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DEVELOPMENT OF CONSTRUCTION METHODS WITH NATURALLY GROWN TIMBER AND BENDING-RESISTANT JOINTS

Kevin Moreno Gata[1], Alex Seiter[2], Denis Grizmann[3], Martin Trautz[4].

ABSTRACT: Timber is a highly versatile material that can be used for a wide range of applications and products, including standardized construction elements such as bars, boards, and beams. However, these traditional timber constructions typically rely on straight logs, with naturally grown irregular elements like tree branches, forks, or curved logs often being discarded.

Advancements in digitization tools, such as 3D scanning and image-based processing in parametric environments, allow architects and engineers to upcycle these discarded materials innovatively. This study proposes a method integrating discarded tree parts collected from timber harvesting forests. We have developed a structural joint-free knot system using timber forks that can be employed in bar-type structures. Therefore, we analyzed the morphological possibilities of the timber forks and used an optimization system based on their length and angle variations. The proposed knot system can seamlessly integrate into architectural designs with minimal processing and rapid assembly, providing a solution to managing this intelligently grown material. This approach can expand the application of grown timber in construction by utilizing naturally irregular elements that would otherwise be discarded. We suggest that this approach can extend the application of grown timber and provide a solution to managing this intelligently grown material.

KEYWORDS: naturally grown timber, image-based modeling, bar structures, construction methodology

1 TREE PARTS AS LOAD-BEARING ELEMENTS IN CONSTRUCTION

Grown timber parts are usually irregular and discarded due to their unique geometry. However, their use is frequent in temporary constructions in agricultural areas, small industrial roofs, or structures for decorative purposes using cultivated structural round timber (SRT), see [1].

Novel digital applications, such as Photogrammetry or Laser Scanning, allow the combination of natural and digital geometries and mapping tree parts as load-bearing elements in construction. Incorporating and cataloging tree forks (bifurcations) [2] with digital standardization techniques enhances the design and manufacturing process for such a construction method [3]. Robotized manufacturing strategies allow for exploring new possibilities for augmenting the design of structures [4]. Other design explorations incorporate tree forks in a digital workflow to assist in creating reticular shells [5].

Furthermore, the study of tree growth allows us to understand its geometry to make alterations or guidance during its early age, being able to design constructive elements that grow [6]. A computational approach and geometric simplification of tree growth enable mechanical growth simulations to understand the internal geometry of the tree and study its cross-sections [7].

In this paper, we explore how to generate bar-type structure typologies based on the characteristic geometric dimensions of the timber elements, Figure 1.

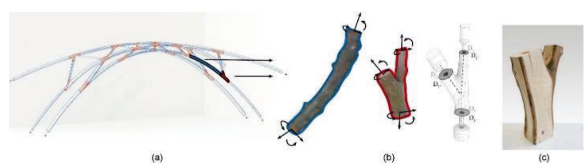

Figure 1: *a) Bar-type structure with naturally grown timber elements: flat, curved bars and fork b) construction detail development. c) Tree-fork as an off-knot element.*

2 RECONSTRUCTION OF GROWN TIMBER BASED ON IMAGES

Theoretically, trees and plants grow according to L-Systems [8] growth rules. However, they adapt to the conditions of the environment generating three-dimensional structures that are difficult to simplify into axes or main growth lines. These shapes are classified into lines, curves, and forks (bifurcations). They can be simplified into three-dimensional axes, which, sectioned into parts, can be contained and approximated in two-dimensional planes. In this work, we have studied methods of simplification and automation to find the most

[1] Moreno Gata, Kevin, Chair of Structures and Structural Design, RWTH Aachen University, Germany, morenogata@trako.arch.rwth-aachen.de
[2] Seiter, Alex, Chair of Structures and Structural Design, RWTH Aachen University, Germany, seiter@trako.arch.rwth-aachen.de
[3] Grizmann, Denis, Chair of Structures and Structural Design, RWTH Aachen University, Germany, grizmann@trako.arch.rwth-aachen.de
[4] Trautz, Martin, Chair of Structures and Structural Design, RWTH Aachen University, Germany, trautz@trako.arch.rwth-aachen.de

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suitable geometries and sections to manage the grown elements for documentation.

2.1 3D SCAN AUTOMATIZATION INTO 2D AND CLASSIFICATION

The process starts with a 3D scan of the elements. We developed an automatization to contain these shapes in bounding boxes. These boxes can be positioned in 3D. Additionally, we vary the scan's position to reduce the box's volume. This box acts as a basic geometry where we contain the scan, and therefore we determine the most optimal 2D positioning for further processing, see Figure 4.

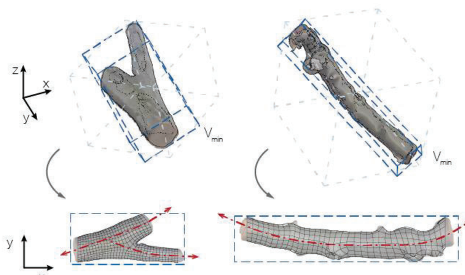

Figure 2: *Minimal volume bounding box automatization and 2D reorientation.*

2.2 GEOMETRIC PROCESSING AND CLASSIFICATION

After the previous procedure, we generate a series of additional automation in which we convert the mesh into NURBS volumes. We can automate and define the main growth line (in red) through this volume, see Figure 3. We finally geometrically process the elements and generate a library of objects with their angle and dimension classification.

Figure 3: *Image-based 3D modeling method, from 3d mesh to NURBS and growth trajectories.*

This process involved 60 elements, which were analyzed and digitized. An example can be seen in Figure 4. The studied specimens of oak, beech, and birch provide geometric variations of angles that were considered for developing constructive structures later in the methodology used in 3.2.

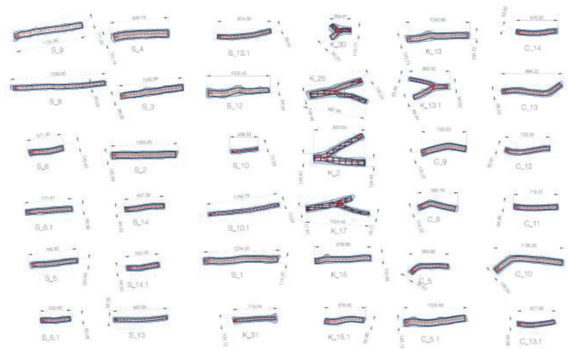

Figure 4: *Analysis of selected elements based on the image-based methodology.*

3 CONSTRUCTION METHODS

The analyzed and documented elements allow for estimating the load capacities of the analyzed elements according to their geometry. These elements can be applied in structures individually, making it necessary to explore structural typologies. Based on the examples in the literature [1-5], we carried out a constructive design approach in bar structures. These elements may be straight, curved, or forks (or bifurcations), and their structural connections (P) must be located at the ends of the growth trajectories.

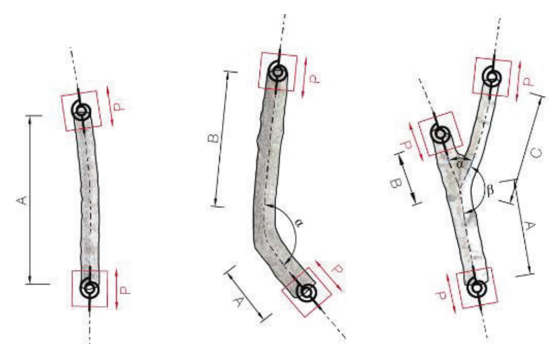

Figure 5 *Elements definition (straight, curved, and bifurcations) and main parameters end (P) as rotational springs, member axis (A, B, C), and angles (α, β)*

3.1 BAR-STRUCTURES DESIGN

Timber bar structures, generally designed as trusses, require complex connection nodes mainly executed with slotted steel plates. These connections are therefore located at the structural nodes. The present design method studies the construction of these trusses and frameworks with rigid nodes. Taking advantage of the capacity of naturally grown timber, we develop free, "off-knot" structural nodes. The moment curves in the frameworks are characteristic of Vierendeel and frame systems.

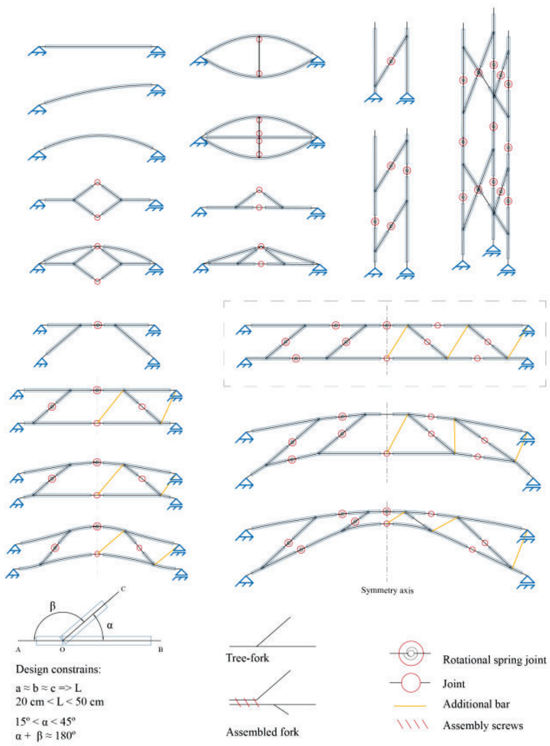

Figure 6: *Above: frameworks and bar-structures design. Below: the design constraints for a joint definition based on grown timber.*

In addition to the cross-sectional dimensions of the tree forks, the position of the joints of the "straight bars" are decisive for the structural design of the grown timber structures. While the bifurcations are optimally suited for moment loads thanks to their bending strength due to the unbent cross-section, the joints of the straight bars should be subjected to normal forces.

3.2 JOINT METHODOLOGY

In this section, we define a method for positioning the joints, and applying it to one of the simplified typologies. The proposed methodology for determining the most appropriate location of the joints utilizes multi-objective optimization. The location of the joints along the member axis ($0 < x_{joint} < L$) serve as input parameters. Joints are implemented as rotational springs. Geometric restrictions derived from databases of raw timber elements, such as maximum and minimum fork angles and lengths, can be considered (e.g., by the following condition $0.1\ L < x_{joint} < 0.9\ L$). Optimization objectives are reduction of total system deflection, maximum deflection, summed bending moments, and maximum fork moment. All load cases are considered.

The automated selection of fitting elements can thus only be done after the static analysis. Such a process see can be based on [2]. In addition to lengths and angles, minimum section dimensions derived from the determined internal forces can be specified as search criteria in the data beacons. This method is similar to the common cross-section optimizations, where only a structural element's minimum and maximum cross-sections are considered. The process integrated the modeling part in Rhino & Grasshopper [9], used MOO engine Octopus [10], [11], and used Karamba [12] for the static analysis.

3.3 OPTIMIZATION RESULTS

Figure 7 shows a Vierendeel-girder under a vertical and 45° inclined traveling load. Each of the 16-point loads (P01-P16) represents a separate load case (LC01-LC16). The joint positions were determined under the optimization objectives of a minimum sum of moments, a minimum sum of deflections, and a minimum maximal deflection of the girder.

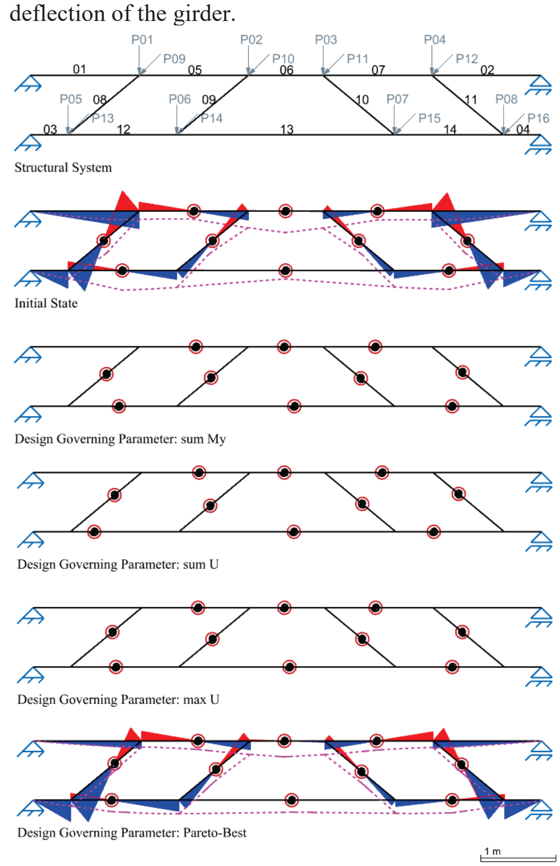

Figure 7: *Vierendeel-girder system*

Table 1 shows that optimization of the joint position results in up to 23% less total deflection (sum U) and 21% less maximum deflection (max U). The total moment summed up over the girder (sum My, magnitude sum) increases by 7% to 78%. For asymmetrical governing load cases or systems, more favorable moment distributions and lower deflection can be achieved by optimization.

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The method is especially beneficial since the grown timber elements from the databases do not always allow joint positions in the center of the member.

			Design Governing Parameter			
		initial state	sum My	sum U	max U	**Pareto-best***
		Relative hinge location from bar starting point				
bar no.	01	-	-	-	-	-
	02	-	-	-	-	-
	03	-	-	-	-	-
	04	-	-	-	-	-
	05	0.50	0.52	0.53	0.52	**0.52**
	06	0.50	0.52	0.54	0.54	**0.54**
	07	0.50	0.52	0.47	0.53	**0.52**
	08	0.50	0.54	0.62	0.59	**0.62**
	09	0.50	0.52	0.56	0.53	**0.48**
	10	0.50	0.53	0.53	0.52	**0.52**
	11	0.50	0.57	0.64	0.59	**0.60**
	12	0.50	0.53	0.78	0.58	**0.62**
	13	0.50	0.54	0.53	0.51	**0.52**
	14	0.50	0.53	0.35	0.52	**0.52**
Results	sum My	*100%*	*107%*	*178%*	*119%*	***126%***
	sum U	*100%*	*84%*	*77%*	*80%*	***79%***
	max U	*100%*	*84%*	*87%*	*79%*	***82%***

Table 1: *Optimization results*

4 CONSTRUCTION DETAILS

The criteria for defining the construction details were to meet the static analysis results. The result of the image processing allows us to know the stock material with its dimensions and the direction of the wood grain. In addition, the optimized bar structure shows the load-bearing trajectories. This combination defines the construction development and its joints.

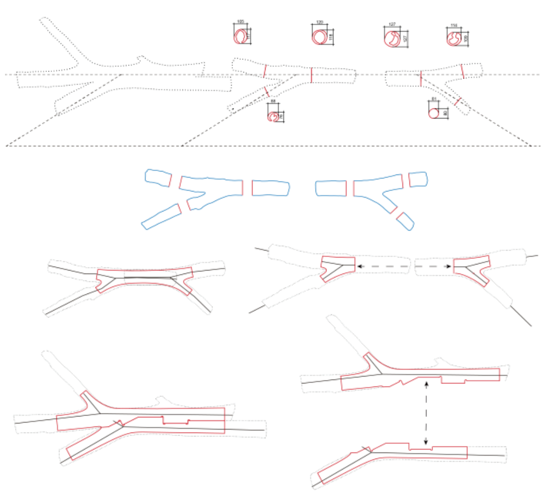

Figure 8: *Framework division in individual off-knot elements, according to their growth trajectories and cross-section.*

4.1 CONSTRUCTION DEVELOPMENT

Using natural timber allows the development of multiple construction details (Figure 1b) based on traditional Timber construction in many cases. The incorporation of robotic fabrication methods also allows to the incorporation of three-dimensional curved elements in a practical way, which also using dowel joints [13] can withstand normal forces and certain bending moments. In this project, we develop 2-dimensional elements based on the examples analyzed in 3.1.

The documented elements (Figure 4) were examined with the optimized structure to determine joining methods. In addition to incorporating interlocked joints with dowels for the connections (Figure 9), the possibility of using fully threaded screws is also experimented with. Examples from the literature [14] [15] show how using these screws enables homogenization in solid wood. This allows us to combine curved/straight elements or forks to generate solid joints as "hybrid" forks (Figure 10).

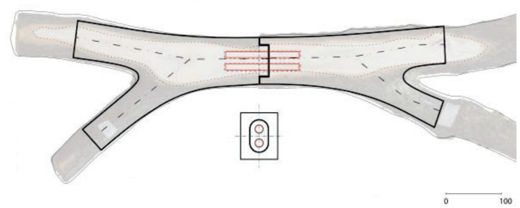

Figure 9: *Detail of a butt joint with two oak elements with inserted dowel. Scale in cm.*

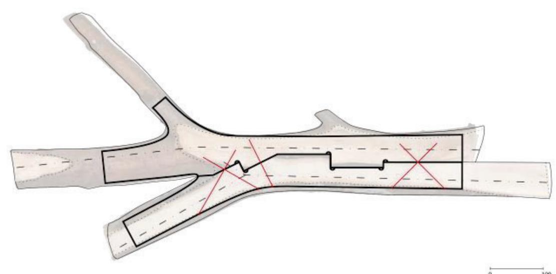

Figure 10: *Detail development of a bending-resistant connection from two elements of maple and beech in a hybrid fork using fully threaded screws. Scale in cm.*

4.2 FABRICATION METHODS

In this manufacturing method, the elements (stock material) are minimally processed with a planning machine following the positioning of the bounding box (Figure 2). As it is a 2D process based on optimization, the pre-processing is quick. After the stock is pre-processed, the construction details are adapted for 2D-CNC fabrication (Figure 8). From the automated information about the positioning of the Bounding box we reposition the cutting lines (in red). Then the stock material position is transmitted through informative sensors and the CNC programming is performed. The manufacturing of butt-joints takes place by milling in 2D the sides of the fabricated parts.

Figure 11: *Projection of the fabrication outlines for the CNC cutting operation.*

5 FABRICATION RESULTS

As a sample, we fabricated several elements. The first specimen was made as the central element of the structural system, manufactured with two oak elements, Figure 12. The ends were made with beech dowels, see Figure 13. Secondly, we made a joint of two parts to form a hybrid element (Figure 14 and 15). This shows that it is possible to use two different materials (beech and maple) to vary the mechanical properties of the construction element. As a last example, we experimented with three-dimensional joints (Figure 16 and 17), which were executed in an interlocking geometry in two birch specimens.

Figure 12: *Photo of a fabricated, grown timber element in oak.*

Figure 13: *Photo detail of the butt joint with dowels.*

Figure 14: *Photo of a fabricated hybrid fork made with two specimens of beech and maple, joined together with fully threaded screws.*

Figure 15: *Photo detail of the butt joint, and the position of the fully threaded screws.*

Figure 16: *Photo of a three-dimensional experimental component produced from two 2D tree forks of birch*

Figure 17: *Photos detail of the interlocked joint.*

6 CONCLUSIONS

The work detailed in this study demonstrates a novel approach for automating the integration of naturally grown elements into structural design, focusing on bending-resistant joints. We propose construction methodologies to incorporate the inherent geometries of these elements into minimally processed structural components. The proposed procedures can be applied to both planar and three-dimensional structures whose constituent parts are described in two dimensions. Furthermore, we leverage image processing techniques to

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automate the design and production processes, as evidenced by construction demonstrations.

7 FUTURE WORK

The subsequent phases of the project will prioritize evaluating the load-bearing capacity of the elements, utilizing their respective cross-sectional dimensions as a basis. The remaining tasks include numerical simulation of the scanned elements and conducting load tests. We are also investigating the feasibility of integrating the joint simulation process with tree felling operations to streamline the selection of suitable specimens within the same forest. Augmented reality tools may also be employed to enhance the integration of tree specimens with the overall structure.

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