# Controlled Anisotropy

## A Design-to-Assembly Method for Resource-Efficient Timber Structures with Fibrous Joints

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1 Structurally informed timber branching structure demonstrating the Controlled Anisotropy design-to-assembly method

## ABSTRACT

This paper presents a novel design-to-assembly method that enables resource-efficient branching timber structures. We introduce a bio-based material system that employs anisotropy-driven design and fabrication strategies alongside a computational design tool for structurally-informed design explorations. Particular attention is directed to connections between timber components, where deviations between the direction of force flow and the fiber orientation in the wood are present, which are recognized as structural weak points. This research investigates how anisotropic nodes can enhance force transfer between individual timber elements, thus allowing for load-adapted, slender component cross-sections. Maintaining precise control over anisotropy represents the pivotal strategy for developing a bio-based, material- and resource-efficient building system. Furthermore, we demonstrate how the concurrent development of a material system, fabrication methods, and an assembly strategy, in conjunction with the development of a computational framework, yields a building system with a distinctive, material-driven aesthetic. The strength of the proposed material system and fabrication strategies are assessed in small-scale tests of three-valent planar nodes and four-valent spatial nodes. Additionally, the scalability and flexibility of a custom-developed design tool, fabrication processes, and assembly strategy are evaluated through a 1:1 demonstrator of a load-bearing, branching structure (Figure 1).

## INTRODUCTION

Wood, as a renewable material, is playing an increasingly important role as a building material towards the goal of sustainable construction. On the one hand, wood acts as a carbon sink by sequestering $CO^2$, and on the other hand, timber's exceptional strength-to-weight ratio makes it well-suited for load-bearing structures, offering a viable alternative to energy-intensive materials such as steel and concrete on large-scale (Churkina et al. 2020).

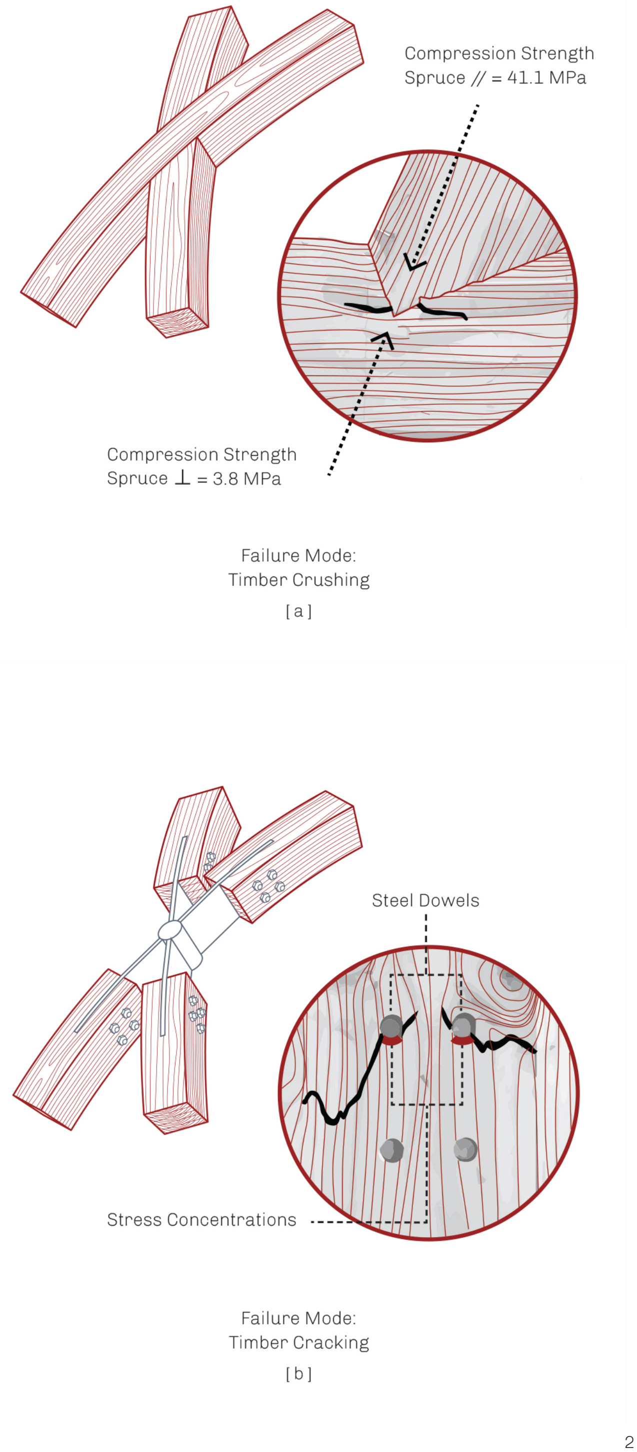
In the context of this development, particular attention must be paid to resource-saving construction methods. Both at a political and technical level, enormous efforts are being made to intensify the use of wood as a building material (BMWSB and BMEL 2023; “The New European Bauhaus” 2024). While this progress is commendable, care must be taken to ensure that the forests' capacity for regeneration is not exceeded (Acevedo-De-los-Ríos 2023; Zhang et al. 2020). The development of resource-saving, material-efficient construction methods, and building systems is therefore becoming increasingly relevant.

Branching structures have been shown to be material-efficient load-bearing systems. By optimizing the grain direction to align with the force transfer direction, it is possible to achieve high-performance structural systems (Jonas et al. 2019). The strategic allocation of axial members ensures that they are predominantly subjected to axial forces, with minimal bending moments. This design approach allows for slender component cross-sections, though it introduces the challenge of complex individual joints.

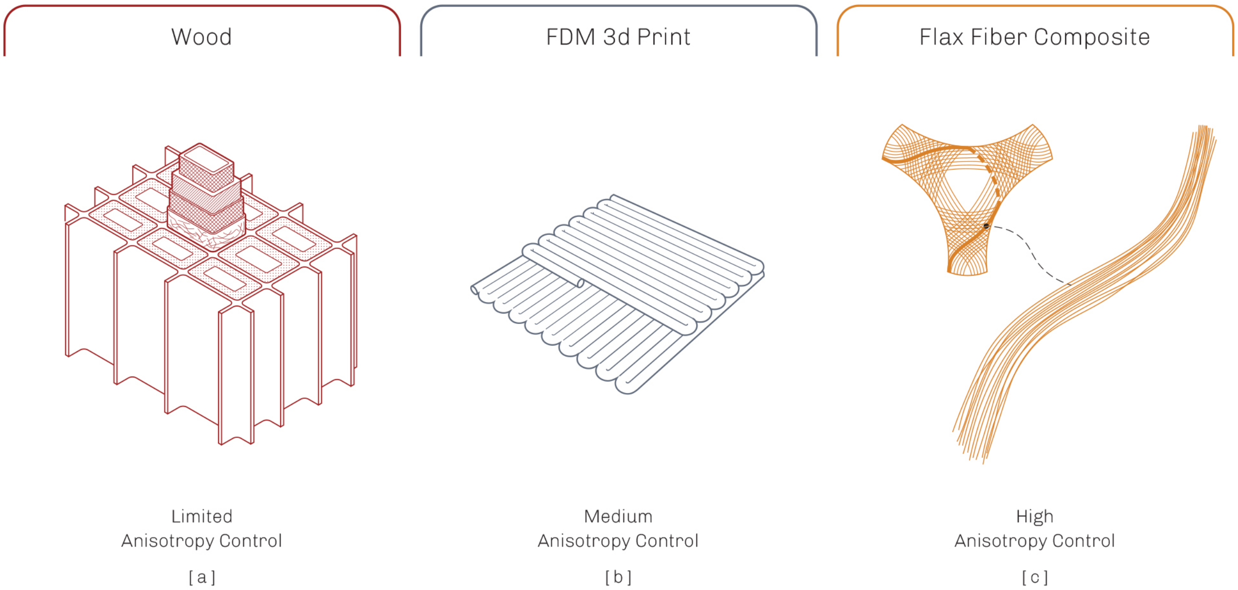
In addition to the geometric challenges posed by individual node geometries - such as varying valences and the mediation between different cross-section sizes - special attention must be paid to stress concentrations in the nodes of wooden branching structures due to their anisotropic internal structure.

Due to wood's non-uniform mechanical properties in different directions, spatial timber connections can result in abrupt changes in strength and stiffness, leading to premature timber failure. In timber-to-timber connections, stiffness and strength decrease as the connection angle increases, with timber crushing being the primary failure mode (Lißner, Rug, and Steinmetz 2007). Conversely, in connections involving punctual steel fasteners such as screws, bolts, or nails, the typical failure mode is wood cracking due to disproportionate local stress concentrations (Hudert and Pfeiffer 2019) (Figure 2).

In conventional timber construction, abrupt changes in




2 Stress concentrations in timber connections: [a] timber crushing due to high stresses perpendicular to the fiber direction (compression strength values: Ross 2021) [b] timber cracking due to high stresses at punctual connectors.




3 Anisotropic material system in microscale: [a] wood: naturally grown anisotropy [b] FDM 3D print: anisotropy achieved through a fabrication technique [c] flax fiber composite: anisotropy through naturally grown fiber bundles with high placement flexibility.

connection strength are typically countered by increasing material usage. The cross-section sizes are hence usually determined by the joint capacity, where fiber continuity breaks and control over fiber alignment is lost (Domínguez et al. 2023). Neglecting the anisotropic properties of wood at the nodes between load-bearing elements leads to oversized components and inefficient material consumption.

This research presents a design-to-assembly system for timber branching structures, aiming to achieve maximum resource efficiency by controlling anisotropy at three scales. At the microscale, a bio-based material system comprising wood, biopolymers, and flax fiber composites is proposed (Figure 3). At the mesoscale, the application of this material system in geometrically complex, load-bearing nodes is investigated. Anisotropy-driven fabrication methods, including FDM 3D printing and spatial fiber winding, are combined to allow load-adaptive fiber placement in these complex nodes. High fiber alignment, particularly at the interfaces between axial timber struts and nodes, enables a well-distributed force flow between the building components, resulting in slender cross-sections. Additionally, the node design facilitates simple assembly without the need for additional scaffolds. At a macroscale, a computational framework is introduced to generate structurally optimized timber assembly designs within a defined design space. This framework utilizes the proposed anisotropic material and node systems and produces the fabrication data for individual components.

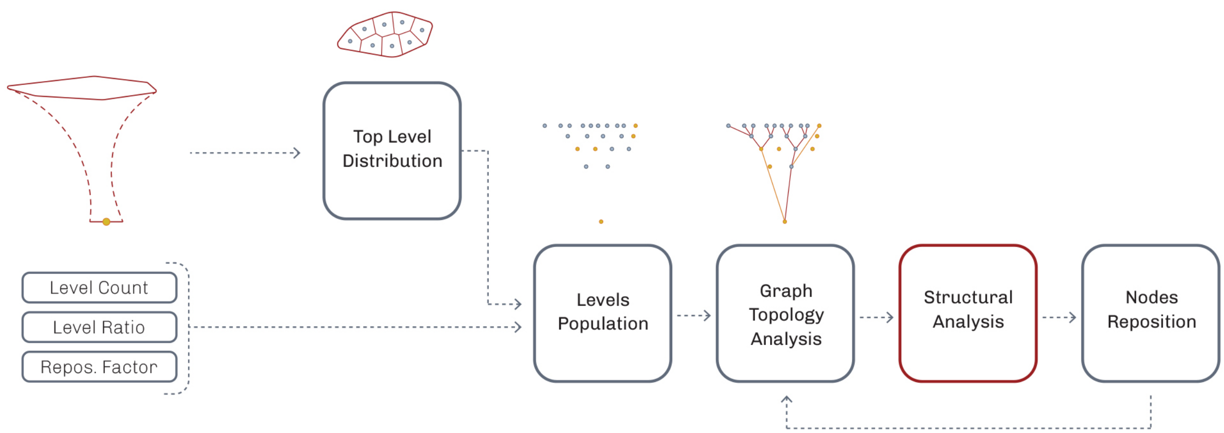
## BACKGROUND

### Geometrically Differentiated Spatial Nodes

Connections with high valency and complex spatial arrangements often rely on energy-intensive steel components, typically welded metal plates or cast iron structures (Jonas et al. 2019). Welded metal sheets are commonly connected to wood using punctual fasteners, which can result in high local stress concentrations and over-dimensioning of timber components. (Hudert and Pfeiffer 2019). The production of cast iron nodes requires individual molds for each node, leading to significant resource consumption (Jonas et al. 2019).
Galjaard et al. demonstrated the potential of steel 3D printing in combination with topology optimization, showcasing high design freedom and mass customization capabilities while significantly reducing the use of steel in complex node connections compared to conventional welded steel nodes. Despite the material-saving benefits of this approach, the manufacture of steel nodes remains primarily an energy- and cost-intensive process (Galjaard et al. 2015).

Efforts have been made to utilize resource-efficient FDM 3D printing process for complex load-bearing nodes. These nodes consist of a non-load-bearing 3D printed shell, providing flexibility in form, and are subsequently filled with isotropic, non-biodegradable epoxy resin to ensure sufficient strength (Bañón and Raspall 2021).

3D printing has been demonstrated as a material-saving fabrication method with high geometric freedom. However,




4 Computational design tool workflow.

the anisotropic properties of printed nodes are not yet fully harnessed. Structural potentials in complex load-bearing components remain unexplored.

### Naturally Grown Anisotropic Nodes

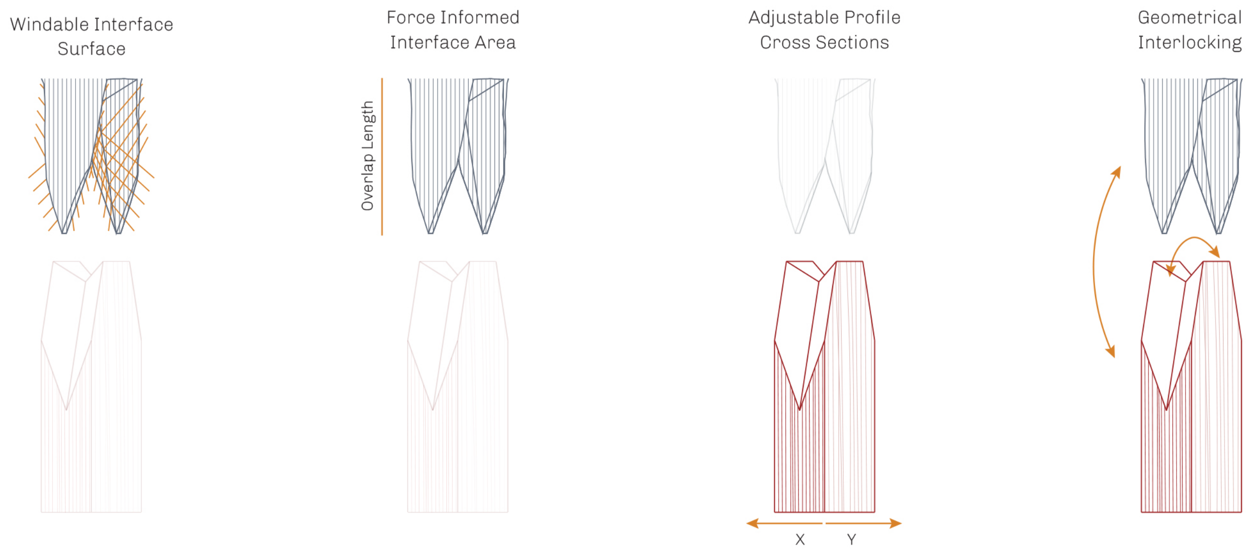
A direct way to create anisotropic nodes can be achieved by using grown branch forks as shown in the Wood Chip Barn Project (Mollica and Self 2016). This approach involves curating, scanning, reworking, and combinatorial joining of the existing parts. The growth form, internal anisotropic structure, and any growth defects or peculiarities are primarily determined by the environmental conditions of the growing tree and may not align with the requirements for a load-bearing node (Mattheck and Kubler 1995). Additionally, the logistical and structural challenges of building with branch forks raise questions about the scalability of this approach (Wagner et al. 2021).

### Artificial Anisotropic Nodes

Historical examples of anisotropic nodes can be found in informal bamboo buildings in tropical regions. Local, natural fibers like lianas, were used to create connections between bamboo poles. Because bamboo canes are hollow and primarily composed of vertical fibers without circular fibers, they are particularly susceptible to splitting when punctual connectors are used (Minke 2022). While winding techniques are employed to avoid stress concentrations in joints, the assembly process must be conducted on-site.

Stitched connections also have historical precedence - in ancient boat building. The shipwreck "Jules-Verne 9" from the 6th century BC demonstrated how individual wooden planks were sewn into boat hulls using cross-stitch patterns with linen threads (Pomey and Boetto 2019). In the reconstruction of a 1:1 replica named "Glyptis," it was confirmed that the connection was tolerance-sensitive, and the assembly of the sewing and lashing systems was highly sophisticated (Pomey and Poveda 2019). Wagner et al. extended the concept of three-dimensional fiber placement as a joining principle to linear elements, employing carbon fibers as tensile elements in trivalent nodes (Wagner et al. 2021). This allowed for in-situ resistive heat curing by simply conducting electricity through the pre-impregnated carbon fibre bundles. However, the placement of components before curing remains a challenging endeavor. Structurally, the combination of high-strength carbon fiber and much softer wood suggests similar stress concentrations at the interfaces as observed with punctual metal connectors.

While existing wound or stitched timber joints often exhibit a significant discrepancy between fiber direction and the global force flow, braided nodes demonstrate a higher degree of load-adapted fiber arrangements in spatial configurations. Jonas et al. illustrate how fiber-reinforced polymer hulls for trivalent nodes can be manufactured using industrial braiding machines. The braided carbon fiber hulls were subsequently cured and filled with concrete, resulting in joints with a high compressive load capacity (Jonas et al. 2018). However, apart from utilizing non-renewable materials the adaptation of the fabrication method to




5 Interface design concepts of the node.

higher-valence joints remains limited.

## METHODS

### Methods Overview

Developing timber assembly connection nodes requires continuous negotiation between interdependent fields of investigation, including structural behavior, fabrication processes, assembly sequence, and global design flexibility. In addition, the research and design methodology is developed across multiple scales. At the macroscale, efforts focus on defining a design-to-assembly system for timber branching structures with fibrous joineries using computational design tools. This phase involves creating a design tool that enables potential users to explore the design possibilities of the system. At the mesoscale, the research specifies the structural and fabrication principles of the node component, including the printed core and the timber-fiber interface geometry. At the microscale, the study explores and tests fiber placement logic and winding strategies. Finally, a full-scale timber branching structure is designed, fabricated, and assembled using the developed method to demonstrate the system's design possibilities and construction process.

### Macroscale: Global Structure Design Method

The global structure design workflow is developed to digitally explore the system's design possibilities, considering material behavior, structural capacity, and fabrication constraints before materialization. This system aims to reconcile architectural morphology with specific requirements, fabricability, and structural optimization at an early stage. The design tool begins with generating global geometry for optimized timber branching structures, incorporating inputs such as the desired canopy layout, permissible column positions, and a bounding volume representing the intended structural space. The objective is to provide users with maximal design freedom while ensuring material efficiency and minimizing architectural constraints. Based on the obtained global configuration, the tool outputs fabrication data for strut processing and node production.

The goal of the design tool is to locally minimize bending moments at the joints, ensuring maximum material efficiency while maintaining the structure within predefined bounds. The global optimization process begins with defining a structural topology, where a predefined maximum tributary area per support determines the minimum number of support points required for a layout. These points, representing the top-level nodes of the structure, are evenly distributed across the layout area using Lloyd's algorithm (Lloyd 1982).

The next step involves constructing the initial topology graph of the structure by populating the bounding volume with mid-level nodes, based on the top-level nodes, column positions, and desired number of levels. To influence the design, users can input a ratio to calculate the reduction required between the number of column nodes and top-level nodes. The nodes are then interconnected, with each node linked to its nearest counterpart in the layer below, and unconnected nodes are disregarded. An analysis with Karamba3D (Karamba3D, 2021) is performed on the defined graph, which includes a global analysis and cross-section optimization. The main outputs are moment vectors for each node, along with maximum deformation, mass, and total strain energy of the structure. The optimization process aims to reduce moment in the global structure within geometric constraints by iteratively repositioning each node to reduce local moments. Geometrical constraints include the bounding volume, maximum strut length limited by the source material, and maximum achievable valences. This iterative process continues until all nodes stabilize around the same position for three consecutive iterations (Figure 4).

### Mesoscale: Component Design

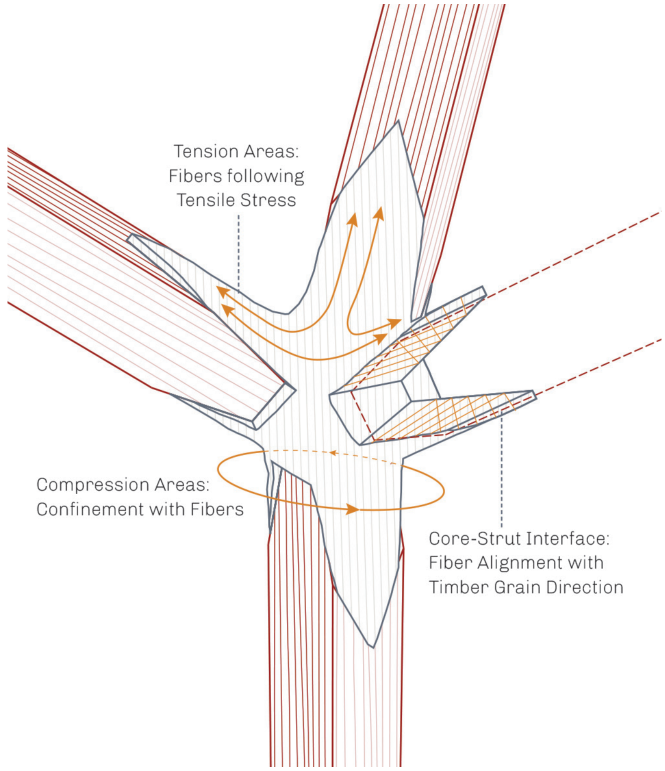
The system considers three distinct materials: timber, 3D printed polymer (PLA), and bio-based fiber composites. The investigation and exploration of the material system come in two parts. First, the 3D-printed core, considering valency, size, and directionality. Secondly, material interfaces and geometries both from structural and fabrication viewpoints. This step takes into consideration the interlocking between elements, the structural efficiency of the fibers, and the minimum gluing area needed for the interface.

The exploration of node configurations begins with an alignment algorithm that analyzes the configuration of an intersection, represented by concentric lines, and orients the members relative to the primary strut. The second part of the algorithm calculates the spacing between the elements' frontiers to prevent timber-to-timber collisions. This procedure detects potential collisions between the frontiers and iteratively adjusts their positions to eliminate overlaps. Node valences ranging from three to six were examined through both digital simulations and physical prototypes.

The interface is designed to ensure a distributed force transfer between the axial timber struts. Grooves are integrated on the printed side of the interface to allow a precise determination of fiber placement in the winding process. The interlocking geometry provides initial stability of the connection in two perpendicular-to-axis directions. Other principles include maximizing geometrical freedom and scalability of cross-sections and providing sufficient gluing area between the node and the timber elements (Figure 5).

### Microscale: Material Composition and Alignment

Inspired by the fiber configuration in a living tree, arranged primarily in stress-following and spiraling fiber reinforcement, the fiber-reinforced printed polymer represents timber in force flow diverging locations to bolster structural integrity via tailoring fiber alignment to force transfer directions within the material system. The core print is segmented into parts and glued together afterward to achieve a force-aligned print using a standard desktop 3D printer. For the

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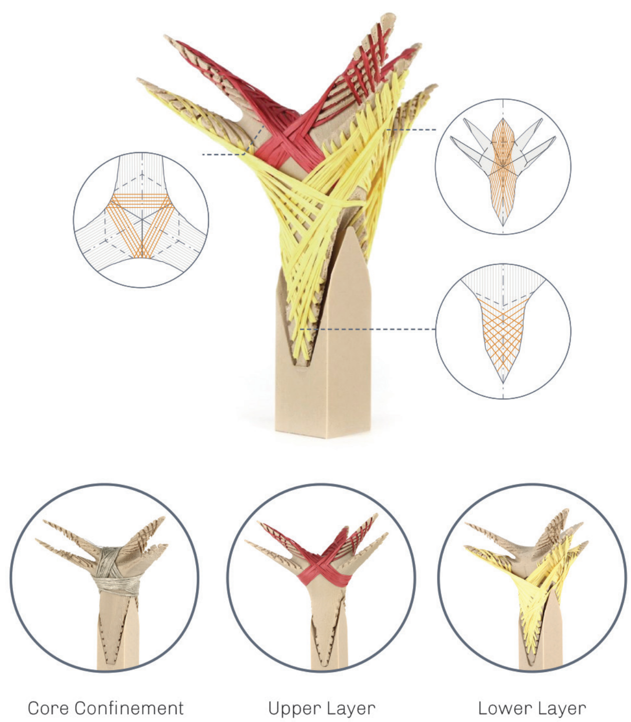


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6 Design concept of fiber placement in node due to high stresses at punctual connectors.

7 Fiber winding syntax layer build-up and design concept explorations on a winding model.

8 Fiber syntax development: fifteen mass-customized nodes with different geometries, valences, and interface types.

spatial fiber winding, the syntax design follows three main principles: 1) spiraling fibers confine the print to avoid local buckling, 2) stress-following fibers address the tensile forces, and 3) maximize fiber alignment on the interface between wood fibers and flax fibers. (Figure 6).

The two main goals - print confinement and tensile stress following - can be achieved for a wide variety of node geometries by combining and sequencing basic patterns into layers of winding syntax. The syntax build-up is composed of three layers. From inner to outer comes the core confinement layer, an upper layer, and a lower layer (Figure 7). Selected patterns were combined to achieve confining, interfacing, and tension bridging reacting to performance requirements at different locations throughout the node. Syntax logics are studied in varying strut configurations. Different pattern combinations allow adaptation to the increased geometrical complexity (Figure 8).

### Full-Scale Demonstrator

The fabrication method involves utilizing a variety of standard timber struts with different cross-sections. The ends of the profiles are simply cut into the interface geometry with a circular saw. Node components are made by first printing the core segments with the print layers aligned to the main force directions, followed by the assembly and gluing of the printed segments, and finally, winding fibers around the printed core using fabrication data generated by the digital design tool. The pre-wound node elements are assembled uncured and held together through a simple plug connection. The ultimate strength of the connection between the wood fibers and flax fibers is achieved after the resin curing with all building parts in place. To prevent premature resin curing before assembly, the pre-wound nodes are stored in a standard industrial freezer at -18° Celsius. The entire structure is built upside down and flipped over upon completion. (Figure 9).

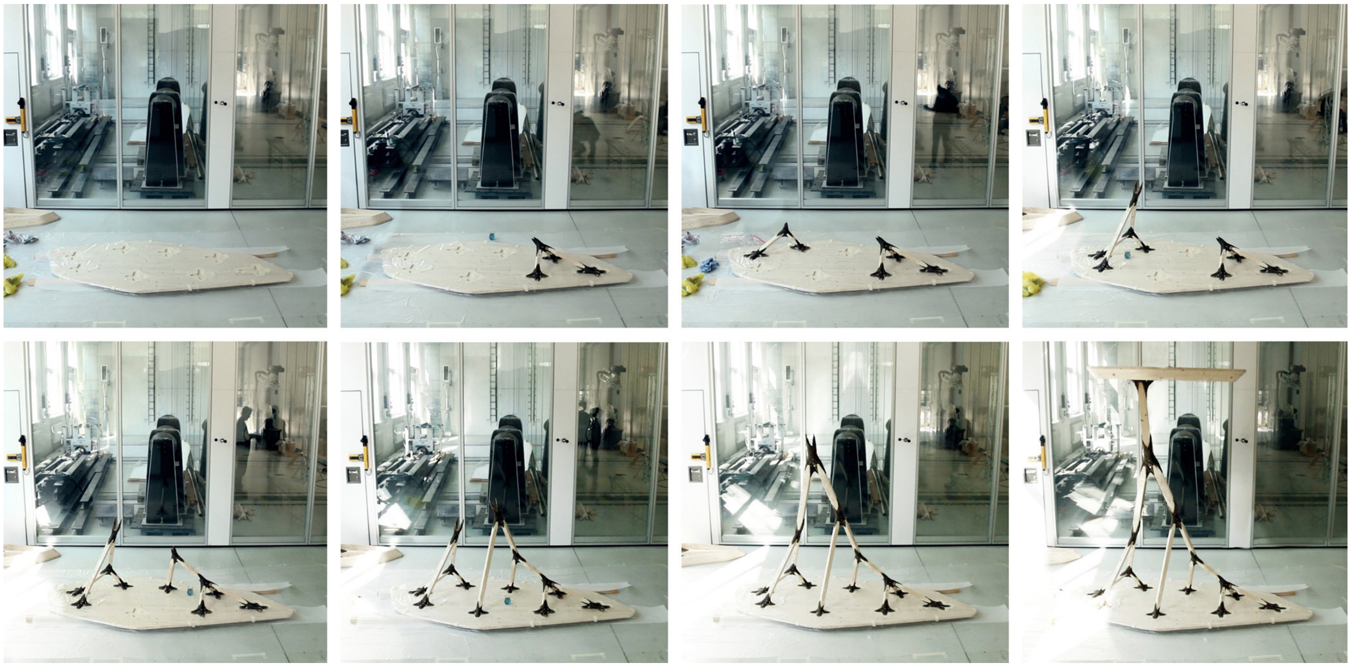
## RESULTS

### Material System Characterization

A series of small-scale compression tests were conducted to determine the relationship between alignment and reinforcement in the material system. The following scenarios were examined: 1) fully aligned - the print path is parallel to the direction of the incoming force, 2) not aligned – print path perpendicular to the direction of the incoming force, 3) alternating aligned – parallel and perpendicular paths alternate between layers and 4) confined fully aligned – the print path is fully aligned with the incoming force direction, with additional fiber reinforcement (Figure 10).

The test results indicated low performance in fully aligned prints due to delamination between layers caused by Poisson's effect. Alternating aligned prints demonstrated improved performance for the same reason. However, by incorporating a confining effect with spiraling fiber reinforcement in the fully aligned print, the compression capacity increased by an additional 75% compared to alternating aligned prints.

Further geometry effects can be observed when considering the joining of timber parts and their orientation. Following



9 Scaffold-free assembly process of the final demonstrator.

the decrease of timber load-bearing capacity as the loading angle changes from parallel to perpendicular, the strength would fall below that of a parallelly aligned print. Substituting timber with an aligned-printed polymer over a joining angle of 30° could start benefiting the integrity of the structural system. Furthermore, with fiber reinforcement providing confinement for the polymer, the compression strength could exceed that of hardwood.

### Joint Characterization

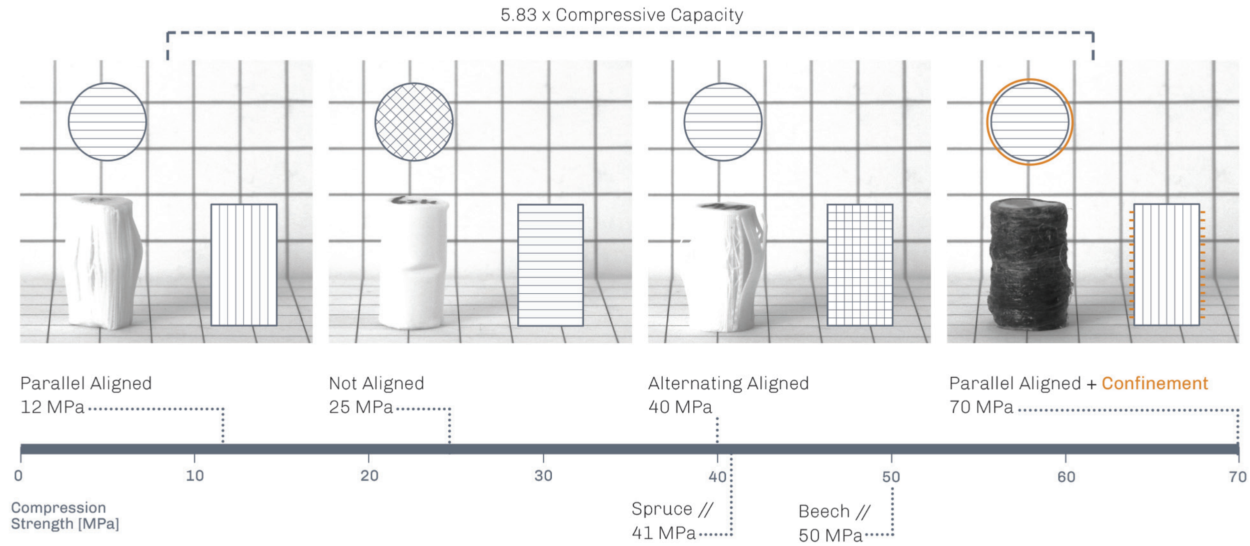
A series of compression tests were carried out to calibrate the strength and stiffness of the hybrid joint. Two standard node configurations, a planar joint connecting three struts and a spatial joint connecting four struts, were designed as test specimens. The research followed test standard ASTM D695 - Compression Testing for Rigid Plastics, carrying out a testing speed of 1.3mm/min under a deformation-controlled process. The tests aim to verify the general structural capacity of the connection method, as well as understand the sequence of failure modes that occur upon extensive loading.

Test specimens are produced with 38x38mm spruce struts, Giantarm 1.75 PLA, and Dehondt Tex 1300 Flax Fiber. The flax fiber bundles are impregnated with bio-based resin LARIT 1800 ECO, mixed with hardener LARIT 1804 ECO. 15 planar nodes (3 valences) and 8 spatial nodes (4 valences) are tested. Geometry details and test machine setup as shown in Figure 11a.

The results of the planar joint test set the base controlled variables for the production of the non-planar joints. Different syntax types resulting from two interface groove designs are tested with the spatial configuration to account for effects from syntax adaptation through increased geometry complexity. A wound node shows a 2.5 times higher average strength compared to that of the unwound core, with a load-bearing capacity increasing from 7.5kN to 19kN (Figure 11b). Observed initial failure modes include timber crushing on the tip of the interface, as well as timber peeling off with the glued interface.

### Demonstrator Construction

Regarding structural geometry and materiality, the 1:1 demonstrator is composed of 15 unique branching joints each with distinct angles, strut configurations, and joining elements with varying cross sections. By integrating a timber canopy into the design, there is potential to expand the system capacity from connecting solely linear elements (Figure 12a) to connecting linear with planar elements (Figure 12b). The introduction of the column-foundation joint design to an eccentrically supported, column-slanted structure attempts to challenge the moment-taking capacity of the node system, leaping forward from the acquired structural understanding (Figure 12c). On fabrication, the 15 unique nodes demonstrate the potential of mass customization by achieving geometrical freedom within one design-to-assembly method. With the designed plug-in connection, the assembly process of the final demonstrator was completed in less than 2.5 hours.

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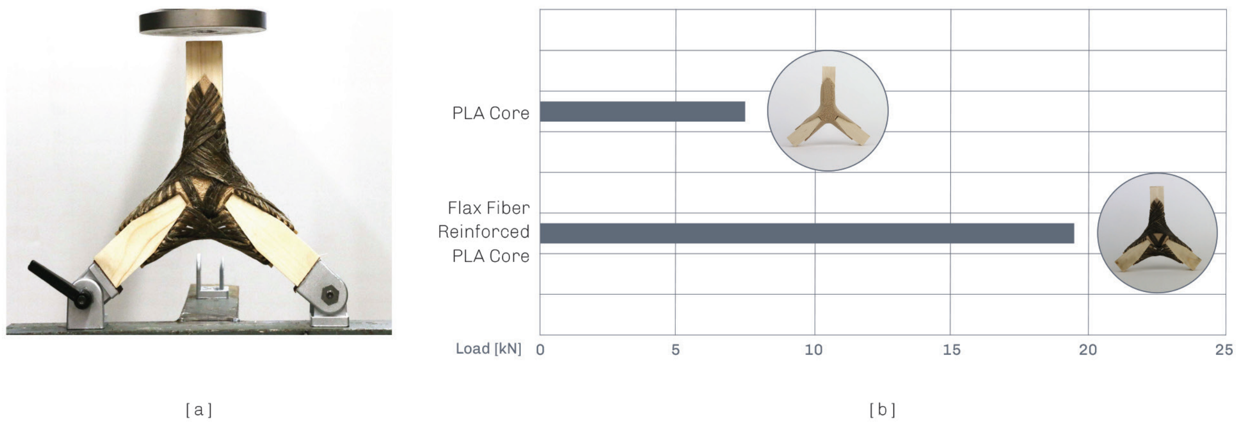


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The demonstrator design attempts to explore architectural expressions that are only made possible on account of cross-linked information between material, structural, fabrication, and construction aspects. Ultimately, the muscle-like display of transitions between inherently fibrous timber elements visually communicates the gradual stress flow from one component to another.

### System Benchmarking and Evaluation

In typical timber-steel joints, the minimum timber cross-section is often governed by the required spacing between fasteners, both parallel and perpendicular to the grain. The spacing between bolts and the necessary edge distances for preventing splitting can lead to an oversizing of the primary structural timber elements (Uibel and Blaß 2024). In the demonstrator model, 6 out of 20 struts would require oversizing if the joint is designed with common slotted-in steel plates and dowels, as the combined diameter of the bolts and the required edge spacing would exceed the available cross-sectional area of the struts.

In contrast, the proposed fibrous joint system enhances resource-efficiency by substituting energy-intensive steel with bio-based materials and reducing material consumption in structural timber. This approach significantly reduces the total cross-section, decreasing the required timber volume by up to 33.5% compared to conventional steel joint designs. By distributing the stress more evenly through the fibrous node, the structural efficiency of the timber elements is improved, minimizing material usage while maintaining the necessary structural performance. The built demonstrator's overall structure weight was 31% lighter compared to a similar structure using traditional timber-steel joints (Figure 13). In a building system scale, weight reduction of the main structure system allows for a lighter foundation, which decreases the environmental impact of foundation construction.

## CONCLUSION

The research presents a novel method for designing, manufacturing, and assembling timber branching structures

[ a ]

[ b ]

[ c ]

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| | Material Consumption of Primary Structure | | |
|---|---|---|---|
| | Material Type | Demonstrator with CA*-Joints [kg/m²] | Demonstrator with Steel Joints [kg/m²] |
| Struts | Spruce (Solid Timber C24) | 3.75 | 5.64 |
| Joints | Structural Steel (S235) | - | 7.21 |
| | Steel Fasteners (8.8) | - | 0.56 |
| | PLA (Giantarm 1.75 mm) | 3.83 | - |
| | Bio-Based Resin (LARIT 1800+1804 ECO) | 1.34 | - |
| | Flax Fiber (Dehondt Tex 1300) | 0.32 | - |
| | **Structural Weight** | 9.24 | 13.40 |

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10 Material test on compressive capacity of print alignment and fiber reinforcement (timber compression strength values: Ross 2021).

11 [a] Test results comparing purely printed trivalent core and wound trivalent core [b] compression test setup with a planar, trivalent joint.

12 [a] Linear-linear, [b] linear-planar joints, and [c] column foundation joint displayed in the demonstrator.

13 Material consumption comparison of the demonstrator structure with Controlled Anisotropy joints and custom welded steel joints.

using tailored anisotropic fibrous nodes to enhance material efficiency. By moving away from conventional steel nodes, the study explores bio-based alternatives and introduces a framework that integrates structural analysis with fabrication techniques. The focus is on optimizing fiber alignment in complex timber joints through the use of natural fiber composites and developing a simplified connection system that facilitates assembly. This approach leverages common timber stock and prefabrication methods, resulting in a streamlined, plug-in connection design for efficient, scaffold-free on-site construction. The exploration of various connection configurations also points to future possibilities for plate-plate joints, broadening the scope of this innovative structural approach. Moreover, a comprehensive life cycle analysis and an evaluation of the environmental benefits at different scales could further illuminate the resource efficiency potential of the Controlled Anisotropy building system.

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## IMAGE CREDITS

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**Jan Knippers** has been director of the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart since 2000. In 2001 he founded Knippers Helbig Advanced Engineering and in 2018 Jan Knippers Ingenieure in Stuttgart. The focus of his practice, research, and teaching lies in the area of biomimetics, resource efficient building structures, and new materials for architecture.