Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich, Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Building with Naturally Grown Timber: Circular Design in Forest Construction – A pedestrian Bridge Case Study

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Abstract

In recent years, timber structures based on minimally processed small-diameter raw wood have gained attention in architectural construction. Naturally grown timber refers to the shaped material derived from trees, primarily crown wood, that have matured without significant human intervention. This shaped timber offers technical applications for tree parts in construction, adding value to material that is primarily discarded from forests and timber production. Naturally grown timber is often irregular, individual, and challenging to integrate into standardized structures. In recent decades, digitization tools have efficiently streamlined this integration, significantly reducing the complexity from digitization to construction assembly. Furthermore, these digital processes can be extended to showcase examples and construction methods within the forest environment. In this paper, state-of-the-art techniques for building with naturally grown timber are applied to present a case study of the construction of a pedestrian bridge, with the motivation to implement it in a local forest. Image-based documentation techniques were employed to systematically categorize timber elements and implement a circular design. A bar-model was utilized for structural load estimation, followed by the application of generalized scaled boundary isogeometric analysis, and finally the development of a design with interlocking joints and fully threaded screws. Additionally, the project demonstrates the use of "off-knot" structural connections and exemplifies a circular design approach. This process entails the creation of a load-bearing structure by the reintegration of discarded natural elements into a structure that is subsequently reimplanted in the natural environment.

Keywords: raw-timber structures, circular design, forest construction, off-knot connections, pedestrian bridge

Figure 1: Design of a pedestrian bridge as a case study using material collected from the forest.

1. Introduction

1.1. Motivation: Forest as material resource

Natural building materials, notably raw wood from tree trunks, have been foundational in construction for centuries, giving rise to the earliest primitive cabins. Today, the drive for sustainability and reducing greenhouse gas emissions is fueling a resurgence in wood construction, bio-based materials, and material-saving production. This trend is driven by environmental concerns, particularly in forestry where the focus is on producing fast-growing and low-knot timber for construction [1]. However, challenges such as material availability and the need for specific tree species persist [2].

Advances in forest digitization [3, 4, 5] are aiding in the adaptation of timber construction to utilize more naturally shaped and irregular timber, reflecting a shift towards efficient resource extraction and innovative use of crown wood [6]. Additionally, climate adaptations suggest a greater implementation of hardwood tree species in construction, as these species often produce more voluminous crowns with irregular wood, necessitating investigations into the use of raw wood with smaller diameters [7]. New interpretations of timber constructions are becoming relevant. Using raw timber constructions with minimal transformation, which keeps the material as grown, offers more opportunities in the lifecycle. Furthermore, minimal transformation leads to reduced energy needs. Using raw materials wisely brings more construction opportunities and less environmental impact. These constructions are particularly suitable for fragile environments to minimize human impact. Especially, local forests serve both as spaces for timber production and for outdoor activities. Constructs implemented with minimal impact are essential. Utilizing naturally grown timber is highly suitable for such applications, providing opportunities for employing materials typically left on-site, as illustrated in Fig. 2. Leveraging this opportunity, new constructions fabricated from local, untreated materials can be employed on a temporary basis, such as in the case of small pedestrian bridges designed to harmonize with the forest landscape, as depicted in Fig. 1.

Figure 2: Collecting raw material from a tree crown in the forest, followed by documentation.

1.2. State of the art in raw timber constructions

The use of raw wood as a structural component is known as naturally grown (or shaped) timber elements, in this paper now on only as timber elements. This terminology underscores the material's organic origins and its utilization in construction without extensive modification, preserving its natural form and properties. This approach not only highlights the aesthetic and environmental benefits of using naturally shaped timber but also challenges and innovates traditional construction methodologies. Recent examples in raw timber construction explore new typologies, including the use of straight, curved, or branching elements in various structural positions. The methodology involved is documented in [8], showcasing applications of raw wood in critical load-bearing nodes. Such methodologies necessitate precise geometric analysis to support documentation, constructive development, and subsequent structural simulations [9].

1.3. Structural analysis

The use of raw timber in construction necessitates verification and justification that the applied elements meet the structure's required conditions. Approaches incorporating mechanical calculations of trees have been advanced as state-of-the-art for decades in finite element simulations with [10] Computer-aided shape optimization, whose applications are further integrated in the Bionic standard [11]. This shape optimization is further included simulating 3D cross-section of growth [12]. However, these analysis methods lack material considerations, while the simulation of wood is still a challenge due to its anisotropy. Modern simulation methods address these material considerations [13]. This is still in its early stages, as the natural material properties of wood need to be modeled more accurately for correct verification. On the other hand, the Isogeometric Analysis (IGA) methods may provide a more accurate approximation, as they allow to go a step further by using the Non-Uniform Rational B-Splines (NURBS) model directly for the analysis. This allows geometric considerations of natural raw wood to be taken into account in the simulation. Combined with an early approach of the Generalized Scaled Boundary Isogeometric Analysis (GSBIGA), simulations can be more accurate in the future [14].

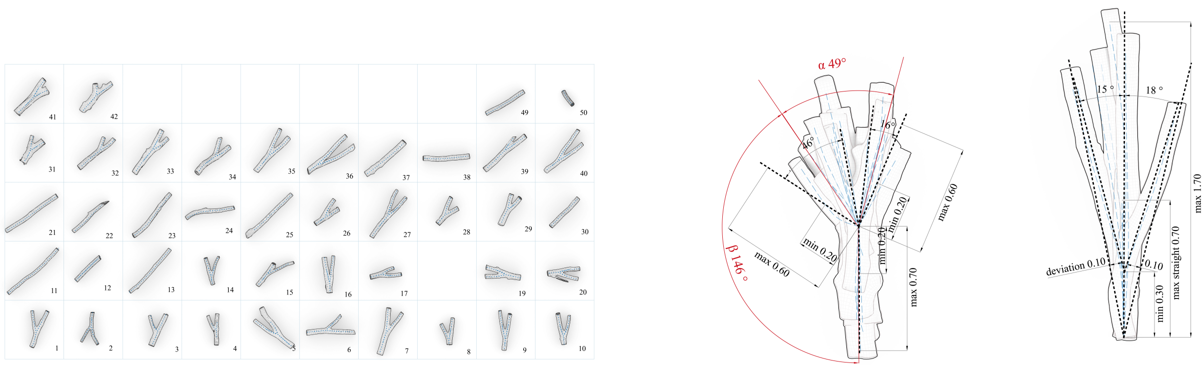

Figure 3: (left) Collected timber library and (right) geometric variations in forks and curved elements, with length in meters.

2. Case Study Design: Forest Pedestrian Bridge

2.1. Structural System Definition

A previous study examined several design methods and illustrated structural topologies that can be used with raw timber elements [8]. Based on a Vierendeel truss scheme, the structural system consists of ”off-knot” rigid elements and articulated joints, made from tree branches. The growth angles of the most common branches are determined from a general survey of trees in the local forest of Aachen (Fig. 3). According to the geometric analysis scheme [9], the angles α, i.e. the most common acute angles found in the forest, range from 22° to 54°. The polygonal topology can be replicated indefinitely, provided there is a relationship between the angles that make it up. Hence the project name ”Growing Bridge”, which combines the most common angles in tree branch branching. This relationship is applied symmetrically: Both longitudinally and transversely. In this topology, the relationship of the four angles of each square polygon is approximately 360°, allowing the configuration of planar elements that will later facilitate 3D scanning and 2+1 axis milling.

Specifically for this bridge, a first proof of concept was decided, simplifying the topology to 4 basic nodes and 16 in total, following the corresponding symmetries. Nodes 1-4 (with angles of 34°, 54°, 22° and 28°, respectively, see Fig. 4 are defined by a study of the implantation of the bridge. The collection took place in the spring of 2022, with different specimens of hornbeam, beech, oak and birch .

2.2. Site-specific bridge design

Parallel to the development of the bridge, an implantation study determines the design constraints. A small stream, located a few meters from where the specimens are collected, is chosen as the test location. The stream – coordinates 50.683672, 6.157928 – is a tributary of the Inde, river in the Eifel Natural Park, and the width varies from 2 to 6 m. A 3D laser scan reconstructs the space (see Fig. 4), determining a potential site for the bridge, with a maximum clearance height of 1.20 m. The site-specific conditions determine the span of the structure as well as the minimum truss height. The structural scheme results in a curved-arch Vierendeel-like truss that is later adapted due to the geometric variations in the collected material. A previous analysis of the collected material, as illustrated in Fig. 3 (right), indicates that the overall dimensions of the fork elements exhibit a range of 20 to 60 cm in each segment, while the angle variation of the segments exhibits a range of 16° and 46°. This information is utilized to determine the average angles α and β, which are subsequently employed in the structure design (Fig. 4). In the case of curved elements, the material collection exhibits a length variation of 70 to 170 cm, an angle deviation of 18°, and a straight deviation of 10 cm.

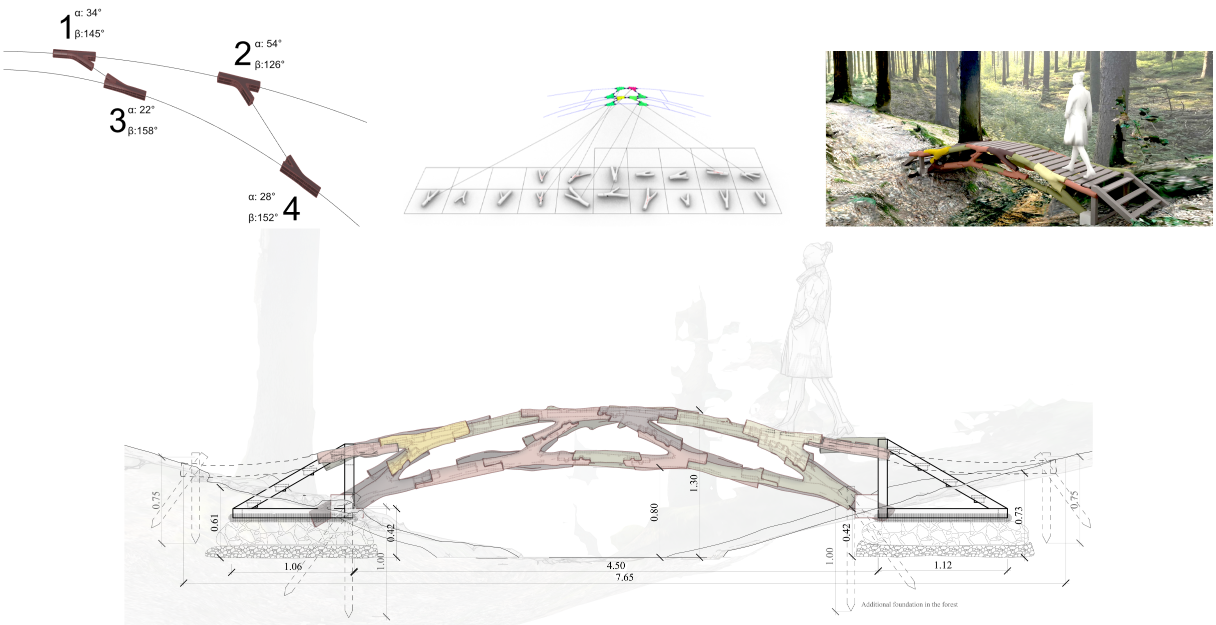

Figure 4: Structure adaptation process based on raw material (left to right): Definition of main angles at the nodes, matching algorithm [15], rendering of the Site-specific structure, and front view.

2.3. Material matching for circular design

The methodology presented in [16, 15] was used to match the target geometry of the bridge with the library of wood samples, see Fig. 3. Initially, the method showed a 98% match with the collected elements. Later, for the structural design, the geometry was slightly modified in 3D. The heavier and stronger wood samples, such as oak and birch, were positioned intuitively around the supports, while lighter or thinner woods, such as hornbeam and beech, were placed in the center of the bridge. The algorithm played a role in this process by informing the modification process and providing feedback on the match score, resulting in an approximate 80% match. In this project, it was important to ensure consistency in the grain direction of all components, which required adjusting deviations in the structural topology to the specific specimen at each node.

3. Static analysis

3.1. Bar-type structural analysis

The structural analysis process is initially conducted through a bar-type analysis system (see Fig. 5). The static case consists of 28 bars with rigid nodes, using the off-knot construction method (defined in [8]). In this construction scheme, the nodes are considered rigid due to the bending capacity of the timber bifurcations. It is a distinctive method because the structural joints are shifted to the bars. The joints on the bars are considered fixed (spring-like), and the specific location is considered in the search for null moments. Subsequently, this joint is executed through Gerber-like joints. The load cases studied include dead weight, a constant vertical load of 2kN/m (LC1), and a variable movable load of 2kN/m at 45° (LC2). In the next step, the diagrams for moments, shear forces, and normal stresses are calculated for all load cases separated and in combination of all positions of movement. The diagrams in Fig. 5 show one combination of them . Initially, with the normal stresses, it is verified that the main loads are compressive, which approves the type of compression joint, varying across different load cases, and up to 6.7 kN at the supports. The shear forces help determine the design of the joints and the minimum wood section required at the joint, which is approximately 8 cm in the thinnest elements. The moment diagram is analyzed to view the magnitude of moments at the joints. These joints are demanded up to 0.3 kNm in supports with load case 2. Therefore, the construction implements fully threaded screws, which are distributed in a triangular pattern to aid in the correct transmission of loads.

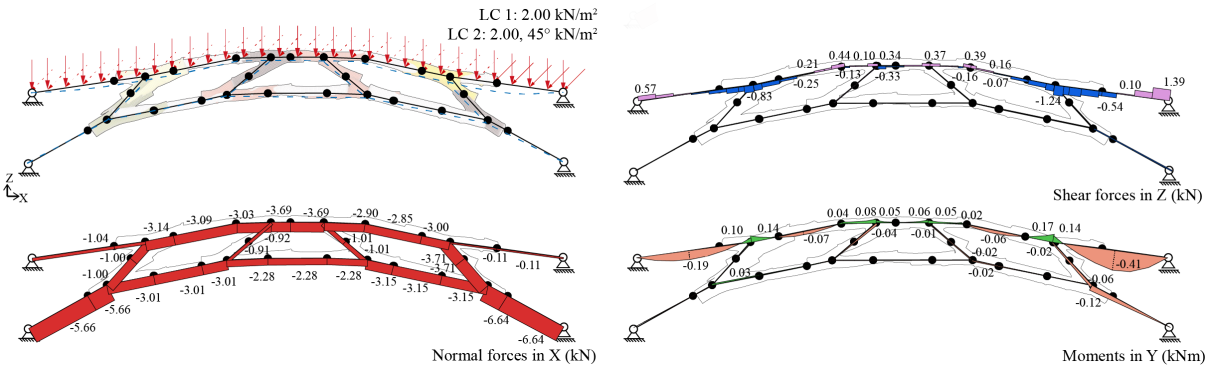

Figure 5: Load cases (LC) 1 and 2 with deformation, and moment, shear and normal forces diagrams.

The structural scheme is a curved arch where the top and bottom beams are not in the same plane, opening the structure toward the supports. This scheme is similar to the Vierendeel scheme in that the tree elements are resistant to bending. The curvature and opening of the structure, in addition to the bracing plates (also used as flooring), helps to resist horizontal loads that are not part of the static analysis. In this construction, all joints are bending resistant, but the degree of bending capacity varies depending on the load and the spring-like connection with Gerber-like joints and screws (see in Fig. 9). This however is not a problem and is taken into account by the oversized wooden elements.

3.2. Isogeometric Analysis

The naturally shaped timber specimens are 3D-scanned and, in an automated process, converted from a point cloud via a geometric mesh to NURBS-surfaces [9]. With the use of isogeometric analysis (IGA), the functions describing any complex geometry can be directly used for solving physical problems. In combination with the principles of the scaled boundary finite element method (SBFEM), the description of geometric bodies only by their boundary surfaces, the scaled-boundary isogeometric analysis (SBIGA) has proven to be a valuable method for analysing complex geometries [17]. Here, the 3D body is only described by the 2D surface and scaled in the spatial direction. This process permits the description of every point within the geometry based on the surface description. Obtuse-angled polyhedrons occur within a patch when the SBIGA is applied to long and slender structures like naturally shaped timber elements, leading to numerical problems. To avoid these disadvantages, a generalized scaled boundary isogeometric analysis (GSBIGA) approach was developed. Scaling the surface on a centre line enables the analysis of slender and curved objects while reducing the numerical error. In this generalized method, only the lateral surfaces are modeled. The general concept of SBIGA remains unchanged. The centre line is modeled according to the position of the medullary canal but can be placed independently in terms of process. In the cross-section, the centre line, like the position of the medullary canal, corresponds to the centre of the polar representation. Therefore, it is suitable for the precise description of polar-dependent material parameters. To model bifurcation areas, the surface patch is divided into several sections. Subdivision takes place at the fork point, to which the different areas are rigidly connected. Hereby the different centre lines are connected in a single point, while the surface patches are connected at the edges [18]. This is done in Fig. 6 for tree forks (branch bifurcations) examples of the bridge described. The loads correspond to the comparative calculation from the bar model. The displacement field is plotted on the deformed body of the branch fork.

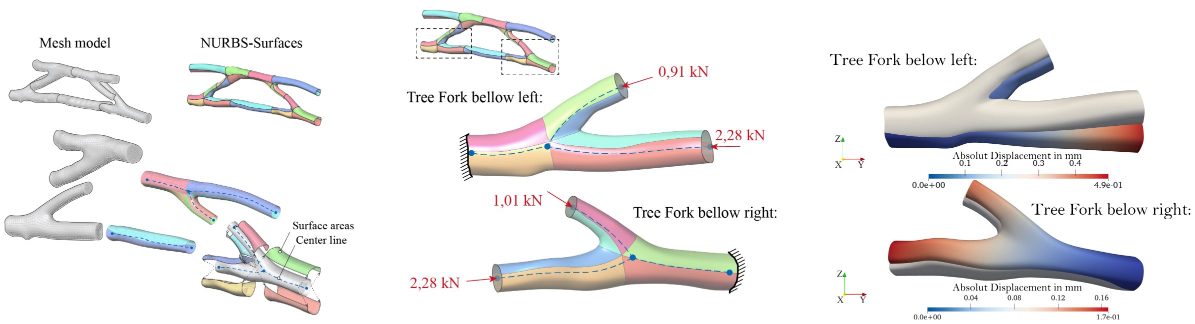

Figure 6: Left to right: Description of the processing towards the NURBS-model, bifurcation model with loads and boundaries, and deformation plots in comparison to the original geometry.

4. Bridge construction development

4.1. Design to fabrication

The design of the construction is impacted by the manufacturing process. The three-dimensional geometries of the timber elements, which were previously scanned, are automatically positioned at each location determined in the previous step using orientation methods based on static calculations. The previous positioning and static plots, which locate the least stressed positions of bending moments and shear forces, influence the segmentation of the wooden elements to determine the joint positions.

The joint design is based on classical carpentry joints, such as a Gerber-like joint. Since the axial stresses are mainly compressive, the joints are designed to match the shape of the overall structure. These joints can aid in the assembly process as the elements can be easily slid into place based on their shape. Additionally, fully threaded screws are utilized to ensure consistency and prevent any potential issues with horizontal loads that may not have been accounted for in the static calculation. The two symmetrical parts of the bridge were later connected with planks for the flooring, and two stairs for the first set-up and test of the structure (see Fig. 7). The two stairs also serve as a foundation, that would be replaced for the implantation in the forest.

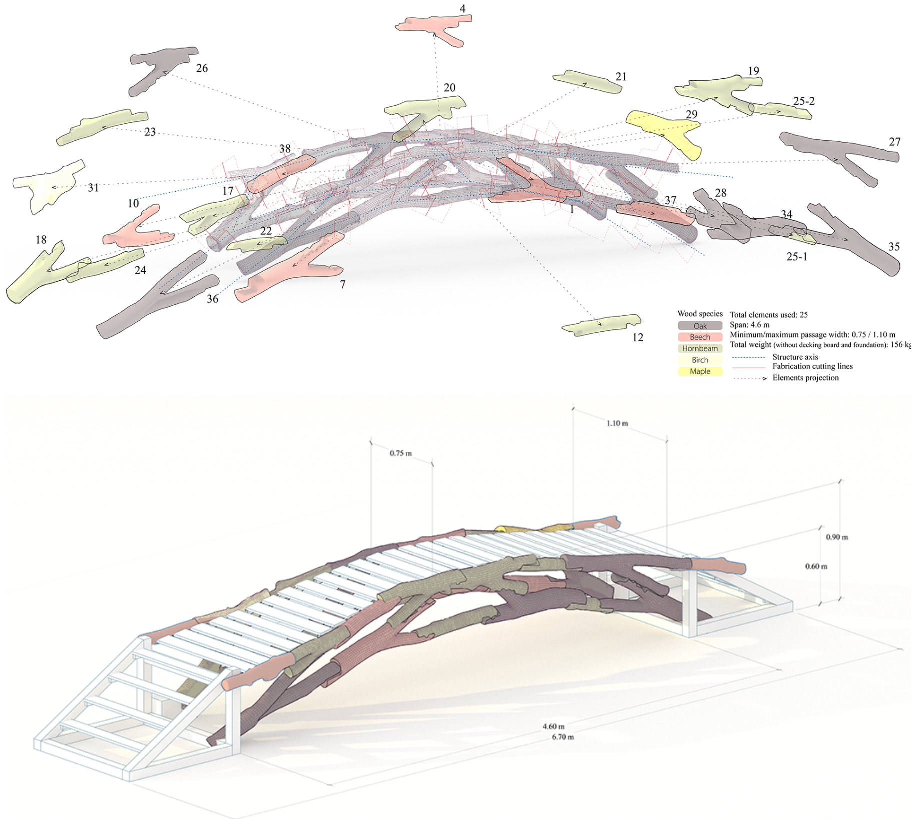

Figure 7: (Above) Exploded axonometric view of the construction design, with different tree species in color, (below) Final construction.

4.2. Fabrication process

The structural scheme determines the location of the joints, taking into account the final position of the timber elements. An algorithm is then used to customize the joint design for each element based on the thickness of the two elements being joined and the deviation of each element's geometric center-line from the structural design. This joint could potentially benefit from a simplified manufacturing process by using a CNC milling machine to cut the flat polygons in two axes. As shown in Fig. 8, the cutting surfaces that define the joint are highlighted in red. Prior to fabrication, each element is planed on one side using a planer, and positioned on a board. The final geometry is calibrated to determine the exact position of the timber element with the board. This step allows for precise placement on the CNC. The next step is machining, which cuts the joints with precision (see figure 9). The assembly process was completed within a few hours by clamping the elements together, while drilling and screwing them together. This method proved effective in achieving a strong and reliable final structure.

The processes were carried out using Rhinoceros 7.0 [19], automated with Grasshopper, and static calculation with the Karamba 2022 [20]. Milling operations were carried out with a 3 axis CNC, with a 180mm lock case end mill, programmed with AlphaCAM 2022 [21].

5. Future works

This research project will continue the study of mechanical properties with particular emphasis on branch cross sections and tree growth simulation. Material properties will be evaluated across species using

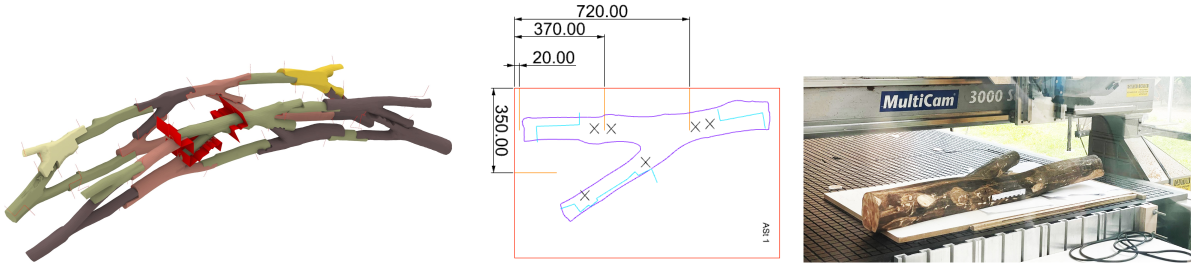

Figure 8: Design to fabrication process: Joint design automatization, CNC milling programming, 2D CNC milling operation.


Figure 9: Resulting fabrication of the Interlocking joints for the off-knot connection: oak element with form fitting joints, detailed photo of the joint, fastening with fully threaded screws.


Figure 10: Final assembly showcasing the pedestrian bridge at its mid-term exhibition.

non-invasive material analysis. Structural validation of the elements will be achieved through improved modeling and simulation using the GSBIGA method and other non-destructive testing techniques.

6. Conclusions

The study concludes that timber constructions should adapt to readily available materials, highlighting the need for resource-efficient construction practices. The case study on the timber bridge, currently displayed in the inner courtyard of the Faculty of Architecture at RWTH Aachen University for 12 months (see Fig. 10), effectively demonstrates this adaptation. The research findings emphasize the practicality and sustainability of using locally sourced timber, which aligns with current trends towards environmental management in construction. This bridge is also planned to be exhibited in the local Aachen forest in 2024. Such practices align with current trends towards environmental management in construction. However, due to the unique nature of each timber piece, individualized construction approaches are necessary as properties can vary among specimens. To overcome these challenges, it is recommended to initiate the process directly within the tree by selectively shorting the tree elements that have potential. This approach will aid in creating a library of timber geometries, improving the identification and utilization of optimal shapes, thus streamlining construction and maximizing the use of the raw material.

Acknowledgement

This research is part of the project titled: "Naturally grown timber elements as basis for load-bearing building structures - structural analysis and growth simulation", funded by Deutsche Forschungsgemeinschaft (DFG). Project number: 512769030. The authors would like to thank the support of the Regionalforestry Office Rureifel-Jülicher Börde, especially Andreas Wintraken for assisting in the selection of wood, as well as the forest owners Landvogt Forestry Company, Aachen-Sief, for providing the raw timber. This work would not have been possible without the help of the research assistant students: Sheldon Stephens, Viktor Wages, Tobias Grüters and Raman Suliman; as well as the student contribution for the construction of the bridge during the Summer Semester 2023, Research Seminar "Growing Bridge"[22]: Yara Almojaber, Adonis Alsaad, Yo han Choi, Ana Hernando de la Fuente, Lana Karamani, Cristian Moscoso Lizama, Irma Softic and Abdullah Sukkar. Finally, the authors would also like to thank Yijiang Huang, for the inspiring development of the matching algorithm [23].

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