FROM MACHINE CONTROL TO MATERIAL PROGRAMMING
SELF-SHAPING WOOD MANUFACTURING OF A HIGH PERFORMANCE CURVED CLT STRUCTURE – URBACH TOWER

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Research Aims and Objectives

Computational design and digital fabrication for architecture focuses increasingly on advanced robotic machine control for the shaping and assembly of pre-engineered building materials to produce structures with complex functional geometries. Intelligent digital planning methods and machine material feedback make processes of additive, subtractive and formative manufacturing incrementally more efficient and tuneable. However, complex shaping is still achieved by combinations of pre-shaped formwork, application of brute mechanical force, robotic manipulation, and subtractive machining from larger stock. In the shaping process, powerful innate material behaviour that influences shape is either viewed as problematic or ignored. In the quest for infinitely more axes, and endlessly more sophisticated end effectors, it's clear we have overlooked the useful capacities found within the structures and tissues of the materials we fabricate with.

This research presents a paradigm shift towards a material-driven self-shaping fabrication method for full scale timber building components. Here the 3D geometry emerges from the designed material arrangement in flat 2D parts that are exposed to an external stimulus (Fig. 2). By utilising the unique capacity of the material to act as an integrated, shaping actuator and the final load-bearing structure, elaborate external forming equipment is eliminated. This simple yet informed material programming replaces typically material, energy and labour intensive shaping process. Using wood, which exhibits strong anisotropic dimensional instability in response to changes in moisture, we developed a material-specific predictive model, and a physical material programming routine that allows for a self-shaping manufacturing process for high curvature Cross Laminated Timber (CLT) building components.

Surface active structures benefit tremendously from curvature in both the overall structural geometry and individual building components. For wooden shell structures, curvature is, however, expensive to produce in terms of costs, material, and environmental impact. In this research, the manufacturability of high curvature CLT components enabled by self-shaping is paired with the development of performative geometry and structural analysis for folded plate cylindrical shell structures. The concept is demonstrated with the design, engineering, manufacture, and construction of a 14m tall thin shell

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tower structure (Fig. 1). Architecturally, the tower serves as a shelter and landmark, showcasing the potentials of innovative high performance and sustainable timber construction.

Research Context

Manufacturing of structural building components can be conducted by combinations of additive, subtractive and forming processes. Advanced digitally-controlled robotic manufacturing builds upon these processes through automation and increased precision but fundamentally still relies on machines to provide the shaping force and logic. Self-shaping systems where shape is generated from physical material programming to actuate based on external stimuli have already been developed at much smaller scales for medical applications, micro robotic applications, and meso-scale mechanisms with a wide range of functions (Studart and Erb, 2014; Tibbits, 2014; Duro-Royo and Oxman, 2015; Wang et al., 2017; Kara et al., 2018; Kotikian et al., 2019). In architecture, similar principles have been applied for self-regulating façade systems that respond continuously to changes in the environment such as temperature and moisture (Correa et al., 2013; Reichert et al., 2014; Holstov et al., 2015; Sung, 2016; Correa and Menges, 2017; Vailati et al., 2017, 2018; Poppinga et al., 2018). Most shape-morphing structures are limited in scale due to the reduced stiffness of the material required for actuation and high costs of the material and processes to produce them. Wood, however, exhibits the natural ability to change shape without electrical input and with incredibly high forces combined with high stiffness, making it ideal for self-shaping large parts (Rüggeberg and Burgert, 2015; Wood et al., 2016, 2018; Grönquist et al., 2018; Grönquist et al., 2019). It is therefore possible to build high strength shape-changing parts; however with increased volume comes reduced actuation speeds (Mannes et al., 2009).

Timber is a readily available and highly sustainable building material undergoing a renaissance in the face of an increased focus on the environmental impact of building construction. CLT, which is comprised of overlapping layers of solid boards with alternating fibre directions, is one of the fastest growing construction markets worldwide. CLT production is efficient and standardised for flat panels. Despite the inherent structural and architectural advantages of curved parts, they are exponentially more expensive to produce. Even with advancements in digital design and fabrication, use of curved wood components is universally limited by the physical forming process (Robeller et al., 2014; Stecher et al., 2016; Svilans et al., 2017). Parts are produced by first

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constructing either adaptable jigs, or solid formwork on top of which layers of lamella are iteratively screwed or vacuum laminated. The bending stiffness and cross section of the wood lamella limit the possible curvature. In contradiction, larger numbers of thinner lamella allow higher curvature, while lower quantities of thicker lamella would be preferred for production and material efficiency. While extreme curvatures can be manufactured for specialty projects, 10mm is the lower limit for standard sawmill production of lamella with 3.5-4.0m radius the highest known curvature for standard industrial production curved CLT.

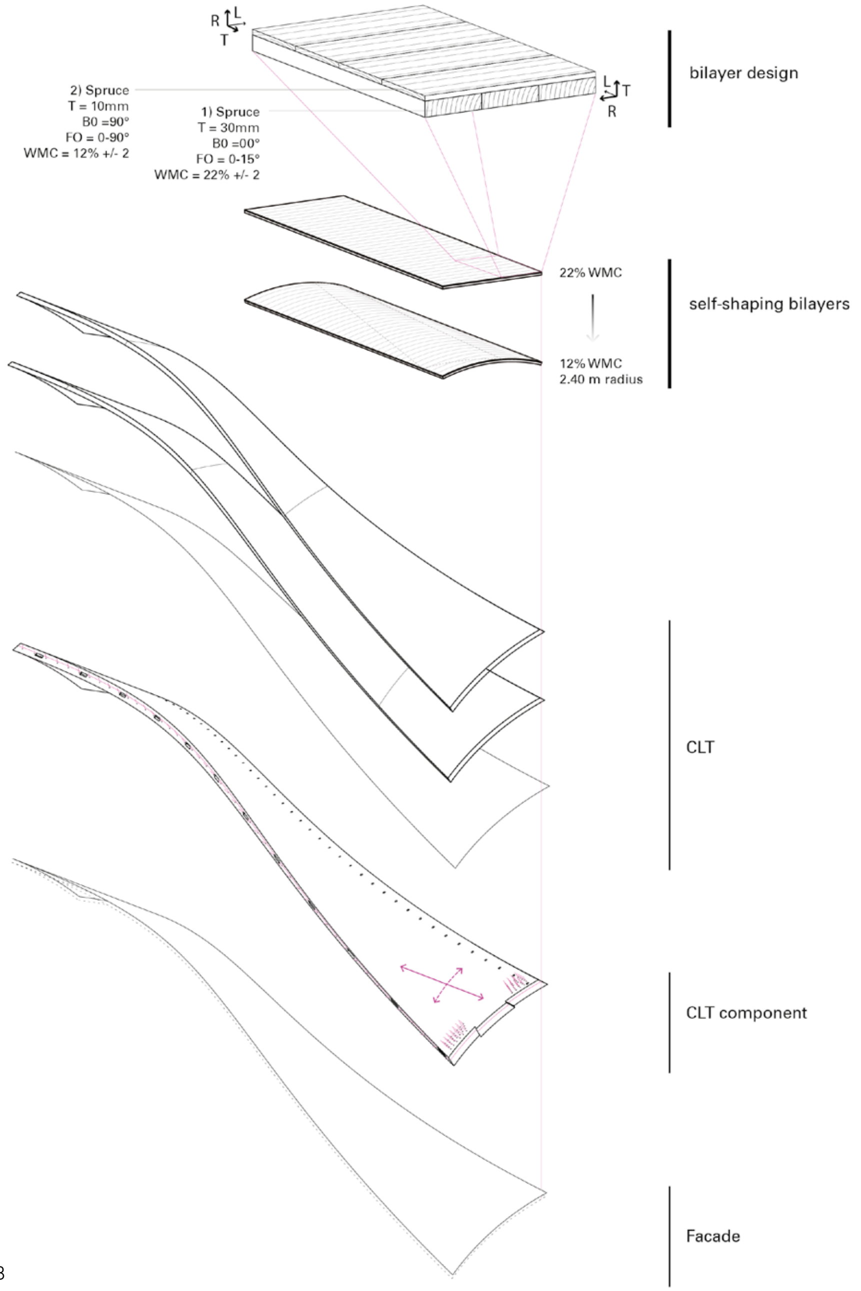
Research Questions

The challenge of applying self-shaping technologies for the building industry is how to upscale basic principles to a size that is suitable for the manufacture of building components while ensuring that both material and building structure are maintained. The fundamental research question centres on how known shape-changing properties of a building material can be used purposely to generate shape. Programming of the shape changes requires an advanced understanding of the underlying mechanisms of deformation, which can only be gained by employing simulations based on specific material models coupled with experimental testing. Critical to manufacturing innovation is the development of a materially-informed digital design methodology that could be used to predict and tune the final shape and translate a design geometry to the material information required for production. To be effective, the predictive model must be accurate using material input parameters and sorting ranges that can be collected and implemented in an industrial context.

1. The Urbach Tower, a high performance timber structure utilising self-shaping wood manufacturing for curved CLT. (Rolland Halbe).

2. The basic self-shaping wood manufacturing process in which curvature is generated from loss of wood moisture content in a designed bilayer structure. A sample 1.2m x 0.6mm x 40mm thick spruce wood bilayer cut from the larger production parts, shown in the flat high moisture (22 % WMC) production state and curved dry (12% WMC) actuated state (bottom). (ICD/ITKE- University of Stuttgart).

3. Integration and upscaling of the self-shaping manufacturing process to produce high curvature CLT components for the tower structure. Bilayer design, actuation, combining/ stacking, edge finishing, and connection detailing. (ICD/ITKE- University of Stuttgart).



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In addition to the manufacturing process, the curved CLT must be designed and assessed for load-bearing construction. Where and in what types of structures can increased curvature and directional build-ups of the parts be best used? Lastly, what types of materially-driven architecture and construction emerge from a new class of self-shaping processes?

Research Methods

The project has been conducted as an inter-disciplinary collaboration bridging better the raw material entering the sawmill to the completed structure. Feasibility was tested in the laboratory before integration and adaptation to industry for production of components for the Urbach Tower as part of the Remstal Gartenschau, 2019.

Material Programming and Modelling

Wood bilayers are the basic part for the self-shaping process (Fig. 2). A bilayer is constructed from elements: active and restrictive layers of boards oriented at 90° to each other and glued together to create a cross ply plate (Fig. 3). When harvested, wood exhibits a high Wood Moisture Content (WMC). Producing bilayers with a high WMC in the active layer and then drying them creates curvature perpendicular to the longitudinal (L-) direction of the active layer. The curvature achieved is dependent on inputs such as wood species, quality, type of cut (which determines the angle of the transversal or radial (T/R) plane known as end grain), the thickness ratio between the layers, and the change of WMC below fibre saturation point induced in the manufacturing. First a sensitivity analysis was conducted using a digital simulation to determine how the input parameters influence the curvature (Grönquist et al., 2018). Next, a rheological model of wood was used in combination with numerical simulations based on the Finite Element Method (FEM), which takes into account all possible strain mechanisms of wood in a fully coupled time- and moisture-dependent model. Data for expansion coefficient, density and moisture-dependent stiffness was collected from physical samples to supplement literature values in the numerical simulations. A range of bilayer configurations was tested physically in the laboratory with two commonly used species, European beech and Norway spruce, using 0.6m x 0.6m x 10-45mm total thickness to verify the accuracy of the model (Grönquist et al., 2019). From the simulation, a database of build-ups and associated curvature and structural capacity was produced within the range of feasible production thickness of lamellas and drying ranges.

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In parallel, a computational design model was developed to parametrically interface between the geometric curvature of the component represented as a trimmed cylindrical NURBS (Non-Uniform Rational B-Splines) surface, the simulated bilayer database for material build and actuation ranges, the overall structural engineering model which includes the CLT buildup and connection detailing, and back to the wood FEM model for tuning and verification (Fig. 6). Simple material information for the flat build-ups was sent to the sawmill for material selection and production, while the geometric model could be continuously adapted to deviations during the process.

Industry Manufacturing Integration
From the integrative design approach, a bilayer made of Norway spruce sourced locally from Switzerland (FSC and HSH certified) with an active layer thickness of 30mm and a restrictive layer of 10mm was chosen. Active layer boards with starting WMC of 22% (+/-2%) and R/T angles in a range of 0-15° were semi-automatically selected and sorted in the sawmill using inline WMC measurement and visual grading. Restrictive layer boards were sourced from a standard 10mm thick wood product with 12% WMC. Active layer boards were planed and edge-glued to create a continuous plate on which restrictive layer boards were press laminated with one component (1 C) PUR adhesive, resulting in a bilayer plate 5.0m x 1.2m x 40mm thick. Bilayers were placed in racks and kiln-dried in an adapted kiln-drying programme lowering the WMC to 12% and shaping to the targeted curvature of 2.4m radius (Fig. 2). To achieve form stability under changing relative humidity, two curved bilayers were stacked together with an elastically bent spruce locking layer and again press laminated using the same 1 C PUR adhesive (Fig. 3). Moisture content and curvature were documented per board at two depths in each production step. Structural capacity of the resulting experimental CLT was verified through testing in a three-point bending test (rolling shear), shear block testing (glue bond strength), and long-term outdoor tests for form stability and delamination.

Building Demonstrator – Urbach Tower
The architectural and structural potentials for high curvature CLT were demonstrated with the design of a 14.2m tall thin shell wood structure that serves as a look-out point and shelter for hikers in the Remstal in southern Germany. The unique design is based on the co-intersection of 12 cylindrical surfaces. Curvature in the individual components increases the bending stiffness of the tower surface, similar to a corrugated sheet, while the primary fibre orientation within the CLT matches the vertical load-bearing direction (Aldinger et al., 2020) computational design, and digital fabrication, as well as a growing awareness for sustainable construction, have led to a renaissance of structural timber in architecture. Its favourable elastic properties allow bending of timber for use in free-form curved beam structures. Such complex geometries necessitate a high degree of pre- fabrication enabled by the machinability of timber and established digital fabrication methods. In parallel, cross-laminated timber (CLT).

To produce the tower, self-shaping bilayers were used to manufacture curved rohlings from which four of the twelve components were trimmed and detailed using a five-axis CNC machine (Fig. 4). As a benchmark, the remaining eight components were produced using a conventional form-bending process requiring a negative formwork and thinner layers. The component-to-component connections are aligned using beech wood blocks and joined using crossed full-thread screws that are structurally optimised in their arrangement and specific angle (Li and Knippers, 2015). Components were preassembled in assembly groups of three components each and a 10mm thick glue-laminated larch wood façade was added (Fig. 5). A metal oxide coating (UVood®) for UV protection treatment was applied to create a surface that will lighten over time (Guo et al., 2017). On site, groups were placed and connected in eight hours (Fig. 7). A curved steel and polycarbonate roof was added to enclose the structure. Over the planned 10- to 15-year lifetime, the structure will be monitored continuously with integrated WMC sensors, climate sensors and iterative laser scanning to detect deformations.

4. Completed curved CLT rohling after the stacking and combining of bilayer panels to create 5-layer, 90mm thick CLT. Shown mounted on a large scale 5-axis CNC machine used for lightly machining the edges and adding the crossing screw connection detailing.

5. Completed prefabrication of assembly groups prepared for transport following in the connection of three components and addition of the Larch wood façade with UVood ® surface treatment. (ICD/ ITKE- University of Stuttgart).

6. FEA modelling of the structural design aspects for the thin shell structure. Global deformations of the structure due to wind loads (left), CLT utilisation including intra component joints (centre) and the range of connection angles for fine-tuning of crossing screen angles per building regulations and fabrication constraints (right). (ICD/ ITKE- University of Stuttgart).

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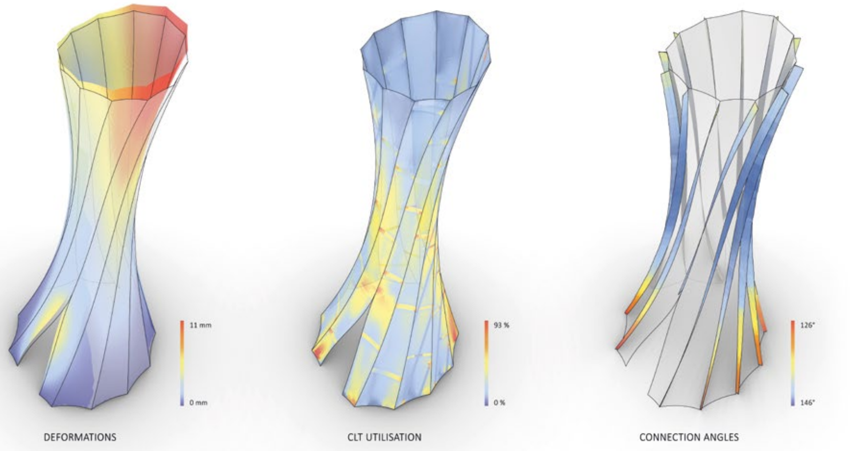
Research Evaluation

On a technical level, self-shaping enables the production of high curvature parts (<3.0m radius). This can be accomplished with fewer, thicker boards, which reduces waste in processing and labour. A CLT build-up with a radius of 2.4m was achieved with 2 bilayers of 10/30mm and a 10mm locking layer resulting in a 5-layer, 90mm thick CLT cross section. While mechanically possible, the equivalent form-bending to this radius is outside normal production ranges determined through initial industry research for using solid wood lamella; this would have required 9 layers of 10-15mm lamella. Using the self-shaping method provides up to a 40% reduction in the number of layers. While curved guides and sorting are still needed to even the curvature variation when gluing the curved bilayers to CLT, the amount is significantly reduced as the pre-shaping of the parts is within 10% of the predicted curvature. Initial observations show a reduction in spring-back after forming, substantially reducing corrective measures and surface finishing. From a manufacturing perspective, these design methods combined with the reduction in custom formwork makes the process highly adaptable, where the bilayer build-up and input parameters can be adjusted to shape different radii in each part. However, in the current state it requires a more careful selection of higher grade wood than used in standard CLT. Testing of structural behaviour of self-shaped parts did not indicate the need for additional safety factors.



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From a design perspective, the use of multiple connected curved CLT parts in surface-active structures allows a new architectural language to emerge from the natural capacity of the material. In the Urbach Tower, the concave curvature of the exterior surfaces results in sharp lines and crisp surfaces, while the convex interior surfaces are invitingly soft, evoking an unexpected tactile material experience within a load-bearing structure (Fig. 8). The integration of structure and skin as well as the hidden detailing of the curved parts results in an elegant expression of form and force. This is backed quantitatively by the relative lightweight and slender nature of the structure (slenderness ratio of 160 to 1). In addition, the structure can be fully disassembled and recycled at the end of use. Combined, these aspects contribute to create a striking landmark and a space of internal reflection that simultaneously reframes our perception of the material and surroundings (Fig. 9).

Conclusion

The construction of the tower demonstrated self-shaping manufacturing for industry level production of curved load-bearing building components. As the same material is both the shaping mechanism and the final structure, the need of larger machines and formwork is greatly reduced. The current process is directly applicable for the solid wood production of lightweight curved roof components, curved vertical shear walls for multi-storey timber construction and cylindrical structures such as silos or turbine towers. It presents an ecological option for performative curved geometries that are often produced with malleable yet energy intensive materials such as concrete, plastic or metals.

A designed self-shaping process is a new approach to digital fabrication at the scale of building components. Rather than outputting machine codes to communicate a position for additive or subtractive shaping, the self-shaping process means geometry is communicated through the specific characteristic and arrangement of material, providing an implicit understanding of the resulting physical transformation. As the scale of parts increase, the self-shaping processes become inherently more valuable as the force and coordination required to bend the parts increase. Similarly, self-shaping enables adaptable and parallel manufacturing within a standard setup, which is valuable for large quantity and high variation production.

Rethinking materials' active role in construction leads to new architectural opportunities as well as increased sustainability in the production and operation of buildings. As our understanding and control of materials become increasingly sophisticated, their symbiotic relationship with the digitally-controlled fabrication machines of the future is brought into question, productively inverting and blurring the relationship between material and machine. Perhaps in the future the materials will do the fabricating and the machines as we know them will rest.

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7. On-site assembly of the prefabricated groups highlighting the slenderness of the load bearing structural CLT (90cm). (ICD/ITKE-University of Stuttgart).

8. Upward interior view with the locally convex curvature creating a soft billowing aesthetic from fully load bearing structural components with hidden connection details. (ICD/ITKE- University of Stuttgart).

9. The sharp edges at the intersections of the concave geometry catching the light as the 14.2m-tall structure stands in the natural landscape. (Roland Halbe).

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