Bending-Active Lamination of Robotically Fabricated Timber Elements

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Abstract — This paper presents a fabrication process that uses elastic bending as both a forming and a clamping process for robotically fabricating curved laminated timber elements. Bending a stack of wooden lamellae that is constrained at its endpoints causes differentiated shortening and lengthening, resulting in pressure between the lamellae. This pressure allows for glue-based lamination without the need for external clamping. This process makes use of the embedded forces resulting from bending, the ability to digitally precompute lengths and positions of wood lamellae, as well as the capability to precisely re-create these positions using an industrial robot arm.

Introduction

Conventional industrial fabrication processes of curved glue-laminated timber rely on external shaping methods such as jigs, formwork, and clamps, and sometimes involve subsequent subtractive milling. Thus, creating a range of unique shapes requires the fabrication of a series of jigs, or at the very least adjustments to an existing jig. This is also true in cases where robotic milling has been utilized as a means of forming curved wood components (Yuan et al. 2016, 203). In contrast, in the method proposed by the authors, jigs and formwork are substituted by robotic elastic bending and positioning, and clamping is replaced by the internal pressure created by controlling the shortening and lengthening of each lamella within one stack of lamellae.

In the proposed fabrication process, an industrial robot holds the end of a stack of wooden strips in place. The elastic bending of a strip with restrained ends results in a shape in energy equilibrium known as the elastica curve (Levien 2008, 4). As the robotic fabrication process does not require the use of any jigs or clamps, a large range of three-dimensional elastica

shapes can be created without incurring additional cost or complexity.
This project is situated within the broader context of material and process-driven architectural research enabled by computational design and digital fabrication, for which spatial timber structures form a suitable testing platform. As a possible application for the bent elements, a large, three-dimensional assembly is proposed, consisting of components in which the wood fiber directions are aligned at all connection points. Prototypes of the aforementioned elements were built to demonstrate the potential of the proposed system.

Background

Glue-laminated timber, or glulam, is one of the earliest engineered wood products and consists of multiple layers of wood glued together, all with the same grain direction (Hoadley 2001, 242). With an end-to-end and face-to-face joining processes, glulam allows the manufacture of structural elements with dimensions larger than those of the source tree. The production of straight glulam elements typically consists of several steps: drying, strength grading, finger jointing of ends, planing, laminating, and finishing (Ong 2015, 125). In the laminated stage, mechanical presses are often used. However, such presses are limited to the production of straight elements.
To form curved elements, lamination processes rely on pressing the lamellae onto a formwork or a jig, and clamping them progressively along their length (Freas and Selbo 1954, 61–64). The time needed for such processes depends on the complexity and size of the jig, the placement of the lamellae and clamps, and on the number of elements that can be created without adjusting the jig. Therefore, despite the possibility of creating curvature, custom glulam elements are most economical when standardized and used in repetition such as in bridges (Ritter 1990, 4).
In comparison, the research presented provides a different approach to forming and pressing, both of which become automated and integrated. The integration between the precision of robotic positioning and the computational precalculation of distinctive elements allows the creation of unique components without increased complexity or extra processes or resources. As a result, fabrication time is reduced while maintaining the freedom of customization. The proposed fabrication method is based on material properties (in particular elasticity) in combination with computational design, bending simulation, and physical prototyping.
Such an integrative approach combining design, material, and processing constraints is not unprecedented, as can be seen in the ancient vernacular mud'hifs of southern Iraq, first constructed 5,000 years ago (Thesiger 1964), or more recently, in Frei Otto's Multihalle in Mannheim (Liddell 2015). Related research into material-based fabrication processes that

increase efficiency and design freedom includes the PhD research by Tom Svilans (Svilans et al. 2017), “All Bent Out” (Schwartz et al. 2014), and the master’s thesis by Martin Loucka at ICD, University of Stuttgart in 2014 (Loucka et al. 2014).

Another example where material simulation is used to create curved wooden elements is the fabrication method based on hygroscopic properties developed at the University of Stuttgart and ETH Zurich. By using a specific layout of initially flat wooden parts, the laminated elements will self-form to reach a precalculated curvature (Wood et al. 2018).

Contribution

We introduce a fabrication process for the robotic fabrication of bent wooden elements. The central step in this fabrication process consists of bending stacks of wooden lamellae beyond their calculated target elastica curve. Bending a stack of lamellae while holding their ends in such a way that no sliding occurs creates inter-lamella pressure, which is useful for the gluing process. The lamellae are precut to their individual lengths, with alignment holes at precalculated positions where the central lamella is the reference elastica curve. The further away lamellae are from the bending axis, the more they are either lengthened or shortened when the stack is elastically bent. Lamellae on the convex side are lengthened; lamellae on the concave side are shortened. To increase inter-lamella pressure, the outside lamellae are produced slightly shorter than their target length while the inside lamellae are produced slightly longer. In this process, the entire stack is bent such that the lamellae’s dowel holes align (fig. 1). Constraining their position while bending exerts pressure toward the reference (central) lamella. In the proposed process, an industrial robot arm bends the lamellae while preventing sliding of the ends of the strips.

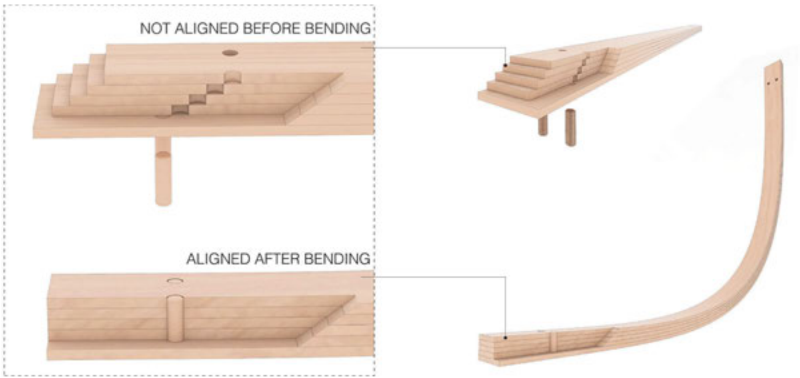


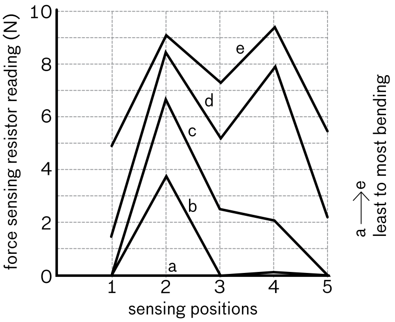
Fig. 1: In the prefabricated straight lamellae, holes are initially not aligned. After bending the stack of lamellae, the holes do align and dowels can be inserted.

Inter-Lamella Pressure

As the physical properties of a glued joint (as well as curing time) strongly depend on the pressure between parts that are glued together, critical questions in the fabrication process are how much pressure is built up during bending, and how is this pressure distributed along the length of the lamellae? In order to test the effect of bending on pressure between lamellae, five InterLink 402 force-sensitive resistors were placed between two 2 cm lamellae of 2 mm thickness to monitor the results of unequal lengthening. No twisting was applied in these tests.

Using an Arduino microcontroller connected to Grasshopper (McNeel 2010), the pressure distribution was visually represented as a curve so that the measurements could easily be observed during the bending process.

The measurements show that, as expected, pressure between the lamellae gradually increases while the robot effector causes the lamellae to bend. Due to natural variation in material properties, certain areas initially showed low or no pressure, but during the bending process, pressure in all areas gradually increased, leading to sensor readings in a range from 4.8 to 9.2 Newtons in the final position (fig. 2). This corresponds to a pressure of approximately 0.038–0.073 N/mm².



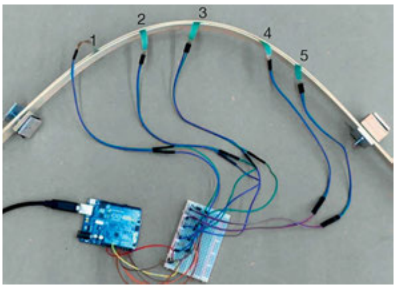


Fig. 2: (Left) Graph showing force-resistive sensor readings from least to most shifting of the holes; (Right) Measurement setup

Length Control

Based on initial experiments, the authors assume that the proposed process of bending-active lamination is effective for the production of double-curved glue-laminated engineered timber due to the ability to precalculate the lengths and positions of each wooden lamella. This precalculation is based on elastica curves, which define the design space of this process. Besides the alignment holes for the dowels, additional holes can be predrilled to facilitate the assembly of finished elements into components as well as the assembly of several components into a larger structure. Additionally, by alternating the lengths of the lamellae, finger joints can be created at the ends of the elements.

Precisely controlling the length of the lamellae eliminates the need for subtractive postprocessing such as CNC milling and drilling.
To customize the ends of the components while maintaining the ability to clamp them, a snap-off detail was designed. Using this detail, the ends of the lamellae remain the same length during the lamination process (fig. 3). This allows the length of the element to remain constant and be easily snapped off after the lamination is completed.

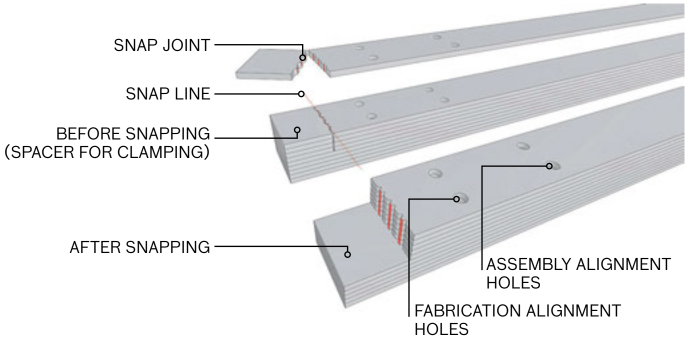


Fig. 3: Precut snap-off detail for finger joint: The top and bottom surfaces of the snapped part are covered to avoid adhesion.

Computational Design Workflow

A computational design workflow was developed to design a network of components and to simulate the bending and geometric formation of all curved elements, providing correct measurements and generating machine code for fabrication. Material properties including size, elasticity, and maximum bending and twisting radii helped define the design space of buildable elements (fig. 4). The workflow was implemented in Rhinoceros's Grasshopper environment, including the Kangaroo plug-in (Piker 2013).

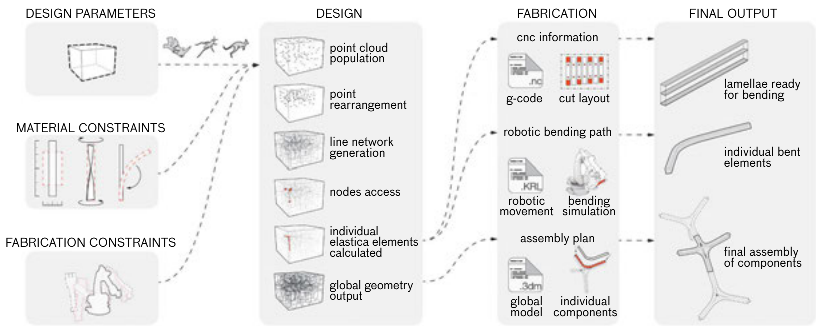


Fig. 4: Overall project scope showing inputs and design stages, fabrication stages, and respective outputs

Fabrication

The lamellae are CNC-cut to their individual lengths, and in the same process holes are drilled into both ends of each lamella at the exact positions necessary to achieve the precalculated elastica curve. The holes are created in order to be able to hold the stack of lamellae using a pin that is part of the robotic effector.

For a fabrication prototype, lamellae of 3 × 100 × 1800 mm each were CNC-cut with accurate dimensions and hole positions in 10 minutes. Then, glue (Titebond III) was manually applied to the lamellae, which were then mounted onto the clamps in 15 minutes, and robotically bent into place in 2 minutes while dowels were inserted. The element was then left for 20 minutes to set (fig. 5), after which it was demounted. After 2 hours, the sides of the element were sanded in order to better reveal potential gaps in the lamination. The fabrication process is illustrated in figure 6.

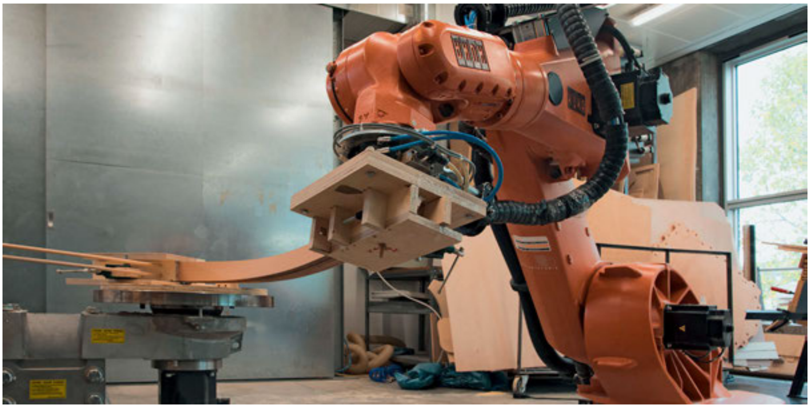


Fig. 5: Fabrication setup consisting of a stationary clamp, a stack of lamellae, and a clamp that is attached to an industrial robot arm

The bending-active laminated elements could be fabricated with angles ranging from 10° to 120° measured between the two anchors where the lamellae are straight. The range of possible angles is dependent on the material dimensions and the number of strips grouped for bending.

Conclusion

This paper introduces a bending-active fabrication method for curved timber elements. Prototypical fabrication tests using a setup with an industrial robot shows that the method is viable (fig. 7), and measurements with pressure sensors confirmed that sufficient pressure is created between wood lamellae to realize a good glue bond with polymer glue.

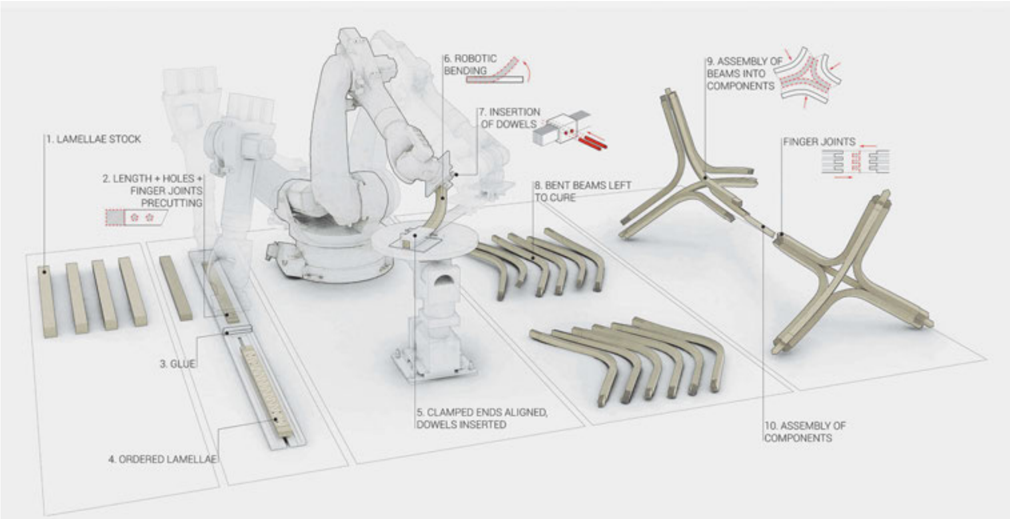


Fig. 6: Fabrication workflow showing the sequence from stock material to assembly

Fig. 7: Final prototypes of laminated elements

This method of forming bent laminated wood elements adds to the endeavors to utilize cross-disciplinarity between materiality, design, engineering, and fabrication in order to produce new forms and properties in ways that would have otherwise been difficult to achieve. This is due to the fact that the proposed method allows material properties to drive the process, necessitating computation for predictability, and robotic fabrication for precision and fabricability.

An architectural investigation demonstrates a potential component-based structural system for creating spatial arrangements with varying density (fig. 8). All elements in such a structure would be unique, but due to the proposed

digital workflow encompassing both design and fabrication, geometric variety would not lead to increased fabrication complexity. The wood's fiber direction in this structure is largely aligned with the force flow.
This proof of concept opens a range of directions for further research, including a more detailed structural characterization of the proposed construction system and an investigation of increasing scale. However, even at its current state, this project demonstrates the high potential of combining computational design with material-informed fabrication methods.

Fig. 8: Rendering of configurations that can be created using the proposed fabrication process

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