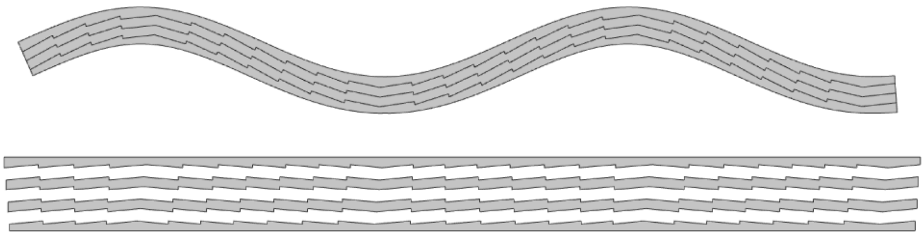
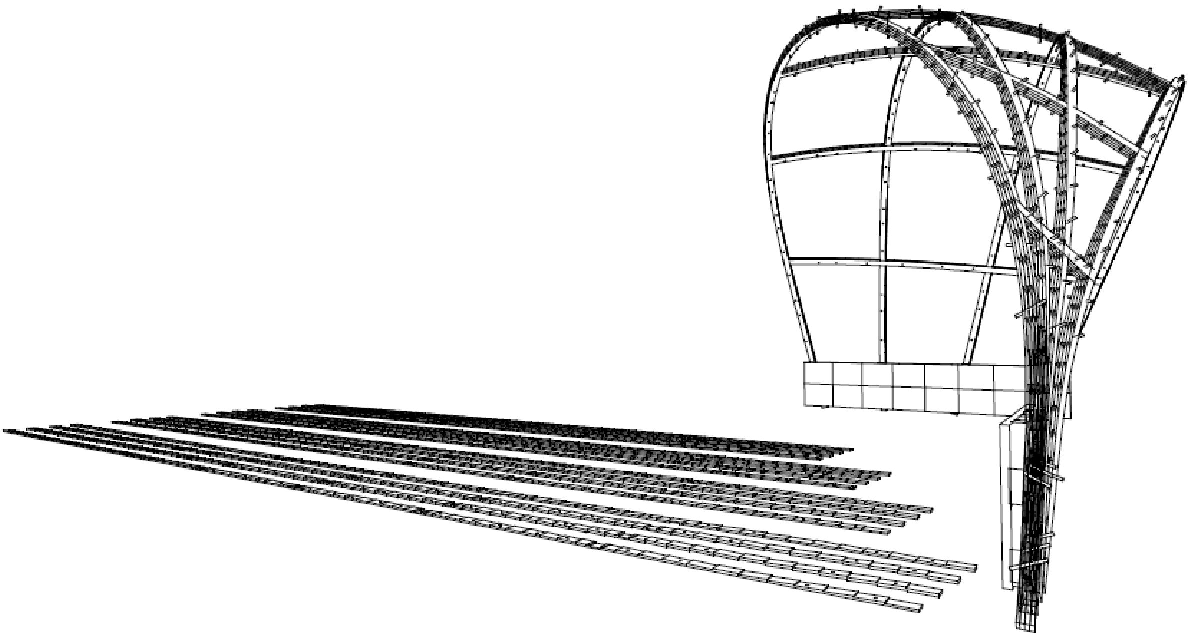


b-CTC

Bent-Computational Tooth Construction – ITECH Masterthesis



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Bent-Computational Tooth Construction

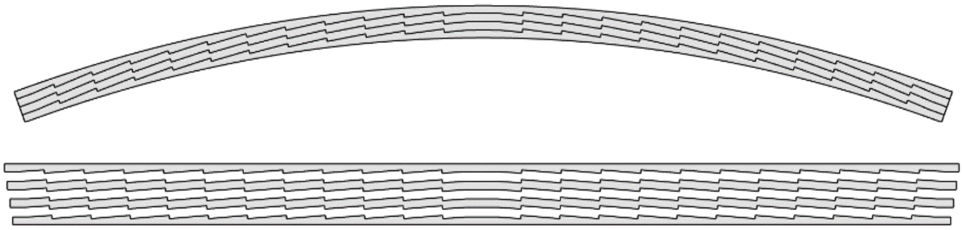


Figure 3: Teeth beam principle, defined curvature through longitudinal teeth patterns

1. Introduction

Bent-Computational Tooth Construction (B-CTC) was developed as an architecture master thesis, aiming to build and design free form structures using bent and interlocked solid timber tooth beams. The timber tooth beam technique, developed by master carpenter Hans Ulrich Grubenmann in the 18th century, allows interlocking bent solid wood beams at a defined curvature. The resulting geometry is determined by a carved tooth pattern on the long side of straight manufactured beam components. The technique has rarely been used since the development of glulam beams, which at the time were cheaper to fabricate than interlocked tooth beams. With contemporary fabrication methods such as CNC machinery and robotic fabrication, however, tooth beams can be fabricated far more efficient than at the time of their invention. Applying integrated digital design to fabrication workflows, the thesis aimed not only to reconsider single tooth beams, but to develop the tooth beam technique further towards its integration into complex architectural and potentially doubly curved shapes. Therefore, the development of beam overcrossings as well as the development of assembly methods constitute important parts of this thesis. Fabricating tooth beam components as flat elements can reduce fabrication complexity significantly and additionally allows efficient transportation. Furthermore, this thesis, with its purely geometrical approach, aimed to use neither glue or glued wood products nor screws. This makes it possible to disassemble a built structure and potentially reuse the wood. Therefore, B-CTC can be allocated within the field of sustainable and ecological architecture.

2. Relevance

2.1. Ecology

A large majority of today’s scientists consider man-made climate warming as a fact [J. Cook 2010]. While climate-change processes have been known for several decades, public attention to them is rapidly increasing only nowadays. It may be viewed as a task of contemporary architecture to respond to this tendency in society and therefore develop more ecological building solutions. Owing to the fact that wood binds CO2, building with wood has a positive impact on climate warming. Therefore, every novel wood building system has the potential to lower the effect of climate warming.

2.2. Economy through a short production chain

To produce conventional complex freeform glulam beams, firstly trees get cut, then the trees are cut into thin lamellas, these lamellas are then glued together again to finally mill the desired shape. B-CTC, a freeform approach as well, has a significantly shorter production chain: The trees are cut, then lamellas get cut, which then directly can be processed into tooth beam components by subtractive milling processes. While the final shape of current freeform glulam beams mostly is milled at curved glued and prefabricated wooden workpieces, fabricating tooth beam components as flat elements reduces the fabrication complexity significantly, and additionally allows more efficient storage and transportation. Further, it must be considered that glued wood cannot be recycled and reused as effectively as solid wood. Glued wood products are, compared to tooth beams, not detachable and cannot be disposed ecologically. To burn glued wood, special permissions and emissions filters are needed.

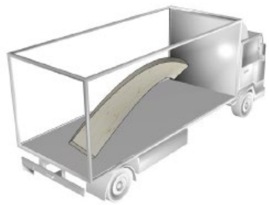


Figure 4:
Transport of a prefabricated freeform glulam beam

Figure 5:
Transport of multiple prefabricated tooth beam lamellas

2.3. Flat fabrication and transportation

Whereas the final shape of current freeform glulam beams is mostly milled from curved glued and prefabricated wooden workpieces, fabricating tooth beam components as flat elements reduces the fabrication complexity significantly and additionally allows for efficient storage and transportation.

2.4. Complex wood design

B-CTC can be applied, similar to well-developed glulam freeform approaches, in complex freeform shapes. As opposed to glulam approaches, b-CTC relies on solid wood exclusively. Therefore b-CTC does not aim to replace existing glulam approaches but rather to complement these as a valid solid-wood-only design and construction alternative.

2.5. In contemporary carpentry

Further, b-CTC is an opportunity for contemporary carpentries and local sustainable economies. CNC-Machines have become, even for smaller carpentries, more and more affordable. Carpenters in need of a curved beam will, with b-CTC, be able to cut their own tooth beam components inhouse, preferably with local wood, instead of ordering a glulam beam from a specialized company far away.

3. Scope: From design towards fabrication and assembly

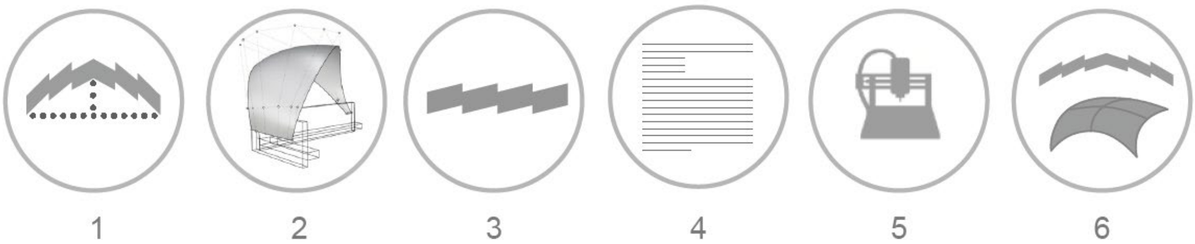


Figure 6: Graphic Scope

In order to integrate the traditional tooth beam technique into contemporary complex wood designs, the scope of b-CTC comprises multiple digital and physical steps: Maximal bending tests (1), digital architectural design methods (2), digital algorithms to calculate tooth geometry (3), CNC-code generation methods (4), fabrication (5) and assembly processes (6). These steps have been investigated and developed in order to fabricate and assemble a 1:1 proof of concept prototype pavilion structure. In this project, b-CTC focused on the loadbearing structural wood construction only and did not investigate any covering façade systems, which would make a tooth beam structure watertight. Further, it was decided to exclude any structural analysis from this research and focus on a purely geometrical approach only.

4. Context and State of the Art Projects

4.1. Between preformed and post-formed wood constructions

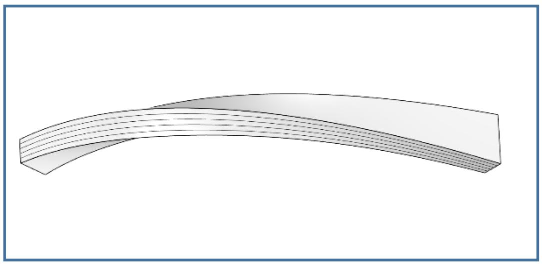


Figure 7: Twisted conventional layered glulam beam

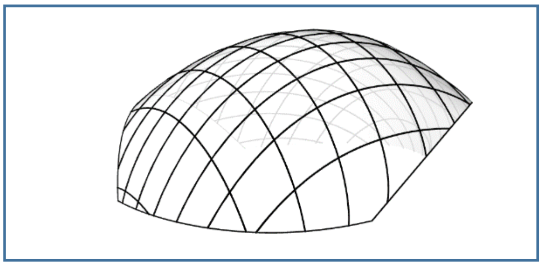


Figure 8: Conventional bent gridshell structure

In today's freeform wood construction, the most common approach to fabricate complex building components is to glue complex shapes from multiple thin layers and further carve them into shape with elaborated and complex CNC-milling processes. Such preformed components can be prefabricated with high accuracy in CNC-equipped companies, and then be assembled relatively easy on site. A typical post-formed construction approach is the grid shell construction system. Multiple layers of solid wood are laid out in a flat grid on site to then be pulled into shape by a crane in a force-consuming process (e.g. Multihalle Mannheim by Frei Otto, 1975). B-CTC, also assembled through an on-site bending process, but from prefabricated lamellas with shape defining tooth patterns, can therefore be allocated between preformed and post-formed construction approaches.

4.2. Historical inspiration

Figure 9: Wintersey bridge

Figure 10: Tooth-beam at the Wintersey-bridge

The technique to define the shape of an arc by bending multiple layers of heavy beams together and interlocking them by a tooth pattern has previously been applied in multiple bridges in Switzerland, by the master carpenter Hans Ullrich Grubenmann (1709 – 1783). The Wintersey bridge, constructed in 1839, (fig. XX) located between the municipalities Hasle and Rüegsau close to Bern in Switzerland, spans 60 meters without pillars [Meyer-Usteri, 2004]. Built with tooth beams as primary structural elements, this bridge is stabilized additionally by a combination of trusses and different wood-joinery methods. At the two sides of the bridge, the bent tooth-beam components form arc-shaped beams, similar as it would be done today with glulam beams. Therefore, both this bridge and the tooth beam method can be considered as having been ahead of their time.

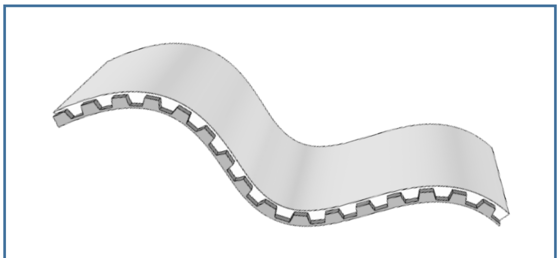


Figure 11: ZipShape

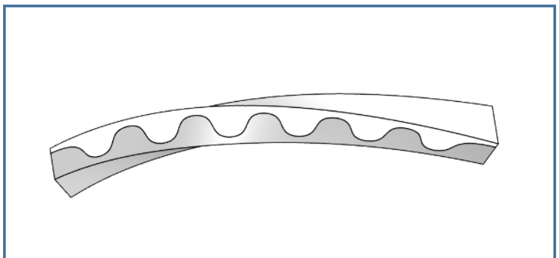


Figure 12: Zippered Wood

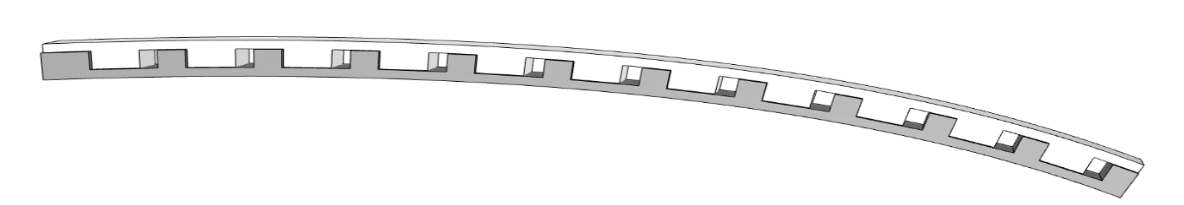


Figure 13: Bend and Block

4.3. ZipShape, a contemporary approach in furniture

Since 2007, Christoph Schindler has been developing the ZipShape as a universal approach to fabricate single curve panels from any plane material without molds [Schindler et. al., 2011]. Like in heavier tooth beams, as used in bridges, interlocked geometry defines the curvature of the product. Unlike the traditional tooth beams, however, the main part of the cross section consists of interlocked teeth, whereas the remaining part of the cross section is very thin in order to achieve a high curvature.

4.4. Zippered Wood

This project, a collaboration of the University of British Columbia's HiLo Lab, the University of Colorado, Denver's LoDo Lab, and HouMinn Practice [Shapiro, 2020], demonstrates the currently increasing fascination of this topic across the globe, as it was developed in parallel with the present work. Zippered Wood is a system development which allows to fabricate curved and twisted wooden beams. The Zippered Wood approach can realize a maximum of possible curvatures due to its geometrical zipp-pattern setup with minimal effective lamella thickness. Yet, this in turn also drastically reduces the effective load bearing capacity because almost all fiber-layers in the wood lamellas are cut. Therefore, Zippered Wood structurally relies on the glue which is used to connect the carved lamellas.

4.5. Bend and Block, A self-shaping dynamic approach

At the University of Applied Arts Vienna, Austria, Efilena Baseta developed a novel approach named «Novel bending-active system with controllable curvature-stiffness relation». Instead of locking beams at a defined curvature as seen in the Ramseyebrücke, by which the beam components are prevented from bending back into their flat state, this approach defines the maximum bending range of beams by preventing further bending by increasing the systems stiffness. This is achieved by blocking them, using rectangular teeth patterns [E. Baseta]. The blocking position and range of possible bending is defined by the size of gaps between the teeth.

5. Method

5.1. Development through digital and physical control loops

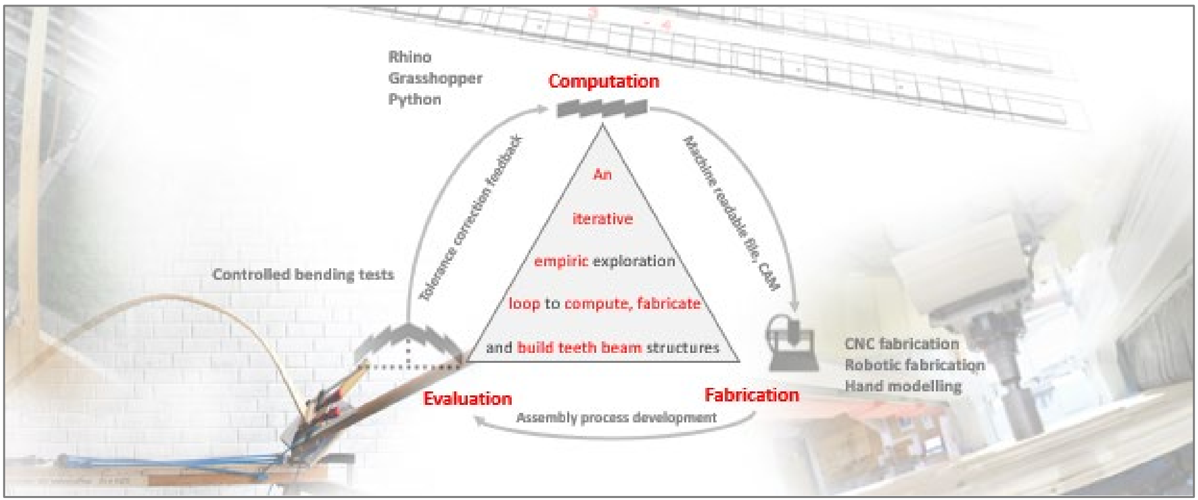


Figure 14: Computation, fabrication, and evaluation principle

Figure 15: First physical tests for evaluation and approximation of a predefined target curvature

To develop a digital workflow within the ecosystem of the Rhino and Grasshopper design and fabrication CAD environment, multiple custom grasshopper codes have been developed. To constantly improve this developed computational model, which is capable of transforming a design input into a fabricable geometry output, the cycle of physical testing, digital development, fabrication and evaluation of the built result was repeated multiple times on different levels. Firstly, the developed codes were mainly applied on single teeth beams to physically approximate digitally defined shapes. To achieve that, it was firstly tested physically how much raw single lamellas of a defined thickness could be bent, then a corresponding digital teeth beam model was set up in order to CNC-fabricate a physical model, which could be compared to the digital one in terms of accuracy and deviation. The result of such deviation evaluations could then be integrated into the computational model to constantly improve the accuracy of the overall workflow.

6. Results

6.1. Forces and geometrical setup of single beams

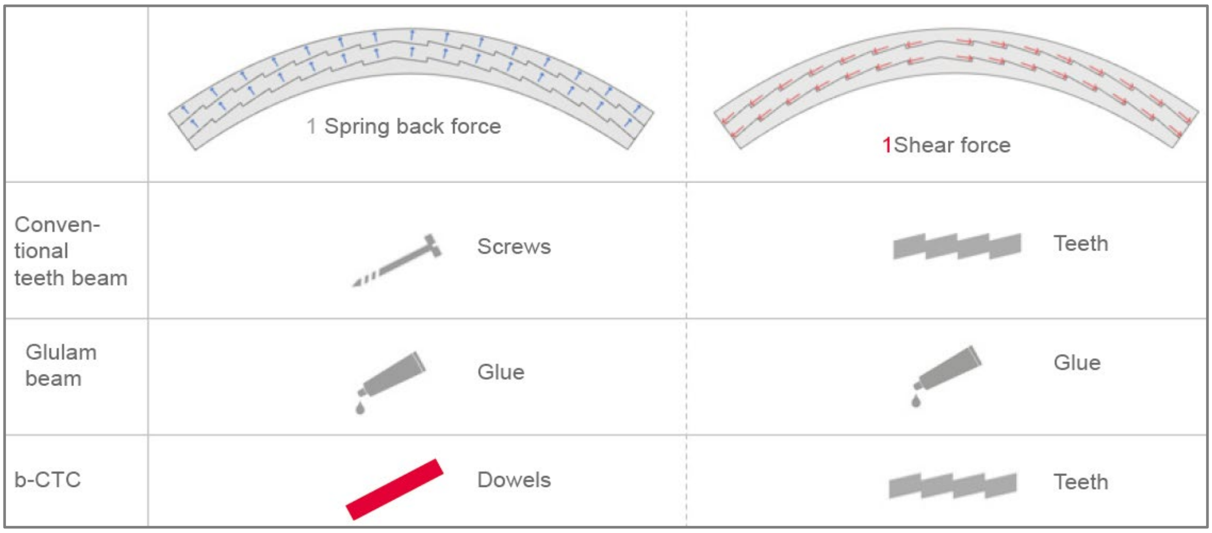


Figure 16: Forces

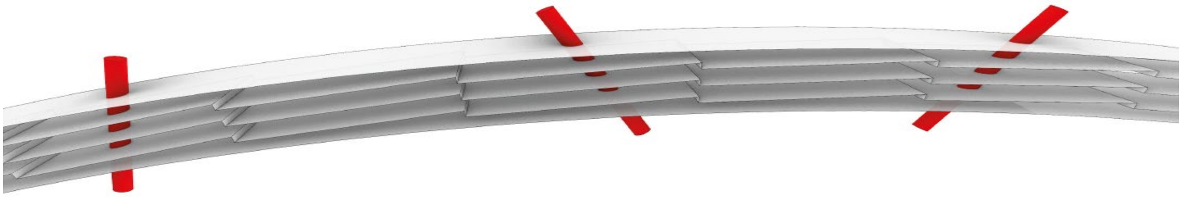


Figure 17: Inclined b-CTC dowels

Tooth beams consist of components which are fabricated in their straight stage and afterwards bent and locked together. Therefore, two main forces occur in a tooth beam: A spring-back force and a shear force. In a conventional tooth beam, the spring-back force is compensated by an iron screw, whereas the shear force is compensated by the tooth-pattern, which is always deployed in the correct direction against the shear force. Aiming to use solid timber only, and neither glued wood products nor screws, inclined wooden dowels are used in b-CTC tooth beams to replace the screws that hold back the snap-back force in conventional tooth beams.

6.2. B-CTC system limitations

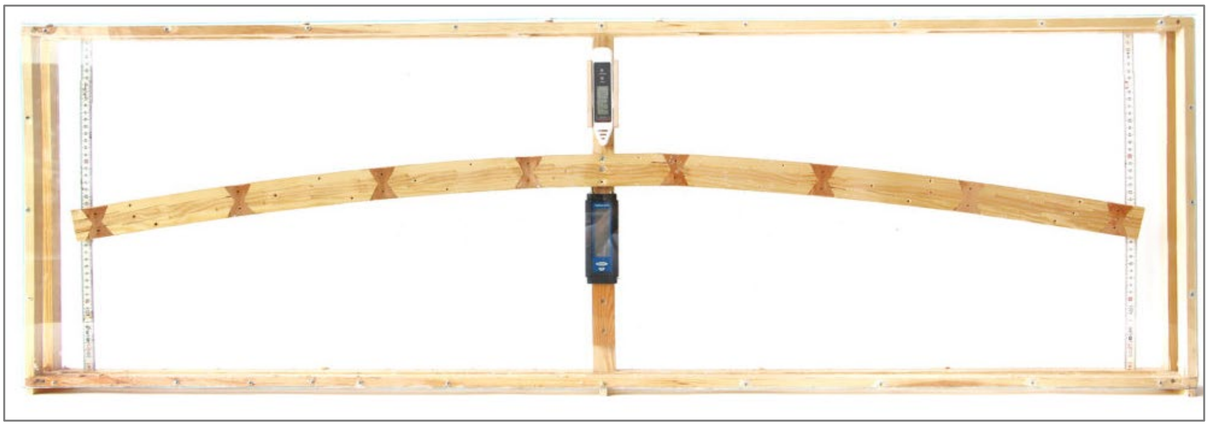


Figure 18: «HygroSim» testing set-up, a plexiglas box to observe beams under humid conditions

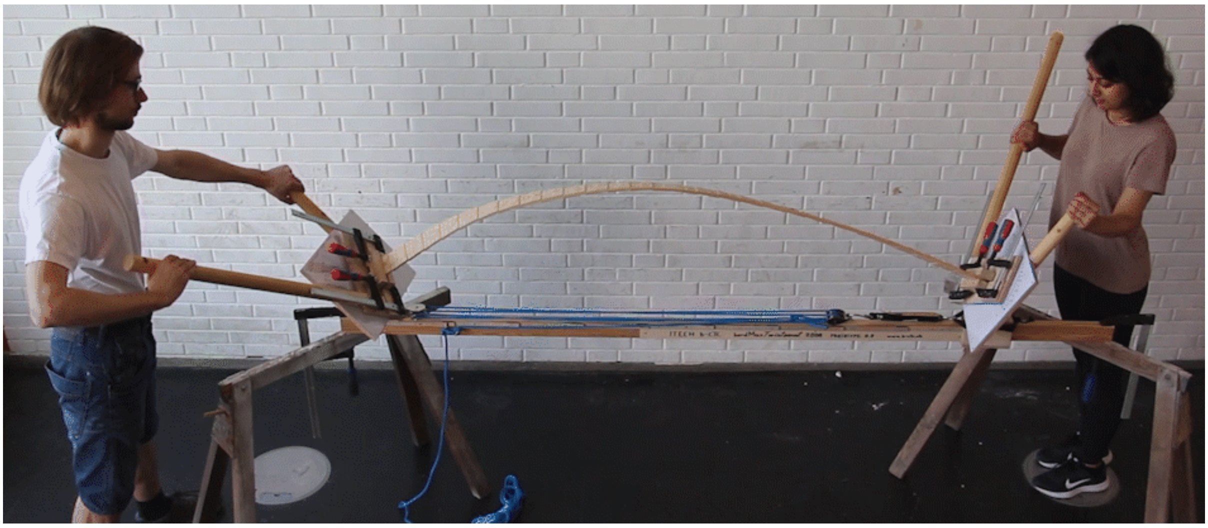


Figure 19: «BendMax-TwistoMat» testing set-up, to simultaneously bend and twist tooth beam lamellas

To explore the limitations of the maximum possible simultaneously twisting and bending of tooth-lamellas (see 7.3 Integration of tooth-beams in doubly curved designs), a custom testing setup was created. 100 degrees of twist at a 2-meter-long lamella of a cross-section of 60 to 12 mm with 3 mm teeth depth, bent simultaneously to a depth gauge of 500 mm, could be confirmed. Thinner lamellas were not tested because they need to be at least 8 mm to fix them on the CNC-table by screwing. The maximal possible simultaneous bending and twisting constraint is important especially in complex doubly curved overall designs with multiple overcrossing teeth beams, since the overcrossing node situation can potentially request additional twisting of the lamellas to align with the overcrossing neighbor beam (see 7.3 Integration of tooth beams in doubly curved designs). Further, a tooth beam test model was observed in a plexiglass box under constant relative air humidity of 90% or more for 17 days. Due to the fact that wood deforms by changing its humidity content, which occurs significantly more in radial and tangential than in longitudinal direction (along which the teeth of a tooth beam lamella are aligned), the change in curvature of a 140 cm long test-tooth beam remained low as expected. Changes were below those that would be of significance for the aimed project at the pavilion scale. In addition, b-CTC beams that are integrated as loadbearing structural elements in built architecture can be completely covered and would therefore not be impacted by moisture.

6.3. Integration of tooth beams in doubly curved designs

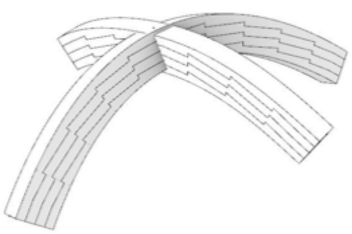


Figure 20: Single curved node

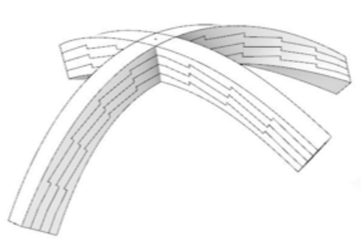


Figure 21: Curved and twisted node

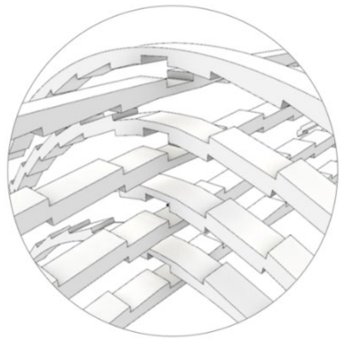


Figure 22: Half-half out cuts

Aiming to develop a lightweight but stable construction system, which is capable of being applied in complex doubly curved designs, it was decided to order the teeth beams in diagrid patterns. To reduce the moment forces at the nodes of the diagrid pattern, the single tooth-beam lamellas cross each other without being cut into shorter elements. To maintain the structural height of the structure, the overcrossing lamellas are interlocked with half-half out-cuts to over cross themselves in their cross-section. This geometrical node setup would be impossible to fabricate with traditional single curved tooth-beams applied in a diagrid pattern on a doubly curved complex shape because the node intersections would be extremely complex and not efficiently fabricable. The solution was to twist the tooth beams additionally to the single curved bending.

6.4. Straight tooth geometry computation – curved and twisted

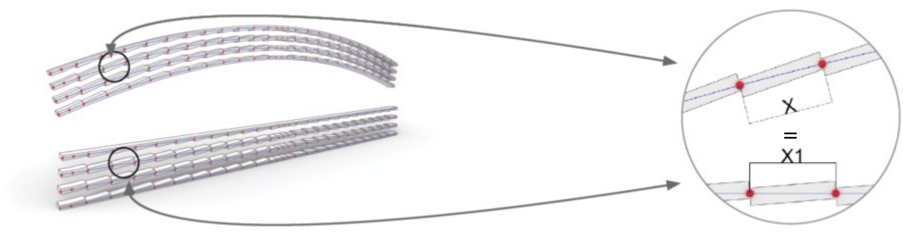


Figure 23: Computation from curved to straight

The core of this research was to develop a computational method that can calculate a straight geometrical representation of a bent target tooth beam component geometry. This was achieved with the following method: The straight stage of a beam was reconstructed depending on those parameters of the beam, which do not change during the bending process: the tooth beam lamellas middle lines and their thicknesses. While the middle line and the beam thickness do not deform, the upsides of the lamellas experience an elongation and the lower sides a compression. To compute the straight geometry is a relatively simple process. Yet, complexity increases as soon as multiple tooth-beams of a whole structure, overcrossing and intersecting each other, have to be calculated. The calculation of the straight representation of bent and additionally twisted beams can be done with the same method as single curved beams due to the fact that the crucial parameter of the beams' non-deforming middle line is not affected and transformed by additional twisting. To approximate the target curvature and to overcome production inaccuracies as well, a tolerance system was integrated into the computation, which allowed to create minor gaps between the teeth contact surfaces by an input parameter.

6.5. CNC – Fabrication

To CNC-fabricate the final prototype, the highly accurate 5-Axis Reichenbacher Vision 3 model 4105 CNC machine of the Treppenbau.ch AG could be used. The CNC-readable file was generated with the AlphaCam software based on the digital geometry that was created with multiple custom codes. With a milling tool of a diameter of 5 cm, all tooth-beam lamellas could be milled efficiently. To rotate the lamellas on the CNC-table 180 degree around their longitudinal axis to mill tooth patterns on their top as well as on their lower side, the lamellas had been fixed not only by screws, but additionally by positioning dowels, which allowed an accurate flipped repositioning. Over one month, this setup was developed and tested repetitively. The effective milling of the prototype pavilion lamellas took approximately three days with 9 hours of CNC-machining.

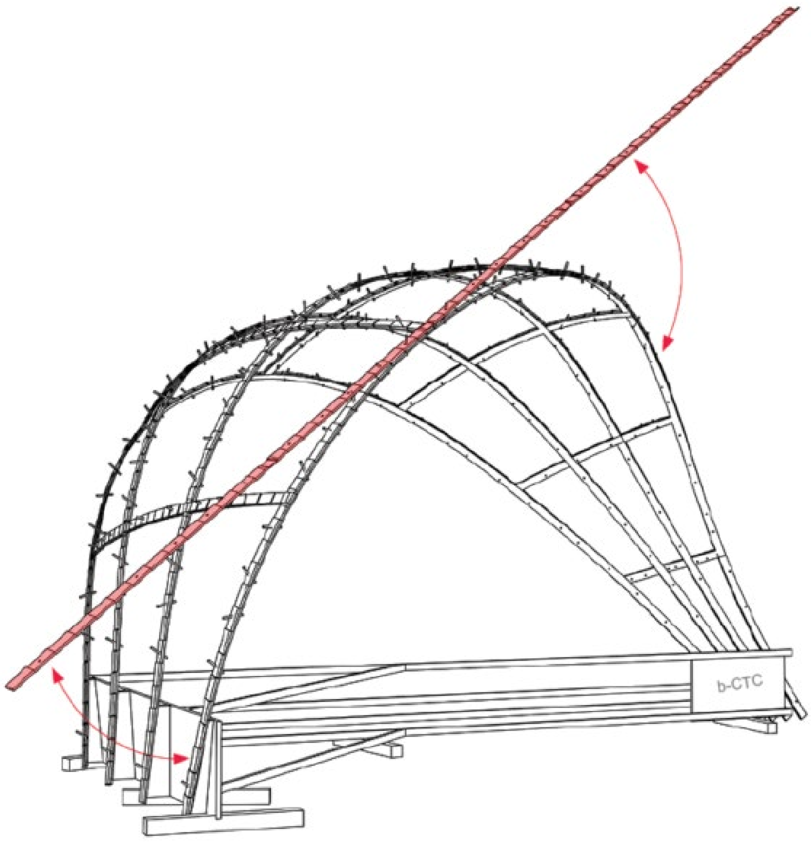


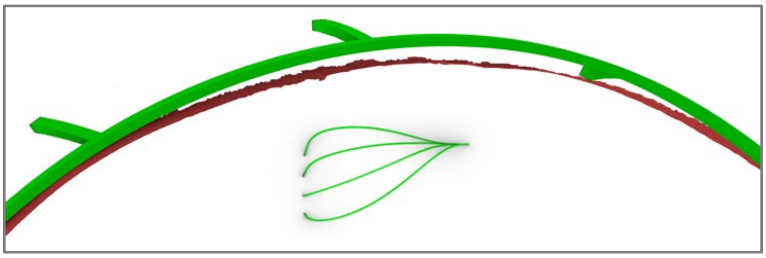
Figure 24: Layer-by-layer assembly process

6.6. Assembly

Having multiple overlaying tooth beam lamellas at the tooth-beam structure nodes, the only possible way to assemble was a layer-by-layer assembly process: By completely assembling every layer, including the overcrossing components, it could be avoided that components cover each other, and therefore overcrossing elements could not be inserted anymore. To assemble a tooth-beam structure as an only wood system without any screws, and relying as conceived on inclined wooden dowels, the following was tested at the prototype pavilion:

In areas of lower curvature, the developed wood-only dowel-connection was shown to work. In areas of higher curvature, several screws were necessary to prevent the lamellas from bending and snapping back.

6.7. Evaluation of the prototype pavilion



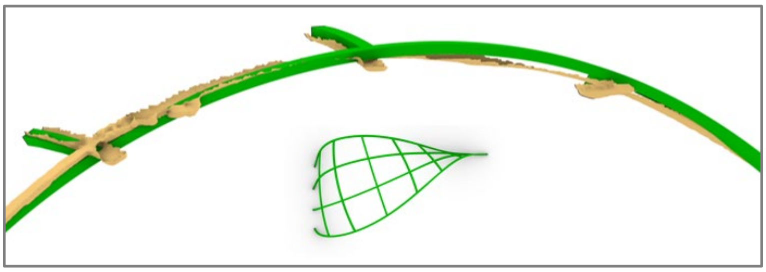


Figure 26: Scan 2, after the complete assembly of all lay-

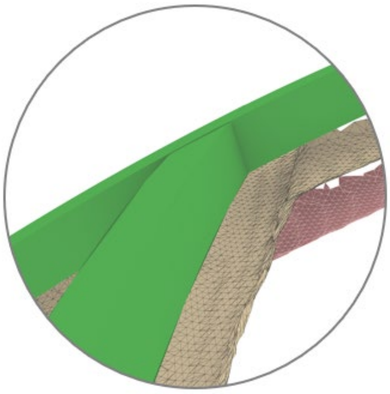


Figure 27: Overlay scan 1 and scan 2

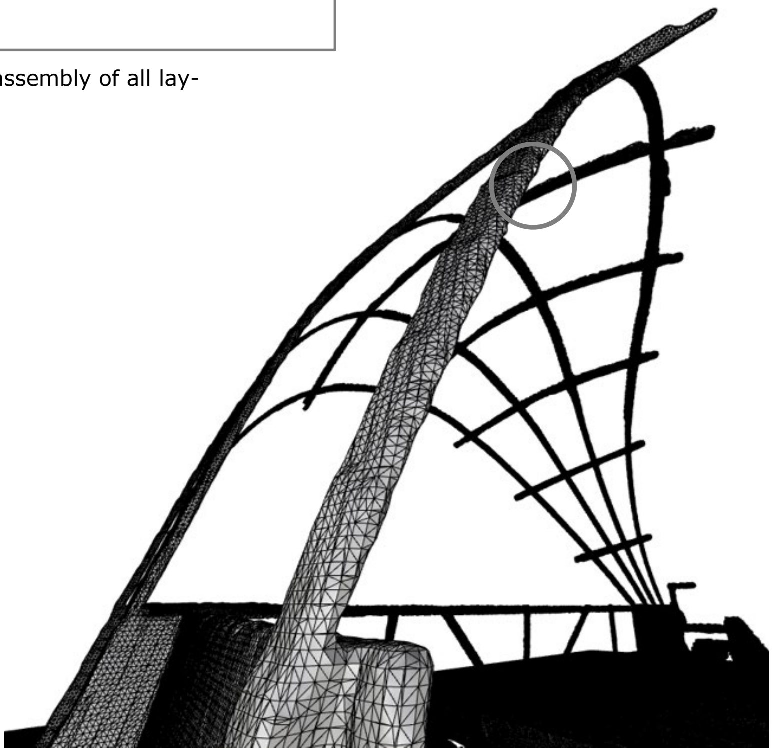


Figure 28: Complete mesh, scan 2

To further improve the developed integrated design towards fabrication workflow, the built prototype pavilion was accurately scanned using a laser scanner. Scanning was performed first during construction after having completed the first layer, and then after the complete assembly. The deviation of the first scan (red, layer 1, with no teeth impact) showed a high deviation of maximally 14 cm compared to the digital twin geometry (green). Scanned after the complete assembly (yellow), the maximal deviation was reduced to maximally 5 cm. In current wood construction, this is still a relatively large deviation, nevertheless it was considered a general success that the structure, with maximal bending close to twisting limits, could successfully be assembled and installed at the planned location, the Zeughaus in Teufen, Switzerland. The measured deviation might derive firstly from the extreme lightweight construction geometrical setup (overall weight of the structure below approx. 62 kg) and secondly from a relatively large digitally implemented security tolerance between the teeth contact surfaces of 1 mm. Therefore, the Autor is confident that accuracy issues can be handled conveniently in future projects.

Figure 29: The finished prototype pavilion at Zeughaus Teufen in Switzerland, spring 2020

7. Discussion and outlook

The conducted research was consolidated into a design, fabrication and assembly workflow for complex contemporary tooth-beam structures. The completed prototype pavilion proves the functionality of the developed systems for small-scale architectural projects. This inherently raises the question whether the developed systems could be used to accomplish large-scale architectural projects as well. Different scenarios in building construction below the achieved complexity are conceivable. Any construction that is commonly built with glulam beams can potentially be constructed using tooth-beams. This range of application covers complex doubly-curved designs as well as less complex single-curved or flat designs with or without beam overcrossings. By being constructed without glue and without glued products, the proposed approach consisting of solid wood only can additionally be interesting for architectural designs following the philosophy of building with pure and low-processed natural materials.

To be applied in such scenarios, the developed systems would need further refinements. With large scale beams, systems would have to be tested concerning accuracy and load bearing capacity. Given this, any contemporary carpentry with a CNC machine at its disposal would be capable of fabricating tooth-beam components and would therefore be capable of accomplishing simple as well as complex designs without being dependent on external specialized glulam beam production companies. Therefore, with b-CTC, possible future production chains could be significantly shorter, less energy consuming, and therefore more ecological than today's building-construction-production chains that rely on common glulam beams.

Figure 30: The prototype pavilion at Zeughaus Teufen in Switzerland, winter 2020

Figure 31: The prototype pavilion at Zeughaus Teufen in Switzerland, winter 2020

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