of the structure—as described in the previous section—provide a practical basis for evaluating its performance across several key criteria: geometric adaptability, construction efficiency, and its environmental impact compared to conventional system.

6.1. Adaptability of computational joint system

The proposed joint system successfully generated all 20 joint

geometries within a unified digital workflow. Its adaptability was then evaluated by examining how effectively it accommodated the diverse spatial configurations and material variations present in the 9.4-m tower, with a focus on variations in geometric configuration, member composition, and material heterogeneity (Table 2).

The generated joints exhibited a wide range of topological complexity, with the number of intersecting members per joint varying from 3 to 7. Angular relationships between members and the primary beam plane covered a continuous spectrum from 19.4° to 90° , demonstrating the system's ability to handle both steep and shallow spatial intersections. The joints also integrated both engineered glulam and solid timber logs, with a nearly balanced ratio between the two material types across the joint set. Each joint consistently combined multiple cross-sectional sizes, showing the system's ability to compensate for dimensional inconsistencies. These results validate the system's core objective: to enable the design of non-standard, multi-member timber joints without relying on standardized details or external mechanical fasteners.

To quantitatively evaluate the fabrication adaptability, a multi-variable Joint Complexity Index (JCI) was formulated. The formula is structured to normalize standard orthogonal Gutou tenon to a baseline



Fig. 16. Case study structure in Shanghai (left) and Louvain-la-Neuve (right).



Fig. 17. Detailed views of Joint 16 and Joint 20.

of 1.0, while measuring the deviation of complex nodes across four aspects:

$$JCI = \left[\frac{N+2}{3} \times \left(1 + \alpha \times \frac{N_{side} - 1}{N} \right) \right] \times \left(1 + \beta \times \frac{N_{log}}{N} \right) \times \left(1 + \gamma \times \frac{T_{sec} - 1}{N} \right) \times \left(1 + \delta \times \frac{\Delta\theta}{90} \right)$$

Where:

N is the number of webs, resulting in a total nodal valency of $N + 2$ (incorporating two continuous beam elements).

N_{side} denotes the *Octant Congestion*, defined as the maximum number of web members located on the same spatial side relative to the beam plane (within the upper or lower four octants).

N_{log} is the count of irregular log members.

T_{sec} is the number of cross-section sizes and profiles participating in the Boolean intersection.

$\Delta\theta$ measures the Angular Range, defined as the difference between the maximum and minimum inclination angles of the webs relative to the beam plane.

To compute the index, coefficients were assigned based computation and process-level assumptions: α for spatial congestion penalty, β for raw log processing overhead, γ for section heterogeneity, and δ for deviation in angular distribution. It should be noted that these coefficient values are conceptual assumptions intended for relative benchmarking; precise quantification of complexity increments would require a fine-

grained calculation based on the specific design features and actual fabrication workload. Here we assigned a uniform weight of 0.5 to all coefficients to represent a balanced assumption of difficulty increments across spatial, material, sectional, and angular domains. Under this evaluation framework, a standard orthogonal Gutou tenon ($N = 1$, glulam-only, single-section) serves as the baseline ($JCI = 1.0$). In contrast, the most critical nodes in the constructed tower—characterized by 5 webs, 3logs, 3 section sizes—achieved a score of 5.63. This quantitative gap demonstrates that the workflow successfully accommodates high fabrication complexities.

6.2. Fabrication and assembly performance

The performance of fabrication and assembly was evaluated based on key metrics derived from the construction of the case study structure. As summarized in Table 3, the 20 spatial joints involved the fabrication of 44 web members and 20 beam members.

Since the precise machining time for each individual component was not recorded in real-time, the processing time was estimated by calculating the toolpath lengths for the components, serve as computational proxies rather than empirical measurements. As detailed in Table 3, the robotic milling process utilized a 12 mm diameter cutter at a feed rate of 4500 mm/min, with a cutting depth of 8 mm per layer. The machining time per end ranged around 6 to 12 min, with variations in path length attributable to differences in joint geometry and cross-sectional

Table 2

Key attributes of multi-member joints.

Joint ID	Member count	Glulam count	Log count	Equivalent rectangular Cross-Section (mm)	Octant(Member count)	Angle with beam plane (°, absolute value)	Joint Complexity Index (JCI)
1	1	1	0	80 × 80	VII (1)	77.9	1.00
2	2	2	0	80 × 80	V (1), VIII (1)	58.6–71.6	1.79
3	2	2	0	80 × 80	V (1), VII (1)	63.4–68.0	1.71
4	2	2	0	80 × 80	VI (1), VIII (1)	67.7–69.4	1.68
5	4	1	3	80 × 80,100 × 100	IV (1), V (1), VI (1), VIII (1)	19.4–71.6	4.99
6	5	2	3	80 × 80,100 × 100	III (2), V (1), VI (1), VIII (1)	23.0–63.4	4.90
7	5	2	3	80 × 80,100 × 100	II (1), III (1), V (1), VI (1), VIII (1)	21.8–68.0	5.03
8	5	2	3	80 × 80,100 × 100	I (1), IV (1), V (1), VI (1), VIII (1)	30.6–77.9	5.06
9	4	2	2	80 × 80,100 × 100	III (1), IV (1), VII (1), VIII (1)	23.0–73.9	4.06
10	2	1	1	100 × 100	III (1), VII (1)	42.9–68.5	1.90
11	4	2	2	80 × 80,100 × 100	II (1), III (1), VI (1), VII (1)	36.1–87.9	4.07
12	5	2	3	100 × 100,120 × 120	II (1), III (1), IV (1), VI (1), VIII (1)	19.4–72.6	5.19
13	5	2	3	100 × 100,120 × 120	I (1), III (1), VII (2), VIII (1)	19.9–71.0	5.14
14	4	2	2	100 × 100	II (1), IV (1), VIII (1), VIII (1)	20.4–73.9	3.65
15	3	1	2	80 × 80,100 × 100	III (1), VI (1), VIII (1)	49.6–87.9	3.14
16	5	2	3	80 × 80,100 × 100,120 × 120	II (1), IV (1), V (1), VI (1), VII (1)	20.5–72.6	5.63
17	3	2	1	100 × 100,120 × 120	IV (1), V (1), VII (1)	52.1–70.8	2.92
18	4	2	2	100 × 100,120 × 120	III (1), IV (1), VI (1), VIII (1)	21.6–65.1	3.93
19	5	2	3	100 × 100,120 × 120	II (1), III (1), IV (1), V (1), VII (1)	20.4–61.5	4.92
20	4	2	2	100 × 100,120 × 120,140 × 140	I (1), IV (1), VII (1), VIII (1)	19.9–66.5	4.43

Table 3

Quantitative results of fabrication and assembly process.

Metric	Result	Note
Number of webs involved	44	
Number of beams involved	20	Associated with 20 spatial joints.
Theoretical machining time (Proxy, per member end)	6 min 25 s (Minimum) 12 min 01 s (Maximum)	Proxies Calculated from toolpath lengths; milling bit diameter:12 mm; feed rate: 4500 mm/min.
Robotic fabrication duration	9 days	
Assembly duration in Shanghai	16 h	4 workers, excluding floor installation time
Dismantling duration in Shanghai	8 h	3 workers
Assembly duration in Louvain-la-Neuve	10 h	4 workers, using a lifting platform

dimensions.

Even if calculated based on the maximum processing time per component, the total estimated robotic machining duration for all joints would be approximately 25 h. However, the actual fabrication process took 9 days to complete. This significant discrepancy indicates that the primary constraint on overall construction efficiency was not the actual cutting process, but rather the cumulative time spent on auxiliary tasks, including tool-path verification, material repositioning, and machine setup changes. The efficiency of the robotic fabrication process was also determined by the operational steps in Table 4. The auxiliary task durations outlined in Table 4 represent average estimates derived from on-site observations. These auxiliary stages collectively extended the total fabrication timeline. This highlights that in integrated robotic timber construction, process design and workflow coordination are as critical as

Table 4

Key stages and estimated durations of robotic fabrication.

Stage	Description	Estimated Duration (Uncertainty ±20%)
Robot Simulation	Determining feasible robot positions and orientations to ensure reachability and collision-free operation.	Within 10 min
Loading	Position the component according to the simulated setup.	Within 5 min
Non-Standard Component Positioning	Locating and aligning non-standard components within the robot's workspace; not required for standard components.	Within 30 min
Machining	Milling the joint geometry.	See Table 3 (Proxy values)
Unloading	Removing the finished component from the work area.	Within 3 min

the cutting operation itself. While robotic milling efficiency is comparable to CNC machining in terms of cutting time, the surrounding processes still require systematic integration and planning to realize the full potential of automated timber fabrication.

The initial on-site assembly took place indoors under constrained conditions in Shanghai and was completed in 16 h by a four-person team, while dismantling required 8 h with three workers. Reassembly outdoors in Louvain-la-Neuve was accomplished in 10 h by four workers, aided by a lifting platform. While these outcomes underscore that the overall construction process remains significantly influenced by on-site conditions, they simultaneously demonstrate the high assembly efficiency achieved through the timber joinery system.

During both assembly cycles, no noticeable joint slippage or rotation was observed, confirming the mechanical integrity of the mortise-tenon

system under gravity loads. During the dismantling process, localized surface damage occurred at a few joints due to incidental impact; however, the subsequent reassembly demonstrated that this did not compromise the overall structural stability, and all components remained reusable without impairment to their load-bearing capacity.

6.3. Life cycle impact

In addition to technical performance, the environmental implications of the proposed timber-only construction system were assessed. The complete elimination of metallic connectors reduces material heterogeneity and facilitates end-of-life disassembly. To quantify the impact, a comparative Life Cycle Assessment (LCA) was conducted, estimating the Global Warming Potential (GWP) of the all-wood structure against a conventional steel-jointed alternative. The assessment adopts a 'Cradle-to-Gate' (Modules A1-A3) system boundary, covering raw material supply (A1), transport to manufacturer (A2), and manufacturing (A3). Transport-related emissions (A4), fabrication energy (A5), and end-of-life benefits (Module D) were excluded to establish a conservative baseline, ensuring that the reported reductions reflect the fundamental material substitution rather than logistical or future-reuse assumptions.

The steel-jointed scenario assumes that all complex spatial nodes are replaced with custom steel connectors of equivalent function (Fig. 18), while the timber volume is correspondingly reduced. All timber was modeled as spruce glulam, applying a density of 480 kg/m³ and GWP factor of 0.263 kg CO₂e/kg (Circular Ecology, n.d.). The dry mass of wood was calculated considering a moisture content of 10%. The steel-jointed alternative adopted spherical connectors typical in complex spatial structures, using Q235B steel with an emission factor of 1.55 kg CO₂e/kg [43], reflecting the high embodied carbon associated with custom-fabricated steel elements. A uniform wall thickness of 8 mm was applied to both spherical nodes and connecting tubes. To align with the structural behavior, the sleeves vary in thickness from 8 mm at the top to 5 mm at the bottom. The GWP for each system was calculated as follows:

$$E_{wood} = V_{net, wood} \times \rho_{wood} \times (1 - MC) \times EF_{wood} \quad (1)$$

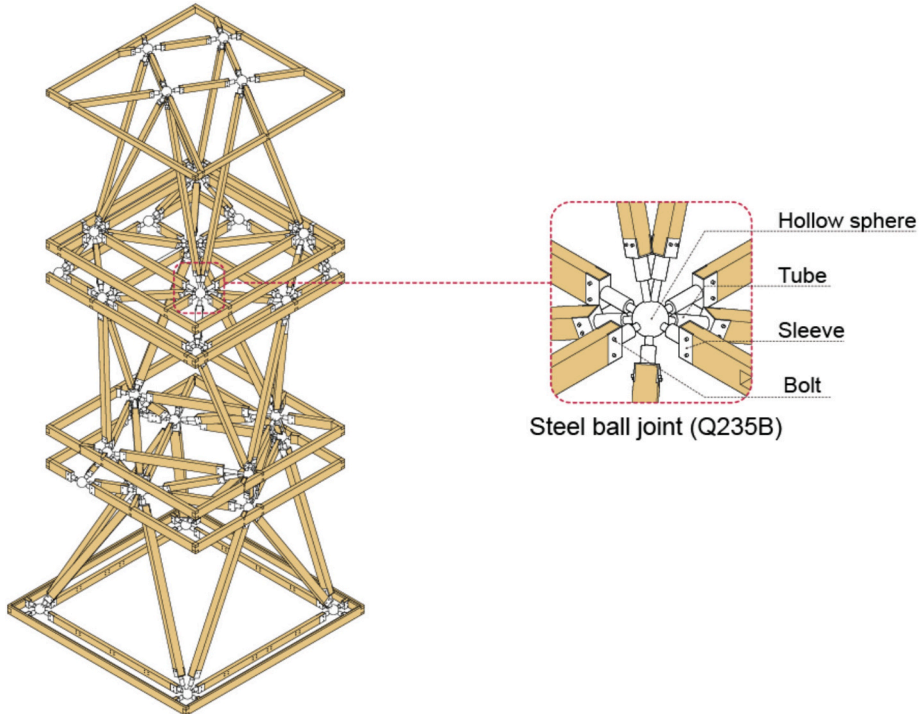


Fig. 18. Design of steel-jointed reference system for comparative life-cycle assessment.

Table 5
Comparative embodied carbon assessment.

Component / Scenario	All-Wood Joint System	Steel-Jointed System
Timber Volume (m ³)	2.1072	1.7543
Timber Waste Volume (m ³)	0.3240	0.0896
Steel Volume (m ³)	–	0.0728
Calculated GWP (kg CO ₂ e)	270.2	1037.8

Notes: Glulam factor: 0.263 kg CO₂e/kg; Density: 480 kg/m³; Moisture content: 10%. Steel factor: 1.55 kg CO₂e/kg; Density: 7850 kg/m³.

$$E_{hybrid} = [V_{net, wood} \times \rho_{wood} \times (1 - MC) \times EF_{wood}] + (V_{steel} \times \rho_{steel} \times EF_{steel}) \quad (2)$$

$V_{net, wood}$, net timber volume after deducting recyclable waste.

V_{steel} , steel volume.

ρ_{wood} , glulam density.

ρ_{steel} , Q235B steel density.

MC, moisture content.

EF_{wood} , embodied carbon factor of Glulam.

EF_{steel} , embodied carbon factor of Q235B steel.

The results indicate that the all-wood system reduces the embodied carbon (A1-A3) by approximately 74% compared to the steel-jointed variant (Table 5). This substantial reduction is primarily attributed to the avoidance of high-impact steel components, despite a higher volume of timber waste in the milling process.

Furthermore, although excluded from the quantitative calculation, the system's reversible, mechanical joinery enables the direct reuse and reconfiguration of components, aligning with circular construction principles. This design inherently supports multiple life cycles without degradation of the primary material, thereby extending the carbon storage period of the timber and reducing the demand for new resources.

6.4. Limitations and scalability

Despite the successful implementation of the computational-robotic workflow, the current scope and methodology present certain

boundaries that open pathways for further refinement and development. These limitations are prioritized below based on their impact on structural application and the feasibility of their resolution.

First, The most critical limitation barring immediate widespread adoption is the absence of systematic physical testing. Although the full-scale prototype demonstrated stability under self-weight and was successfully assembled and disassembled, the mechanical properties of the joints—such as stiffness, strength, ductility, and failure modes—remain unquantified. Future work should include comprehensive experimental campaigns, including monotonic and cyclic loading tests on representative multi-member joints. Such data would not only validate and calibrate the numerical models but also support the development of standardized design guidelines, enabling the wider adoption of these joints in real-world, large-scale timber construction.

Second, while the VGS-based graphic statics has been effectively integrated into the computational design pipeline to generate and size components under axial-force assumptions, the structural modeling remains inherently simplified. The adoption of linear-elastic material models and pin-jointed connections, though appropriate for early-stage form-finding and force-flow visualization, does not fully capture the anisotropic, nonlinear behavior of timber or the semi-rigid characteristics of interlocking joinery. Future implementation could benefit from incorporating more advanced finite element modeling that accounts for orthotropic material properties, contact interactions. This would enhance the predictive accuracy of joint performance under varied load cases.

Regarding scalability, a critical distinction must be drawn between computational and physical scalability. The digital framework exhibits linear scalability, where the computation of joint geometries, assembly sequence and robotic toolpath remains efficient even for complex networks. Conversely, physical implementation faces non-linear bottlenecks, primarily driven by tolerance accumulation and assembly logistics of timber-only system. In larger-scale applications, minute machining errors or moisture-induced deformations can propagate globally, necessitating stricter tolerance controls and more sophisticated, zone-based erection strategies than those required for the current prototype.

7. Conclusion

This paper established an integrated computational-robotic workflow for timber-only construction. Through the development of a timber-only joint system and its validation in a 9.4-m full-scale prototype, this study demonstrated a reproducible, data-continuous framework that unifies design, analysis, fabrication, and assembly within a single digital environment.

Methodologically, the system translated traditional joinery principles into a parametric logic capable of generating complex multi-member intersections. By mapping force vectors derived from Vector-based Graphic Statics directly onto joint geometry, the workflow aligned structural requirements with fabrication constraints. The robotic execution confirmed that geometrically interlocked, timber-only structures could be assembled and disassembled without adhesives or auxiliary fasteners.

This paper contributed to the field of automated timber construction in three principal ways. First, it presented a generalized multi-member timber joint system that extends traditional mortise-and-tenon logic to spatially complex intersections typically requiring steel connectors. Second, it introduced a joint-informed workflow where the connection serves as the fundamental computational unit linking structural analysis and fabrication feasibility, enabling concurrent rather than sequential design processing. Third, through the full-scale prototype, it validated the technical feasibility of an integrated digital chain, quantifying the system's capacity to handle geometric complexity, control fabrication tolerances, and achieve significant embodied carbon reductions.

Beyond the specific prototype, the presented workflow signals a

broader shift in automated timber construction toward a connection-centric design logic, wherein structural performance, fabrication constraints, and assembly strategies are co-generated rather than sequentially resolved. This approach inherently enables reversible assembly, allowing complex structural frames to be assembled, disassembled, and reconfigured without material degradation. Consequently, the study establishes a materially coherent paradigm that embeds circular construction not as a remedial afterthought, but as an intrinsic, algorithmic property of the building system—effectively minimizing embodied carbon and material waste throughout the entire lifecycle.

Future research could expand the current system from a single joint prototype toward a broader family of timber-only joint typologies capable of accommodating more diverse structural configurations. In this regard, data-driven computational paradigms, such as Graph Learning, could support the negotiation of multi-scalar constraints and the optimization of such geometric interlocking systems across larger design spaces. Driven by continuous joint research and development, the practical deployment of connection-centric workflow can be pushed toward a wider range of architectural scenarios, including multi-story timber frameworks and large-span spatial grids. Ultimately, translating experimental prototypes into real-world building systems requires aligning these novel joinery techniques with existing building codes, thereby necessitating rigorous empirical testing to satisfy certification requirements for fire resistance, seismic stability, and long-term structural integrity.

CRedit authorship contribution statement

Hua Chai: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Tianyi Gao:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Junwang Yu:** Software, Methodology, Investigation. **Sylvain Rasneur:** Software, Methodology, Investigation, Conceptualization. **Yige Liu:** Visualization, Resources, Methodology. **Denis Zastavni:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Conceptualization. **Philip F. Yuan:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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