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MATERIAL PROGRAMMING FOR FABRICATION

Integrative Computational Design for Self-Shaping Curved Wood Building Components in Architecture

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Edited by Professor Achim Menges, AADipl(Hons)

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ISBN 978-3-9819457-6-8

Foreword

Dylan Wood's dissertation investigates the self-forming of wood as a novel approach to the fabrication of curved, load-bearing wood components and their contextualisation in architecture. In this approach, the change in shape of a building component is achieved solely through the inherent shrinkage or swelling of the wood as its moisture content decreases or increases, respectively. With this doctoral dissertation, Dylan makes a valuable contribution to the field of "Material Programming" for large-scale building components. The dissertation is impressive not only for its particular scientific originality, but also for the unusual depth of study, which ranges from basic research findings and their impact on architectural design methods, to embedding them in the applied context of the timber construction industry and evaluating them on the basis of a demonstrator building, the Urbach Tower. This experimental building demonstrates in an exemplary manner how scientific insights and technical developments also enable novel, impressive forms of architectural expression.

Die Dissertation von Dylan Wood untersucht die Selbstformung von Holz als einen neuartigen Ansatz für die Herstellung gekrümmter, tragender Holzbauteile und deren Kontextualisierung in der Architektur. Die Formänderung eines Bauteils wird dabei allein durch das materialinhärente Schwinden bzw. Quellen des Holzes bei abnehmendem bzw. zunehmendem Feuchtegehalt erreicht. Mit der vorliegenden Promotion leistet Dylan einen wertvollen Beitrag im Feld einer solchen „Programmierung des Materials" für großmaßstäbliche Bauteile. Die Dissertation besticht nicht nur durch ihre besondere wissenschaftliche Originalität, sondern auch durch die ungewöhnliche Bearbeitungstiefe, die sich von grundlegenden Forschungserkenntnissen und deren Auswirkung auf architektonische Entwurfs- und Planungsmethoden, bis hin zur Einbettung in den angewandten Kontext der Holzbauindustrie und die Evaluierung anhand eines Demonstrator-Gebäudes erstreckt, dem Turm Urbach. Dieser zeigt auf vorbildliche Weise, wie wissenschaftliche Erkenntnisse und technische Entwicklung auch neue, beeindruckende architektonische Ausdrucksformen ermöglichen.

Professor Achim Menges, AADipl(Hons)

The presented work is a cumulative dissertation representing an interdisciplinary research project starting in 2014. The research was conducted at the intersection of computational design and construction, architecture and wood materials science. The results are relevant technically to these fields, and the overall approach provides a framework for how architectural design and building construction can benefit from a reciprocal integration with research and science.

The introduction frames the work in the context of architectural design and building construction and describes the driving motivations. The background and current state of technology are described in relation to scientific research in the area of self-shaping and current approaches to shaping functional wood building components. The methods provide a summary of the methodological approach to the work across the included publications. The results are described in three areas: development of a material programming approach to computational design and fabrication, the upscaling and industry integration of a self-shaping method from manufacturing curved wood building components, and an architectural application in a building demonstrator, the Urbach Tower.

Article A was published as a peer-reviewed research article in the International Journal of Architectural Computing (IJAC) in 2016

Article B was published as a peer-reviewed research article in Construction and Building Materials in 2018

Article C was published as a peer-reviewed research article in Science Advances in 2019

Article D was published as a peer-reviewed article and presentation in FABRICATE 2020: Making Resilient Architecture in 2020

The research was first supported by seed-funding from the Getty Foundation's GETTYLAB. The primary research project was funded by Innosuisse – The Swiss Innovation Agency, previously known as the Commission for Technology and Innovation (Eidgenössische Kommission für Technologie und Innovation – KTI) as a research and development project with the SME industry partner Blumer Lehmann AG (KTI 25114.1). Development of the construction system for the demonstrator building was further supported by the German Federal Foundation for the Environment (Deutsche Bundesstiftung Umwelt – DBU) (DBU Az. 34714/01) and the University of Stuttgart. The author discloses that he is an inventor in the related patent applications (PCT/WO 2019/180006 A1 1, EP3543000 A1 and EP20216959.5)

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Integrative Computational Design for Self-Shaping Curved Wood Building Components in Architecture

A dissertation approved
by the Faculty of Architecture and Urban Planning of the
University of Stuttgart
for the conferral of the title of
Doctor of Engineering Sciences (Dr.-Ing.)

Submitted by
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D.Des, Diplom-Ing.

Date of the oral examination:
10.05.2021

Institute for Computational Design and Construction of the
University of Stuttgart

2021

MATERIALPROGRAMMIERUNG IN DER BAUFERTIGUNG

Integratives Entwerfen und Berechnen für die Selbstformung Gebogener Holzbauteile in der Architektur

Von der Fakultät Architektur und Stadtplanung der
Universität Stuttgart
zur Erlangung der Würde
eines Doktor-Ingenieurs (Dr.-Ing.)
genehmigte Abhandlung

Vorgelegt von
Dylan Wood
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Tag der mündlichen Prüfung:
10.05.2021

Institut für Computerbasiertes Entwerfen und Baufertigung der
Universität Stuttgart

2021

Acknowledgements

I would like to thank Prof. Achim Menges and my friends and colleagues at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart for creating a unique research environment for design and science combined with a genuine spirit for building. This context has fostered a tremendous enthusiasm for research and a daringness to tackle difficult challenges with fresh ideas. Special thanks to Steffen Reichert, Oliver Krieg, David Correa, Moritz Dörstelmann, Marshal Prado, Lauren Vasey, Benjamin Felbrich and Karola Dierich who provided their mentorship and, above all, friendship. I am indebted technically to my computer science assistant Long Nguyen, my talented material programmers Tiffany Cheng and Yasaman Tahouni, my former students turned colleagues Hans Jakob Wagner, Sam Leder and Laura Kiesewetter as well as Ramon Weber and Rob Faulkner for their genuine design talents, and the many students who have supported my research. I owe much of my inspiration to two leading women, Prof. Doris Sung and then-provost Elizabeth Garrett, who, at the University of Southern California, introduced me to research in a design context and encouraged more than one leap of faith.

Such interdisciplinary research would not have been possible without the expert knowledge, patience and dedication of Dr. Philippe Grönquist, Prof. Markus Rüggeberg and Prof. Ingo Burgert from the Wood Materials Science group at ETH Zurich, and Empa Dübendorf, Urs Basalla and Anette Schmitt from the Institute of Engineering Geodesy Stuttgart (IIGS) – University of Stuttgart, and the inspiration of Prof. George Jeronimidis at the University of Reading. Thanks to Lotte Aldinger and Simon Bechert from the Institute of Building Structures and Structural Design (ITKE) – University of Stuttgart for their critical discussion and motivation, Prof. Jan Knippers and James Solly for their many challenges and lessons, and Daniel Piker for his interest and conversations, as well as Andreas Kulla and Michael Schneider. I must also acknowledge the generous support from Katharina Lehmann, David Riggenbach, Steffen Biscoff, Kai Striefle, Urban Jung, Richard Jussel, Martin Antermann and the amazing team at Blumer Lehmann AG for their enthusiasm and critically in advancing my research. In the final stages of the research I must thank Prof. Martin Bechthold, director of the Material Systems and Process Group (MaP+S) at the Graduate School of Design – Harvard University for his critical and timely review of my dissertation. A special thanks to Matthias Helmreich, Martin Loucka and those at ETH for hosting me during many weeks in Zürich, always making these trips an adventure.

Most of all, thank you to my family for the continuous support. My life is inspired by your passion, work ethic and down-to-earth thinking. Similarly Emily, for inviting my research into every aspect of life and answering all of my questions wholeheartedly.

Dylan Wood

Contents

List of Abbreviations

E_L Young's moduli – Longitudinal axis

E_R Young's moduli – Radial axis

E_T Young's moduli – Tangential axis

Beech Beech Wood – Buche – *Fagus*

BIM Building Information Modelling

CLT Cross-Laminated Timber, engineered wood (BSP – Brettsperrholz or KLH – Kreuzlagenholz)

Component Defined here as a collection of parts / CLT building component

Dowellam Dowel-Laminated, engineered wood (Brettstapel)

Element Defined here as the smallest element that can be adjusted, typically per board

EMC Equilibrium Moisture Content

FE Finite Element, method, modelling

FSP Fibre Saturation Point

Glulam Glue-Laminated, engineered wood (BSH – Brettschichtholz)

Green Wood with a high moisture content directly after harvesting

L Longitudinal axis in wood materials

Maple European Maple Wood – Ahorn – *Acer pseudoplatanus* Acer pseudoplatanus

MC Moisture Content, used here equivalent to MC

NURBS Non-Uniform Rational B-Splines

Part Defined here as a collection of elements, typically a bilayer

PUR Polyurethane, adhesives

R Radial axis in wood materials

R/T Angle Rotation angle of the plane defined by the Radial and Tangential axes – end grain angle

R/T/L plane Coordinate plane formed by the Radial, Tangential and Longitudinal axes, where as the L is the normal of the plane, in relation to the orthographic structure of wood

RH Relative Humidity

Spruce Spruce Wood – Fichte – *Picea*

T Tangential axis in wood materials

TBM Thermo Bi-Metals

WMC Wood Moisture Content

α_L Swelling Coefficient – Longitudinal axis

α_R Swelling Coefficient – Radial axis

α_T Swelling Coefficient – Tangential axis

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Abstract

Form and structure play critical roles in architecture yet the processes required to produce performative geometries often require tremendous resources and physical effort. Advances in computational design and the programming of digital fabrication machines have increased variety, precision and automation in the production of building components. However, the underlying processes of generating material form still rely predominantly on brute-force methods of shaping. This research presents an alternative, material programming approach to the fabrication of building components in which shape is generated by activating the material's inherent capacity to change shape in relation to external stimuli. The concept is investigated through the development of an innovative method of self-shaping manufacturing for load-bearing curved wood building components. The dissertation introduces material programming in the context of architectural design, fabrication processes, wood materials and existing self-shaping technology. The self-shaping method is investigated through physical experiments and development of a computational design-to-fabrication approach. In parallel the challenges of upscaling and predictability are addressed through computational mechanics and physical prototyping. The concept is then adapted and implemented through the design and production of components for a building demonstrator, the Urbach Tower, highlighting both the technical efficiencies and architectural performance of the material system. The material programming approach is therefore shown as a simple yet sophisticated method of fabrication for a novel, ecological and effective architecture.

The research is presented as a publication-based dissertation comprising an introduction and contextualisation, a summary of the research results, and the following four research articles:

Wood, D., Correa, D., Krieg, O. and Menges, A. (2016), **Material computation – 4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces**, International Journal of Architectural Computing (IJAC), Vol. 14 (1), pp. 49–62. DOI: 10.1177/1478077115625522

Wood, D., Vailati, C., Menges, A. and Rüggeberg, M. (2018), **Hygroscopically actuated wood elements for weather responsive and self-forming building parts: Facilitating upscaling and complex shape changes,** Construction and Building Materials, Vol. 165, pp. 782–91. DOI: 10.1016/S0950061817325394

Grönquist, P., Wood, D., Hassani, M., Wittel, F., Menges, A. and Rüggeberg, M. (2019), **Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures,** Science Advances, Vol. 5 (9), eaax1311. DOI: 10.1126/sciadv.aax1311

Wood, D., Grönquist, P., Bechert, S., Aldinger, L., Riggenbach, D., Lehmann K., Rüggeberg, M., Burgert, I., Knippers, J. and Menges, A. (2020), **From machine control to material programming: Self-shaping timber manufacturing of a high performance curved CLT structure – Urbach Tower**, in J. Burry, J. Sabin, B. Sheil and M. Skavara (eds.), FABRICATE 2020: Making Resilient Architecture. UCL Press London, pp. 50–57. DOI: 10.2307/j.ctv13xpsvw.11

Zusammenfassung

Form und Struktur spielen in der Architektur eine entscheidende Rolle, doch die Prozesse, die zur Herstellung leistungsfähiger Geometrien nötig sind, erfordern oft enorme Ressourcen und physischen Aufwand. Fortschritte in der rechnergestützten Konstruktion und die Programmierung digitaler Fertigungsmaschinen haben die Vielfalt, Präzision und den Grad der Automatisierung bei der Herstellung von Bauelementen erhöht. Die zugrundeliegenden Prozesse zur Erzeugung der materiellen Form beruhen jedoch immer noch überwiegend auf Methoden der Formgebung durch rein maschinelle Kraft. Diese Forschungsarbeit stellt einen alternativen, auf Materialprogrammierung basierenden, Ansatz für die Herstellung von Bauelementen vor, bei dem die Form durch die Aktivierung der dem Material innewohnenden Fähigkeit, sich in Relation zu äußeren Reizen zu verändern, erzeugt wird. Dieses Konzept wird durch die Entwicklung einer innovativen Methode der selbstformenden Fertigung für tragende gekrümmte Holzbauteile untersucht. Die Dissertation führt zuerst Materialprogrammierung im Kontext des architektonischen Entwurfs, der Herstellungsprozesse, der Holzwerkstoffe und der bestehenden selbstformenden Technologie ein. Die

selbstformende Methode wird zunächst durch physikalische Experimente und die Entwicklung eines rechnergestützten Entwurfs- und Fertigungsansatzes untersucht. Parallel dazu werden die Herausforderungen der Hochskalierung und der Vorhersagbarkeit durch rechnergestützte Simulation und physikalischen Prototypenbau adressiert. Das Konzept wird dann angepasst und durch den Entwurf und die Herstellung von Komponenten für ein Bauwerk als Demonstrator sowohl der technischen Effizienz als auch des architektonischen Reizes umgesetzt. Der Ansatz der Materialprogrammierung wird somit als einfache aber raffinierte Herstellungsmethode für eine neuartige, ökologische und effektive Architektur aufgezeigt.

Die Forschung wird in Form einer publikationsbasierten Dissertation präsentiert, welche aus einer Einleitung und Kontextualisierung, einer Zusammenfassung der Forschungsergebnisse und den folgenden Forschungsartikeln besteht:

Wood, D., Correa, D., Krieg, O. and Menges, A. (2016), **Material computation – 4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces**, International Journal of Architectural Computing (IJAC), Vol. 14 (1), pp. 49–62. DOI: 10.1177/1478077115625522

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Figure 1.1: Programmed self-shaping of a spruce wood bilayer as a result of air-drying. Top: flat configuration with a high moisture content. Bottom: curved configuration with a low moisture content. Dimensions: 1200 mm x 500 mm x 40 mm, 2400 mm radius in curved configuration.

1

Introduction

Buildings as we know them are made of materials arranged and shaped into spatial compositions in relation to architectural, structural, sociocultural and, increasingly, ecological performance. Amongst a growing need for high-quality construction and a competing lack of sustainable resources, the use of form as structure is frequently considered a valuable design approach for multifaceted effectiveness in architecture. However, the process to achieve specific forms physically in contemporary architecture requires elaborate refinement and engineering of materials, often followed by reshaping through heavy mechanical processes. Thus the performance benefits of specific shapes are limited and largely negated by the added complexity and costs of fabrication.

In the digital age the default approach to solving this problem is to resort to the design of geometries in virtual modelling spaces before realising these physical complexities by implementing digital control over existing fabrication techniques. Most commonly this is achieved by the programming of machines to emulate shaping procedures currently undertaken by humans or the automation of existing industrial manufacturing methods. These shape-giving methods can be described by combinations of processes such as: forming, bending, casting, extruding, subtracting and/or adding [96]. For all of these, shape is achieved primarily by applying external force to the material against an existing shape or tool. Advances in digital design and computer-controlled fabrication machines have extended such shaping processes, enabling manufacturing of more complex geometries with increased standards of precision and repeatability. For example, industrial robots can carve intricate shapes from solid blocks of stone or aluminium, formwork for concrete casting can be produced in nearly any shape, and powerful industrial presses can deform wood to form curved shapes. Fundamentally, these processes still rely on the same rudimentary and demanding physical shaping methods. On this level, automation through digitally programmed mechanical manipulation is limited in its effectiveness, leading to only marginal efficiency gains in narrow areas of increasingly longer production chains. The problem with this approach is that it neglects the fact that many materials with which we build possess capacities to play an active role in physical form generation. Utilising advances in computation to rethink the role of the material itself as a leading player in the form-generation process sets the stage for a profound shift in how performative building geometry is shaped: a shift towards programming materials as machines.

Wood is a natural smart material with the inherent capacity to compute its shape in response to moisture. When wood absorbs and desorbs moisture, bundles of cellulosic microfibrils within the walls of its cells expand and contract respectively. This change in shape can be correlated to changes in equilibrium with the moisture held in the air or with direct loss or addition of water. The corresponding hygroscopic phenomenon in wood is not new to science

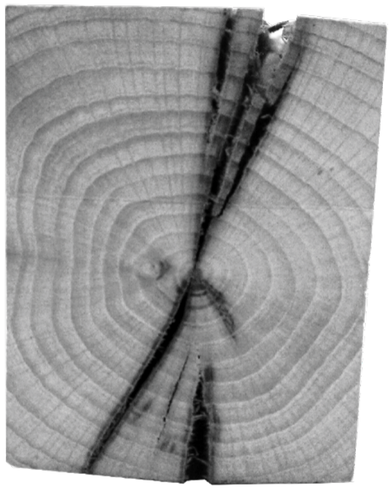

Figure 1.2: Deformation and cracking in a heart-cut piece of beech wood induced by air drying.

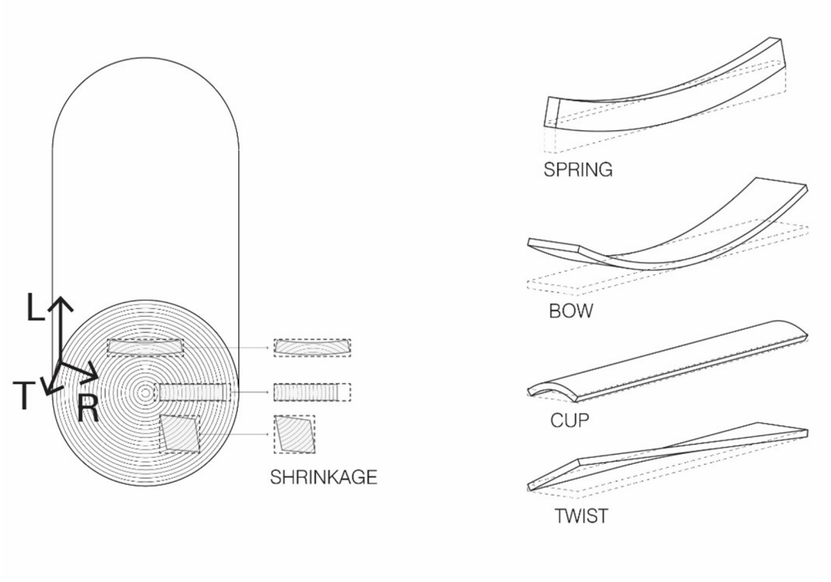

Figure 1.3: Deformation patterns of wood when dried based on the cut location and natural growth rings of the tree. Left: end grain section with typical cut types. Right: common types of geometric deformation.

or construction, nor is it an engineered feature; rather, it results from the unique natural anatomy of the material, a byproduct of the cell's function as a living organism. Typically, the hygroscopic nature of wood causes unwanted deformation as its moisture content decreases to equalise with the surrounding environment after harvesting Figure 1.2. The geometric effects of this drying are well known as cupping, twisting, bending, springing and bowing, and relate to the cut of the board Figure 1.3. While known, they are difficult to precisely predict in production [62]. As a result, in large-scale building construction they are ever prevalent but largely viewed as problematic hygroscopic forces that must be carefully accounted for or corrected.

As a feature, this shrinking and swelling has historically been used, for example, in the making of wood barrels for storing liquids such as wine, where moisture causes the wood boards to expand

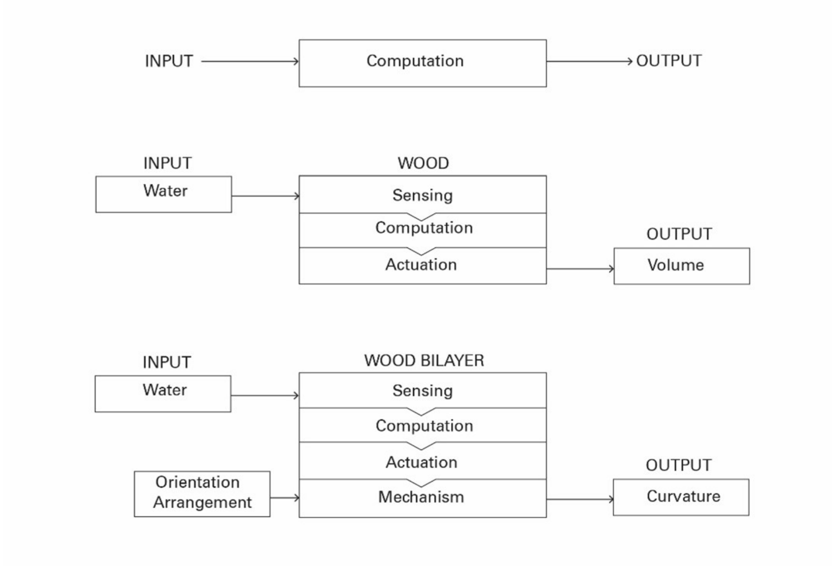

Figure 1.4: Material programming concept described in relation to the hygroscopic capacities of wood. Top: a simple programming concept of input, computational function and predictable outcome. Centre: wood as a material with existing physically programmable features, in this case hygroscopic shape-change. Bottom: an example of programming a further function in wood by the addition of a bilayer mechanism and the related inputs to produce curvature.

into each other to create a water-tight container. Similarly, the use of water and temperature through steaming is a well-known method of temporarily modifying the mechanical properties of wood, making it easier to bend. Steam bending of smaller curved parts in furniture production is a common technology. In contemporary construction the hygroscopic actuation in wood can also be used as a fixation method, for example in the production of dowellam where dried hardwood dowels expand once driven into softwood planks to create tight connections [80; 62; 41].

From this perspective, hygroscopic deformation in wood can be viewed as a programmable physical feature. Programming in this context is defined broadly in the sense that an input is provided, a computational process is carried out and a predictable result is output. Using this logic, wood naturally has the ability to compute physical form based on an input stimulus Figure 1.4. Providing a simple input, in this case moisture, the cellulosic microfibrils carry out an integrated function of sensing and actuation resulting in a predictable change in dimensions. Thus wood as a material is naturally programmable and the key to utilising this unique capacity lies in deciphering and building upon its existing functions, a concept introduced here as material programming.

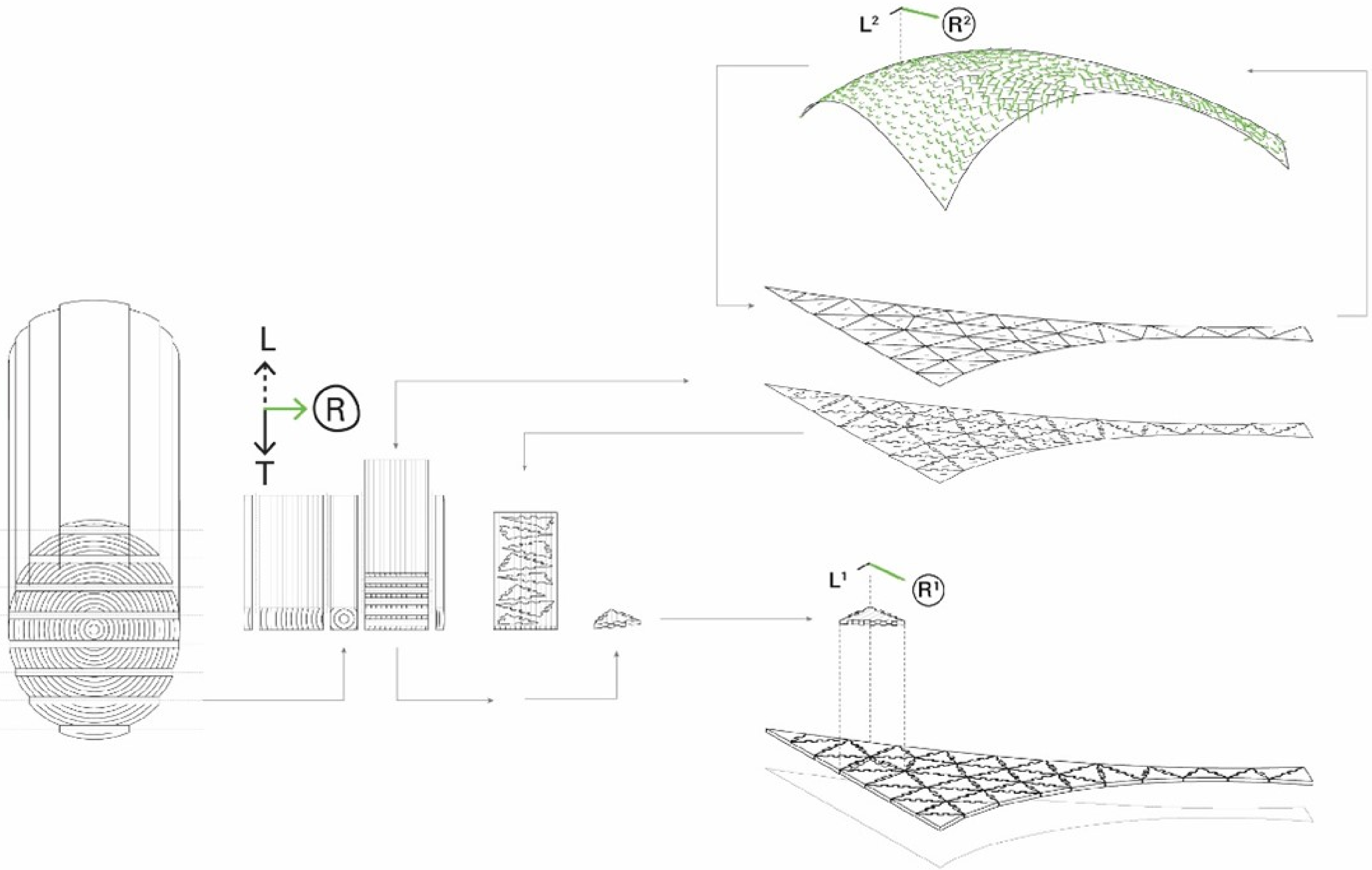

Figure 2.1: A material programming approach for self-shaping wood.

2

Aims and Objectives

This thesis introduces and demonstrates the concept of material programming as a novel, material-driven approach to computational design and fabrication in architecture. In this context, material programming is defined as an integrative method of design and fabrication in which physical functions, such as shaping, can be generated through logics utilising a material's natural capacities in place of external electro-mechanical shaping machines.

In this research, this is achieved by first decoding and then utilising the hygroscopic material capacities of wood as a shaping force during the fabrication of curved building components. Following this methodology, the action of shaping is directly integrated within its material and structure, replacing shaping through heavy mechanical force and avoiding any intensive re-engineering of the materials. The programming, through the construction of design logics, assembly of larger material arrangements and movement mechanism, enables and steers the material's capacity to generate predictable form Figure 2.1. The aim is therefore to introduce and study the capacity of wood to be materially programmed, and more specifically to develop a strategy to employ this material programming as a self-shaping manufacturing process for curved cross-laminated timber building components and the associated performative architecture.

Figure 3.1: Frei Otto assisting in the experimental construction of an elastically bent wood lamella gridshell for the Montreal Expo ’67, Körschtal, Germany, 1966.

3

Context and Research Questions

3.1 From machine control to material programming in architecture and construction

The shaping of raw materials is a fundamental part of building construction [3]. Forming and shaping of curved components is of particular interest because of the structural and architectural benefits inherent in curved geometry. Form-active structures are designed in an integrated way to carry loads through their geometry. They include flexible building systems such as cable nets or membranes, but also simple curved geometries, for example arches made from shaped rigid materials like stone [33]. Following these principles in architecture, properly designed curved-surface geometries such as domes, shells and vaults can conceptually carry higher loads with less building material than flat surfaces or rectilinear members [79; 87; 33]. The resulting material efficiency leads to lightweight and resource-efficient building construction. This integrated architectural and structural performance should be distinguished from the purely decorative and ornamental use of complex curved geometries in architecture. Historically, the effectiveness of curved geometries is well known and, as a result, the shaping of materials for building construction has progressed from primitive methods tied directly to the material's behaviours and human interaction [72], to the work of highly skilled material-specific craftspeople, to complex multi-step industrial methods requiring production lines and machines vastly larger than the materials themselves. This progression was especially prominent during the Industrial Revolution, when advances in mechanisation and the abundance of electrical power enabled more elaborate control and increased mass production in construction [3]. With industrialisation, the dominance of machine over material was firmly established.

Since then, digital geometry generation has advanced while at the same time the gap between digital form and its materialisation appears to have widened. While it can be argued that design processes are informed by the material and manufacturing methods later used for physical construction, the design process is fundamentally separate from the majority of a material's physical capacities [66]. Philosophically, even advanced contemporary digital fabrication methods revert in principle to the ancient Greek hylomorphic view in which form (morphe), despite its digital and geometric intelligence, is imposed on matter (hyle) from the outside, be it by divine force, the engineer or a robotic manipulator [23]. In contrast, computational design is at least in theory poised to adopt a performative and morphogenetic approach to architectural design, especially through the example of wood materials [67]. In an attempt to link digital design methods to the physical fabrication processes, the field has more recently recalibrated towards highly sophisticated, cyber-physical fabrication systems enabling more interactive material relationships [68]. However, in practice, at the level of physical shape generation, a material's active and dynamic influence is still dwarfed by that of the external machines. While we have developed sophisticated methods for programming machines to manipulate and correct materials, our ability to program materials themselves remains relatively underutilised.

Engineers have developed technical methods to understand the problems typically associated with active materials; for example, metals that change volumetrically in relation to temperature are extensively analysed for large-scale construction and can be modelled in many structural engineering software packages. In parallel, attempts have been made to understand and introduce advances in the science of smart materials to design and architecture, from both theoretical and technical perspectives [9; 2; 97]. Yet active material capacities, where physical changes result from external stimuli rather than force interaction, remain elusive in digital design and in architecture. This defines the overarching research questions for this dissertation: fundamentally, how can a material programming approach be used to engage material capacities in the design and fabrication of architecture? Architecturally, what types of novel and performative tectonics emerge from a material programming approach?

3.2 Biological inspiration and wood materials

Self-shaping mechanisms are commonly found in natural systems, but rarely implemented as man-made engineering solutions due in large part to the difficulty in predicting and reproducing their behaviours [88]. One example of self-shaping in nature is the opening of plant cone scales in response to changes in moisture Figure 4.1. Biologically, this self-shaping functions as a seed-release mechanism when the cone falls from the tree and is cut off from the nourishment of the plant [22]. The passive change in shape in each scale is a result of the complex arrangement of fibrous cables and tissue which functions as structure, environmental sensor and hygroscopic actuator [78]. Naturally, the self-shaping function of the scales is retained in the non-living tissue of the cone following its intended biological function, meaning the scales are still capable of continuous changes in shape in response to moisture or relative air humidity [78]. Effectively, each and every scale of the plant cone is capable of autonomous shape change, a function comparatively difficult to achieve using an equivalent electro-mechanical system. These functions of the scales are especially astounding given the robustness of their structure, compact form and the sheer quantity of independent mechanisms in just a single cone. Similar biological mechanisms are observed in a range of seed pods, some even producing explosive, high-force, high-stiffness hygroscopic movements [37]. The advantages of this type of material programming in natural systems is that they operate based on external environmental stimuli and require zero operational energy (metabolic or electric) to perform their changes in shape [13]. This makes them highly reliable, cost-effective in terms of energy, and capable of vast distribution. One limitation is that their natural programming is intended to perform a specific

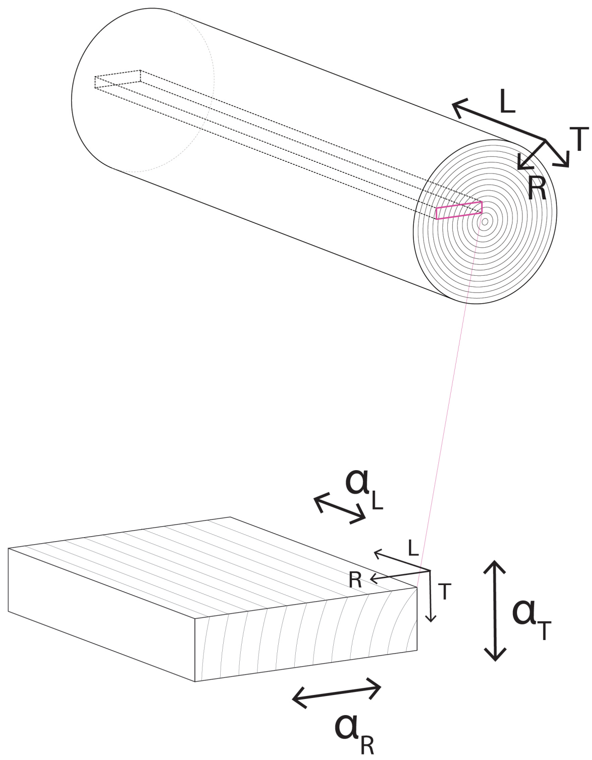

Figure 3.2: Definition of the natural R/T/L coordinate system and associated swelling/shrinking directions in wood materials. Top: in an unprocessed log. Bottom: in a typical quartersawn board.

function, and cannot therefore be reprogrammed or adjusted. Additionally, in contrast to modern industrial machines, movements may be considered imprecise despite their extreme reliability.

Similar to the scales of the pine cone, many natural materials containing cellulose fibres are capable of hygroscopically actuated changes in shape. In this thesis, wood is chosen as a natural material that is capable of changing shape hygroscopically. Living wood is highly water saturated, and when cut it begins to desorb its held moisture, trending towards maintaining an equilibrium moisture content (EMC) with that related the the relative humidity (RH) of

	Tangential (α_T)	**Radial (α_R)**	**Longitudinal (α_L)**
		α[%/%]	
Spruce	0.33	0.16	0.01
Beech	0.45	0.22	0.01

Table 3.1: Differential swelling in spruce and beech wood measured as coefficients in % of dimensional change per 1% change of WMC per the R, T, and L axes [76]

the surrounding environment. The speed at which this equalisation occurs is dependent on the dimensions and species of wood [84]. The amount of moisture in wood is described as a percentage of weight, and known as wood moisture content (WMC) or simply Moisture Content (MC). At high saturation levels, just harvested wet wood, known as green wood, does not exhibit changes in dimensions in relation to its WMC until desorbs below the fibre saturation point (FSP), which ranges between 25 and 35% WMC. Below the FSP, wood shrinks and swells in response to changes in moisture, reversibly and orthographically by a three-axis coordinate system (R/T/L) defined by its anisotropic cell structure [30; 95; 84]. These axes are described by the radial (R) (perpendicular to the annual rings), tangential (T) (parallel to the annual rings) and longitudinal (L) (vertical in the standing tree) directions, and can be defined in the cylindrical log and later in sawn boards Figure 3.2. Typically, the highest swelling and shrinking occurs in the tangential axis (α_T), second in the radial axis (α_R), and only marginally in the longitudinal axis (α_L) along the length of the cells [76] Table 3.1. Swelling coefficients are a result of wood's natural structuring and thus vary between different trees and species.

		Tan. (E_T)	**Rad. (E_R)**	**Long. (E_L)**
	WMC[%]		E[MPa]	
Spruce	9.5	660	1,800	12,200
Spruce	16.1	580	1,520	9,000
Beech	8.7	680	1,990	14,400
Beech	17.9	460	1,470	11,600

Table 3.2: Moisture-dependent stiffness of spruce [48] and beech [55] wood measured as Young's moduli at low and mid moisture content per the R, T, and L axes.

The hygroscopic properties of wood are commonly studied in relation to the deformation and cracking that occurs as it is processed from its freshly cut green state to a building material [49] Figure 1.3. In industrial-scale timber construction, wood is dried from its initial green state, with a high moisture content, using kiln drying, a sophisticated technical process for reducing the impact of the hygroscopic deformations on the final product. Air drying or traditional seasoning is also a viable method of drying timber, with significantly longer time required. Methods of cross lamination and glue lamination in engineered timber products further help to reduce the impact of shrinking and swelling, but hygroscopic forces remain and must be considered in construction.

Compared to other stimulus-responsive shape-changing materials, wood is certainly special. First, its directionality means that the dimensional change can easily be steered by orienting and assembling the material based on the orthographic three axis coordinate plane constructed from the R, T, and L axis (R/T/L plane) of its natural structuring. This orienting is already apparent structurally in the layups of multi-element engineered wood parts such as cross-laminated timber (CLT). Second, the hygroscopic forces within wood operate with incredibly high force (measured at 91

MPa (13,200 psi)) actuated within achievable stimuli (either water or moisture in the air) [95; 63]. Combined, these properties are so powerful they have been documented in both Egypt and Greece as methods to split stone. In this case a block of wood could be orientated to expand in a certain direction with an incredible force, actuated by simply adding water [84; 38]. Third, the mechanical properties of wood change in relation to both its direction and moisture content, which aids its ability to be shaped while retaining a relatively high overall stiffness Table 3.2. Lastly, different from many synthetic smart material systems, the hygroscopic shrinking and swelling is deeply integrated into the naturally efficient structure of wood. As a result, the same material can be considered dually and nearly equally as actuator and structure. Other benefits of wood as a construction material include its renewability, its abundance in much of the inhabited world, ease of harvesting, manageable machining and excellent structural properties (high strength-to-weight ratio) [80]. More recently these properties, as well as its ability to serve as a method of carbon sequestration, mean wood has become a promising sustainable building material across all scales of building construction [80].

In both the spruce cone and wood, a natural, fibrous material serves ambidexterously as sensor, shaping actuator and structure. In this work, biology is thus taken not just as biomimetic inspiration, but as the generator of the material itself. In theory, the identification and use of these inherent natural behaviours drastically reduces the effort required to produce, refine and engineer a material for such a sophisticated functional use. But natural materials also come with specific difficulties in that they exhibit high variation in their structures and properties. In the case of wood, if this can be understood and overcome, it is uniquely suitable as both a programmable shape-changing material and a structural building material. This leads to the more specific questions: How can the known natural hygroscopic capacities of wood be understood and converted into movement mechanisms to generate predictable and repeatable self-shaping? And based on the magnitude of hygroscopic force and the favourable structural properties of wood, how can this self-shaping be extended and upscaled beyond its natural occurrence for use in shaping load-bearing building components?

3.3 Shape and shaping of building components

From a designer's perspective, a building material's obvious visual, geometric and static properties are widely understood and implemented in architectural design and construction processes. The influence of a building material's structural features and geometry on architectural form is clearly established in practice and exemplified empathetically by Louis Kahn's famous conversation with a brick, in which he asks the brick what it would like to be, and it responds "an arch!" [53]. The process of how the inanimate, rectilinear bricks, or further the clay they are made of, might like to become the curved shape of an arch remains ambiguous and decoupled from the building material itself. Equally, when a material's qualities become more complicated to precisely understand, they are less likely to be utilised. Dynamic qualities, such as elastic or active bending, are valuable structurally and result in a stunning architectural geometry, yet are rarely used in mainstream practice [60]. A material's dynamic structural involvement in physical form generation can have a profound impact on the performance and efficiency of both the structure and construction process. This is perhaps best demonstrated in the design and construction of the Mannheim Multihalle by architect Frei Otto in 1975, where the form was produced by post-formed bending of a thin wood lath grid to a double-curved gridshell [73], and other recent examples with flat lattices with internal structuring specifically designed for bending to shell shapes [110]. The form is therefore the result of the combination of the material's elastic properties and/or the mechanism of the gridshell, rather than a direct shaping of each individual member. The downside of such methods is that they require tremendous amounts of coordinated lifting, pushing, pulling and tensioning into place Figure 3.1.

Notably, continuous timber shells have also been constructed at larger scales. In hyperbolic geometries construction is possible using layers of straight members along the ruling axis followed by elastically bending lamellas in the directions of curvature and fixing the layers with nails or adhesives on site, a process which requires ridged edge supports to resist the bending during construction [47; 51; 11]. In synclastic dome shapes, curved timber shells have been built using multilayers of thin lamellas bent onto underlying negative formworks [71]. The question thus arises, what if the lamellas could be physically programmed to shape themselves to a curved configuration in a distributed yet coordinated fashion? Exactly this concept is shown for wood gridshells in a digital design study and functional scale models in [42] A.3.

Similar problems of forcing wood materials into shape arise in the production of pre-formed wood building components, where layers are typically bent and fixed together to create a stable curved shape in the factory and assembled onsite to larger structures. In this case, the technical and architectural limits arise from the elastic properties of the wood lamellas and the amount of mechanical force required to bend and press them into place. In addition, each shape requires a corresponding negative shape to be pressed against. In response to these challenges, this thesis addresses the following: from a technological perspective, how can self-shaping be employed as a resource-effective method of prefabricating curved timber building components?

3.4 Material computation in design and fabrication

In the fields of design and engineering, concepts for incorporating material-specific qualities as an integral part of the design and fabrication system have been identified and described from a number of perspectives: in structural design as *material behaviour* [35], in architectural design as *material computation* [66] and *material culture* [69], as concepts for digital production as *fabrication information modelling (FIM)* [31], and most specifically for timber construction as *integrated material practice* [93]. The term *material programming*, as described in Figure 1.4 and Chapter 2, has in parallel to this research been introduced in the field of human-computer interaction [103], and is defined in relation to the design concept of programmable materials [74; 99]. The presented work focuses on the design steps of **programming** rather than the development of new **programmable materials**. In a broader sense, the noted examples above either describe methods related to passive material characteristics, or active material capacities that were until now, limited in scale, structure and application in practice.

The incorporation of active material behaviours for useful, designed functions is challenging, especially within current practices of digital design and fabrication where prediction, precision and standardisation are highly valued. The challenge from a computational design perspective is not to only understanding the material's capacities technically, but in developing digital processes in which these behaviours can be explored, predicted and repeated. Predictability and the ability to interact with a material's specific capacities are here considered core constituents in the material programming approach. The goal is not to focus only on the implementation of natural material behaviours one-to-one, but to develop a computational understanding to activate and design new functions with added value. The best example of this approach is described by Manuel DeLanda as the morphogenetic process a blacksmith uses to tease out the shape and performance of an iron sword [23]. For wood, a similar discussion of the relation and order of material and form has long been a topic in practice [82]. A re-evaluation of this concept could prove beneficial in contemporary digital design and fabrication.

On a technical level, computational mechanics provides a wealth of material and mechanical information, but difficulties in simplification and translation more often than not exclude it from design and architecture dialogue. In current processes, rarely does a designer possess such a direct material uplink and downlink from raw material to the final geometry to actually utilise building materials to their full potential. At the same time, many behaviours and capacities may at face value appear to be useless, while computational design methods can reveal entirely new performance [65]. Thus both theoretically and practically this thesis will describe the following: how can computational design and digital fabrication be used to harness and integrate a material's active capacities as part of the design process? Further, how can this approach lead to new, highly-effective material systems and architectures?

Figure 4.1: Hygroscopically actuated opening of scales in a spruce cone initiated through drying.

4

Current State of the Technology

This section describes the current state of the technology for building construction and methods of self-shaping in four sections related to the context of the dissertation.

4.1 Curved timber architecture and digitisation

The use of bending and curvature is well known in timber building practices, and historically has been found for centuries in curved arches and smaller-scale indigenous architecture [65]. Material engineering approaches such as glue lamination provide structural integrity, scale and consistency in contemporary timber building components beyond that of traditional practice, but also assert standardisation, which has made curved geometries specialities.

The most common use of curved wood is in medium-span structures such as roofs with shallow curvature beams carrying load in a single primary direction. Structural curvature is even more exemplary in curved-surface structures such as cylindrical shells or vaults where surface action can be utilised to further increase efficiency [87; 44]. From an architectural perspective, the integration of structure and enclosure in a surface component is valuable as it simplifies the construction, but is considerably more difficult for curved geometries. Curved wood surfaces in large building components exist as roof [90] and interior speciality components made of single-curvature CLT with thin lamellas and custom double-curved geometries constructed from small cross-sections. Lightweight wood surface structures have also been constructed in double-curved geometries, and while the materials savings in the final structure are substantial, the massive curved formwork required to form the structure must be considered in its overall performance [89]. Alternatively, large double-curved surfaces have been emulated/approximated from flat engineered timber plates arranged as surface segments [57] and with shells constructed from curved wood and foam sandwich panels [18; 8]. More typically, surface-active structures with curved geometries are constructed from more malleable or viscous materials such as concrete or plastic. These require substantial temporary curved formwork and shaping of internal reinforcement. Ironically, these formworks are often built from wood panels bent along a supporting structure or custom subtractively machined from solid blocks of material to serve as a temporary placeholder for the surface shape, but not the structure itself.

In timber construction, digital design and manufacturing has extended the use of wood for complex and performative geometry [70; 10]. More contemporary examples include the use of digital planning for pre-formed curved grid structures made from glue-laminated beams [91]. These examples are aided by digital planning combined with the flexibility and precision of numerically controlled subtractive milling and robotic fabrication for detailing and surface finishing. For the few structures with large curved plates, digital design and robotic fabrication is especially useful for more complex connection details and assembly sequences [83]. However, these design and fabrication approaches rarely interface at the material level or extend to include the earlier production steps in regards to the shaping of large building components.

4.2 Manufacturing of curved wood components

The largest quantities of wood are harvested as straight logs given the natural vertical structure of many species. The most universal approach is to bend linear or flat wood elements by first reducing the cross-section, and as a result the bending resistance, to a thickness that can be more manageably deformed and then fixed in the curved configuration. On a smaller scale, shaping to curved and even double-curved geometries is achieved by simultaneously pressing and laminating multiple layers of thin veneer between a pre-shaped formwork. This approach was pioneered by Ray and Charles Eames as a method for mass-producing curved chairs, leg splints, and even panels for aeroplane shells, taking advantage of the lightweight structure of wood combined with the stability of curved geometry [52]. The major drawback is that the size, weight and production of the formwork is extensive, limiting the variation and size of geometries that can be produced. Other shaping methods at this scale include weakening the material to aid in bending, such as kerfing, or steaming to temporally reduce the bending resistance.

Larger-scale curved components must carry significant load beyond self-weight. Structural curvature can be gained through the post-forming of curved geometry as in the case of elastically deformed thin lath grids and shells, or through pre-forming individual components. Pre-forming of either beams or surface components, such as CLT, requires sawing, drying and planing boards, assembling into layers and laminating against curved formwork. The formwork can be adjustable and even digitally controlled, but remains in place during the gluing process Figure 5.4. Different variations of the process use hydraulic actuators, vacuum pressure, or screws to provide the required lamination force. Higher curvature requires an increasing number of layers with smaller thickness or cross-sections, with the standard minimum radius of 6.60 m [25; 26]. Additional sawing and assembly steps make higher curvature and more complex geometries more expensive, laborious and materially wasteful to produce. As an industry rule of thumb, single-curved beams cost twice that of equivalent straight beams, with the cost increasing exponentially with the complexity of the curvature and geometry. Part of this expense comes from the inaccuracy of form-bending caused by elastic spring back after releasing from the formwork. This must be accounted for by pre-calculation or, more commonly, by producing oversized components which require extensive subtractive machining. In many cases the difficulties of bending outweigh the material performance benefits, making it more cost effective to machine curved parts from much larger rectilinear stock components. This results in material waste and discontinuity in the fibre directions, which is both structurally and aesthetically unfavourable.

More experimental, less common methods for bending, including robotically controlled bending and lamination, have been demonstrated in a laboratory setting with smaller cross-sections [4; 61]. At larger scales, mechanical steam-bending of sliced round logs has been used as a method of curving for load-bearing components, as in the Saw Mill Shelter Roof at the Architectural Association's Hooke Park in Dorset, England. Alternatively, combinations of subtractive toothing and bending have recently been explored as methods to physically encode a bending configuration into multilayered beams and furniture pieces [32; 86]. Historically, this approach was used in the 18th century as a method for producing large-scale curved beams for bridges built by the Swiss engineer Hans Ulrich Grubenmann [56]. The process of bending the thick wood beams into place remains a mystery, but it is thought to have involved combinations of tensioning, fire and ice. In any case, it is difficult to avoid the fact that large amounts of brute force must be delivered in a coordinated way to overcome the bending resistance of wood to achieve this curvature. This is a problem that becomes increasingly demanding as the geometry of the parts becomes larger in cross-section, and dimensionally as surfaces.

4.3 Self-shaping technology from small to large scale

Self-shaping, and more specifically self-shaping surfaces, and the fabrication methods to produce them represent a large field of research spanning scales from nanometers to meters. Examples described here show the advantages these systems offer in terms of simplicity and reliability, but also the limitations of scale. At the smallest scale, technology for incorporating shape-changing materials have been investigated, primarily for bio-medical application at the microscale (<1 mm), where small form factor and autonomous operations are advantageous [34]. At these scales, soft shape-changing materials that react to different stimuli such as water, heat or magnetic fields can be fabricated with specific geometries to tune the shape and overall performance. In other fields, passive actuation in bio-based shape-changing materials has been used for power generation and culinary applications [14; 105].

At the macro scale (1–1000 mm), stimuli-responsive, shape-changing materials have long been employed in the fields of architecture and design [2], and revered for use in self-regulating building systems and adaptive architecture. Heat-responsive thermo bi-metals (TBM) with relatively simple motion mechanisms have been implemented in self-shading façade systems that operate without electricity or computer-numeric input [92]. Similarly, humidity-responsive wood bilayer composites have been developed for use in self-regulating building skin prototypes that open and close in response to the weather [81; 18; 102; 50; 21; 1]. These systems take inspiration from biological movement mechanisms and have been further advanced through the use of additive manufacturing methods and bio-based materials which allow for precise placement of both active and structural materials [19; 20; 77; 59; 109] A5, A7. For these applications, the size and speed of actuation is notably restricted by the poro-elastic limits of the materials themselves [43]. In studies of granular materials, large quantities of self-shaping particles of ca. 150 mm have also been demonstrated as reversible and distributed mechanisms for tensioning and connecting [24] A3. Additionally, larger self-shaping systems have been explored with a variety of synthetic materials and plastics at the table-top and mock furniture scales, typically requiring high temperature or full water saturation to actuate [104; 98; 75].

At a larger macro scale (1000+ mm), designed self-shaping and deployable systems have also been developed based on elastic actuation, in which a part is produced pre-stressed and actuated by releasing or changing the stress state [6]. In these cases, the stored elastic energy can cause a shape change, but an external physical force is required to initially stress the piece and contain it before actuation. These systems can be scaled to create lightweight, materially efficient structures, using active bending in large rods or plates. The force of actuation and the constrained energy increase dramatically in relation to the stiffness of the shaped part. At a similar scale, wood has been used to attempt self-shaping of larger monolayer surfaces and explored in macro-scale humidity-responsive space trusses [36] A4, C2. At the scale of building structures there are no known examples of intentional use of self-shaping from external stimuli. However, seasonal weather-related hygroscopic deformations in wood beam structures have long been thought to be the cause of substantial visible twisting in church steeples across Switzerland and Southern Germany [45].

4.4 Self-shaping wood bilayers

In the majority of studies using the responsive properties of wood, dimensional changes are converted to a bending movement using a bilayer mechanism. Modelling of bilayers was first described analytically by Timoshenko in 1925 to calculate the deformation in metals used for thermostats [100]. Bilayer mechanisms are also found in many plant structures with responsive movement and are defined generally by an active layer which expands and contracts, and a restrictive layer which limits the movement on one side of the mechanism, resulting in curvature. Bilayers can be constructed from isotropic or anisotropic materials, with directionality leading to greater control of the bending direction within a part. Comparatively, with isotropic bilayer materials the boundary geometry and proportion of the parts are the primary method of controlling the in-plane direction of bending. Thin wood bilayers in the range of 0.5–3.0 mm thickness have been extensively modelled, fabricated and tested [85; 40]. The most common application of these smaller bilayers is for weather- and humidity-responsive building systems, such as adapting the angle of a solar panel to match that of the sun, or self-shading louvres to reduce the heating loads as previously described in section 4.3. These applications focus on responsive systems that remain in continuous motion in relation to the dynamics of the surrounding environment and focus on increasing speed in discrete curving elements [101]. In comparison, the current research will investigate not only upscaling of the self-shaping movement, but a method of locking and blocking the movement after the shaping has occurred – an aspect that is critical when using load-bearing components in current construction practice.

In parallel, upscaling of wood bilayers to meter-scale in length and width represents a new field of research that has so far been investigated primarily through work associated with this dissertation using wood bilayer and fibreglass composites [107] and hybrid methods of additive fabrication and self-shaping bilayers [15; 17]. In principle, two physical challenges for upscaling bilayers can be identified and compared to existing research: the upscaling of the thickness of both active and passive wood layers to add the structural depth and stiffness needed in larger parts, and the combination of multiple wood elements (typically boards) to produce parts beyond the natural width and length of a single wood element. While wood materials have been studied for centuries, no known method exists for accurately predicting the hygroscopic deformations in large multi-board bilayer parts as described here.

5

Research Structure and Methods

This dissertation introduces the concept of material programming as a computational design and fabrication method for self-shaping curved timber building components. The research was initiated through a study of the computational design and fabrication process for macro-scale wood surfaces and its relevance in architecture as described in Article A. From this study, the topics of upscaling and prediction were identified along with the coordination of disciplinary expertise in wood materials science that would be required to address them. At this stage, research was conducted as an interdisciplinary study led by research partners in materials science. First, the topic of computational modelling and prediction was identified as a critical aspect for introducing self-shaping in nearly any application. In parallel, further upscaling would be required to reach the thickness, length and width required for building components. These topics are addressed jointly in Article B through initial laboratory tests and prototyping. This was followed by the identification and development of an applied method for self-shaping for the manufacturing of curved CLT building components introduced in Article C and described technically in the associated patent applications B1 and B2. In Article C this manufacturing concept is explored through the manufacturing, modelling and prediction of thick multi-board wood bilayer plates to prove its feasibility in relation to the proposed manufacturing process. A refinement and simplification of the process was then conducted based on a number of industry-specific boundary conditions. Here, the study was led by the architectural and computational design team in consultation with the industry partner and the materials scientists. The adaptations of the process for the building industry are visible as parts of the studies in Article C, discussed in Article D and described further in Chapter 6. The simplified scientific findings and material related development were reciprocally integrated into the digital design process for the architectural design, engineering and production of a building demonstrator, the Urbach Tower, described in Article D. Conceptually and technically, the material programming approach introduced in Article A is revisited and evaluated in Article D as an innovative method for full-scale, sustainable production of load-bearing components for architecture with performative curved geometries.

5.1 Research methods

This section provides a summary of the research methods. A more detailed technical methodology is included in the research

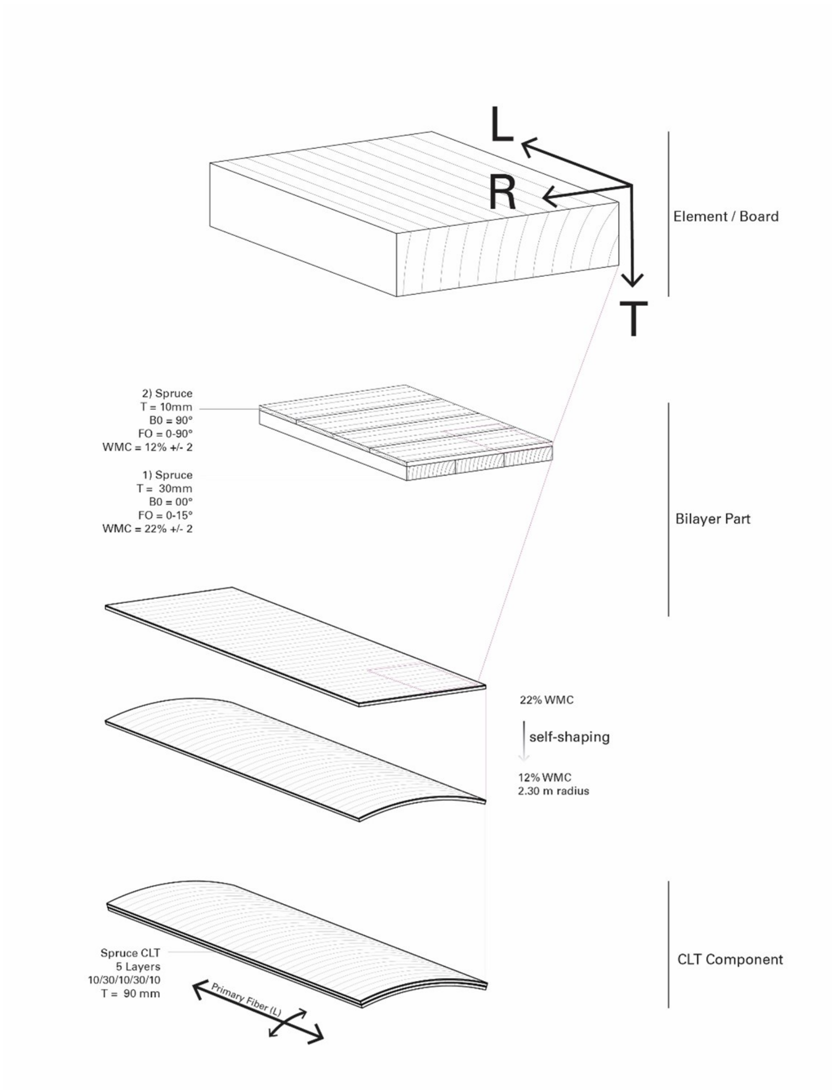

Figure 5.1: Physical description of the material programming and self-shaping manufacturing process from the wood material elements, bilayer parts and final curved CLT component.

articles and patent applications. The research was initially conducted through an experimental approach in the laboratory and in-house fabrication setting through physical tests and development of digital design methods. Following these proofs of concepts for large-scale self-shaping, the approach shifted to adaptation and prototyping in an industrial timber construction setting. In parallel, the material system and design methods were rapidly implemented for production of the demonstrator building described further in Chapter 6.

While material programming throughout is viewed as a holistic approach, the associated methods are broken down into individual topics: a digital computational design framework, materials, material and mechanism modelling, and the physical fabrication process. The following sections describe the computational design framework and its relation to the material and mechanism modelling and fabrication processes.

5.2 Computational material programming framework

The computational design framework was developed throughout the research, and is described in Article A and Article D as a digital overview model to enable material programming. The framework was developed in the 3D NURBS and mesh-modelling environment Rhinoceros 3D (Robert McNeel Associates) and the visual programming software environment Grasshopper 3D (Robert McNeel Associates, David Rutten). This environment hosts the geometric surface modelling and the numerical data needed for the adjacent processes. It is chosen for its high-precision geometric surface-modelling capabilities, use in typical architecture and design fields, and development freedom. In Article A the full computational design workflow is built in the Rhinoceros and Grasshopper modelling environment with the assistance of the Kangaroo Physics plug-in (Daniel Piker) for an abstracted modelling of basic shape-changing elements composed in larger mechanisms. This was implemented using a proportional mesh hinge angle method to describe the shaping, and later using a "shape-matching" method developed for computer graphics applications [12]. This allows for a faster and more flexible design environment but at the expense of accuracy and a simplification of the material behaviours to that of a change in volume. A similar process incorporating a direct, two-way connection to a finite element (FE) model was further developed and described technically and geometrically in [108] A.1 Figure 5.2. Using this process, the arrangements of elements is flexible, allowing for more complex layouts and layups. The process described in Article D uses custom-developed Grasshopper components written in C# and Python programming languages to translate key parameters between more advanced software models for both the material and bilayer mechanism as well as numerical and geometric data used for fabrication. In addition, geometry and material information at different levels is bilaterally shared with the modelling setups for the structural engineering of the components, connections and overall structure in the case of the building demonstrator.

5.3 Materials

The wood species of beech, spruce and European maple were chosen for this study because they exhibit high coefficients of shrinkage and swelling as well as good stiffness values Table 3.1 Table 3.2. In the initial prototypes of Article A, beech and maple

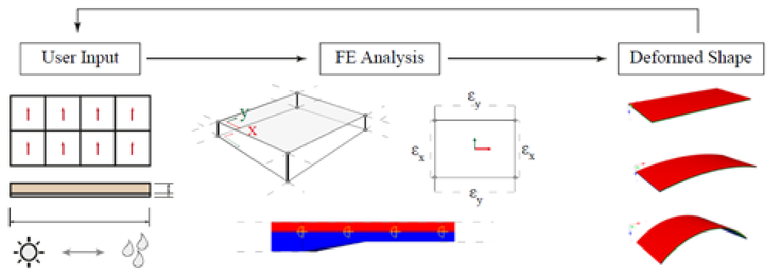

Figure 5.2: Technical description of the computational steps for designing the curvature of a multi-element wood bilayer part [108] A.1

Figure 5.3: Self-shaped wood bilayer parts with identical overall dimensions and actuation conditions, designed via inter-element layups and orientations to produce specific changes in shape.

Layer	**Input**		**Production**	**Tolerance**
Active	Species	S	Spruce	C24
	Thickness	T_1	30 mm	0.01
	Width	W_1	150 mm	0.01
	R/T Angle	R_1	0°	+/-15
	L Angle	L_1	0°	0
	WMC Initial	MC_{1i}	22%	+/-2
	WMC Final	MC_1	12%	+/-2
	WMC Change	ΔMC_1	10%	
Restrictive	Species	S	Spruce	
	Thickness	T_2	10 mm	0.01
	Width	W_2	150 mm	0.01
	R/T Angle	R_2	0-90°	90
	L Angle	L_1	45°	0
	WMC Initial	MC_{2i}	12%	+/-2
	WMC Final	ΔMC_2	12%	+/-2

Table 5.1: Physical input parameters for the material programming of self-shaping wood bilayers to a radius of 2.40 m used in the production of self-shaped CLT for the Urbach Tower building demonstrator.

active layers are used in combination with glass-fibre-reinforced plastics or spruce wood as resistive layers. In the latter studies spruce and beech wood were chosen as industry-relevant materials that are also locally available in Southern Germany and Switzerland. Beech, a hardwood, is favourable because of its higher coefficients of expansion, incredibly high stiffness values and the anticipated increase of harvesting in Europe. Beech is less commonly used in the construction industry precisely because of the difficulties of controlling shape-change. Spruce, a softwood, is widely used in wood construction, has reasonable coefficients of expansion and a much lower density and stiffness, making it an ideal material for lightweight construction. Economically, both species are lower-cost, non-speciality products and require no treatments or engineering beyond drying prior to use. Spruce was chosen as the material for industry adaptation based on the expertise and market of the industry partner. For laboratory tests, spruce wood was sourced directly from the sawmill and equilibrated or air dried to the desired initial WMC. Beech wood, when not available directly from the sawmill, was in some cases kiln-dried prior to delivery, but not chemically or heat treated. All wood was Forest Stewardship Council (FCS) certified or above.

Moisture-activated adhesives were used to bond the active and restrictive layer of wood to create the bilayer structure. Industry-standard single-component polyurethane (PUR) adhesive for gluing engineered wood parts was used (Loctite HB S309 PURBOND, Henkiel AG and RP2760, Collano AG). The stack bonding of the curved bilayers was tested with the same single-component PURs and a two-component PUR which requires less lamination pressure and lower surface quality.

5.4 Material and mechanism modelling

To determine the impact of the design parameters, accurate models of the wood materials and the bilayer mechanism were developed. While the focus of this thesis is not on computational mechanics specifically, these models and the ability to understand and access them are an invaluable part of the material programming approach. The three models used throughout the studies are described here for reference. In all material and mechanism models, the material data was sourced first from literature and second the key characteristics (as determined by a sensitivity analysis) such as swelling coefficient, R/T angle and density measured in specific wood samples per experiment.

5.4.1 Analytical modelling with the Timoshenko model

An adapted version of the Timoshenko model initially developed for designing bilayer thermostats was used for modelling the curvature of wood bilayers. The bilayer wood model for thin layers [40] was further adapted for thicker bilayers. In addition to the design parameters, models required moisture-dependent stiffness values and a coefficient of expansion for each axis. This is the simplest model, but it is limited to two dimensions and parts with bilayers in a single configuration and orientation.

5.4.2 Numerical modelling with FE

Finite-element modelling offers a numerical, more flexible approach to the design of bilayers than the analytical approach. A simple linear and non-linear elastic FE model of a wood bilayer was created by adapting an existing description of stimulus-responsive dimensional change for thermal expansion and contraction [40]. The software Abaqus/CAE (2018, Dassault Systèmes) was used for a model incorporating the board layout and layup of a wood bilayer with per-element/board definitions of the design parameters. The Python programming language was used to setup and interface with this model.

5.4.3 Numerical and rheological modelling with FE

In parallel to the simple FE model, an existing rheological model of wood was implemented by research partners to describe the unique visco-elastic mechanical properties of wood. The rheological model [46] incorporated additional material parameters and allows for in-depth examination of deformation specific to wood materials. The material model was reduced and implemented as a subroutine of the mechanical Abaqus FE model allowing for parametric modelling of a simplified bilayer configuration. This model is considerably more accurate, but requires more input parameters, geometric simplification and is computationally heavy. A comparison of this model and the experimental results are described in Article C and in relation to the specific industry-relevant bilayer configurations in Article D.

5.5 Self-shaping manufacturing

The physical steps of the self-shaping manufacturing process described here were built around existing wood processing and manufacturing technologies found in typical timber firms and later in a large-scale industrial timber manufacturing setting.

5.5.1 Pre-manufacturing: sorting and equalisation

To achieve the design and production parameters Table 5.1, wood boards were first acquired and sorted. In most cases the boards were cut to a specified rough thickness and sorted for a standard quality and R/T angle. Boards were then equilibrated to the desired initial WMC through placement in an environment with the RH equivalent to the required EMC. Ideally the boards were sourced with a naturally high WMC as close to harvesting as possible and desorbed to reduce the need for artificial equalisation.

5.5.2 Bilayer manufacturing

Following equalisation to the initial target WMC, boards or elements were planed and machined to the required dimensions. The elements of the active layer were connected edge to edge through edge gluing or an all-wood connection detail such as an in-plane finger joint. The active and restrictive layer boards were then

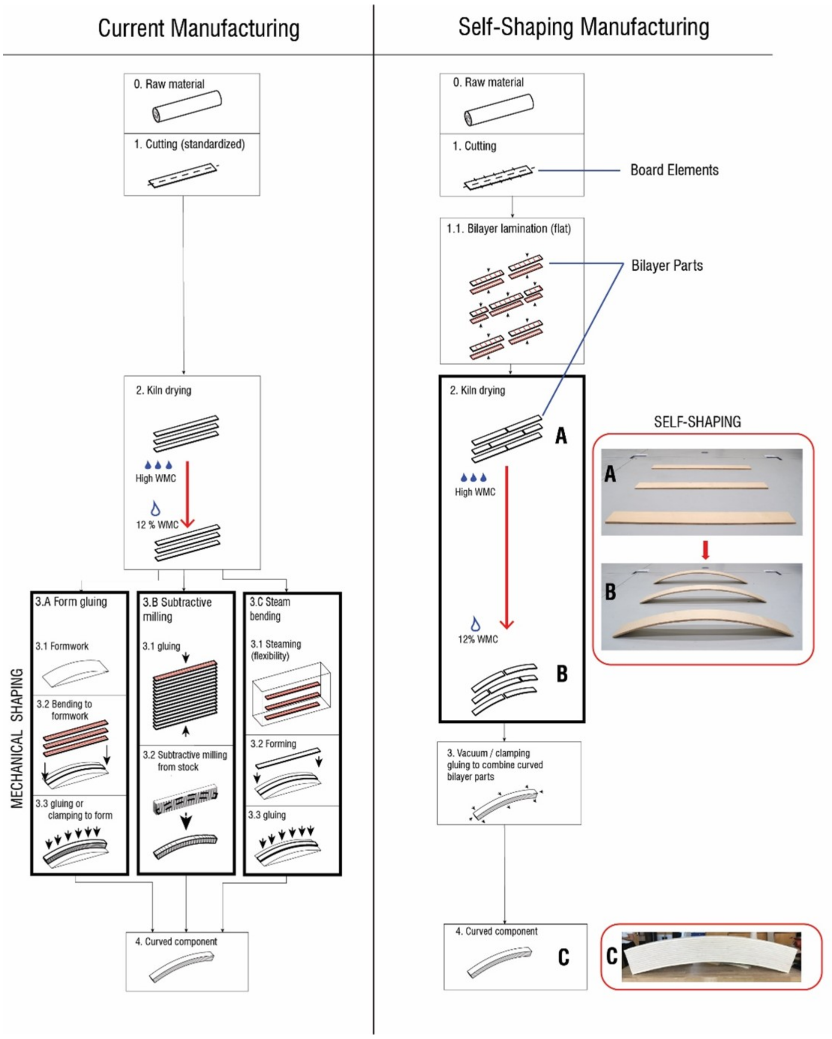

Figure 5.4: Comparison of the self-shaping manufacturing method (right) with the steps of a typical industry method of manufacturing curved glulam beams (left). The self-shaping method was later adapted for the production of curved-surface components such as glulam beams or CLT panels. A: Flat bilayer lamellas with high MC. B: Curved bilayer lamellas with a low MC. C: Curved beam constructed by stack-laminating the self-shaped curved bilayer lamellas.

press-laminated to each other using a PUR adhesive and either a vacuum membrane press, standard mechanical press or simply by loading with mass. After lamination, the resulting flat bilayer plates were planed or drum sanded on the surfaces and trimmed at the edges. When possible the bilayers were produced in an environment with controlled RH and temperature with a RH and EMC as close as possible to the initial WMC of the active layer.

5.5.3 Actuation: flat to curved

To actuate the plates from flat to curved state, the moisture content of the active layer was changed. This was achieved by equilibration of the bilayers in a relative humidity relating to the required change in WMC. Air-drying or slow equalisation in a climate-controlled environment was used in the laboratory but was not suitable for an industrial context. Alternatively, oven or kiln drying was used when speed in a drying situation was needed. In both cases, the shaping remains reversible if a similar change in WMC and timing is applied.

5.5.4 Mechanical locking

For using load-bearing building components, maximising form stability in the final-use state was deemed critical for further implementation in construction. Mechanical locking was achieved by the stacking and fixing of multiple pre-curved bilayer plates while in the actuated curved state. The pre-curved bilayers were stack-laminated with the addition of an elastically bent wood-locking layer and a moisture-actuated PUR adhesive, and the stack was then pressed using a vacuum bag or screw-press lamination to create multi-layer cross-ply layups similar to classic CLT.

5.6 Measurement

The measurement of the key material parameters and the resulting geometric output is critical to developing a usable description of the self-shaping process. As wood has a natural variation in its structure, all measurements represent a range of values and a large sampling size was required. As a rule of thumb, measurements were recorded, at a minimum, per element within each bilayer part, for example for each triangular element in Article A and each board in Article D.

5.6.1 Material grading

Material grading was based on visual inspection and measurement of the R/T angle using manual measurements with a protractor and measured photography to determine an average R/T angle per element. The same method is used for the measurement of the L axis in the case of varied orientation of grain along the length of the board. Density was approximated by measuring the volume and weight of an element at a known WMC. In an industrial setting the described grading was conducted in addition to grading standards [27] with the possibility of further machine grading based on [28].

5.6.2 Wood moisture content

Wood moisture content was measured using either a resistive non-intrusive device (FMW, Brookhuis Applied Technologies BV), screw-inserted resistive devices (HygroFox, Scanntronik Mugrauer GmbH), weight and volume combined with a dry weight test, or in the industrial sawmill setting an inline non-intrusive device. Measurements were recorded during the sorting and prefabrication setup to determine the initial WMC just before bilayer lamination, throughout the actuation process, and in the final actuation state. For long-term tests, measurement of WMC continued beyond the actuation step as the material remains in constant desorption and absorption to retain equilibrium with the surrounding conditions.

5.6.3 Curvature

Curvature was measured at the same steps as WMC, using either manual length measurements of three points to generate an arc, a handheld laser scanner or a rotating 3D laser scanner. In the initial stage of production, spot measurements were made using a steel bar to verify the flatness of pieces in the L axis. The effects of self-weight in the curvature measurements were not considered, but when possible, samples were placed in a configuration to minimise the effects of self-weight and support friction.

Figure 6.1: Curved geometry of the Urbach Tower building demonstrator, a 14 m tall, high-performance timber structure built from self-shaping curved CLT.

6

Additional Research Development and Implementation

This section describes research and development topics further investigated in relation to the industry adaptation and application in the building demonstrator, the Urbach Tower, as a supplement to Article D and B.1.

6.1 Implementation of bilayer self-shaping

6.1.1 Digital workflow in practice

From a combination of the computational workflow and initial material tests, achievable target radii were determined to maximise curvature using available material sizes and the resources of the industry partner. A simple set of instructions for the self-shaping CLT manufacturing was developed based on practical guidance from the industry partner. From the digital planning models described in section 5.2, a single-page drawing was developed to state the bilayer panel size, the thickness of the boards, the requirements for the WMC and the range of allowable end-grain angles, and how the boards should be specifically arranged in the bilayer. The drawing was generated parametrically for testing different configurations. In this way the resulting curvature was initially communicated through simple material parameters, shown in Table 5.1, rather than geometry, calculation or specific 3D machine code, making it highly accessible and lightweight. Geometric data required for the later stages of the CLT component production and building assembly was communicated parametrically during the design phase and later as solid NURBS models in accordance with industry protocols.

6.1.2 Implementation approach and training

One goal of the industry adaptation was to show that self-shaping manufacturing could be implemented using only existing machinery and methods at the industry partner's local site, and to minimise any specialised training. After the design and method had been adapted based on industry insights, moisture control and timing were identified as major points to manage during implementation. Prior to production, the entire working team, from project managers to trainees, was briefed on the importance of monitoring and controlling the WMC throughout the production process. This step was crucial as the instructions to maintain a high WMC during the processing and gluing is counter to the standard methods in technical education. An open conversation between the materials scientists and the production team was maintained to ensure that errors were reduced, as the production crossed conventional knowhow at many levels. Two sets of full-scale test

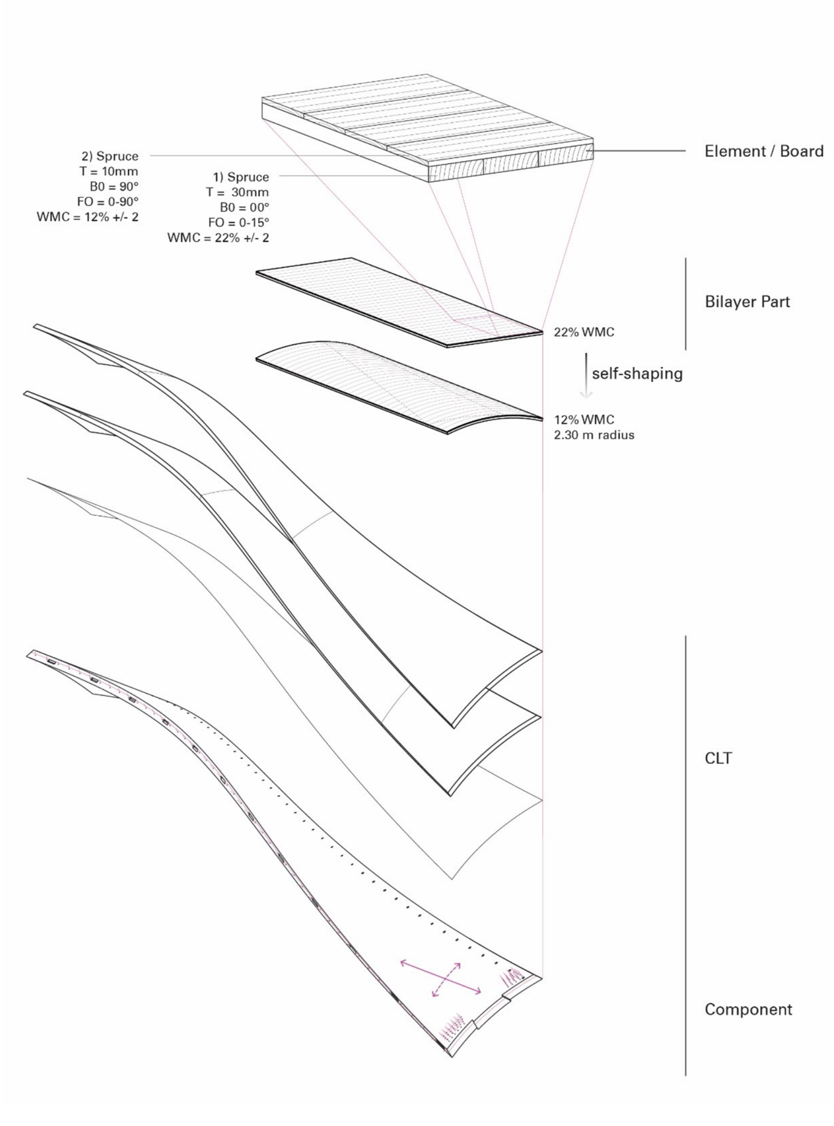

Figure 6.2: Integration of self-shaping wood manufacturing in the production of curved CLT building components for the Urbach Tower building demonstrator. Basic input parameters are shown at the element level and the resulting geometry at the component level.

bilayers were manufactured by the industry partner based on the shared guidelines to identify any mistakes and build confidence in the team that the process worked physically in their context. This approach proved valuable for the staff to see first-hand the viability of the scientifically validated process.

6.1.3 Actuation through industrial drying

6.1.4 Material selection and bilayer production

As all wood materials arrive at the sawmill with natural variability in structure and moisture content, the planned cutting and sorting of the boards was of equal importance to the digital planning and prediction methods. Moisture content requires consistent monitoring and supervision throughout each stage of the production process. First the boards were cut to standard sets of thicknesses and passed through the normal production line. Grading based on R/T angle was required and implemented using standard procedures to ensure a max of +/-15 degrees from vertical and structural grading to C24 [27; 29]. The industry partner used an inline WMC measurement device to inform the grader of boards with suitable WMC (target 22% +/- 2) which were then semi-automatically sorted from the line to the sorting wheel, stacked and wrapped, and stored inside the production hall two to five days prior to bilayer production Figure 6.3. Boards for the restrictive layer were sourced from an existing board product with 10–12% WMC, therefore no specific sorting or grading was required. Spot measurements were taken in the material stacks before planing, and just before the active layer was glued to the passive layer. Immediately after the flat bilayer gluing, the research team took WMC measurements of every board of the active layer at three locations (20 cm from both ends, and in the middle) and at two depths (10 mm and 20 mm) using a resistive non-intrusive moisture-measuring device. At this

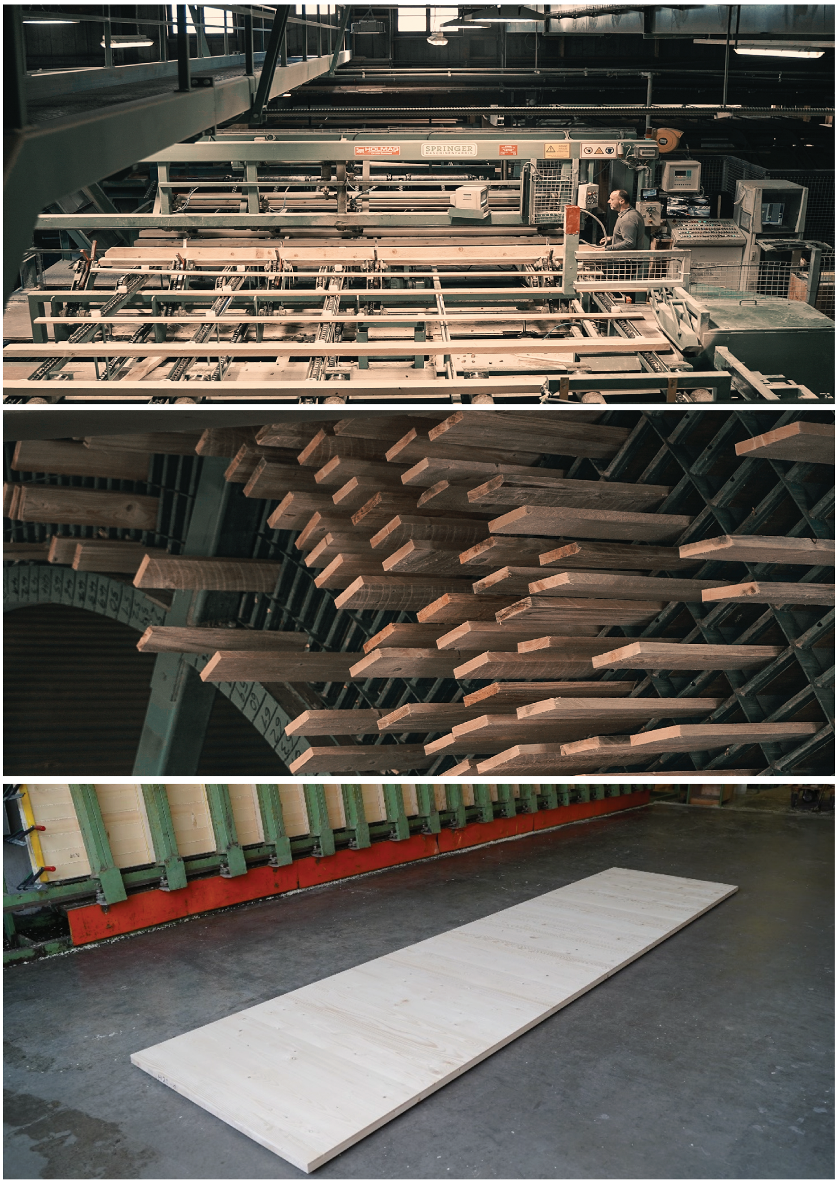

Figure 6.3: Sorting of boards on the sawmill production line. Top: Standard grading and inline measurement of WMC. Middle: Semi-automatic sorting and collection of the boards in the sorting wheel. Bottom: Assembly and flat pressing of the selected boards into bilayer plates.

Figure 6.4: Kiln-drying of the spruce-wood bilayers. Top: Bilayer racks being loaded into the drying kiln with other stacks and sensors installed for monitoring WMC. Bottom left and right: The flat bilayers with a high WMC before drying, and curved bilayers with a low WMC after drying

stage the geometry was considered flat, with zero curvature, and surface evenness ensured by belt sanding of the completed bilayer plate on both sides.

After lamination, the flat bilayer plates were placed in racks and loaded into the drying kiln Figure 6.4. The bilayers were then dried from 22% WMC to 12% over four to five days using an adapted proprietary drying schedule. All the bilayers for the demonstrator project were dried in one load with the remaining space in the kiln filled with standard stacks of 40 mm thick spruce-wood boards with variable WMC. Upon opening the kiln, the bilayers were curved and the stacks were transported to a climate-controlled production hall for measurement. The moisture-measurement procedure was then repeated and the curvature measured first by measuring the arc manually (three-point measurement) and second using a 3D laser scanner with a resolution of +/- 1 mm. Due to the stiffness of the plates and the curved configuration, the influence of self-weight was marginal and was checked by comparing measurements of the curvature in the racks where they are supported at two axes on the edges, and by supporting only along a single central longitudinal axis Figure 6.5. The laser-scanning results were analysed by measuring the Gaussian curvature to check for areas of anticlastic curvature, and by measuring curvature at 10 section planes along the length of each bilayer to evaluate the consistency of the curvature in each section and throughout the plate Figure 7.8.

6.1.5 Arrangement, stacking and locking

After measurement, the pre-curved bilayers were arranged side by side and stacked in two overlapping layers to create large CLT parts as drawn in Figure 6.2 and shown in Figure 6.6. The two layers of bilayers were then press-laminated together using a series of wood beams perpendicular to the curvature direction and screwed together through the CLT, creating an adaptable method of press-gluing pre-curved parts. A single 10 mm thick locking layer made of standard spruce boards was simultaneously elastically bent and laminated to the inside of the curved CLT to prevent further hygroscopic deformation. A limited number of CNC-cut wood guides were used simply to position the bilayers during the lamination process, while the pressure was applied using the straight wood beams and screws. All of the supporting materials used for pressing were reused for multiple laminations and repurposed as supports for machining and transportation, after which they were donated to a local farmer adjacent to the building site.

Figure 6.5: Curved wood bilayers displaying the added stiffness resulting from the curvature. Top: suspended from a central point for transport in the production hall. Bottom: suspended along the longitudinal axis for measurement.

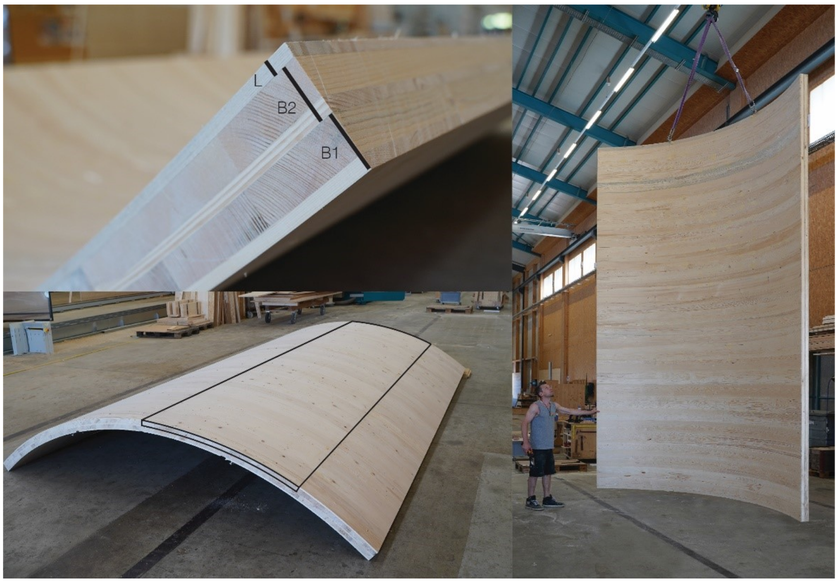

Figure 6.6: A self-shaped curved CLT test component produced at the industry partner, constructed from the arrangement, stacking and glue-locking of multiple bilayer parts. Top left: The completed cross-section of 90 mm made by combining two self-shaped bilayers (B1, B2: 30-mm active layers and 10-mm restrictive layers) and an elastically bent locking layer (L: 10 mm). Bottom left: The completed curved component with indication of a single bilayer part. Right: The curved component in a vertical configuration.

6.1.6 CNC machining and detailing

The component connections still rely on precise machining of the contact surfaces and the location of the connection screws. The goal of the machining was to maximise the amount of physical information prefabricated into the part while minimising the machining time. From the digital model, the geometry of the contact surfaces was defined with 0.001 mm accuracy and transferred as NURBS geometries to the industry partner's custom large-format five-axis CNC machine Figure 6.7. In addition to the geometry, a series of planes and vectors were used to define the milling paths and drill holes. The required machining included the surfacing of the four curved edges (90 mm thick) of each component and the pre-drilling of connection holes (3 mm diameter) Figure 6.8. Surface machining was avoided entirely. From this workflow, the machining time was reduced to between 60 and 90 minutes. Structurally, the careful digital definition and manufacturing of the connection detailing allowed for the standard detail to be adapted from the normal constraints and implemented without specific physical testing.

6.1.7 Weather protection and façade

The Urbach Tower is a partially enclosed structure, but not a weather-sealed building. A weather-protection approach was developed to prevent direct contact of rain/water on the CLT components while at the same time allowing for proper ventilation to avoid accumulation of moisture inside the structure. A removable waterproofing membrane was added in the factory to prevent water from entering through the exterior surfaces of the CLT. Further, a thin 15 mm thick larch-wood façade was added to the surface of each component. The façade panels were produced from larch wood because of its known weathering performance. To reduce the

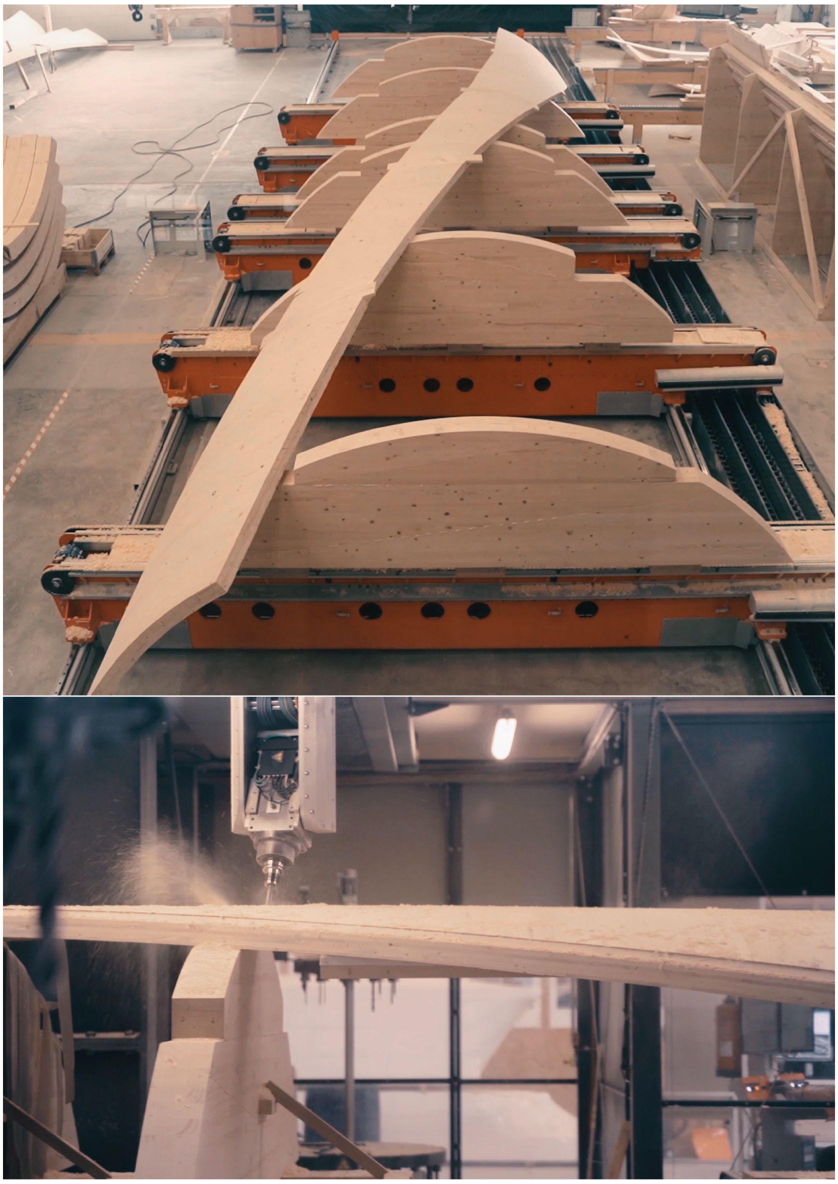

Figure 6.7: CNC detailing of the curved connection edges for the curved components of the Urbach Tower. Top: A 15 m long component positioned on the CNC carrier for final detailing. Bottom: Precision 5-axis CNC trimming of the connection edges.

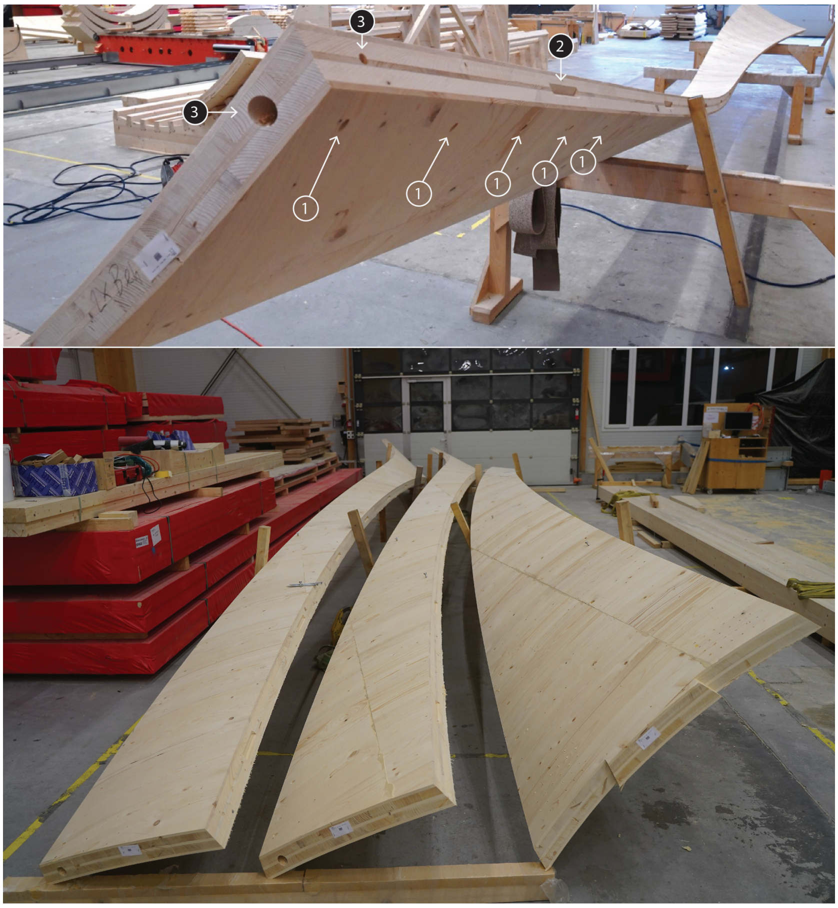

Figure 6.8: Completed self-shaped CLT components for the Urbach Tower. Top: Close-up of the CNC detailing. (1) Pre-drilled holes for crossing screws used for onsite connection of assembly groups from the interior, 12 mm face drill hole and 3 mm pre-drill hole for 6 mm diameter 120 mm long fully threaded stainless-steel screw, variable spacing based on loading. (2) Cutout for placement of square cross-section hardwood alignment block, 19.5 x 19.5 x 150 mm spaced ca. 1200 mm). (3) Holes for connection and storage of fabric strap for lifting during assembly and planned disassembly onsite. Bottom: Three completed components prior to assembly into groups

risk of cracking, the panels were produced using an engineered laminated wood manufacturing method borrowed from the production of smaller-scale pieces in the automobile industry. First, a straight 15 m x 1.2 m x 0.30 m glulam beam was constructed from 50 mm thick boards. The beam was then band-saw cut to produce 15 mm thick sheets with boards just 50 mm wide and a nearly continuous surface along the 15 m length. Each façade piece was then nested and five-axis CNC cut. An experimental metal oxide surface treatment (now UVood®) was suggested by the industry partner as an option to prevent the discolouration over time of the larch-wood cladding without the need for continued reapplication. Rather than darkening, the surface of the wood would lighten in colour, eventually turning to a light white. For the demonstrator, the treatment was tested at large scale for the first time using larch wood and on curved surfaces. The weatherproofing and cladding were applied after preassembly of the groups of three components in the factory Figure 6.9.

6.2 Mechanical performance

FE modelling and destructive three-point bending tests for rolling shear were used to verify compliance of the mechanical strength of the resulting curved CLT components with building regulations. The industry partner used two types of adhesives for the first production tests. A 1-K PUR adhesive was determined suitable for the full production run. Additionally, block samples were cut adjacent to each component, and the glued joint strength-tested using a block shear test. Further details of these tests are described in [39]. The relevance of the tests in relation to the CLT construction system of the building demonstrator is described in [5] and to the material programming process in Article D.

Figure 6.9: Completed prefabrication and assembly grouping of the curved CLT components including the installation of the weatherproofing and cladding, nested for transport to the building site.

6.3 Long-term performance

The long-term performance of the curved CLT in real-world conditions was a relevant concern and challenge for proving the new manufacturing procedure and the building demonstrator. In large timber structures, daily and seasonal changes in RH and radiant heat cause swings in WMC which over time can result in deformations that cause concern for the structural integrity of the building. In the case of the building demonstrator, the CLT was applied as load-bearing components in a partially exposed condition with cladding protection only on the exterior surface. The CLT is protected from direct contact with water on the top and exterior, but is left exposed to changes in moisture in the air and blown-in rain on the interior to allow for investigation of the long-term geometric and material performance of the structure.

6.3.1 Moisture measurement

To record the WMC of the components, a resistance-based moisture monitoring system using pairs of electrodes was installed directly into the self-shaped CLT components during prefabrication. Eight sensors were placed at two different heights (ca. 4 m and ca. 10 m) on opposite sides (southeast and northwest, components 3 and 9) of the tower at depths of 20 mm and 50 mm from the exterior of the CLT Figure 6.13. The sensing area of the electrodes is therefore the 30 mm thick active layer boards in which moisture change would cause the greatest impact on the geometry. The sensors and wires were recessed in the CLT and covered with the waterproofing isolation tape and the façade for protection Figure 6.10. The measurements are recorded at an interval of 15 minutes by a battery-powered data logger which transmits data weekly to an online server. This allows the measurements to be recorded autonomously over the next 5 to 10 years.

6.3.2 Weather and environmental measurement

In addition to the WMC, the material temperature, surrounding RH and air temperature are recorded to measure the conditions the timber structure is exposed to over time. Three RH and temperature sensors are installed on the exterior at 10 m height, on the interior at 10 m height, and at 1 m height between the interior of the structure and the foundations Figure 6.11, Figure 6.13.

Figure 6.10: Installation of WMC sensors in the self-shaped curved components during prefabrication.

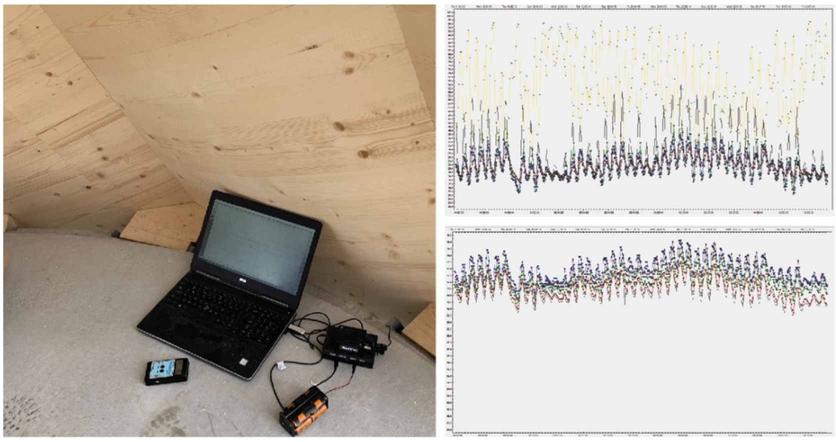

Figure 6.11: Ongoing data collection for long-term monitoring studies. Top: On-site data collection and calibration of the WMC and weather sensors after assembly. Bottom: Sample data showing the daily fluctuations in RH, temperature and WMC.

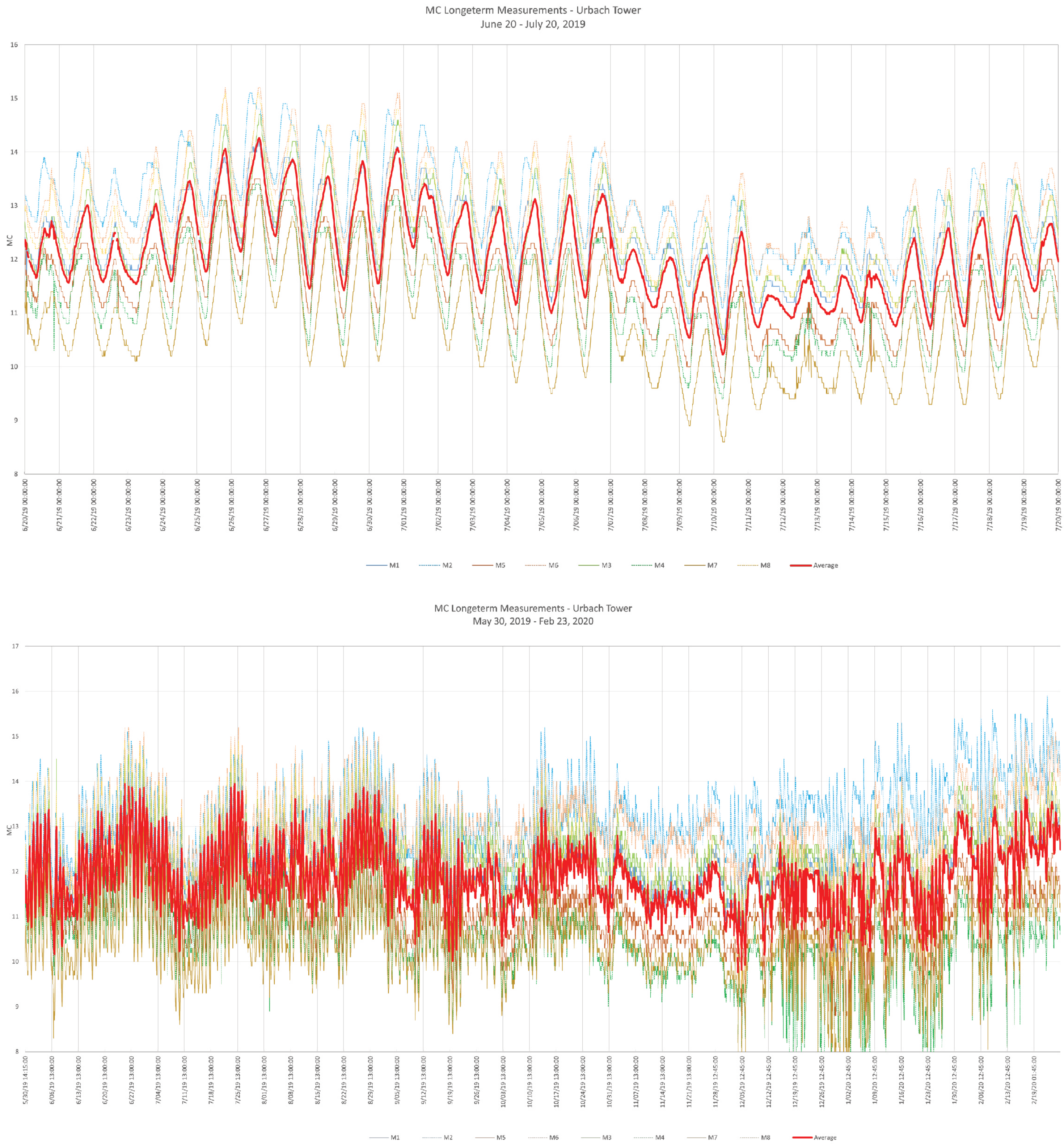

Figure 6.12: Long term MC measurements of the inner layers (20 mm 30 mm) of the partially exposed self-shaped CLT in the Urbach Tower. MC fluctuations of +/- 1-4 relate to daily and weather related changes in RH and Temperature. See Figure 6.13 for approximate locations of the MC sensors.

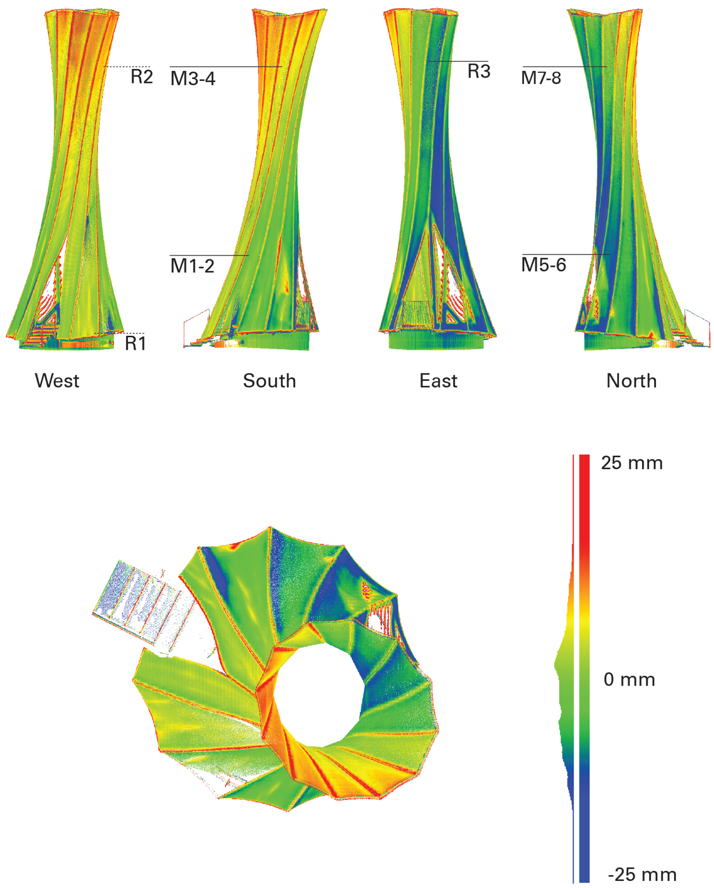

Figure 6.13: Initial results from the iterative 3D laser-scanning of the Urbach Tower structure. Comparison and measurement of absolute differences between scans of the exterior surfaces from March 2020 (1 year after construction) to March 2021. Additionally the location of the integrated WMC (M1-8) and RH/Temp (R1-3) sensors is indicated for reference in Figure 6.12

6.3.3 Geometry measurement

The overall geometry of the structure is measured iteratively every three months by research partners from the Institute for Geodesics at the University of Stuttgart. A 360-degree laser scanner is used to record a point cloud of the exterior structure with +/- 1 mm accuracy. The lower interior of the structure is also measured with similar accuracy. A series of locating points have been installed in the foundations and across the site to ensure calibration of the scans. Scans have been compared between June 2019 and March 2021, a period in which initial construction deformations have settled and over which any deformation related to changes in the seasonal climate should be visible Figure 6.13.

Figure 7.1: The Urbach Tower building demonstrator, a 14 m tall, high-performance timber structure built from self-shaping curved CLT.

7

Results and Discussion

This section highlights and discusses major findings of the research related to the overall aim of developing and demonstrating a material programming approach as a method of design and digital fabrication. Section sec:resultsBuildingDesonstrator describes the architectural results through a discussion of the building demonstrator as an example of performative architecture. Section 7.3 presents the technical results of the self-shaping manufacturing process and discusses the potentials and challenges for application in timber construction. Section 7.4 provides a wider conceptual discussion of the material programming approach in architecture as an innovative and highly effective method of computational design and fabrication.

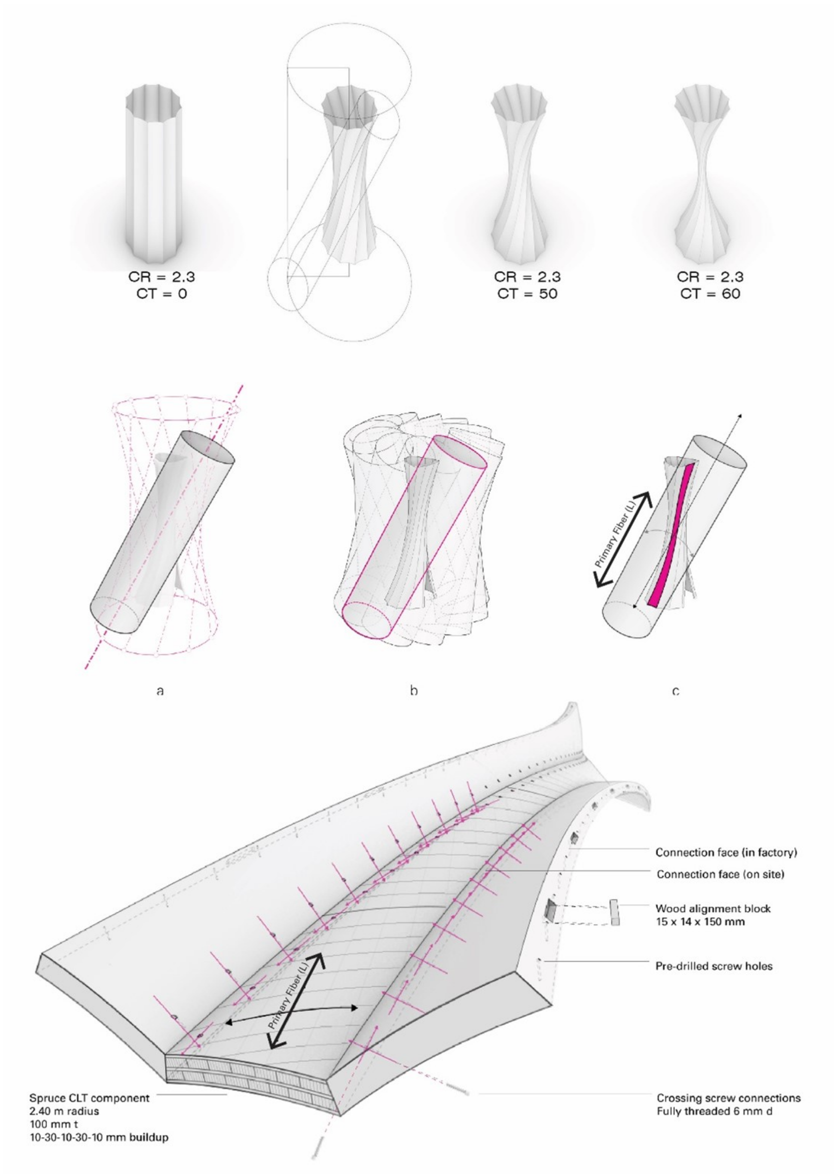

Figure 7.2: Architectural geometry and constructional system based on the highly curved self-shaping CLT. Top centre: Overall geometric principles for generating the component-based surface-active structure of the Urbach Tower. Bottom: Cross-section and perspective drawing of the curved CLT building system showing the layup, fibre orientations and hidden crossing-screw connection detail.

7.1 Experimental building demonstrator – the Urbach Tower

The results of the work illustrate that the material programming approach to design and manufacturing enables an innovative curved-timber construction system for performative architecture. Article D presents the use of this technology and the developed tectonics for the design and production of highly curved CLT components for a building demonstrator – The Urbach Tower. The tower is composed of curved CLT components arranged radially in a vertical configuration connected at their intersections Figure 7.2. The design of the tower results directly from this new type of surface-active wood structure that employs both an overall curved geometric form and local single curvature in each component [5]. The building is performative in that its architecture and curved structural form emerge through the investigation and integration of the material's capacity to efficiently self-shape to highly curved configurations.

While architecture and structure cannot be entirely disentangled, especially in a monocoque system such as this, the performance of the material and construction systems of the demonstrator is described distinctly in these contexts. Architecturally, the curvature and materiality together create a unique spatial experience representing a novel expression of a common building material. On the exterior, the concave curvature of the overall structure gives it a natural and dynamic appearance, while the intersections of the components generate sharp vertical lines and shadows defining it as a landmark Figure 7.4. Structurally, the tower performs primarily as a surface-active structure, the combination of a single-curved shell and folded plate system. The curvature in each component perpendicular to the cantilever provides local stiffness and a suitable connection angle between components. This allows the load-bearing structure to be made entirely from 90 mm thick, five-layer CLT with steel used only in the connection screws and interfaces to the roof and foundations [7] A.8.

At the material level, the layup of self-shaped CLT is oriented so that the primary fibre directions (defined by the L axis of the active layer) are aligned with the cantilevering direction of the tower where the highest stresses are exerted (vertical axis of the tower). On the interior, the convex curvature of the components creates a soft textile-like appearance despite the load-bearing function. The exposed material works with the curvature to create a friendly and tactile surface Figure 7.5. From inside, the curved walls frame a view to the sky above from which natural light washes the surfaces. The tower is located in a rural location, without electricity, and is publicly accessible only on foot, bicycle or horseback Figure 8.1. As a result, architecturally it relies on its fundamental geometry and material presence Figure 7.6. Beyond pure analytical efficiency, the materials are used effectively as both the structure and primary enclosure of the building, indistinguishably defining the architecture. Despite the current limits of the self-shaping to single-curved geometries, the computational design procedures allow for clever combinations of parts and the arrangement of the components to produce a novel but smart architectural form.

In this research and the architectural application, self-shaping is used only in the prefabrication of the building components, and traditional transport and onsite assembly is required. Despite this, the design of the components and construction system are developed to minimise the time and impact on the natural site. This results in the assembly of the timber structure in just eight

Figure 7.3: Assembly of the prefabricated curved building components on the building site.

Figure 7.4: The sharp defining lines of the exterior of the Urbach Tower.

Figure 7.5: The soft interior curvature of the Urbach Tower, looking up through its oculus.

hours with a team of four craftspeople, a single crane and minimal scaffolding, drastically reducing the ecological impact on the building site compared to other methods of construction. The construction system is also designed for disassembly, with the plan to remove the timber structure after its 10- to 15-year occupancy of this site for reassembly elsewhere. There is also the possibility for re-cladding the structure to extend the lifespan of its structural components.

Figure 7.6: Completed structure of the Urbach Tower.

7.2 Self-shaping manufacturing

From a technical perspective, the research results in an industry-adapted implementation of material programming demonstrating self-shaping as a viable and resource-effective method of pre-fabricating curved wood building components. The physical upscaling in thickness and the combination of multiple elements to create larger parts and components is shown. A method of predicting curvature in large-scale bilayers is established, including measures to ensure reliable input parameters. Thus, it is demonstrated that the natural material capacities of wood to shrink and swell can be well understood and employed in the generation of physical shape, even in an industrial setting.

Article B shows that self-shaping wood manufacturing can be upscaled and expanded for the production of different types of curved surfaces that contain multiple active and passive elements. This is further exemplified in Article C and Article D, which prove that the self-shaping can be further upscaled to bilayers with a total thickness of 40 mm and a size of 1.45 m x 4.90 m. In the laboratory tests, the beech bilayers could be predicted well (< 5% deviation), while in both the laboratory and industry tests spruce bilayers were more difficult to predict (< 15% deviation). The reason for this is thought to be tied to the specific mechanics of spruce wood at inclined R/T angles. As a result, the allowable R/T angle is a critical parameter to control in an industry context and reasonable predictability could still be achieved in the large-scale production cycle for the building demonstrator.

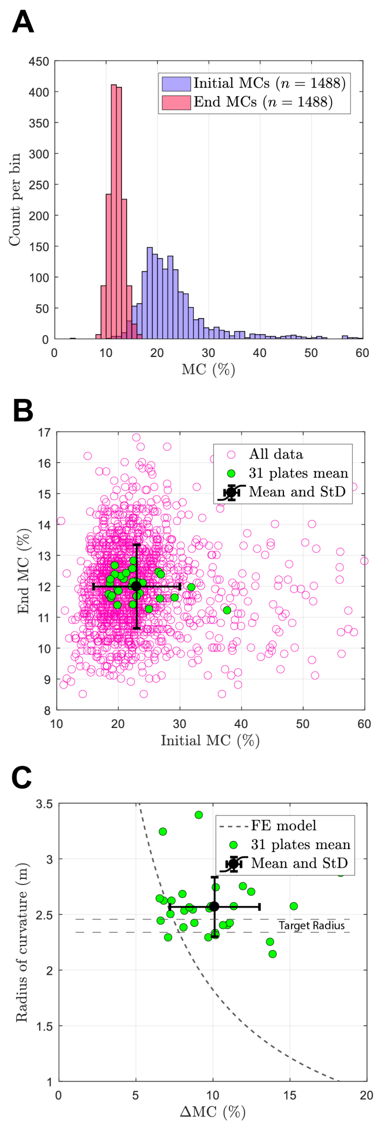

Figure 7.7: Results of the industry production cycle of 31 wood bilayer plates. A: Distribution of the input WMC, initial (manually sorted boards) moisture contents (MC) versus MCs after technical kiln-drying at 70C. B: Integral data of board-MCs. C: MC difference versus achieved radius of curvature of plate versus FE model prediction.

7.3 Self-shaping manufacturing

Most critically, the self-shaping process was successfully adapted to an industry context and proven versatile enough to be implemented in a real-world building process including design through the material programming framework. The results of the study show what is believed to be the largest purposeful self-shaping of surfaces, and the first known application of self-shaped surfaces in building construction. Adaptation of the process was able to overcome industry constraints, particularly in the sorting and preparation stages which created large variation in initial wood moisture content and more natural variation in the wood structure than in a laboratory test Figure 7.7. Still, the large multi-board bilayer plates self-shaped successfully and were suitable structurally for use in the final load-bearing building components. Notably, the five plates with curvature outside the prediction range and usable curvatures could be traced back directly to outlier boards and errors in the bilayer production Figure 7.7 . Despite the continued challenges of modelling the behaviour of wood, this study shows that sorting and precise material characterisation of a material with natural variation remains the most significant challenge for accurate prediction of self-shaping. Digital inspection and more advanced sorting of the raw boards would be the logical next step to improve the prediction and modelling, an aspect that is already implemented at the industry partner's site and is increasingly common in the wood industry. Advanced categorisation of the boards to include density, R/T angles and WMC would also allow for a more sophisticated digital interface and arrangement of the boards in the bilayer production beyond the simple instructions used in the current production. In the same way that boards are now sorted digitally for varied structural properties in

CLT and glulam manufacturing, they could be sorted automatically based on inputs for self-shaping, a purely digital step towards incorporating this function in the manufacturing process.

The physical results of the self-shaped curved CLT building components are promising and revealed a number of advantages. Article D briefly describes these results as benchmarked qualitatively with similar curved panels produced with a form-bending and curved formwork. First, the self-shaped panels exhibit excellent continuity of curvature per component Figure 7.8, while the form-bent parts have clear areas of discontinuity in curvature and flat areas. This can be attributed to the overall coordination of the self-shaping process which creates a fully distributed bending over a longer period of time compared to a formwork press which applies pressure at discrete points of time iteratively. The distribution of the shaping as a feature is especially useful as the parts become larger and the application of even force becomes more challenging. Third, after the locking of the bilayers the self-shaped components exhibit little elastic spring-back, as each of the primary layers requires little mechanical force or reshaping. These aspects contribute to an overall higher accuracy in the curvature and surface geometry of the components which dramatically reduces the amount of corrective surface machining and finishing necessary. Structurally, the complete CLT components perform equivalent to CLT standards, indicating that the experimental manufacturing does not negatively impact the overall structure. This is partially due to the sequencing and separation of the shaping and locking steps in the manufacturing. A more integrated interlayer or global locking mechanism is already the topic of future research.

Overall, self-shaping enables the production of curved components in which the material serves dually as the shaping actuator

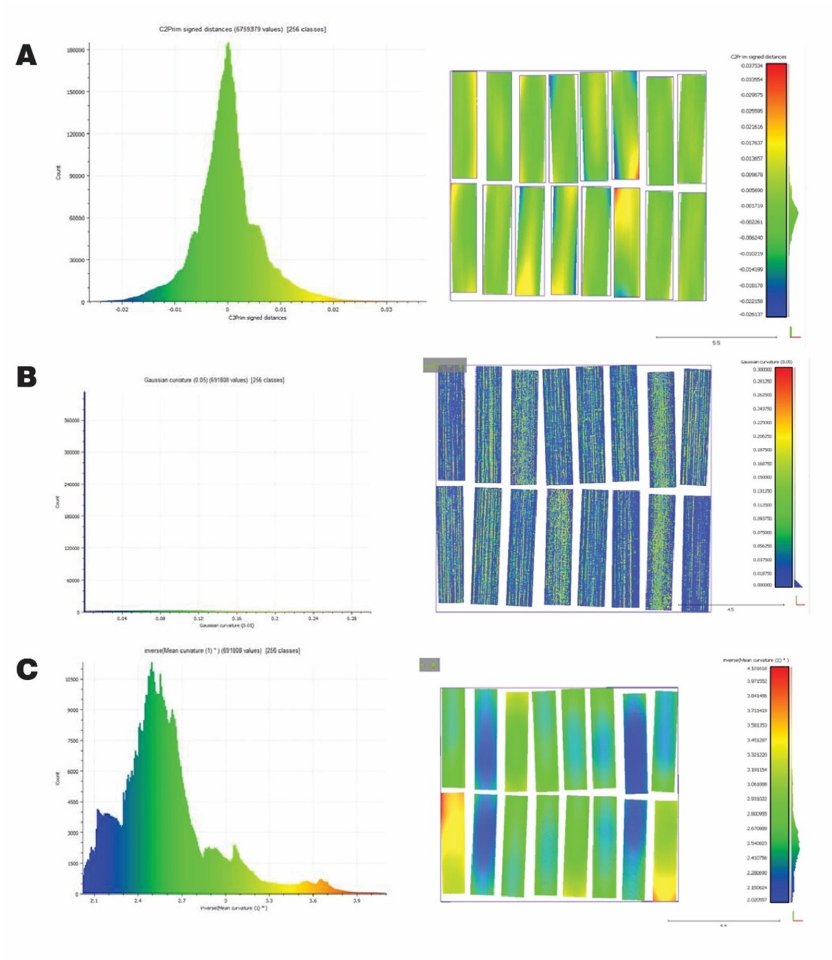

Figure 7.8: 3D laser scans of the 31 individual bilayer plates after self-shaping. Plots on the left and far right show the distribution of measurements for all plates and images while the plot in the centre shows the 3D scan results from the top view for a sample selection of plates. A: Signed deviation of the measured surface from a best-fit cylinder to evaluate the continuity of curvature in each plate. B: Measured Gaussian curvature per plate to evaluate double curvature. C: Radius of the local curvature in each plate.

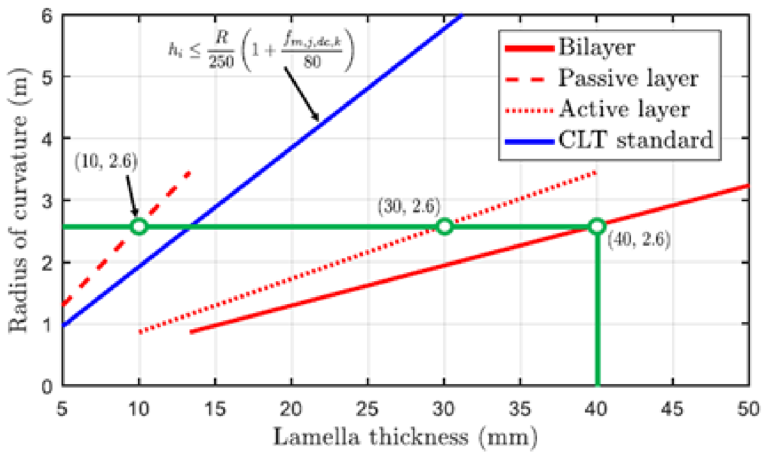

Figure 7.9: Theoretical comparison of achievable radii of curvatures of standard and self-shaped curved spruce CLT per lamella thickness. CLT lamella thickness of conventional curved CLT calculated from BS EN 16351:2015 (blue line). Lamella thickness in bilayers self-shaping calculated per layer (red dash and red dot) and per bilayer part (red solid). The green circles show the bilayer configuration used in the production of the demonstrator. Graph provided by Philippe Grönquist, adapted from [39]

and the structure of the final part. In concept, this integration reduces the amount of external shaping required as well as the impact of some manufacturing constraints. Results in practice showed that while similar curvatures could be produced using form bending, they require thinner average lamella thicknesses and more formwork. The self-shaping process could be used with thicker average lamellas and reduced total number of layers Figure 7.9. While some curved guides were needed for production, these were lightweight and used to position the curved bilayers and to provide only minimal correction during the lamination of the CLT. As a consequence, the self-shaping process increases the curvature that can be achieved with lamellas produced in ordinary sawmills (10–15 m thickness) and makes production of mid- and lower curvatures more material- and labour-efficient. More importantly, the self-shaping process is potentially highly adaptable in that different curvatures can be produced simply by adjusting the parameters of the boards in the flat bilayers Figure 5.3.

From an industry perspective, the self-shaping process presents a number of challenges, mainly that it contradicts decades of practice in terms of how to prevent hygroscopic deformation in wood during production and in use. An advantage is that many industry experts know exactly how to monitor these properties and all that is required is a simple rethinking of how to use them. One of the major practical challenges is how to equalise the boards reliably at the start of the bilayer production. As sawmills typically classify raw boards with a high range of WMC above the saturation point before drying, the precise sorting to a range around or below the saturation point is challenging. For example, sorting to 22% WMC was achievable without any addition of moisture simply through timing and selection within the production line. However, an initial WMC between 16 and 20% was considered unfeasible without an additional preconditioning of the boards between selection and bilayer lamination. This issue could potentially be solved through a combination of digitised input sorting, equalised storage chambers, or by simply fixing the initial WMC above the FSP, where dimensional changes do not occur, and using other parameters to tune the curvature.

In the industry-adapted process, kiln drying is used to actuate the bilayers. While kiln drying is the most energy-intensive step in wood processing and production [80], here it is dually used to replace additional shaping steps. The same self-shaping process could alternatively be used with air-drying with the tradeoff of speed. Controlling the initial WMC of the boards is also a problem that must be considered when production chains are spread between multiple locations and times. As a benefit in these studies, the self-shaping process could be implemented directly into existing physical infrastructure in a single location, replacing a shaping step that would typically require transportation of material over 100 km and back. This aspect alone provides a strong argument for the benefits of a simpler, material integrated manufacturing process. A more in-depth evaluation of the environmental impact of the manufacturing process is needed in the next steps of the research, while lifecycle analysis of the building material can be compared directly to existing studies of CLT building components.

7.4 Material programming approach

Material programming was successfully applied as a guiding principle and technical methodology connecting digital and physical design methods. The approach demonstrates a rethinking of digital fabrication to include and utilise material capacities as primary features. Computationally, a collection of digital to fabrication workflows are presented that interface with materially informed models. These were developed for a relatively narrow application and still require a number of manual communication and production steps. Further development can be described in two paths: (1) the detailed refinement and connection of these steps for a specific material programming application, and (2) the generalisation of the computational approach so that it can be better integrated in a wider range of design applications. The second is already part of further work to introduce a computational design tool that introduces simple material behaviours such as shape-change in a design modelling environment. Inevitably, advances in machine learning will contribute to both paths in terms of design integration and design exploration in self-shaping material systems, as shown in recent studies in related fields that incorporate simplified physics models to expand machine path planning [64] and computational approaches to programming and designing kinematics through material arrangement in living biological systems [58].

On a technical level, the material programming approach resulted in a manufacturing process based on the control of a limited number of low-level parameters that could be implemented entirely from existing production setups and technologies. By relying on the material for the most extensive production steps of shaping and forming, the barriers to production are dramatically reduced. Physical programming of the material early in the production process does, however, require a remarkable amount of trust in the design and prediction methods. Different from more direct shaping through force or subtraction, there is a considerable gap between the control input and the visible geometric results. Similarly, small corrective measures are still required to produce precise geometric results. The results of these studies successfully show that material programming can be used to produce this precision, but raise the larger question of the value of this objective. Embracing these types of material-driven processes may lead the way towards highly performative load-bearing architectures that retain a certain performative elegance as well as acceptable precision.

Figure 8.1: Visitors arrive at the Urbach Tower by foot and gravel bicycle.

8

Conclusions and Outlook

While timber construction is in the midst of a resurgence around the world, the Urbach Tower displays a unique approach to timber architecture. This dissertation highlights that a sustainable and well-known building material can be used to produce elegant and highly performative geometries. At the same time the use of material programming and self-shaping as design and computational fabrication methods proves to be a clearer, simpler and more effective production method than typical less materially integrated digital fabrication methods. Thus the use of a sustainable and regenerative natural material is promoted not only as an alternative but as an enabler for a new form of ecological and elegant architecture. Such lightweight, high-curvature, surface-active geometries could be valuable in spanning roof structures such as barrel vaults that traditionally require large formwork and heavy materials. In infrastructure, the high curvature and material efficiency of the process make it a potential lightweight and natural alternative for cylindrical structures such as wind-turbine towers or tubular masts constructed from reinforced concrete or steel. The added control and resolution of the computational tools and material programming approach also alludes to other methods of structural efficiency emerging from spatial patterns and folding structures already demonstrated at smaller scale in Article A and with bio-based 4D printing for curved-folding structures [94; 16] A7.

From an industry perspective, self-shaping has the potential to become a disruptive technology in terms of how shape and variation in shape is manufactured. This study shows that the technical challenges can be overcome, yet implementation requires a rethinking of how a material's capacity is viewed. In manufacturing this is a switch from requiring material correction to material utilisation enabled by a digital approach. Shaping through moulds remains a major financial and design barrier in manufacturing across many industries outside of architecture. Self-shaping through material programming may appear futuristic, but in many ways represents a true paradigm shift towards the core concepts of an Industry 4.0, in which digitally controlled and informed processes are highly adaptable by design. Imagine, for example, a factory in which natural materials are analysed, individual geometry is digitally calculated and physically produced by simply arranging the materials in a flat configuration from which completely different 3D forms emerge when actuated. With a single highly adaptable process an entire range of products or components could be manufactured. The shift from a mechanically driven manufacturing process to a material-oriented process expands many of the boundaries present in even the most sophisticated industrial robotic setups.

In this context, material programming for self-shaping is shown as a method of prefabrication, while development will certainly allow this approach to be incorporated into further aspects of construction. Self-shaping on-site of even larger multi-component structures would dramatically impact building construction. Such systems could erect silently with zero electrical input, for example, all but eliminating mechanical noise and air pollution on a construction site. In these cases, physically embedding the knowledge required for on-site shaping and assembly would be even more valuable than in a factory, allowing the low-tech autonomous construction of performative geometries without the presence of skilled workers, architects or heavy machines. Principles of this work also apply directly to responsive shape-changing material systems which are of particular interest in reducing the operational energy of buildings and systems that benefit form demand autonomy and reliability. Given the strength and actuation force of wood, such applications as responsive actuators should not have to be limited to either the small-scale parts or purely environmental actuation. Hygroscopic wood actuation can be tangibly imagined as integrated material actuators combined with digital control strategies, replacing hydraulic mechanical actuators currently used in large-scale adaptive structures [106]. Further, in responsive and/or fabrication systems, self-shaping is valuable as a distributable low-tech method of generating highly effective geometries in many parts of the world where technical building knowledge is limited, in extremely remote environments on Earth, underwater or in Space.

While this work showcases the material and computational aspects of material programming, it is undeniable that smart use of physical electro-mechanical mechanisms further enables the exploitation of a material's capacities. The outlook is therefore not to present self-shaping as a singular isolated solution, but as an example of an intelligent approach to a material-led machine relationship in which the material will play an increasingly important role as digital understanding and interaction grows. Such relationships are already becoming apparent as smaller, more agile and distributed machines are able to quickly learn to work more fluidly with dynamic and varying material characteristics such as bending [54]. It is clear that investigating this material–machine relationship from a fresh perspective opens entirely new avenues in architecture for many natural materials that may have otherwise been disregarded in contemporary construction.

In conclusion, this research demonstrates a material programming approach through an industry-adapted study of self-shaping manufacturing and an architectural building demonstrator. It highlights that computational design can enable innovative new manufacturing methods and architecture through the careful rethinking of existing materials and processes. On a conceptual level it presents a tangible vision for a material-driven approach and a paradigm shift in thinking towards how we can build more ecologically in the future.

9

Article A
Material computation – 4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces

Wood, D., Correa, D., Krieg, O. and Menges, A. (2016), **Material computation – 4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces**, International Journal of Architectural Computing (IJAC), Vol. 14 (1), pp. 49–62. DOI: 10.1177/1478077115625522

This article describes a forward-looking introduction to self-shaping wood surfaces from the perspective of architecture and construction. This includes a material programming approach for the digital design and fabrication of surfaces in which the orientation and arrangement of elements within a part impact the overall shape. A number of prototypes at the scale of 10 to 100 cm are produced, actuated and evaluated to validate the programming method. The article identifies a number of challenges for further upscaling the self-shaping and describes a wide range of applications.

The original research is by D. Wood and builds upon a number of concepts first explored in [107]. The research was inspired and guided by early work by A. Menges and S. Reichert on small-scale weather-responsive wood bilayer composites. The work was contextualised by D. Wood and A. Menges. O. Krieg contributed expertise in timber construction and digital fabrication, and D. Correa in the area of additive approaches to hygromorphic systems. D. Wood created the concept for and developed the custom digital workflow and was responsible for the production of all prototypes. D. Wood designed and evaluated all experiments. The manuscript was written by D. Wood and revised by D. Wood, D. Correa and O. Krieg.

Article

International Journal of Architectural Computing
2016, Vol. 14(1) 49–62

DOI: 10.1177/1478077115625522
jac.sagepub.com

Material computation—4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces

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Abstract

The implementation of active and responsive materials in architecture and construction allows for the replacement of digitally controlled mechanisms with material-based systems that can be designed and programmed with the capacity to compute and execute a behavioral response. The programming of such systems with increasingly specific response requires a material-driven computational design and fabrication strategy. This research presents techniques and technologies for significantly upscaling hygroscopically actuated timber-based systems for use as self-constructing building surfaces. The timber's integrated hygroscopic characteristics combined with computational design techniques and existing digital fabrication methods allow for a designed processing and reassembly of discrete wood elements into large-scale multi element bilayer surfaces. This material assembly methodology enables the design and control of the encoded direction and magnitude of humidity-actuated responsive curvature at an expanded scale. Design, simulation, and material assembly tests are presented together with formal and functional configurations that incorporate self-constructing and self-rigidizing surface strategies. The presented research and prototypes initiate a shift toward a large-scale, self-construction methodology.

Keywords

Hygroscopic, self-forming, computational design, autonomous actuation, wood structures

Introduction

The integration of active materials with the capacity to compute behavioral response based on environmental conditions represents a growing field in architecture and construction in which digitally controlled mechanisms are replaced by material systems that are based on the design and organization of the material itself. The value of a material's computational and physical power, however, is exposed only by the ability to design material systems with increasingly specific responsive characteristics. Programming a system response at the material level requires the development of material-driven computation strategies that incorporate a range of design, fabrication, and actuation parameters. These parameters are most heavily influenced by the material's ability to compute a physical response itself.

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The ability to design increasingly larger and physically stronger material systems that can form, assemble, or construct based on the material's embedded computational intelligence represents a fundamental shift toward a self-construction-based methodology. While the recent integration of Building Information Modeling, digital fabrication, and cyber physical construction techniques facilitate the flow of design information from the digital design space to construction site, the physical construction and assembly itself remain mechanically, labor, and energy intensive. However, by embedding construction information as well as the physical act of construction directly into a material system, the material can embody formative roles that have traditionally delegated to humans, computer-controlled automation, or direct mechanical output of form (extrusion, pouring, milling, etc.). Implemented at the building scale, self-construction systems that possess enough intelligence and strength to autonomously construct on-site stand to replace even the most highly sophisticated means of machine-assisted construction.

Current research in self-forming and self-assembling systems that implement reactive, shape-changing materials such as shape memory alloys, heat curling carbon fiber composites, or phase- or state-changing polymers is limited in scale by the quantity of required external actuation energy and the strength of the actuation itself.[1] However, the innate hygroscopicity of timber, specifically its ability to shrink and swell with high force in response to everyday changes in relative humidity, combined with its material strength presents a unique opportunity to implement environmentally actuated shape-changing behavior on an architectural scale. The presented research focuses on techniques and technology for encoding existing material intelligence and strength of timber for the purpose of developing large-scale, self-constructing timber surfaces.

The ability for single discrete timber elements to self-compute and execute changes in shape based on the surrounding environment presents the opportunity to assemble multiple parts into larger systems. Using digital computational techniques, the behavior of larger assemblies can be designed, simulated, and fabricated to perform complex movements when exposed to previously specified changes in relative humidity. Specifically, the methods presented describe the implementation of a timber bilayer composite systems designed and fabricated as two-dimensional (2D) flat surfaces that through self-forming actuation become self-stabilized rigid three-dimensional (3D) surface assemblies (Figure 1).

Context

Hygroscopicity in timber

Understanding the specific characteristics and associated functions of a natural material offers further insight into the possibility to re-conceptualize the material use in new applications. As both a living and dead tissue, wood cells possess the ability to absorb and release water to maintain equilibrium with their surrounding environment. Even after harvesting, the complex fiber arrangement within the microfibril structure of the cell walls and the anisotropic cellular arrangement result in strong anisotropic performance properties.[2,3] Of particular interest is the directionality of the microfibril structure as these cells provide a simple mechanism to control the direction of responsive dimensional changes and are directly correlated to changes in the relative humidity and temperature of the surrounding environment. Compared to traditional sensing and response systems where mechanical and electrical systems are composed of separate units for sensing, control, and actuation, the responsive properties of wood encompass all functions in the material itself, but at a micro-scale. Additionally, the material response operates autonomously without the need for external electro-mechanical input. This energy neutral, yet active responsiveness, combined with the extremely low embodied energy of air dried timber makes wood a sustainable and smart material, in both production and implementation of large-scale systems.[4]

The magnitude, strength, and actuation range of hygroscopically actuated changes in timber are remarkable when compared to synthetics. Across a range of common species with dimensional changes between

Figure 1. Self-constructing timber surface in a flat and a fully actuated three-dimensional state.

6% and 30%, wood moisture content occurs on average 7.95% tangentially, 4.39% radially, and a negligible amount longitudinally.[5] The extremely high forces extorted by the dimensional changes occurring at the cellular level measured as the swelling pressure of wood have a measured value of 91 MPa (13,000 psi) and a theoretical value of 158 MPa.[6–8] Qualitatively, this force is exemplified by the known use of hygroscopic expansion in wood wedges as a method for splitting granite stone from quarries in ancient Egypt.[9] The large expansion force is of particular importance when considering that although the speed of actuation decreases with increased thickness, the actuation occurs with in typically inhabitable environments. Specifically, the relationship between moisture content, saturation point, and maximum geometric deformation in wood occurs at relative humidity ranges between 25% and 100%. A careful correlation between species selection and the desired functionality can replace the need to highly engineer new materials at multiple scales. This reliance on the existing material and the environment conditions of inhabitable spaces simultaneously reduce the need for additional energy input (to operate) and the level of processing needed to apply the material in a functional context.

Bilayer-responsive material systems

In the prototypes presented, a bilayer timber composite system is used to transfer hygroscopically actuated dimensional changes into responsive bending in timber surfaces. Bilayer theory, developed for thermally responsive bimetallic alloys, describes the curvature resulting from combining multiple layers with different coefficients of expansion.[10] The application of bilayer material systems as environmentally responsive façade systems has been previously studied using thermally responsive bimetallic alloys and humidity-responsive wood composites.[11,12] The bilayer wood composite system used in this research has been developed based on previous work by the Institute for Computational Design in the fabrication and material programming of single-part wood veneer and glass fiber bilayer composite elements designed for fast and reliable response to environmental conditions.[12] Additionally, single-element, hygroscopically responsive bilayer wood systems are currently being developed and tested as actuators for large-scale mechanical systems.[13] Both systems employ an active wood layer combined with a non or less active restrictive layer with opposing or isotropic fiber orientations. The presented research aims to expand the size, application, and complexity of movement of the responsive wood systems by further exploiting the material's hygroscopic behavior in large-scale surfaces with formal and functional variation in responsive curvature.

Embedded material intelligence in construction

The introduction of computational design and fabrication techniques in relation to material properties allows for increased local variation within the material and building system. On an architectural scale, methods of encoding system behavior have so far been limited to the predefinition of geometric properties that require external actuation. This method of pre-encoding geometric form that takes into account material behavior in a large-scale system is exhibited by Frei Otto's Mannheim Multihalle, erected in 1975. Of particular interest is the design methodology Otto employed to physically simulate the behavior of the global form and abstract the information to engineer and construct a full-scale 2D grid that is precomputed to form a designed 3D geometry when manually raised and constrained.[14] By implementing a responsive material system into a similar design methodology, large-scale systems can also be encoded with self-formation behavior, thus eliminating the need for additional manual or mechanical input to achieve its final state (Figure 2). The proposed material system allows the designer and engineer to build up large, initially flat, timber surfaces with locally encoded responsive behavior that can autonomously self-form into pre-established 3D configurations in response to defined environmental conditions. Pre-programming a global surface with local changes in direction and magnitude of curvature allows for an expanded range of functional and formal responsive behavior. While the design of such active systems is based on the existing material properties themselves, the integration of computational techniques enables increased control, calibration, and tailoring of the system for a specific application.

Advances in computational control and material distribution have allowed for the introduction of both passive and active performative heterogeneity into material systems at nano-, micro-, and meso-scales.[1,15,16] Micro- and meso-scale tailoring of hygroscopically responsive material systems with anisotropic performance has been previously demonstrated by the Institute for Computational Design, with 3D printing of natural and

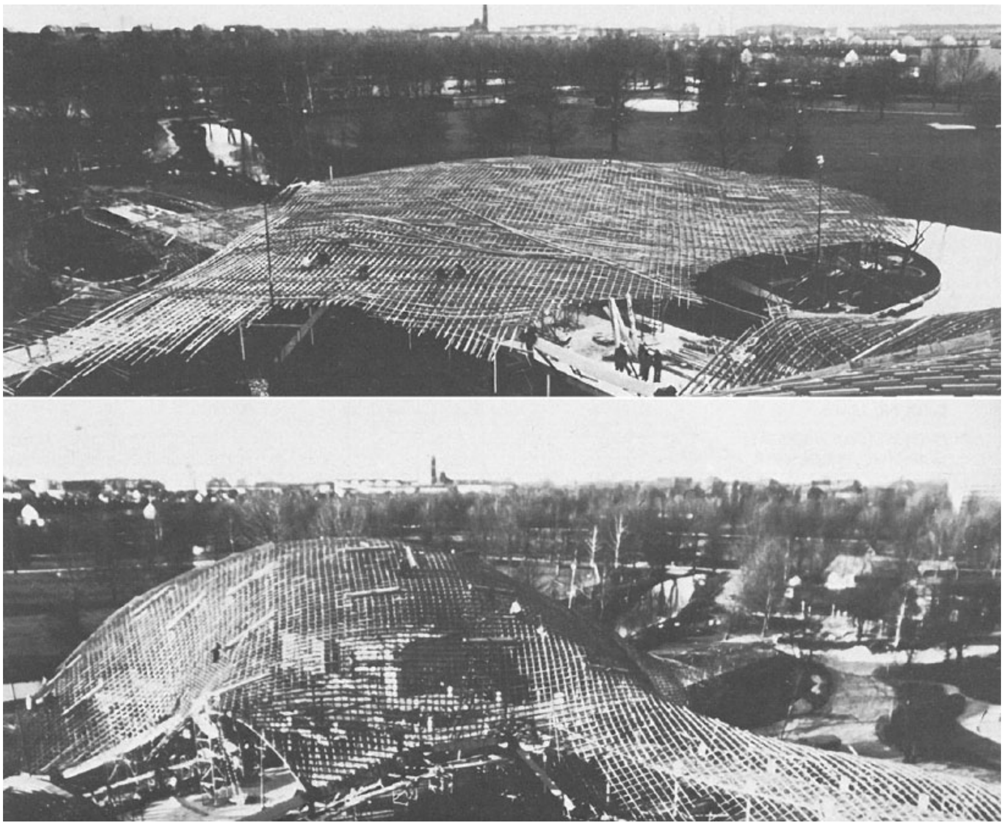

Figure 2. Mannheim Multihalle, grid before and after lifting procedure. (Institut für Leichte Flächentragwerke, Universität Stuttgart)

synthetic polymers.[17] Proven principles and techniques for creating variation in responsive deformation can be transferred from the micro- and meso-scale to the macro-scale systems presented in this research.

Methods

The research presented proposes a methodology of macro-scale behavior tailoring through an assembly of multiple discrete elements that are developed with an emphasis on augmenting the existing material qualities at a resolution suitable for large-scale systems. The proposed design, simulation, and fabrication methods rely on the close integration of material performance criteria and selection, industrial wood processing technology, digitally controlled fabrication, and post-actuation analysis. By initializing the largest possible naturally occurring wood element as the basic unit/component in the material assembly, the overall size of the assembly can increase while retaining a response magnitude relevant to the global scale and the existing structural integrity of the material. Similar nonresponsive engineered wood systems composed from small low-value wood parts were used by Philibert de l'Orme in 15th-century France. In response to shortages of large pristine timber, de l'Orme developed these assembly techniques to build large wooden vaults using principles of "carpentry of small pieces."[18] In addition to an increased economy of material, the multipart systems offered an expanded array of structural and aesthetic options—as it is free from the geometric and dimensional constrains of raw lumber.[19] The method presented builds on these assembly techniques by incorporating additional material performance qualities both affecting the structural performance of the systems and enabling new possibilities for self-forming. In combination, this assembly strategy allows for the production of increasingly larger systems.

Integrated design and simulation

Two simple manipulations are used at the element level to control the behavior in the global assemblies. The primary parameter is the orientation of the interactive length of each element. Given that the boards used have been cut so that both radial expansion and contraction occur perpendicular to the grain (in the width of the board), it is possible to define this parameter by simply orienting the element geometry with its derived angle of curvature perpendicular to the grain. By setting the direction of the interactive length of each element within the global arrangement, the designer is effectively reconfiguring the grain direction within the global surface. When activated, this new grain orientation directly transfers to the direction of principle curvature in the surface. As a secondary manipulation, the thickness of the active elements is used to control the speed and magnitude of the curvature, with a thinner active layer actuating faster to higher curvatures and a thicker layer actuating slower to lower curvatures. Combing these two parameters allows for the preprogramming of direction, speed, magnitude, and strength of responsive curvature.

Computational design strategies are used to simulate, visualize, and calibrate the material in order to control specific movements of the system and therefore enable an expanded range of designed application. While the basic single-directional responsive curvature in an individual bilayer element can be estimated mathematically using Timoshenko[10] and verified using physical testing, predicting the interaction between multiple parts is a computationally intensive task that requires a simplified model of the material behavior. Through multiple physical tests, the magnitude of curvature of an individual, single-curvature bilayer element has been verified in relation to active layer thickness. The results of these tests have been implemented into a computational model and simulation tool that allows for the design of the direction and magnitude within each element or the design of more general global behavior. This informed design tool is also directly connected to digital fabrication process, outputting the geometry, orientation, machine code, and assembly information of each active layer component.

Digital simulation of a global surface transformation over time serves as a crucial part for the development of the system within the limits of the material properties, as well as orchestrating the design of more complex behavior in multipart systems. The developed tools allow for a combination of both top-down and bottom-up design strategies. Initial form-finding simulations, using spring-based physics engines, are used to develop forms with areas of single curvature within the known responsive range while still constrained by the elastic limitations of the material. From this model, values of principle curvature (vector and magnitude) can be locally evaluated to inform the proposed grain orientation and thickness of a corresponding high-resolution 2D fabrication mesh. This mesh information is then reduced into a low-resolution mesh consisting of individual parts constrained in size by the interactive dimensions of the material. Following this initial cycle, a simulation of the proposed fabrication mesh is performed by transferring the digitally proposed grain orientation into weighted values for hinges along the internal edges of a dense triangular mesh. This second simulation ensures the system functions within the tested behavior of the material while taking into account the low resolution of fabrication. Adjustments in the local behavior of single or multiple elements can be made by the designer at any point in the simulation process, therefore allowing for visual evaluation of changes of the encoded orientations and magnitude of response.

With the ability to accurately simulate and fabricate specific local behavior, the responsive performance of the material system can be designed to achieve more specific functions. In the large prototypes presented here, this directional articulation is used to generate more complex formal and functional configurations. These global surface design strategies are aimed at providing global self-stabilization as the system shifts from a flat surface with low stiffness to a designed, rigid 3D geometry. While uniform single-directional curvature can be used to create a simple arch, local variation of curvature direction, and areas of opposing curvature directions can be used to increase rigidity in larger responsive surfaces.[20,21] In the prototypes shown, curved creased folding, a method of curving a surface in opposing directions along a shared fold or crease, is used to produce geometrically stable 3D configurations that are formed from a previously flat and continuous surface. Curved folding techniques can be tested physically or digitally in order to simulate how a surface can fold from independent actuation. Moreover, by embedding fabrication parameters, the developed computational design can at any point be translated directly to material fabrication data, as well as re-simulated based upon the correlating intra-material bending data of each local element. This second method serves as both a link in matching the material behavior to the top-down design process and a way for the digital exploration of geometric configurations beyond what can be understood through the top-down design method. Integration of specific material characteristics, such as wood species, tensile and compressive strength, joint strength, and the full integration of structural analysis software into the design simulation, will be used to further reduce the gap between physical testing and digital design.

Material selection, processing, and analysis

Material selection of both wood species and board type (processing technique) was based on the desired combination of expansion and contraction in both tangential and radial directions, structural integrity, material consistency, and current and future local availability. Plain-sawn timber cut through the center of the tree, also known as heart-sawn timber, was selected as it provided larger stock parts with consistent radial fiber orientation throughout each piece. The center or heart was removed, and the stock was custom-processed into thinner boards and equalized at the desired moisture content of the flat configuration of the end-designed piece. Each board is photographed and analyzed using image recognition tools to calculate the average grain angle at a resolution of 100 mm, thus creating a digital database of natural variation in fiber orientation in the stock material. In the context of this research, Beech (*Fagus*) and Maple (*Acer saccharum*) timber were selected as the active layer due to a combination of high expansion and contraction properties (5.5% radial, 11.9% tangential, and 4.8% radial, 9.9% tangential), respectively, high material strength, and local availability.[6] Additional interest in the use of Beech wood arises from the fact that the species represents nearly a quarter of the wood being harvested from local south German forests, with nearly 50% of the harvested timber being disregarded or used as fire wood.[22] Through a reevaluation of the material's innate properties, it may be possible to affect this historical deflation of the value of the species as a construction material while further contributing to its repurposed value in a large-scale responsive system.

Fabrication and production

Individual triangular elements are mapped on the stock sheets based on the fiber orientation required by the direction of principle curvature at their corresponding location; this is based on the digitally simulated, 3D curved surface (Figure 3). Finger joints are places on the interior edge of each part with the angle and size of the joint varied based on the relationship between the joint angle and the grain direction. The elements are individually cut on a three-axis computer numerically controlled (CNC) routing machine with tolerances precisely adjusted to allow for friction-based manual assembly. Once assembled, the active surface is again equalized to the pre-design required state and the restricting layer is laminated to the active layer. In some cases, the assembled surface is robotically milled to locally adjust the thickness of the material to match the desired magnitude of curvature.

Actuation and analysis

Completed surfaces are stored at the relative humidity corresponding to the moisture content in the designed flat state. The surfaces are actuated by raising or lowering the surrounding humidity compared to the preparation and production environment (Figures 4–7). During actuation tests, geometric changes are

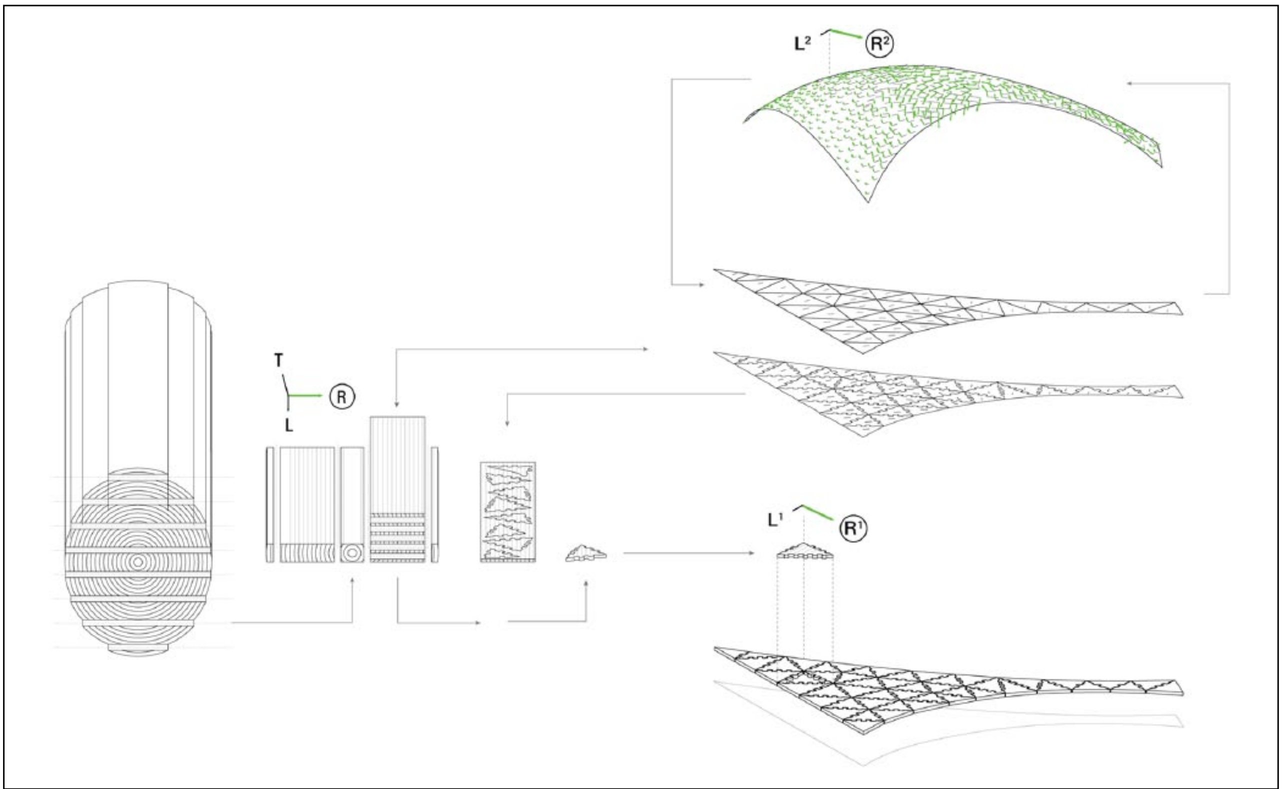

Figure 3. Material processing, design/simulation, and assembly of responsive timber surfaces. Radial (R), tangential (T), and longitudinal (L) fiber orientations in harvested timber are reassembled to create local variation in grain orientation (L^1, L^2) and direction of consistent expansion and contraction (R^1), resulting a specific direction of curvature in simulation and actuation (R^2).

monitored using 2.5D optical scanning. Deformation measurements are compared in relation to the time spent at varying relative humidity and the moisture content of the material system, which is measured using the double weight and resistance methods. When the surfaces have reached equilibrium with the target environmental conditions—a process that can take between 1 h and 10 days depending on the thickness of the active layer—the moisture content is again measured and parts are 3D scanned using a high-resolution optical scanner (Figure 8). This process verifies the local and global geometric changes as a function of moisture content and time and is used to further calibrate simulation and design methods.

Case studies

Maple veneer/composites

A series of initial prototypes of 0.3 m × 0.2 m (approximately) were developed to demonstrate the ability to introduce multiple fiber orientations in a single wood composite surface. The surfaces were produced using 1.2 mm maple veneer, 40 g/m^2 glass fiber textile, two-part epoxy resin, and fabricated at below 6% wood moisture content. The surfaces were tested by placement into a climatic chamber oscillating in 1-hr cycles between 30% and 90% relative humidity (RH) environment. Given the minimal thickness of the veneer, full deformation could be observed in approximately 15 min. The resulting surfaces show the capacity of the system to quickly transform from a thin flat surface to a rigid curved folded geometry in a reliable manner throughout multiple testing cycles.

Figure 4. Self-forming and self-rigidizing responsive veneer surfaces.

Figure 5. Self-forming and self-rigidizing responsive veneer surfaces, 60 min at 95% relative humidity.

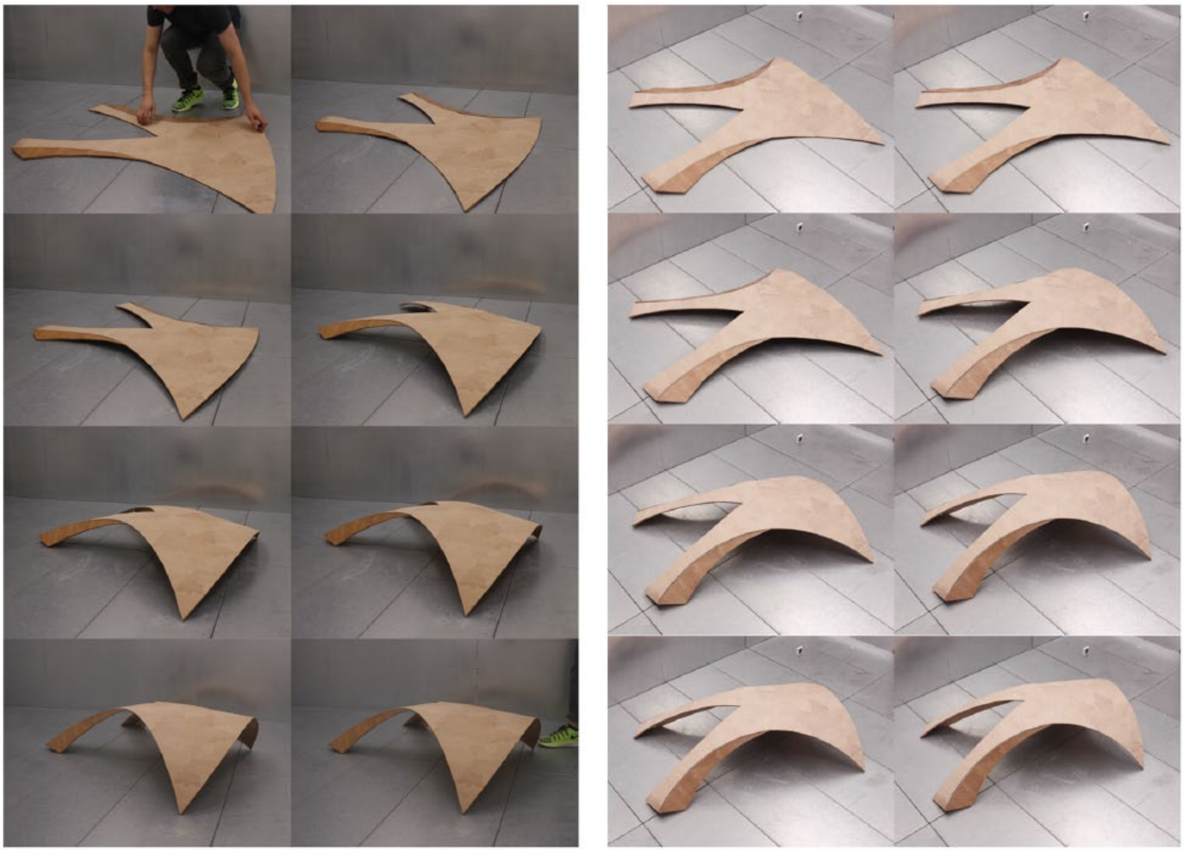

Figure 6. Self-constructing and self-rigidizing responsive timber composite surfaces, 2 views.

Beech/glass fiber composite

Larger composite prototypes of 1.5 m × 1.0 m (approximately) were developed to test the scale and strength of the material system. Two distinct surfaces were designed to test the capacity of the computational and fabrication methods to adapt to both formal and functional criteria. Surfaces were produced using 12 mm Beech, 80 g/m^2 glass fiber textile, and epoxy resin and fabricated at 10%–15% wood moisture content to allow for responsive movement in both directions. Following lamination, the surfaces were robotically milled to create a local variation in thickness of 6–12 mm. The surfaces were primarily actuated by placement in 90% RH and actuated into a rigid 3D geometry after 24–72 h. Analysis of the actuated surface shows the ability of the material system to combine the responsive curvature of discrete elements to create a designed multi-directional response in a global surface.

Maple/spruce

Further prototypes of 1.5 m × 1.0 m were produced using an all-wood bilayer system, allowing for precise control of the fiber orientation of both the active and restrictive layers, an increase in bending strength across the joint between active elements, and a reduction in the reliance of synthetic materials. The active layer was produced

Figure 7. Self-constructing and self-rigidizing responsive timber surfaces.

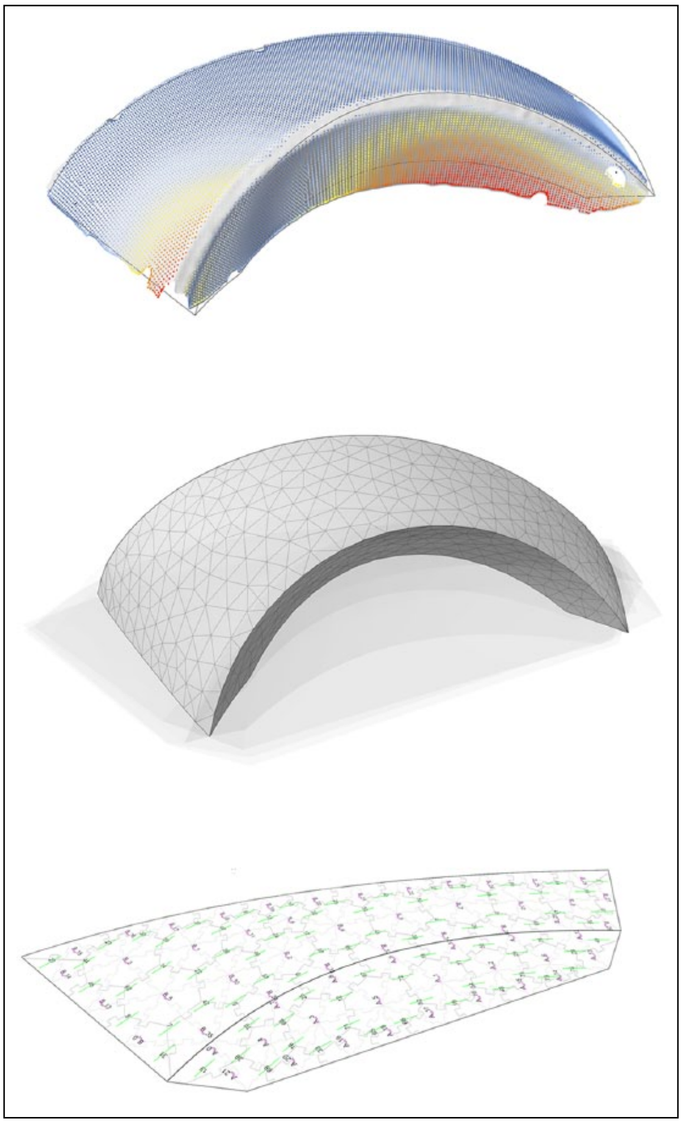

Figure 8. 2D fabrication information generated from digital simulation and comparison of digital simulation and 3D scan of Maple/Spruce bilayer surface at 95% actuation.

using triangular elements of 10 mm maple. An overlapping restrictive layer was computed using the dual mesh of the active layer and produced from 2.0 mm spruce veneer, chosen for its high tensile strength and flexibility. Prototype C was fabricated at over 30% wood moisture content (MC) and actuated by drying to equalization at 30% RH. A wet/flat, dry/actuated process allows for increased stiffness in the final 3D form as the material stiffness of wood is inversely related to moisture content. Prototype C also incorporates 3D printed compliant hinge joints inserted at the fold between areas of opposing curvature. These joints are printed in the 3D configuration and held flat by the self-weight for the piece, thus providing a small material-driven guiding force during the actuation process. Preliminary analysis and load testing of Prototype C showed an increase in overall stiffness in the actuated state that can be attributed to the combination of increases in material stiffness, material system stiffness, and the use of curved folding as a global design technique. A comparison of the actuated surface to the digital simulation shows an average deviation, measured at the center of each triangle of ±10 mm.

Discussion

By successfully integrating multiple wood elements into a single responsive surface that self-constructs to a designed geometry, the system solves the primary material constraints of limited size and material irregularities. Additionally strategies for increasing geometric stability in the high curvature stage have undergone limited testing through finite element method (FEM) analysis, empirical loading of the samples to simulate point or uniform load conditions, and nondestructive load testing. The development of material-driven computational strategies of design, simulation, and fabrication exposes the potential for a readily available natural material to perform large-scale high-strength responsive movements beyond that of synthetics.

Further utilization of the simulation and evaluation tools is needed to fully explore the design potential and application of the material system as a building-scale surface or shell. Additionally, methods for adjusting discretization resolution in areas where both the desired behavior and material constraints allow could optimize production and enable additional functional performance. The integration of structural analysis and physical structural testing will allow for a functional evaluation of the designs as the scale increases. Exploration of additional material assembly strategies will allow for the development of advanced functional behavior. While the current material system is limited to the combination of areas of primarily single-curvature, initial studies have shown that anticlastic and synclastic curvature, as well as production of bi-stable effects, is possible through bilayer systems. Advances in robotic online fabrication could provide an interface between material and machine to more easily create precise complex assemblies from active natural materials.

Conclusion

The research presented describes the potential to enhance digital design and fabrication technology using the innate material characteristics of timber to produce self-constructing surfaces at an architectural scale. Further development focuses on techniques to increase the scale and complexity of both natural and composite material systems. The increased scale and ability to compute design-specific responsive material systems greatly expand the future application of self-construction. The ability to tune the material system to meet specific responsive performance criteria of large-scale surface transformation could be used to form self-rigidizing shell structures. Designing the system to be produced at the extremes compared to conditions in which it will be deployed, the system could then achieve a permanent shape transformation when released on-site. Comparatively, the robustness, reliability, and capacity of the material to continuously reprogram itself in correlation with long-term changes and environmental patterns make it ideal for building applications such as water collection and adaptive shading and ventilation systems. An expanded scale also enables for entire buildings or complex building elements to be produced and transported in a compact form, placed on-site and allowed to self-assemble/construct. From an economic, social, and environmental context, the integration of the construction process into the material system could radically impact construction methodology. Economically, the near elimination of on-site labor and machine assembly drastically reduces the time, cost, and safety concerns of construction by removing humans and failure-prone electrical mechanical equipment. Socially, the embedding of construction knowledge and information directly into a material system itself would decrease the reliance of highly skilled designers and contractors to produce high-quality architecture. This could allow a self-constructing material system to be deployed to remote or undeveloped areas and the construction to be reliably executed automatically as designed. The potential to design the behavior of such system reveals a new role for the architect, designer, and material scientist, focusing on the ability to embed design into active, material-driven, building-scale construction.

Acknowledgements

The research presented was initially conducted as an MSc thesis project under the Institute for Computational Design's ITECH program at the University of Stuttgart. The authors would like to extend their thanks to Steffen Reichert of the Institute for Computational Design, Prof. Jan Knippers of the Institute for Building Structures and Structural Design, Andreas Kulla of the Faculty Wood Workshop, and colleagues Matthias Helmreich, Yassmin Al-Khasawneh, Tobias Grün, and Emily Scoones. Scientific support and advice for the project were graciously aided by Prof. George Jeronimidis, University of Reading, and testing and verification was supported by the Wood Material Science group at the Institute for Building Materials, ETH Zurich.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

Research funding provided by the Getty Foundation's GettyLab.

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Article B Hygroscopically actuated wood elements for weather responsive and self-forming building parts: Facilitating upscaling and complex shape changes

10 Article B
Hygroscopically actuated wood elements for weather responsive and self-forming building parts: Facilitating upscaling and complex shape changes

Wood, D., Vailati, C., Menges, A. and Rüggeberg, M. (2018), **Hygroscopically actuated wood elements for weather responsive and self-forming building parts: Facilitating upscaling and complex shape changes,** Construction and Building Materials, Vol. 165, pp. 782–91. DOI: 10.1016/S0950061817325394

This article describes the steps required for upscaling self-shaping in wood surfaces in the context of material science and engineering. Through physical experiments, analytical prediction and physical evaluation it defines a range in which larger multi-part surfaces can be produced and actuated. In parallel it describes the potential and initial studies for producing self-shaped anticlastic and synclastic curvature in complete surfaces, the limits of which are discussed. The results are presented in the context of applications for both weather-responsive building systems and self-shaping production.

D. Wood and C. Vailati are co-authors of this original research. D. Wood is jointly responsible for the concept guidance and basic scientific work. The concept and scientific objectives were defined by M. Rüggeberg, and applications and upscaling discussed with A. Menges. Experiments for the multi-part bilayers were designed and conducted by D. Wood with the supervision of M. Rüggeberg, and for the smaller single-part bilayers by C. Vailati and M. Rüggeberg. The prediction methods were completed by M. Rüggeberg and material characterisation was carried out by C. Vailati. Results of the experiments were by all authors. The manuscript was written by D. Wood and revised by M. Rüggeberg with input from C. Vailati. The article formed the scientific basis of the research funding proposal. The article is included in the PhD dissertation of C. Vailati [102].

Construction and Building Materials 165 (2018) 782–791

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Hygroscopically actuated wood elements for weather responsive and self-forming building parts – Facilitating upscaling and complex shape changes

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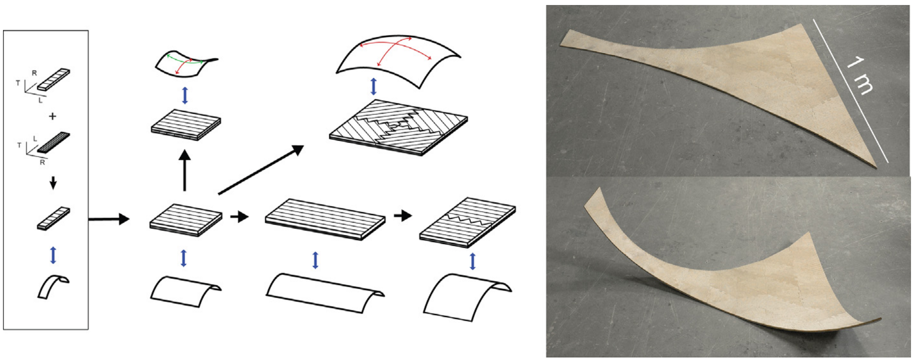
HIGHLIGHTS

- Wood bilayers self-deform in response to changes of relative humidity.
- Monoclastic, anticlastic and synclastic curvature can be achieved.
- Curvature pattern is controlled by material related design principles.
- Upscaling of wood bilayers to metre scale is feasible.
- New applications for wood in construction and climate adaptive architecture.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form 18 December 2017
Accepted 19 December 2017

Keywords:
Wood
Bilayer
Upscaling
Surface curvature
Shell
Climate adaptive architecture
Complex shaped building components

ABSTRACT

For the performance of wood as a building material, its dimensional changes in response to alterations of relative humidity are commonly perceived as an adverse effect. Recently, this material inherent property has been proposed to be utilized in a smart way. Employing the bilayer principle, controlled and reversible shape changes in response to changes of relative humidity were demonstrated. Wood naturally inherits a unique combination of material properties specifically suitable for large-scale shape-changing parts. While being environmentally responsive, it offers high mechanical stiffness throughout shape-change, ease of machining and working, and sustainable availability in large sizes and quantities. In this study, we demonstrate design principles for achieving a range of shape changing patterns such as uni- and bi-directional surface curvature of wood and wood-hybrid bilayers with both negative (hyperboloid curvature) and positive Gaussian curvature (spherical curvature). In parallel, we have developed suitable joints to join multiple elements to facilitate upscaling in length and width while maintaining shape-change. The ability to design and control the type and magnitude of curvature for specific sizes, shapes, and aspect ratios open the opportunity for a new class of large-scale weather responsive elements and self-forming building components.

Abbreviations: CNC, computerized numerical control; E, elastic modulus; FE, finite element; GFRP, glass-fiber reinforced polymers; L, longitudinal; R, radial; T, tangential.

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https://doi.org/10.1016/j.conbuildmat.2017.12.134

1. Introduction

The dimensional instability of wood in response to water uptake and loss is regarded as one of the major drawbacks and limitations for its use as a building material. Various strategies have been developed to increase the dimensional stability of wood by either structural adaptation, e.g. formation of plywood, or its chemical modification. In contrast, the perception of the swelling of wood as basis for creating smart, shape-changing wood elements and building parts has only emerged recently [1–4]. Inspired by natural responsive bilayer structures such as the scales of pine cones [1,5] or the awns of wild wheat [6], wood has been taken as the responsive material for developing humidity driven shape changing bilayers, which reversibly bend in response to changes in ambient relative humidity [7,8].

The bi-layered element acts as an integrated sensor and motor; as a result the shape change of these elements is entirely autonomous. Such adaptive elements can be components of a new generation of sustainable, simple, "zero-energy" weather adaptive building components [9] being solar driven and controlled with the long-term stability of the shape change already proven [10]. Next to this, wood bilayer elements may also drive the self-deformation of wood parts from an initially flat state at manufacturing to the desired, programmed, complex curved state by simply altering the wood moisture content by changing ambient relative humidity [11,12]. In case of using the self-deformation capabilities for manufacturing curved wood parts, any further change of wood moisture content and, thus, shape change needs to be blocked, which may be challenging in some cases. The utilization of the self-deformation capacity may be especially suitable for the manufacturing of curved shells. Such shell geometries can be used to increase structural performance by adding depth to an overall geometry to increase stiffness [13]. In the case of double curved shell geometries, taking advantage of membrane forces allows for reducing material thickness and, thus, weight in building components and complete structures [14].

These innovative applications require an upscaling of the size of wood bilayers and a precise control of the pattern of shape change rather independent of their initial shape and geometry. Wood offers a unique combination of responsiveness with high force, high mechanical stiffness during shape-change, and good machinability, which makes it a highly favorable material for such large-scale multi-element responsive systems [12]. Yet, manufacturing large-scale wood bilayers with low aspect ratios leads to new opportunities as well as material specific challenges. Whereas bi-layered wood strips at small scale show unidirectional (monoclastic) curvature (Fig. 1a), bi-directional, anticlastic curvature will occur [4,15] for wood bilayers with low aspect ratio as both layers are responsive in an anisotropic manner (Fig. 1e). Whereas this enables the construction of anticlastic forms, other large-scale applications will demand retention of monoclastic curvatures as obtained for bi-layered wood strips on small scale [8], if, e.g., straight edges for fixing are necessary (Fig. 1b and c). Next to this, the diameter of the tree trunk imposes a natural limit for the width of boards (Fig. 1a R) and, thus, the length perpendicular to fiber orientation. Using rotary pealed veneers, this limitation could be bypassed; however, the thickness of the layer would be restricted to 1–2 mm for ensuring good-enough quality.

By applying geometric and material adapted design principles and multi-element assemblage, we demonstrate the possibilities and requirements in geometry and structure of wood-composite and wood bilayers for obtaining the different types of curvatures, namely monoclastic, anticlastic and synclastic curvature (Fig. 1). In particular, we show how to retain monoclastic curvature for wood bilayers with low aspect ratio (Fig. 1b–d). With a large wood –GFRP (glass fiber reinforced polymer) composite bilayer comprising an assemblage of wood elements (Fig. 1f), we demonstrate synclastic curvature by the anisotropic swelling of wood and the restrictions in swelling introduced by the specific orientation of the wood elements (Fig. 1f). We demonstrate the principals of wood bilayer deformation with combinations of three different common European wood species, which are beech, maple and spruce. Hereby, we take the two hardwood species beech and maple wood as drivers of the deformation, as in particular beech wood has a very high swelling coefficient, whereas we use spruce wood as important construction wood for the resistive parts of the bilayers. As joining is in general essential for upscaling, we present a joining pattern that ensures structural stability during service while retaining maximum shape change.

2. Material and methods

2.1. Bilayer manufacturing and conditioning

For manufacturing bilayers, in principle, any wood species can be taken. The individual differences in swelling and shrinking of different wood species as well as in their mechanical properties, workability and availability can be utilized and specific combinations of wood species for different applications can be chosen. For the present study, wood bilayers were manufactured from combinations of beech (*Fagus sylvatica*), European maple (*Acer pseudoplatanus*), and spruce (*Picea abies*) wood by gluing together two layers of wood using 1-component-polyurethane glue (HB-S309 and HB-S709, Henkel, Germany) according to the guidelines given by the manufacturer. Prior to gluing, the wood was equilibrated to the relative humidity and temperature present at gluing in climate chambers. The wooden bilayers were weighed before and after gluing in order to estimate the weight of the added glue. For all wood bilayers, fiber orientation of the two layers was orthogonal to each other and parallel to the edges of the bilayers, which represent the x- and y-axis of the sample coordinate system used throughout the present article (Fig. 1a).

2.1.1. Beech-spruce bilayers

Beech-spruce bilayers were manufactured using a 4 mm thick beech wood sheet (Paul Aecherli AG, Regensdorf, Switzerland) and a 0.8 mm thick spruce wood veneer (Hess & Co. AG, Döttingen, Switzerland). Beech wood with its very high swelling capacity was used in tangential-longitudinal orientation with fibers (L-direction) along x-axis and T (tangential)-direction along the y-axis of the bilayer for maximum dimensional change along the x-axis. The spruce veneer was used in longitudinal-radial (L-R) orientation with fibers along the y-axis and the R-direction along the x-axis. With this choice of orientation pattern and the thickness ratio of 1:4, it was intended to promote monoclastic curvature independent of the aspect ratio of the bilayer. The y-dimension of all beech-spruce bilayers, which corresponds to the T-direction of the beech layer, was set to 120 mm, whereas the x-dimension, which corresponds to the R-direction of the spruce layers was set to either 20, 40, 80, or 120 mm. For each configuration, three replicates (samples) were manufactured. Samples were equilibrated at 85% relative humidity and 20 °C prior to gluing. The bilayers were transferred from 85% to 35% relative humidity. Wood moisture content and curvature were measured at 0, 1, 2, 4, 6, 8 and 24 h after the transfer of the samples.

2.1.2. Beech bilayers with low aspect ratio to produce anticlastic curvature

Beech bilayers were manufactured from a rotary peeled beech veneer (LT-plane) with a thickness of 1.2 mm for both layers

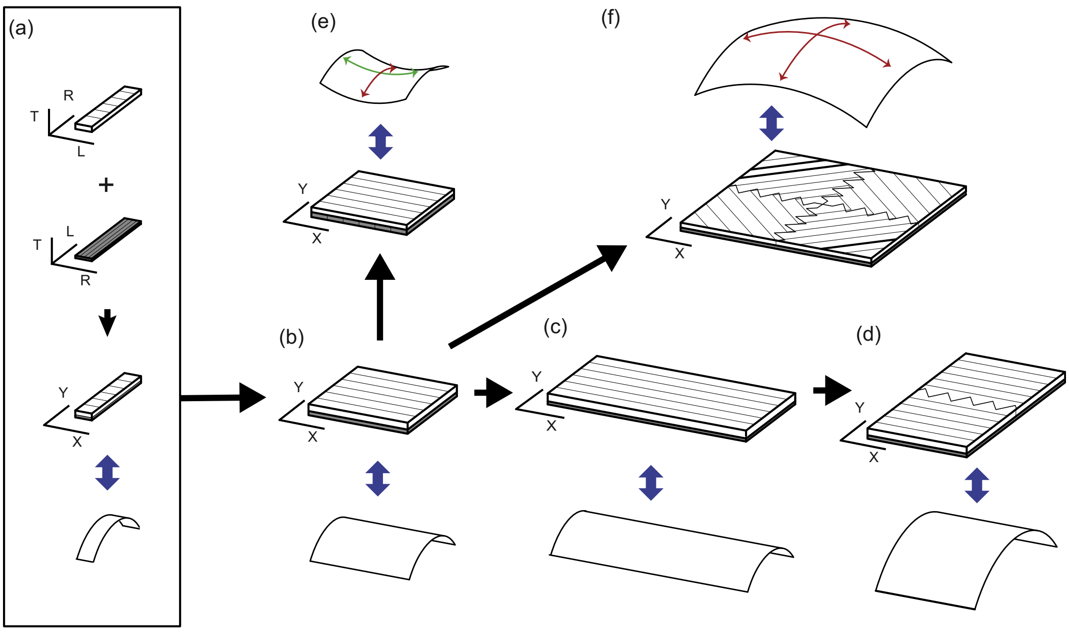


Fig. 1. Upscaling and diversifying shape changes of wood and wood – composite bilayers as a result of adapting geometry and introducing multi-element assemblage. (a) Small scale wood bilayer actuator with high aspect ratio show monclastic curvature (bending). (b) Wood bilayer with low aspect ratio and adjusted thickness ratio of the two layers show monoclastic curvature. (c) Upscaling in x-direction of the active layer (width). (d) Upscaling in y-direction (length) by joining elements parallel to the wood fiber orientation, (e) Bilayers with low aspect ratio and thickness ratio of one show anticlastic curvature. (f) Multi-element assemblage with designed variation in fiber direction of the single wood elements within the active wood layer results in synclastic curvature. Solid lines indicate fiber direction of the respective wood layer. Arrows in (e) and (f) indicate conforming or opposing curvature.

(thickness ratio of one) and with orthogonal fiber orientation of the individual layers. Three different sample geometries were chosen. Samples with a length of 120 mm along the y-axis and a width (x-dimension) of 20 mm (strip configuration), square samples with an edge length of 120 mm, and rectangular samples with a length (y-direction) of 240 mm and a width (x-direction) of 120 mm. Five samples were manufactured for each configuration at 85% relative humidity. The bilayers were then transferred to 35% relative humidity. Wood moisture content and curvature were measured at 0, 1, 2, 4, 6, 8 and 24 h after the transfer of the samples.

2.1.3. Maple-spruce bilayers with joined elements to upscale length

European maple wood (Wider GmbH, Stuttgart Germany) and spruce wood veneer (Metz Furniere, Stuttgart, Germany) was used to manufacture bilayers. The maple wood sheets represent the longitudinal-radial plane and were cut to 195 mm length in R-direction of the sheets (y-direction) and 190 mm width (x-direction). Sheets were then planed to a thickness of 4.7, 8.8, 12.4, 17.0, 21.0 mm respectively. The wood was equilibrated at around 40% relative humidity. Parts for the active layer were connected parallel to the fiber direction using a custom designed CNC face milled finger joint creating a connecting zone of 20 mm length (∼5% of sheet length) (Fig. 2). Compared to other methods of joining such as edge gluing and edge finger joining, this custom joint allows for shrinking and expanding in the joint without jeopardizing stress transfer across the joint. The second layer was produced from a single continuous piece of 2.4 mm thick spruce veneer (LR plane) with the fibers oriented along the y-direction. Both layers were the equilibrated at 90% relative humidity/20 °C and glued together resulting in bilayers with various thickness ratios and with a length (y-direction) of 370 mm. The bilayers were then transferred to 50% relative humidity, which resulted in a bending of the bilayers. Curvatures along the y-direction were evaluated for the entire length as well as along the length of the individual maple elements (Fig. 2a) ten days after transfer.

2.1.4. Multi-element wood-GFRP composite bilayer to produce synclastic curvature

A multi-element wood-GFRP composite bilayer was designed for testing synclastic curvature upon change of relative humidity (Fig. 3). A digital design process was used to determine the fiber orientation in each element of the active layer to achieve the desired curvature in the overall part upon change of wood moisture content. In an iterative process, fiber orientations for each face of the 2D design mesh were generated by interpolating between drawn guide vectors to create smooth transitions (Fig. 3a). Using these orientations, a digital form finding method using a spring-based physics simulation previously developed by the authors [12] and a bilayer finite element (FE) model (SOFiSTiK AG) was used to generate curved surfaces (Fig. 3b). Once a suitable curved surface was obtained, a 2D fabrication mesh was generated by discretizing into larger triangular elements based on the dimensional constraints of the material in y-direction (Fig. 3c). The y-direction of each triangle is defined by the direction of maximum principal curvature and digitally oriented on and cut from 12 mm thick boards of beech wood (Wider GmbH, Stuttgart Germany) with the y-direction perpendicular to the fiber orientation.

The boards were equilibrated at a relative humidity of 40% and the parts were milled with finger joints as described for the maple samples. The restrictive layer consists of a continuous multi-axial 40 g/m^2 woven glass-fiber fabric. The triangular elements were arranged and connected in the designed configuration using only the friction finger joints. The multi-element wood board was then re-equalized at 85% relative humidity, and the glass-fiber fabric was laminated (without vacuum) to the top of the wood sheet with a two component epoxy resin. After finishing, the result is a multi-element wooden-composite bilayer with a 10 mm thick, active wood layer and a 0.13 mm thick, passive glass-fiber reinforced plastic layer. The sample was transferred from flat configuration in 85% relative humidity to 50% relative humidity. The sample was scanned with a 3D scanner as described below ten days after the transfer. In all experiments, temperature was kept at 20 °C.

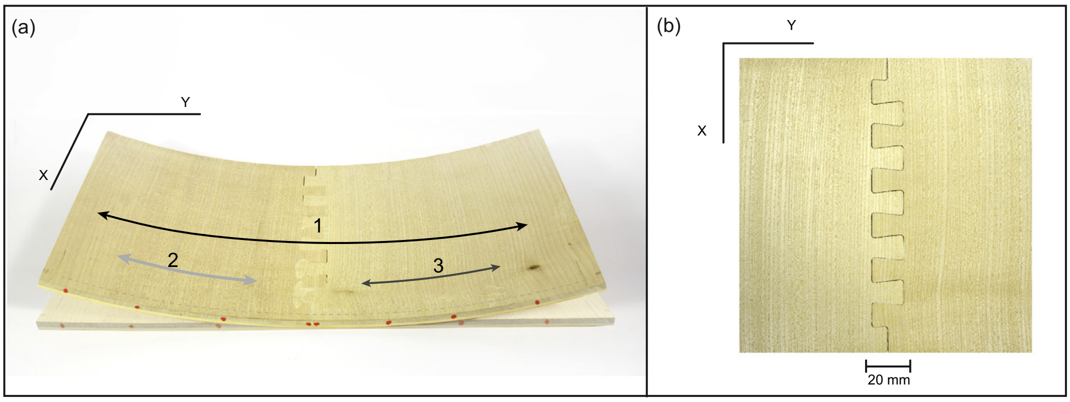


Fig. 2. Upscaling length perpendicular to fiber orientation of maple-spruce bilayers. (a) Image of flat and curved configuration (equilibrated at 90% and 50% relative humidity) with marked distances 1, 2, 3 for curvature determination, top layer with finger joint connections: maple wood, bottom layer: spruce wood. (b) Top view detail of finger joint of the layer of maple wood.

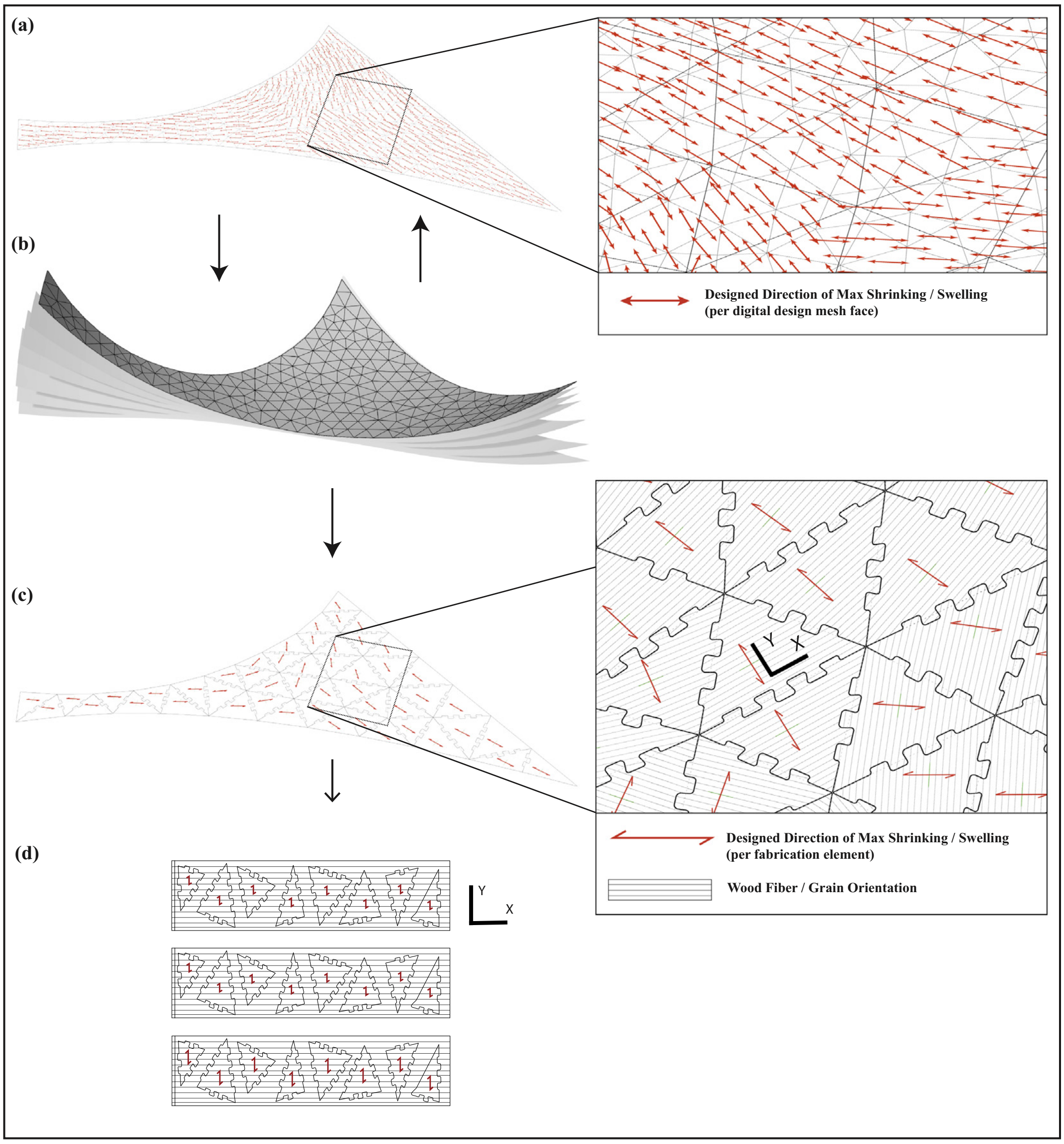


Fig. 3. Digital design and manufacturing of a multi-element wood-composite bilayer for achieving synclastic curvature. (a) Designed variation in fiber orientations, input for simulation. (b) Simulation of curvature of the multi-element part from flat to actuated state. (c) Fabrication information: discretization of surface based on material size constraints into individual wood elements with specific fiber orientation and joining details (inset). (d) Layout of elements on wood boards for robotic assisted cutting.

2.2. Moisture content

The moisture content of the wood bilayers was determined by the double-weight method. Hereby, the initial moisture content and the dry weight of the single layers was determined via reference samples, which were weighed at the same time and then dried at 103 °C for 24 h.

2.3. Curvature measurement

2.3.1. Definition of curvature

For the present study, the surface curvature of the samples is described as monoclastic, synclastic and anticlastic as illustrated in Fig. 1. Monoclastic curvature is defined as uni-directional, cylindrical curvature with zero Gaussian curvature (Fig. 1a–d). Bi-directional curvature can be either synclastic (spherical) with positive Gaussian curvature (Fig. 1f), or anticlastic (hyperboloid) with negative Gaussian curvature (Fig. 1e).

2.3.2. Experimental determination of edge and surface curvature

Curvature along the edges of the wooden bilayers was determined by applying marker dots on the edges of the samples and taking images at the same time when weighing the samples. The coordinates were extracted via image evaluation (ImageJ) and curvatures were calculated with a Python script fitting a circle to the coordinates assuming constant curvature along the edge.

The beech wood bilayers and the wood-composite bilayer were additionally scanned after having reached equilibrium using a handheld stereoscopic infrared assisted 3D scanner (HandyScan 300, Creaform) for evaluating surface curvature. The resulting point cloud was evaluated (Cloud Compare V2) [16] to calculate Gaussian curvature of the multi-element wood-GFRP-composite bilayer. For calculating principal curvatures, sections along principal directions were extracted from the point cloud and circles were fitted to the points of the extracted sections (Rhino and Grasshopper, McNeal).

2.3.3. Theoretically calculated curvature (2D)

The theory of bi-metal thermostats of Timoshenko [17] was taken for calculating theoretical curvatures for the spruce-maple bilayers and for the beech-spruce bilayers. Hereby, thermal expansion coefficients are exchanged for swelling coefficients and moisture content differences were taken instead of temperature differences. Table 1 gives an overview of the assignment of symbols and the values taken for the relevant input parameters. With (c-c_0) taken as difference in moisture content, h as the total thickness of the bilayer (h_1 and h_2 being the thickness of the individual layers), and E_i as respective elastic modulus in y-direction of the of the bilayer elements (E_L for the spruce, E_T for the beech, and E_R for the maple layers), the curvature $1/\rho$ is calculated by Eq. (1) [8,17]

$$\frac{1}{\rho} = \frac{6(1+m)^2}{\left(3(1+m)^2 + (1+mn)\left(m^2 + \frac{1}{mn}\right)\right)} \frac{(\alpha_2 - \alpha_1)(c - c_0)}{h} = k\frac{\Delta\alpha\Delta c}{h}, \quad m = \frac{h_1}{h_2}, \quad n = \frac{E_1}{E_2} \tag{1}$$

Table 1
Input parameters for Eq. (1).

Bilayers	α_1 [%/%][a]	α_2 [%/%][a]	E_1/E_2[b]
Maple-spruce	0.01 (spruce, L)	0.15 (maple, R)	10
Beech-spruce	0.01 (spruce, L)	0.26-(beech, semi-R)0.40 (beech, T)	10 20
Beech-beech	0.01 (beech, L)	0.40 (beech, T)	20

[a] α = Differential swelling coefficient [strain $\varepsilon/(c-c_0)$], 1,2 = layer number, values for maple are taken as average from [18,19], values for beech and spruce are taken from studies performed for [8].
[b] Ratio of elastic modulus E (E_L/E_R or E_L/E_T), calculated from values taken from [20,21].

3. Results

3.1. Influence of bilayer aspect ratio on curvature for a thickness ratio of one

After transfer from 85% relative humidity to 35% relative humidity, the beech bilayers with strip configuration (120 x 20 mm) develop monoclastic curvature (Fig. 4a). Yet, anticlastic curvature is visible for the bilayers of 120 × 120 mm and 240 × 120 mm size (Fig. 4a). Fig. 4b shows the curvature along the edges as determined by the applied marker dots and image evaluation for all bilayers within 24 h after transfer. Hereby, curvature in y-direction is defined as positive. The strip configuration shows a curvature of $3.7 \cdot 10^{-3} \pm 0.1 \cdot 10^{-3}$ mm^{-1} in y-direction. No curvature was visible along x-direction. The square samples show curvatures of $3.8 \cdot 10^{-3} \pm 0.1 \cdot 10^{-3}$ mm^{-1} in y-direction and $-2.0 \cdot 10^{-3} \pm 0.1 \cdot 10^{-3}$ mm^{-1} in x-direction. The large rectangular samples of 240 × 120 mm size show a curvature of $4.3 \cdot 10^{-3} \pm 0.2 \cdot 10^{-4}$ mm^{-1} along y-direction, which is comparable to that of the strip configuration, whereas a curvature along x-direction of $-1.5 \cdot 10^{-3} \pm 0.3 \cdot 10^{-4}$ mm^{-1} is seen.

3D scans were performed on the samples, which allowed evaluating principal curvatures (Fig. 3a). The directions of curvature are in line with those measured on the edges of the sample, suggesting that there still is a dominating direction of curvature.

3.2. Monoclastic curvature can be retained for asymmetric bilayers with low aspect ratios

The beech-spruce bilayers were subjected to the same changes of relative humidity than the beech bilayers. Monoclastic curvature along y-direction is visible for all samples (Fig. 5a) as all samples remained straight in x-direction (Fig. 5b). The moisture content decreased from around 17% to 9% within 24 h. A loss of more than 40% was calculated for all configurations (Fig. 5c) with a higher loss rate being visible for the samples with a width of 20 mm and 40 mm compared to that of the two other sample geometries. Curvature in y-direction after 24 h was lowest ($6.7 \cdot 10^{-3} \pm 0.2 \cdot 10^{-4}$ mm^{-1}) for the square configuration and highest ($8.4 \cdot 10^{-3} \pm 0.1 \cdot 10^{-4}$ mm^{-1}) for the samples with a width of 20 mm (Fig. 5d). The same is true for the loss in wood moisture content during 24 h, which was highest for the 20 mm wide samples (9.7 ± 0.3%) and lowest for the square configuration (10.5 ± 0.1%).

To elucidate the influence of the geometry, i.e. aspect ratio of the samples, on the amplitude of curvature, specific curvatures were calculated by normalizing curvature to the change of wood moisture content. Specific curvatures showed differences of up to nearly 20% for the different sample configurations (Fig. 5e); however, no pattern as a function of aspect ratio (width) could be assigned. The experimentally determined curvature closely matches with the calculated values by using Timoshenko's theory with $R^2 = 0.97$ (Fig. 5f).

3.3. Multi-element bilayer configuration enables synclastic curvature

The multi-element wood-composite-bilayer (Fig. 6a) was transferred from 85% to 50% relative humidity (Fig. 6b & Supplementary Movie S1). By 3D scanning, Gaussian and principal curvatures were quantified (Fig. 6c and d). For the central parts of the structure, positive Gaussian curvature is visible, indicating synclastic curvature, whereas zero or negative Gaussian curvature (anticlastic curvature)

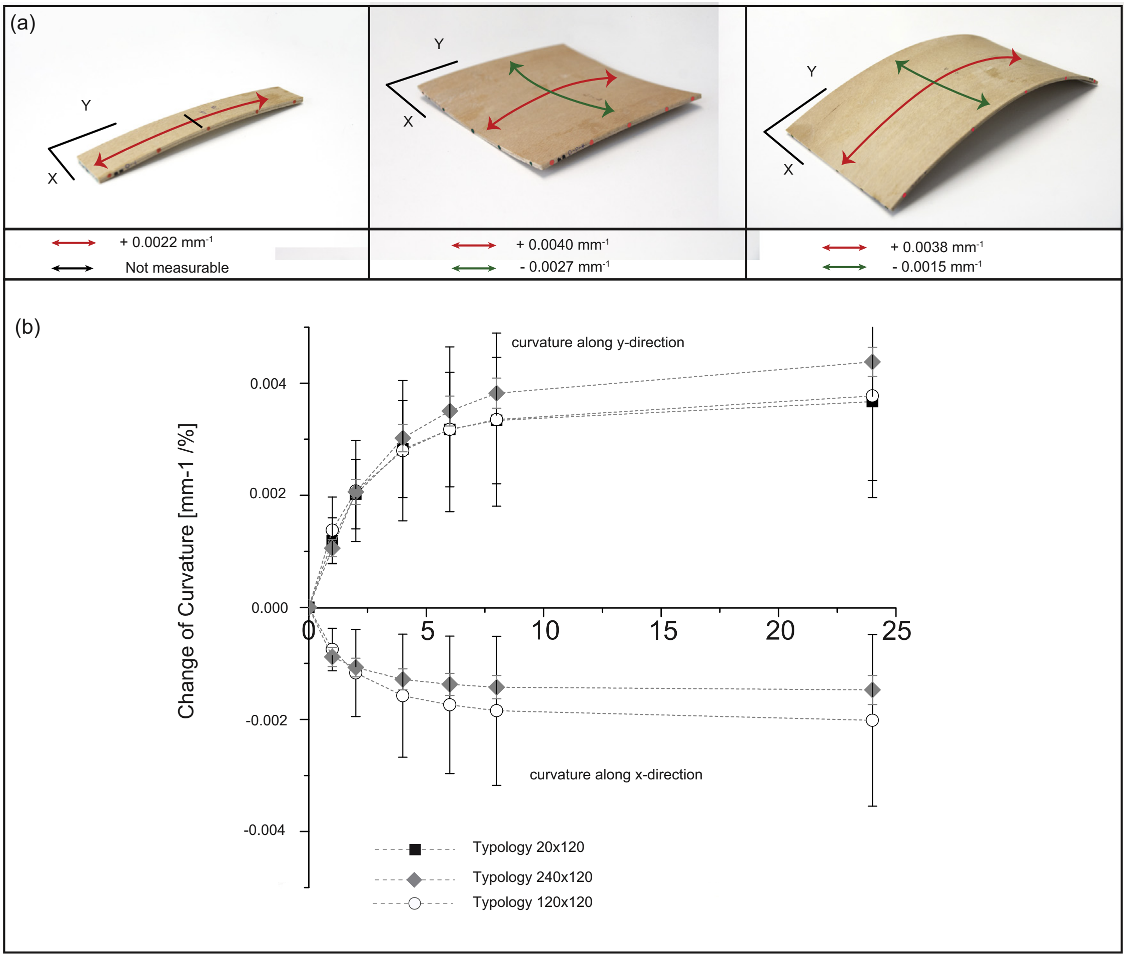
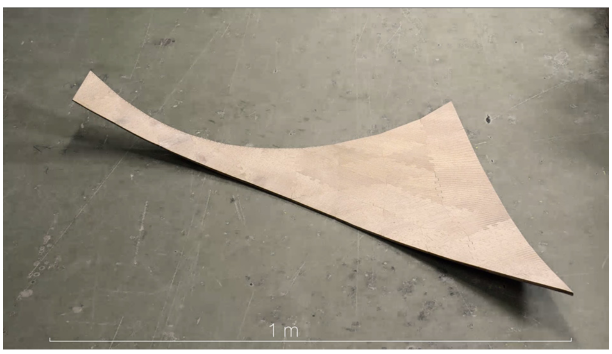


Fig. 4. Curvature of beech bilayers with thickness ratio 1. (a) Images of bilayers with marker dots for tracking curvature on the edges (see (b)) and principal curvatures (red and green double arrows on the samples) derived from 3D scans of representative samples of 20 × 120 mm, 120 × 120 mm 240 × 120 mm size in curved state. (b) Curvature at the edges of the samples evaluated from tracked marker dots: black: 120 × 20 mm, white: 120 × 120 mm, and grey: 240 × 120 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is measured towards the edges. The calculation of the direction of maximum principal curvature shows that the fiber direction of each discrete element produces a corresponding maximum principal curvature perpendicular to the fiber direction in the actuated global system (Fig. 6d and f). This suggests that the coupling of multiple elements does only slightly alter the behavior of each individual element. However, the magnitude of principal curvature differs by a factor of four between different areas within the part with the minimum curvature occurring in the central part and maximum curvature being recorded for the strip-like part (Fig. 6d).



Supplementary Movie S1.

3.4. Upscaling by joining wood elements does not influence the bending of bilayers

The maple-spruce bilayers with serial connection of two maple sheets were equilibrated at 85% relative humidity and then transferred to 50% relative humidity. The average wood moisture content of the maple-spruce wood bilayers decreased from 16.4% to 9.4% ten days after the transfer. Curvature was evaluated in y-direction for the overall length as well as for the length of the two maple elements separately (Fig. 7a). Curvatures along the respective length of the two maple elements were only slightly different from the curvature measured for the entire length of the bilayer. The different thickness ratios and total thickness of the bilayers result in different levels of curvature (Fig. 7b). Curvatures were also calculated with the theory of Timoshenko which gave reasonable accuracy for the different configurations with a maximum of 20% difference (Fig. 7b, top part).

4. Discussion

The unique combination of responsiveness, excellent mechanical properties and good machinability of wood offers the chance to develop humidity-driven shape changing parts and structures on large scale using the bilayer principle. Hereby, only one layer may consist of wood for providing swelling and shrinking, while

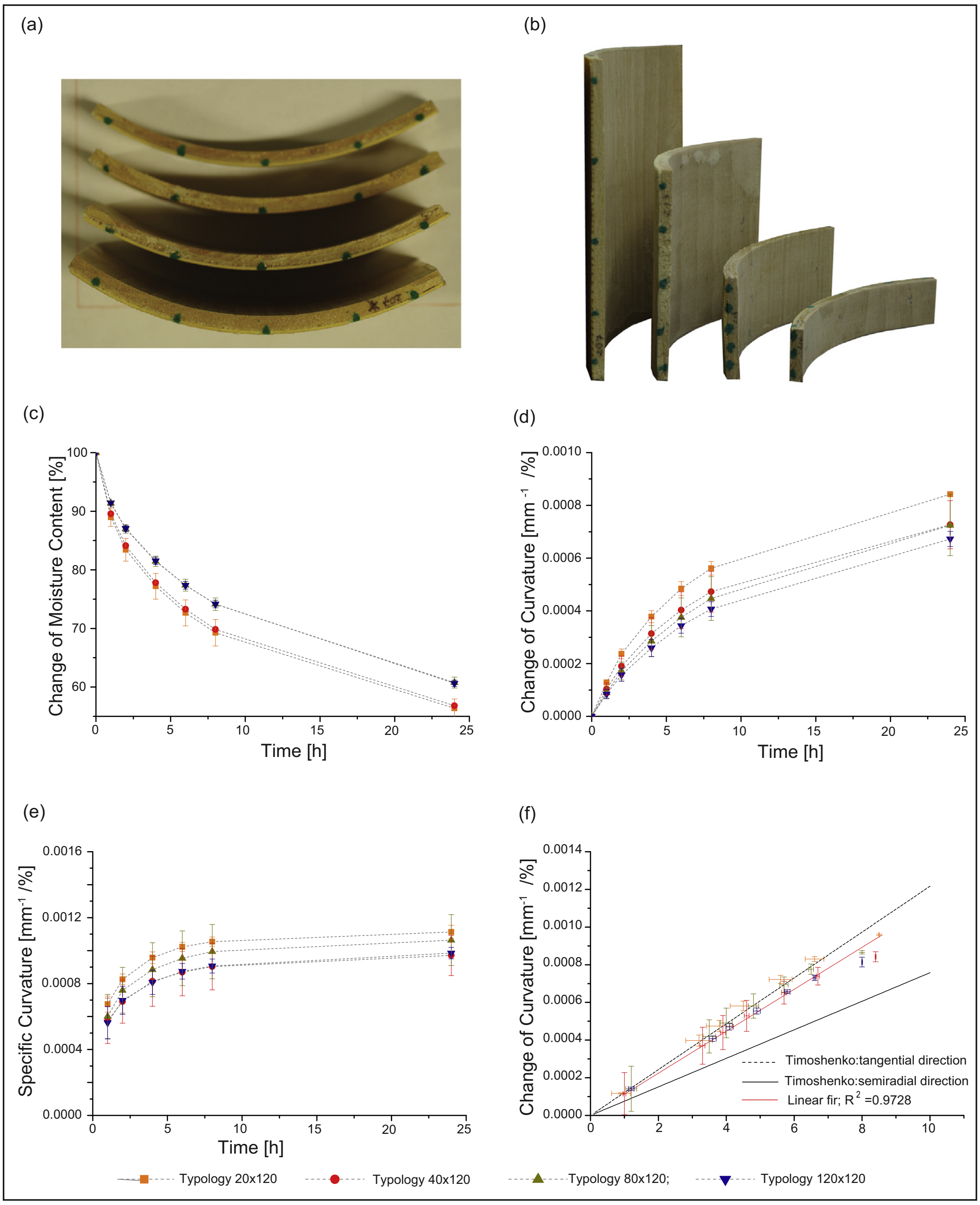


Fig. 5. Actuation of beech-spruce bilayers with a thickness ratio of 1:4 (spruce: 1 mm, beech: 4 mm). (a) Image of the curvature along the length (120 mm) of representative samples with a width of 20, 40, 80 and 120 mm (top to bottom). (b) Samples remain straight along the width. (c) Relative wood moisture content loss. (d) Curvature. (e) Specific curvature as curvature per change of moisture content. (f) Comparison of experimentally determined curvatures (symbols with standard deviations) with calculated values using the theory of Timoshenko (lines), upper limit: tangential orientation, lower limit: semi-radial orientation; red line: linear fitting; colour code indicates the dimension of the samples in y-direction: orange = 20 mm; red = 40 mm; green = 80 mm; blue = 120 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the second layer may be essentially passive transforming the dimensional change of the wood layer perpendicular to fiber direction into unidirectional, monoclastic curvature [7]. On the other hand, wood bilayers have been manufactured with orthogonal fiber orientation, resulting in both layers being responsive to humidity changes. For small sizes and high aspect ratio, monoclastic curvature had been obtained comparable to the pattern of hybrid bilayers. Here, we establish material adapted design principles for obtaining either monoclastic (zero Gaussian curvature), anticlastic (negative Gaussian curvature), or synclastic (positive Gaussian curvature) curvature with either wood or wood-hybrid bilayers of different sizes and aspect ratios. Furthermore, possibilities of upscaling the size of bilayers are shown.

For the beech bilayers with a layer thickness ratio of one, monoclastic curvature was obtained for the strip configuration with small width and high aspect ratio. Upscaling the width (x-direction) results in anticlastic curvature due to the mismatch in swelling and shrinking of both layers. This behavior is in accordance to theoretical considerations [15] and to previously reported results on bilayers consisting of anisotropic polymers. By changing the thickness ratio to a value of four (configuration of the beech-spruce bilayers), monoclastic curvature was obtained for

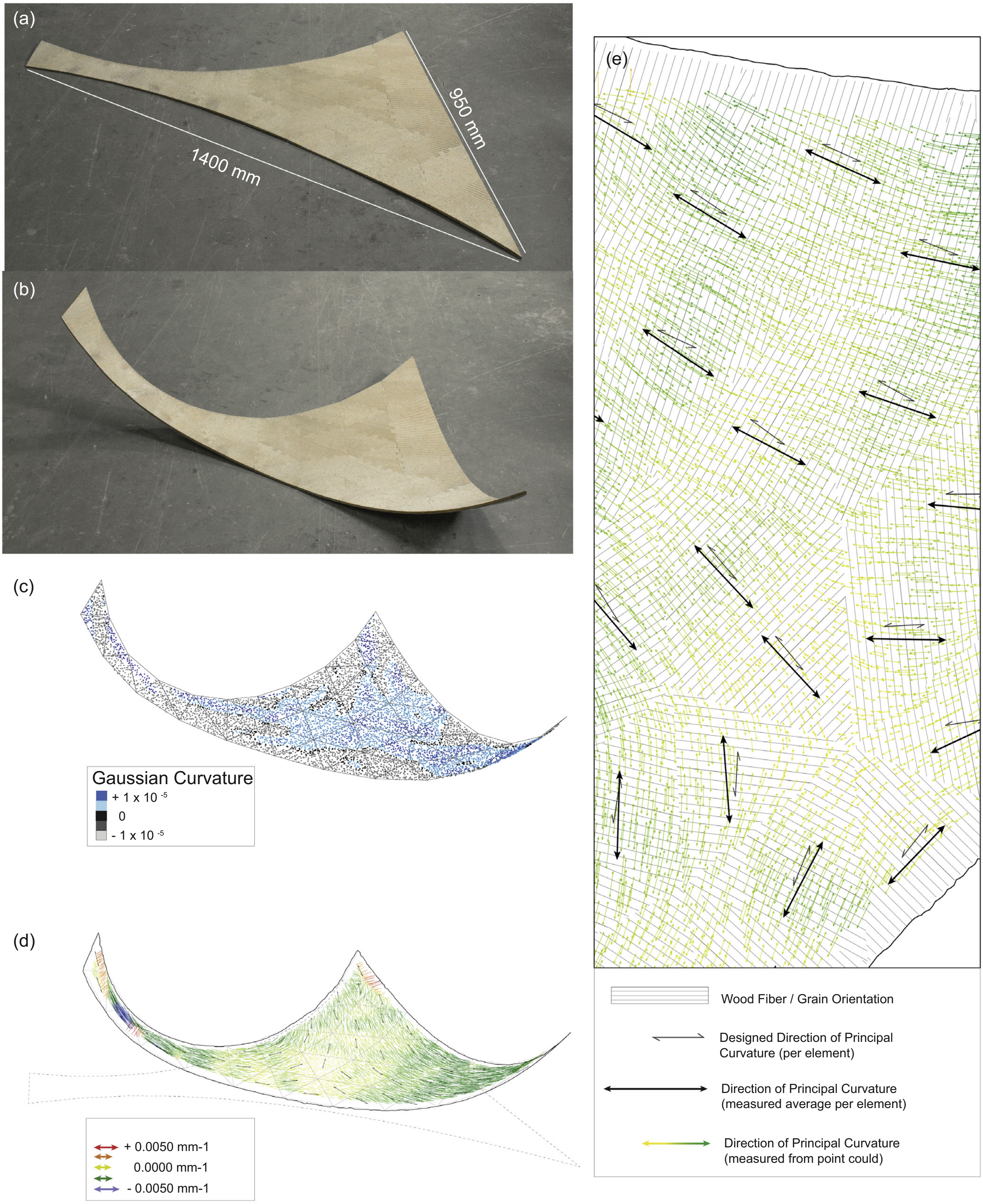


Fig. 6. Synclastic curvature of a multi-element wood-GFRP bilayer. (a) Flat state (detail within the frame is shown in (e)). (b) Curved state. (c) Gaussian curvature of the curved configuration. (d) Amplitude and direction of maximum principal curvature. (e) Detail of the connection of the multiple wood elements.

all configurations regardless of their width. It seems that the thicker layer dominates the overall shape-change of the bilayer. Next to setting the thickness ratio, the magnitude of the dimensional changes of the individual layers perpendicular to fiber direc-

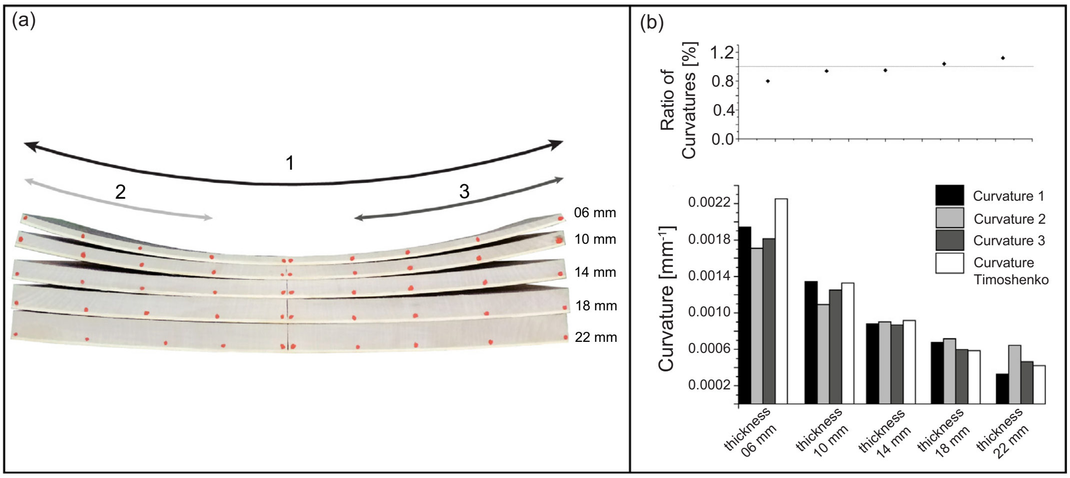


Fig. 7. Actuation of serially joined maple-spruce bilayers with up scaled length and thickness. (a) Image of actuated parts of different thickness ten days after transfer from 85% to 50% relative humidity, the numbers 1,2,3 denote the different measurements of curvature as shown in (b). (b) Curvature along 1, 2, and 3, and as calculated with Timoshenko's equation (Eq. (1)) and the ratio of measured and calculated curvature along 1.

tion can be adjusted by setting the orientation of the annual rings. The thicker beech layer exhibits longitudinal-tangential orientation and the thinner spruce layer longitudinal-radial orientation. Due to the pronounced swelling orthotropy of wood with a factor of around two between swelling in tangential and radial direction, the dimensional change perpendicular to fiber direction is approximately twice as high for the beech layer in y-direction than for the spruce layer in x-direction [22]. The combined setting of thickness ratio and differential swelling of the two layers seems to largely suppress curvature perpendicular to the fiber direction of the spruce layer (x-direction) resulting in monoclastic curvature of the bilayer. Furthermore, all configurations show a very similar amplitude of curvature and the measured values for the curvature fit reasonably well to the values calculated with the equation of Timoshenko as already reported in a previous study (Rüggeberg, 2015). This is rather surprising, as Timoshenko had developed the theory for thin and narrow bilayers with high aspect ratios, which does not apply with the present samples. Thus, next to retaining monoclastic curvature for different aspect ratios, the amplitude of curvature is not severely influenced by the aspect ratio.

Next to monoclastic and anticlastic curvature, synclastic curvature could be demonstrated using a wood hybrid bilayer comprising multiple connected wood elements with differential fiber orientation of the single elements. The required fiber orientation of the elements was calculated beforehand in the process of the digital design. The change of Gaussian curvature requires growth of the surface in two directions, which is achieved by the specific orientation of the wood elements. The anisotropic growth or shrinkage of wood coupled to the geometric restrictions imposed via the specific fiber orientations of the elements leads to out of plane deformation. The thin GFRP-layer works as supporting layer, which allows for the growth and may support the bending [10]. Yet, presently, it cannot be further distinguished, whether the positive Gaussian curvature originates from the out-of-plane deformation of the bilayer or, at least partly, from a rotation in the joining zones of the connected elements. In the former case, an additional very shallow curvature would be imposed along the fiber direction perpendicular to the expected curvature. Such a curvature would be the result of the differences in fiber orientation of adjacent elements and would be maximum for perpendicular fiber orientation.

The direction of maximum principal curvature well correlates with the fiber orientation of the single triangular elements indicating a retention of the deformation principle of a bilayer despite its embedding in a multi-element system. However, changes in fiber orientation between adjacent (but also between more distant) elements impose restrictions on the actuation of the single elements perpendicular to fiber orientation. This is clearly visible by the difference in the magnitude of the maximum principal curvature between a centrally located element and one being part of the strip-like geometry at one edge of the element. Maximum restriction is introduced for adjacent elements with perpendicular fiber orientation. This multi-element configuration makes predicting the final shape of the part complex as the magnitude of actuation depends on the location and the orientation of the single elements and their immediate surroundings within the whole part.

Both, synclastic and anticlastic curvature increase the global structural performance for a specific overall thickness of the bi-layered part by employing membrane forces. Yet, monoclastic curvature may be required for other practical applications. A fundamental understanding of the relationship between material, (bi-layered) element, and (multi-element) part behavior presents an opportunity to design geometries capable of increasingly sophisticated and coordinated responsive movements. This utilization of material capacity to achieve designed functionality allows for implementation of the material system in a range of both reversible and non-reversible shape-changing and actuation systems.

Such practical application requires upscaling the size of these bi-layered parts and, in case of being utilized as weather adaptive elements, also suitable rates of shape change. The current rates observed during the experiments in climate chambers reflect the diffusion limits and more point towards daily changes [8]. Through direct solar radiation, rates may significantly increase. For construction applications, rates of shape change are less critical.

As shown for the synclastic curvature, which requires a multi-element setup for differentiated fiber orientation, upscaling requires joining of elements due to size limitations of wood pieces especially for dimensions perpendicular to fiber direction. The design of the joint is the result of an optimization strategy within opposing boundary conditions such as fabrication efficiency, structural integrity and continuity of shape change within the bi-layered part. While simple serial joining by edge-gluing ensures the latter, it introduces failure planes in case of internal and external stresses especially during drying. Joining parallel edges with an industry standard finger joining machine increases stability and also surface area for bonding, but prevents any shape change in y-direction within the joining zone as swelling and shrinking is inhibited by the glue. For the maple-spruce bilayers with two maple pieces, the overall length of the joining zone for the applied finger-joints seems to be small enough for avoiding a noticeable reduction of the curvature of the bilayer. Next to structural stability, the finger-joint pattern also ensures mechanical interlocking of the serially connected layers while allowing some shrinking and swelling. Comparison with curvature values calculated with the theory of Timoshenko proved reasonable correlation with a maximum of 20% deviation given the fact that literature values were taken for the different input parameters. For further industrial upscaling the benefits and trade-offs of each joining method would need to be weighed carefully with the desired shape-change.

5. Conclusion

The unique combination of stiffness, responsiveness, anisotropy, and good machinability makes wood a highly favorable material for creating large-scale shape-changing bi-layered systems actuated solely by changes in relative humidity. Focusing on perpendicular fiber orientation in the two layers, the curvature of such wooden bilayers can be controlled by adapting geometric and material related parameters, such as annual ring orientation, thickness ratio, and aspect ratio. For strip configuration, monoclastic curvature can be obtained. Larger sized bilayers with low aspect ratios can be designed in specific ways for either obtaining anticlastic or monoclastic curvature. The upscaling introduces the necessity to join wood elements within one layer. This joining can be used to achieve synclastic curvature with wood-GFRP hybrid bilayers. Thus, shape change can be adapted and programmed into the elements and parts in accordance to the requirements of a particular application.

Such bilayers can be used in continuously responsive systems such as façade components and or as elements in an innovative manufacturing technology for curved wooden parts. Building shell components could autonomously transform from simple 2D configurations to 3D geometries. Such bi-layered parts with embedded design and fabrication parameters have the ability to operate autonomously receiving energy and control from the environment. This allows for the development of intelligent and sustainable shape changing systems that are independent from access to energy, high tech equipment or skilled labor, a quality that becomes increasingly valuable at large scale.

Acknowledgements

We would like to thank T. Schnider, A. Kulla, and M. Helmreich for their help with sample preparation and O. Krieg and D. Correa for their mentoring.

Funding

This study was supported by the Swiss National Foundation (Project No. 163191) and by the GETTYLAB.

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Article C
Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures

11 Article C

Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures

Grönquist, P., Wood, D., Hassani, M., Wittel, F., Menges, A. and Rüggeberg, M. (2019), **Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures,** Science Advances, Vol. 5 (9), eaax1311. DOI: 10.1126/sciadv.aax1311

This scientific research introduces self-shaping manufacturing and locking as an innovative production method for large-scale curved timber structures. The process is presented technically with a focus on the enabling computational mechanics modelling and experimental analysis. It identifies the key material parameters that influence the self-shaping in thicker wood bilayer configurations. The numerical and rheological modelling is compared to physical experiments using beech and spruce wood. A baseline for predictability is defined and the challenges for further modelling and application are highlighted. The publication is an introduction to the self-shaping manufacturing process and a feasibility study for further research and development.

D. Wood is the second author of this original research work published in a scientific and engineering context. The self-shaping manufacturing concept was developed by D. Wood, M. Rüggeberg and A. Menges. The modelling and analysis is the original work of P. Grönquist with support for computational mechanics from F. Wittel, including the adaptation of a rheological model of wood developed by M. Hassani. Physical experiments were designed by P. Grönquist and conducted by P. Grönquist and D. Wood. The manuscript was prepared by P. Grönquist with contextualisation and concept adaptation by D. Wood and A. Menges. Revisions and answers to reviews were by P. Grönquist, M. Rüggeberg and D. Wood. The article is included in the dissertation of P. Grönquist [39].

APPLIED SCIENCES AND ENGINEERING

Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures

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The growing timber manufacturing industry faces challenges due to increasing geometric complexity of architectural designs. Complex and structurally efficient curved geometries are nowadays easily designed but still involve intensive manufacturing and excessive machining. We propose an efficient form-giving mechanism for large-scale curved mass timber by using bilayered wood structures capable of self-shaping by moisture content changes. The challenge lies in the requirement of profound material knowledge for analysis and prediction of the deformation in function of setup and boundary conditions. Using time- and moisture-dependent mechanical simulations, we demonstrate the contributions of different wood-specific deformation mechanisms on the self-shaping of large-scale elements. Our results outline how to address problems such as shape prediction, sharp moisture gradients, and natural variability in material parameters in light of an efficient industrial manufacturing.

INTRODUCTION

Wood is a vastly abundant, sustainable, and well-performing construction material. From its biological origin, it inherits material characteristics such as anisotropy and hygroscopy, which are still seen as drawbacks in wood technology, as they limit traditional uses. In nature, many biological systems have been identified as being capable of large shape changes in response to changes in humidity. The unique combination of anisotropy and hygroscopy with their smart structure makes this possible (*1–13*). Large shape changes can reciprocally be achieved by wood cross-ply laminates with layup (0°/90°), referred to as bilayers, when changing moisture content by either drying or wetting. Making use of the seeming inherent disadvantage of swelling and shrinkage of wood, thin wooden bilayers with fast dynamic responsiveness have recently been highlighted for diverse applications, predominantly as functional elements in biomimetic architecture (*14–23*).

Using wood, we demonstrate the unique ability of upscaling the self-shaping mechanism of bilayers on the meter scale to obtain large-scale components with high curvature. The shaping process by drying of large wood bilayers is shown in Fig. 1 (A to D), and an exemplary time-lapse video is shown in movie S1. After drying, multiple curved wood bilayer plates can be laminated together to produce curved cross-laminated timber (CLT) plates, which are fully form stable, independent of further changes in moisture (Fig. 1E). Application concepts as efficient CLT roof or wall structural elements are shown in Fig. 1 (F and G). Using this innovative manufacturing approach, material waste by subtractive milling to shape is eliminated, while extensive cold bending of thick lamellae is rendered unnecessary. In addition, higher curvature than in standard form-giving processes is enabled, while, at the same time, thicker wood lamellae can be used. This concept is arbitrarily scalable in any in-plane direction of the CLT plate with respect to the size of available material. We suggest a four-dimensional (4D) production approach (*24–26*), where a simulated target element shape enables design of the initial flat-shaped structure in function of boundary conditions (BCs) such as change in wood moisture content (WMC), lamella thickness, or growth ring inclination. The shown approach has the potential to revolutionize mass timber production and application, for which the promotion is seen as a key step toward improving sustainability in the modern building sector (*27*).

To make use of this novel approach, a fundamental understanding of the mechanics of shape change on a large scale is required and will be in focus of this study. Inspired by the analysis of bimetal thermostats (*28*), elastic models for predicting bilayer shape change were developed and adapted for diverse swelling systems (*29–33*). In the case of bilayers made out of hardwood species, such models have shown to perform reasonably well in predicting shape change of thin layers of thickness below 10 mm (*14*, *34*). However, they do not give suitable insight into the mechanical behavior of wood bilayers. Too many simplifying assumptions, such as restriction to linear elastic deformation, 2D geometry, or steady-state moisture conditions, are not valid for bulk wood. Under time-dependent loading conditions as well as under simultaneous changes in WMC, wood displays more complex behavior. Under the high residual stress state induced by self-shaping (*34*), phenomenological deformation mechanisms such as viscoelasticity, mechanosorption, and plasticity may simultaneously occur (*35–37*). In addition to time- and moisture-dependent mechanical behavior, effects of moisture diffusion due to bilayer drying (or wetting) of exposed surfaces need to be considered. In the bulk, diffusion time is proportional to squared diffusion path when assuming Fickian transport laws. Thus, bilayer equilibration time in the target climate is drastically increased with lamella thickness, and moisture gradients may heavily affect the time-dependent mechanical response.

We address the mentioned issues by 3D finite element (FE) analysis using an elaborate rheological model for wood. Experimental data of self-shaping by drying of three wood bilayer configurations made out of the abundant hard- and softwood species European beech and Norway spruce are shown. Hereby, the total bilayer thicknesses range from 15 to 45 mm. The numerically and experimentally investigated layer thicknesses are chosen in the optimal scale range for industrial timber production. Thus, direct application is enabled without the need of further upscaling studies. To capture influence of the inherent natural variability in material parameters on resulting shape, a global-type sensitivity analysis (*38*) is conducted.

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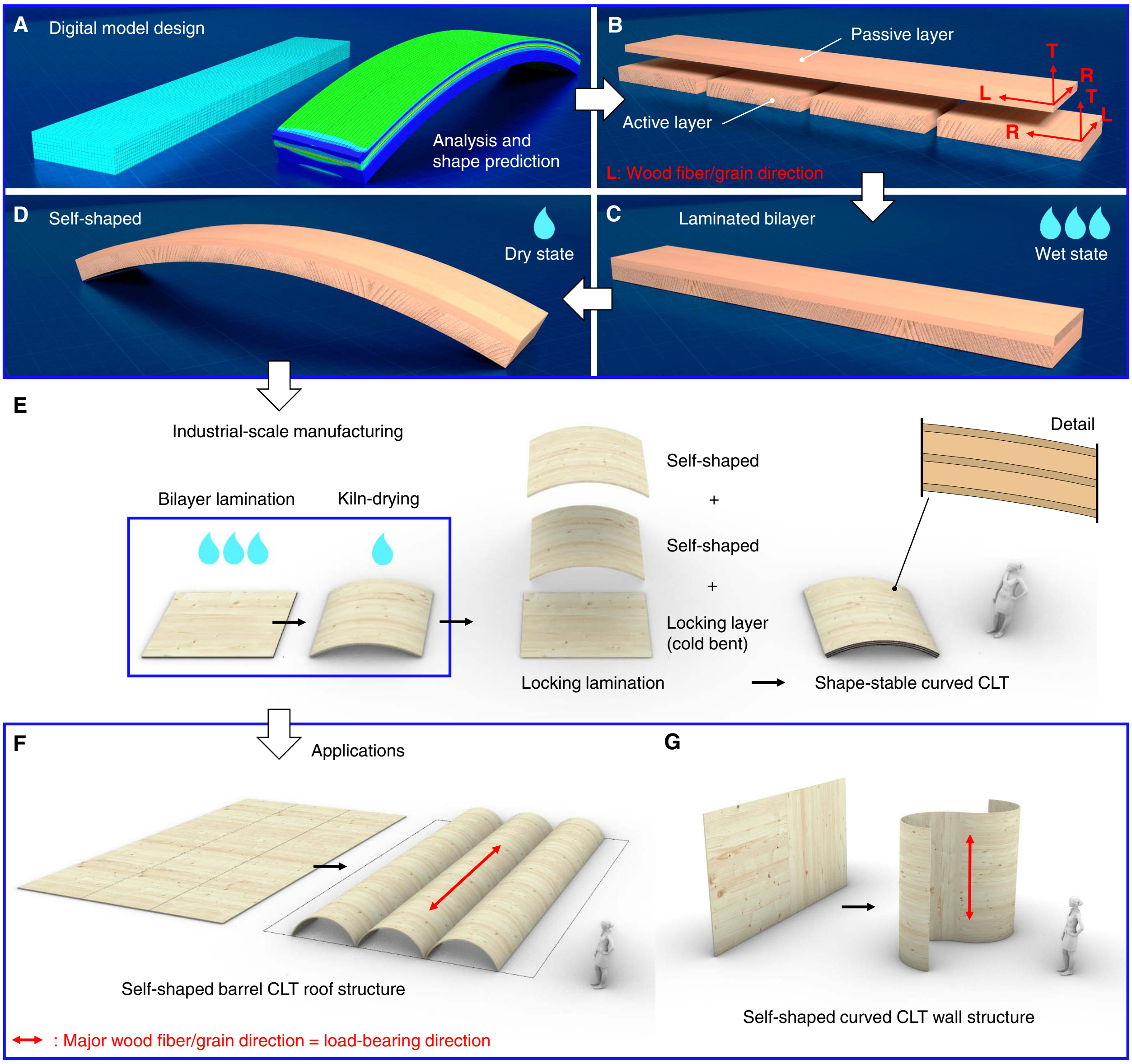

Fig. 1. Self-shaping wood bilayer application at large scale. (**A** to **D**) Analysis and design process at laboratory scale. (**E** to **G**) Industrial scale, same thickness but increased length and width of bilayers toward plate geometries. (A) Parametric digital model and FE analysis for shape prediction of arbitrary configuration. (B) Example bilayer strip configuration (here, European beech wood) with passive and active layer components with wood anatomical directions radial (R), tangential (T), and longitudinal (L). (C) Laminated wooden bilayer strip in initial, wet, and flat shape. (D) Curved self-shaped bilayer after drying. (E) Industrial-scale manufacturing (here, Norway spruce wood) in plate and shell configurations. Plates can be air-dried or kiln-dried to achieve self-shaping. Multiple shaped bilayer plates can be stack-laminated and additionally laminated with a thin cold bent locking layer (with same thickness as a passive layer) to form shape-stable curved CLT. (F) Application example as barrel vaulted CLT roof structure with wood fiber direction of thick lamellas (active layers) in load-bearing direction. (G) Application example as curved CLT wall with wood fiber direction of thick lamellas (active layers) in vertical direction.

RESULTS

Shape change after drying

Climate-induced shaping of three investigated bilayer configurations, i.e., increase in curvature and decrease in WMC over time are represented in Fig. 2 for two wood species, European beech and Norway spruce, respectively. The investigated experimental samples showed neither cracking in the bulk wood nor delamination at the bond lines during the shaping process, in which they were relocated from a high to a low relative air humidity (RH) climate at 20°C. WMCs were approximately equilibrated after 400 hours in the dry target climate, except for the bilayer series with a thickness of 45 mm, for which an equilibration is not visible after 900 hours. Beech bilayers reached an equilibrium WMC of around 14.5%, representing a difference of 7.5% as compared to the initial state. Spruce bilayers reached around 12.5% with a difference of approximately 9% in WMC. Despite the larger difference, curvature of spruce bilayers was lower than that of beech bilayers for all three configurations. In the case of beech bilayers (Fig. 2A), curvature is simulated with reasonable accuracy, including light overestimation. In contrast, for spruce (Fig. 2B), considerable overestimation can be recognized. Comparing both beech and spruce

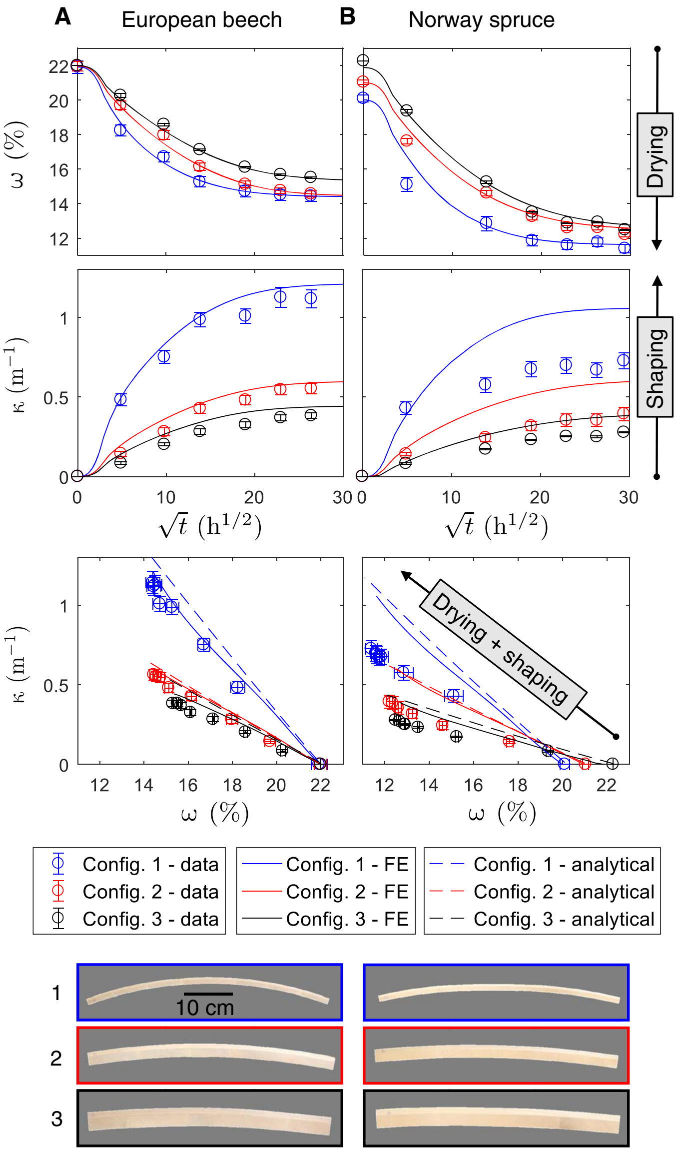

Fig. 2. Shape change after drying. Bilayer samples (configurations 1 to 3, depicted at the bottom) made out of beech (**A**) and spruce (**B**) wood during 900-hour drying time. Drying dynamics (WMC, denoted ω) as simulated by the FE models and measured on experimental samples (error bars denote ±SDs). Curvatures (denoted κ) versus square root of time, and curvatures versus moisture contents with comparison to model predictions.

FE simulations with the performance of a simple analytical model derived for shape prediction, a matching trend can be observed. The predictions by both models are close and, especially for spruce, do not appear to considerably differ in comparison to the data.

Stress and strain states

Bilayer axial stresses and strains as a function of square root of drying time are shown in Fig. 3 for all configurations and at four relevant points of interest, namely, at the outer edge and interface of both passive and active layer, respectively. Maximum compressive stresses of around 30 MPa for beech and 25 MPa for spruce are found at the passive layer interface. At the passive layer edge, the tensile stresses range between 17 and 24 MPa. No distinct difference between species or any dependency on bilayer thickness of the stresses can be recognized. However, in the active layer, stress is generally found to be higher for beech than for spruce. At the edge of the active layer, tensile stresses up to 6 MPa are developed until approximately 100 hours of drying. After that, they reverse into compression. The opposite pattern is observed at the active layer interface, where final tensile stresses range between 2 and 8 MPa. Across the entire bilayer cross-section and after 900 hours, the stress states show the typical bending stress shape of two bonded layers (*28*).

For the elastic strains, a similar pattern as in the case of the stresses can be observed. The highest elastic strains reach 0.25% in the passive layer and 0.55% in the active layer. No systematic influence of bilayer thickness or species can be seen. The viscoelastic strains are in the same order of magnitude as the elastic strains. However, here, an apparent difference between the two species beech and spruce can be observed. Viscoelastic strains are approximately twice as high for beech than for spruce. Noticeably, the viscoelastic strains do not converge even after 900 hours, while curvature and WMC remain constant after 400 hours already. Mechanosorptive strains for the passive layer are lower by approximately one order of magnitude compared to the other two strain components and show convergence after 900 hours. Plastic strains do not appear for any configuration.

Sensitivity analysis

A global-type, nonlinear sensitivity analysis for quantification of uncertainty in model input parameters is presented in sections S1 to S3. For beech wood bilayers, variability in simulated shape is obtained as being entirely dependent on variability in the axial swelling (or shrinkage) coefficient of the active layer. In the case of spruce, the variability in axial stiffness of layers appears to dictate variability in shape change.

DISCUSSION

Self-shaping by drying within the hygroscopic range of wood has been demonstrated for lamellae thicknesses up to 30 mm and for two abundant European wood species, one hardwood and one softwood. Commonly, wooden cross-ply laminates such as CLT experience extensive cracking and delamination due to high environmentally induced residual stresses (*39*). Especially for hardwood species, standard-conform gluing for structural applications is still challenging. To avoid moisture-induced delamination, the application of priming solutions before applying polyurethane adhesive is recommended (*40*, *41*). For the case of self-shaping wood, this is not necessary. The mechanical compatibility of bilayer structures, allowing large unconstrained deformations, prevents delamination even for very high changes in WMC.

The computational model fairly predicted the curvature of beech bilayers, while the spruce bilayer curvature was overestimated for all configurations. Unknown material nonlinearity in wood or inaccuracy in used material parameters may contribute to the observed deviation. In addition, a more accurate model may be provided by considering the next smaller representative elementary volume. At the intra-growthring scale, spruce shows considerably larger inhomogeneity compared to beech because of more pronounced differences in material properties of early- and latewood. Such localized mechanical behavior may considerably affect mechanics at large scale. However, the required material parameters are still missing,

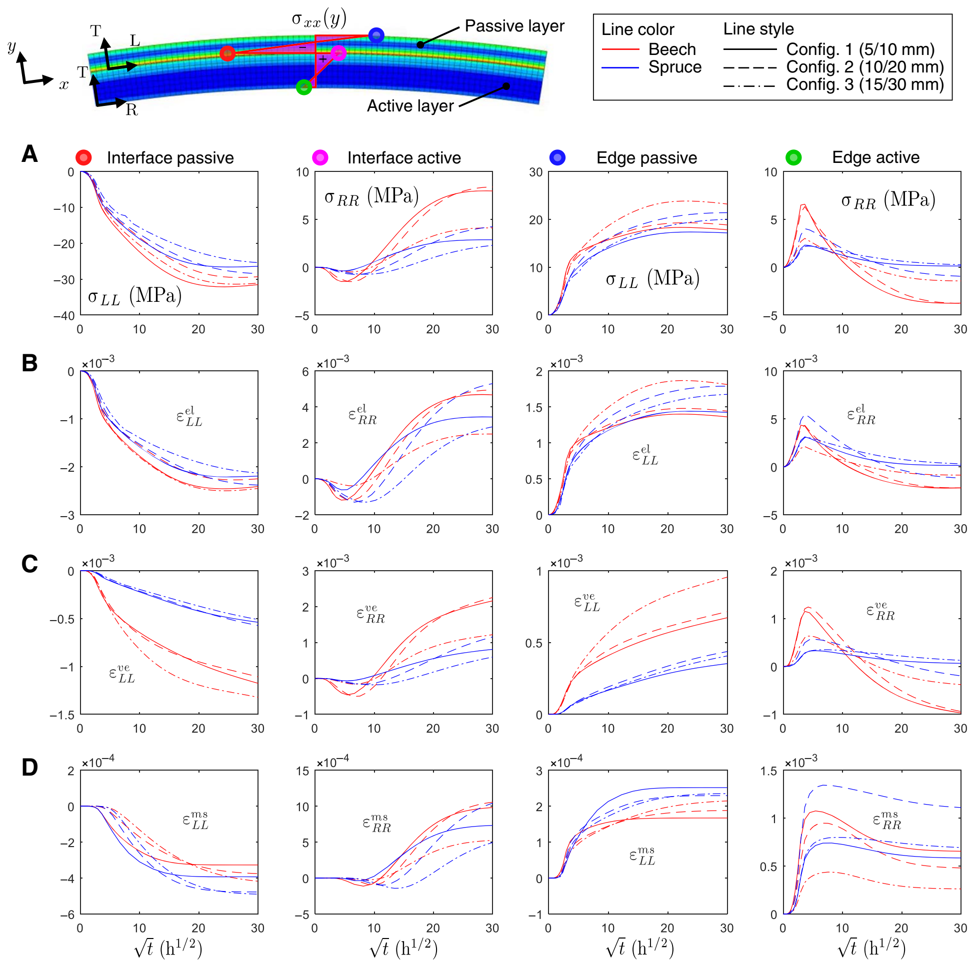

Fig. 3. Shaping-induced stresses and strains. (**A**) Bilayer axial stress states (σ_{xx}, indices *LL* for passive and *RR* for active layer corresponding to local wood anatomical coordinate system) at four points of interest versus time (*t*) for configurations 1 to 3 and both wood species. Strain state (ε_{xx}) separated in individual contributors. (**B**) Elastic (ε_{xx}^{el}). (**C**) Viscoelastic (ε_{xx}^{ve}). (**D**) Mechanosorption (ε_{xx}^{ms}). Irreversible plastic strains (ε_{xx}^{pl}) equal zero for all configurations. Total strains (ε^{tot}) and hygro-expansion strains (ε^{ω}) are not shown.

and collecting them is a nontrivial task. Considering that Norway spruce is one of the most widely used construction woods, a future clarification is certainly of great interest.

The sensitivity analysis revealed that in the case of beech wood, all model variability can be attributed to the natural variability in swelling coefficients. Therefore, a statistical analysis thereof needs to be conducted to increase model prediction (an example is shown in section S3). The other input parameters are of negligible relevance in terms of reducing uncertainty in shape prediction, given the model is valid as in the case of beech. This finding is relevant for application cases where there is a large apparent variability in quality of available material. In the case of spruce wood, a single dominating parameter could not be identified. Effectively, even by attributing a coefficient of variation of 10% to the most important considered parameters, identified as being the axial elastic layer stiffnesses, total model variation is found to be 4% only (section S1). Because the probability that the model-propagated uncertainty decreases is low, further parameters remain to be investigated to explain the more complex behavior of spruce wood.

A further insight provided by the sensitivity analysis is that the parameters of the adhesive layer, namely, its thickness, stiffness, and shear modulus, do not influence shape change. This can be explained by the fact that in bilayer laminates, the edge stresses dictate deformation due to the bending regime, although stresses are found highest at the interface. The exclusive task of the adhesive bond is to block relative deformation of the two layers with respect to each other. This implies that modeling and accounting for an adhesive layer is not necessary for self-shaping bilayer composites where bond thickness is small compared to the lamina thickness. However, modeling an adhesive bond accounts for correct moisture and drying behavior, as it represents a diffusion barrier.

In terms of predicting shape change alone, simple analytical models proved to be equally suitable even for thick lamellae. However, axial stresses developing over drying time were found considerably lower in the FE analyses than if the analyses were conducted using a 2D linear elastic-only model (*34*). In the FE analyses, relaxation occurred in both passive and active layers simultaneously, seemingly canceling out influence on curvature. Independent of the thickness or species, viscoelastic strains did not fully converge after 900 hours of drying, although curvature change has already ceased before, indicating a layer-wise compensation. As a consequence, mechanical energy dissipation can here not be correlated with shape change. Accordingly, bilayer shape change can be interpreted as originating from a ratio of axial stresses of active to passive layer, and thus is unaffected by stress magnitudes. This can be used to explain the observed accuracy of analytical models that neglect complex deformation mechanisms. In such models, elastic material parameters enter a simple expression in terms of ratios (*14*, *28*).

The FE analyses showed that bilayer thickness does not affect axial stress magnitudes, which confirms findings in (*34*). Thicker wood bilayers resulted in lower curvature solely due to the cross section's higher second moment of area increasing the bending stiffness. For industrial large-scale application, this implies that any arbitrary lamella thickness can be used in consideration with the trade-off in target curvature. Design principles valid for thin layers at small scale can therefore also be applied at large scale.

It was seen that no plastic strains develop and that the maximum axial stresses for beech and spruce are far lower than theoretical yield stresses or strengths. For beech and spruce, axial stresses in passive layer after 900 hours roughly reach 60% of the theoretical yield stress in L-direction [e.g., at $\omega = 14.5\%$, $f_{c,\,L} = 53$ MPa for beech (*35*)]. In the active layer, the maximal stresses scale as 70 and 50% of the strengths in R direction for beech and spruce. The fact that no irreversible strains were accumulated can be attributed to the slow drying dynamic allowing time for relaxation. These findings imply that in the case of application of bilayers as climate-regulated actuator elements, shape-change dynamics and shape reversibility are affected by rate-dependent deformation mechanisms. This may be relevant for any dynamic bilayer structure made from biological materials. However, as mentioned above, the final shape in a state where moisture- and time-dependent deformation mechanisms converged is mainly influenced by factors affecting stress state and bending stiffness, such as layer thicknesses, expansion coefficients, or elastic material properties.

Moisture gradients were shown to have substantial effects on the developing stresses and strains. This was demonstrated in Fig. 3 where, for the case of the active layer edge, stress and strain states inverted over the drying time. The outer active layer edge, which is drying first, will shrink and develop tensile stresses and set the still wet core under compression. Later in time, when moisture gradients decrease, bending regime takes over as the bilayer bends and stresses invert to compression. A critical moment is identified when the strongest moisture gradients, caused by BC-driven drying, are created. For the investigated samples, this critical time can be identified as being 10 to 20 hours after climate relocation. There, the gradient-induced tensile stresses of the active layer edges are maximal and close to theoretical strength values. A fast drying procedure creating sharp moisture gradients may thus lead to cracking in the active layer. When using drying kilns at industrial scale, a mild drying procedure is thus recommended to avoid potential cracks, which would affect target curvature.

Summary

Self-shaping was presented as a novel concept for industrial production of form-stable curved mass timber elements. The combination of a computational mechanical analysis, a sensitivity analysis, and an experimental investigation has revealed insights into the complex behavior of the self-shaping mechanism of wood. Specific large-scale problems, such as predictability of shape, sensitivity to natural variation in material properties, or drying procedure were addressed and discussed for two wood species, for which considerable differences were identified. Target curvature remains constant if layer stress ratios remain balanced under the influence of different deformation mechanisms. Creep mechanisms prevent exceeding strengths and yield stresses during shaping. Axial stress levels remain independent of bilayer thickness given that the layer thickness ratio is the same. A critical moment is reached when axial stresses in the active layer are of tensile nature due to the initial BC-dictated drying phase. The findings enable application of the biomimetic self-shaping of wood at large scale and promote its integration into mass timber industry.

MATERIALS AND METHODS

Constitutive material model for wood

Bulk wood was modeled using a 3D orthotropic, moisture- and time-dependent constitutive material model. The model is based on a representative elementary volume as shown in Fig. 4A. It considers all up-to-date known deformation mechanisms in coupled manner by

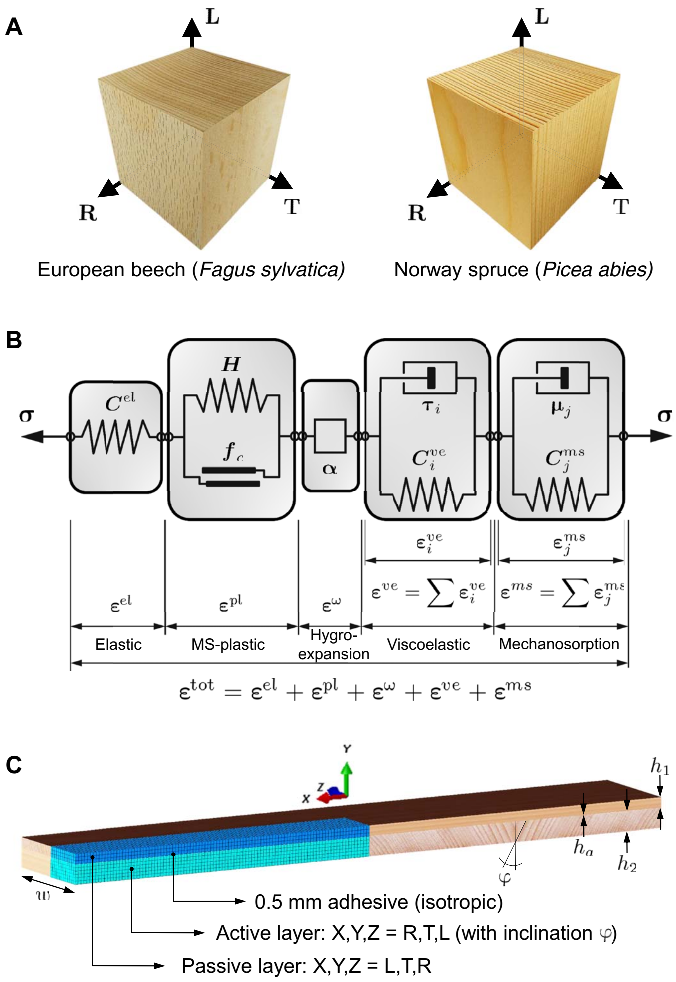

Fig. 4. Simulation model. (**A**) Representative elementary volume for wood material model (beech and spruce wood) with anatomical growth directions R, T, and L. (**B**) Schematic rheological model for bulk wood as in (*35*). (**C**) Setup and BC for the FE bilayer models (quarter model with XY and YZ symmetry). *C*, stiffness matrices of springs for respective deformation modes; *H*, hardening moduli; f_c, yield functions; α, differential swelling coefficients; τ_i, characteristic retardation times; μ_j, moisture analogous to τ_i; $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$, stress and strain tensors.

additive decomposition of the total strain tensor assuming infinitesimal strain theory. Following (*42*), the Helmholtz free energy function Ψ is defined as

$$\Psi = \frac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{el}}\mathbf{C}^{\mathrm{el}}\boldsymbol{\varepsilon}^{\mathrm{el}} + \frac{1}{2}\sum_{i=1}^{n}\boldsymbol{\varepsilon}_i^{\mathrm{ve}}\mathbf{C}_i^{\mathrm{ve}}\boldsymbol{\varepsilon}_i^{\mathrm{ve}} + \frac{1}{2}\sum_{j=1}^{m}\boldsymbol{\varepsilon}_j^{\mathrm{ms}}\mathbf{C}_j^{\mathrm{ms}}\boldsymbol{\varepsilon}_j^{\mathrm{ms}} + \frac{1}{2}\sum_{l=1}^{r} q_l\alpha_l \quad (1)$$

The Cauchy stress tensor $\boldsymbol{\sigma}$ acting on a material point is in relation to the total strain tensor $\boldsymbol{\varepsilon}^{\mathrm{tot}}$ by $\boldsymbol{\sigma} = \partial\Psi/\partial\boldsymbol{\varepsilon}^{\mathrm{tot}}$, where $\boldsymbol{\varepsilon}^{\mathrm{tot}}$ decomposes as shown in Fig. 4B into elastic, plastic, viscoelastic, mechanosorptive, and swelling and shrinkage strain components. In the first term of Eq. 1, $\mathbf{C}^{\mathrm{el}}$ represents the elastic stiffness tensor. $\mathbf{C}_i^{\mathrm{ve}}$ is the *i*th viscoelastic stiffness tensor, and $\mathbf{C}_j^{\mathrm{ms}}$ is the *j*th mechanosorptive tensor of the respective Kelvin-Voigt rheological elements connected in series ($n = 4$ and $m = 3$) (Fig. 4B). The last term in Ψ considers the isotropic hardening energy standing for irrecoverable plastic deformation accumulated by a multisurface plasticity model (*r* denotes the number of active yield mechanisms, q_l denotes the plastic hardening functions, and α_l denotes the internal hardening variables for l = R,T,L). All element entries of the mentioned compliance tensors ($\mathbf{C}^{-1}$) for the species European beech and Norway spruce are considered as functions of moisture ω. Further, hygro-expansive ($\boldsymbol{\varepsilon}^{\omega}$) and elastic ($\boldsymbol{\varepsilon}^{\mathrm{el}}$) deformations are rate independent, and $\boldsymbol{\varepsilon}^{\omega}$ is independent on $\boldsymbol{\sigma}$. A detailed description of the material model, used material parameters, and numerical implementation into the FE framework Abaqus CAE as a user material subroutine is found in (*35*, *36*).

Computational model

Wood bilayers were modeled using the FE method with the above described material model. The geometrical model and BCs are presented in Fig. 4C. The dimensions were chosen according to the experimental sample set described below. The interface region, acting as a diffusion barrier, was modeled by a 0.5-mm-thick and isotropic one-component polyurethane adhesive (1cPUR) by tie connection. The moisture diffusion process (BC for surface moisture flux) was inversely fitted to experimental data of average moisture content evolution over time by comparing the volume-weighted average WMC. Analogy between temperature and moisture was made for modeling transient diffusion using Fick's second law; $\partial\omega/\partial t = \nabla (\mathbf{D} \nabla \omega)$ is equivalent to $(\rho c_T)\partial T/\partial t = \nabla (\mathbf{K} \nabla T)$ when $\rho c_T = 1$ so that the matrix of diffusion coefficients D equals the matrix of thermal conductivity coefficients K. In a first step, heat transfer analyses were conducted using 20-node quadratic brick elements. The resulting temperature evolution fields were then used as predefined fields for static analyses with same mesh and elements. A large deformation theory was applied. The resulting bilayer curvature was calculated as $\kappa = -2u_y(u_y^2 + (l + u_x^2))^{-1}$, using the tip displacements u_x and u_y and assuming a uniform circle-arc-segment–shaped bilayer of initial length l.

Analytical model

An analytical model, derived in (*34*), was used to alternatively model the investigated wood bilayer configurations. The model follows Timoshenko's work on bimetal thermostats (*28*) but further represents the anisotropic and moisture-dependent material behavior of wood in 2D by assuming a plane-strain state. A linear elastic deformation mechanism is considered exclusively.

Experimental samples

Using European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) wood conditioned at 95 and 85% RH, respectively, three bilayer configurations were produced for each species. Beech was conditioned in adsorption and spruce in desorption equilibrium from the green state. This setup targeted a similar initial moisture content for comparability of both species. The used wood was defect free and cut from the same stem. A scheme of the bilayer setup is given in Fig. 4C, where the local wood anatomical orientations R,T,L are given in terms of global orientations X,Y,Z for passive (layer 1, top) and active (layer 2, bottom) layers. The components were bonded using 1cPUR adhesive (HB S309 Purbond, Henkel & Cie. AG, Switzerland), as curing by poly-addition enables gluing at high moisture contents. A constant thickness ratio of $h_1 : h_2 = 1 : 2$ (passive:active) was maintained in all configurations. The total thicknesses $h_1 + h_2$ of the three configurations were chosen to be 15 mm (configuration 1), 30 mm (configuration 2), and 45 mm (configuration 3). Width and length of bilayers were chosen to be 100 and 600 mm. In the active layers, growth ring inclinations (φ) of 0° to 20° for the beech and 0° to 30° for the spruce were measured on reference samples (details in section S3). After production in initial climate, the beech samples were relocated into 65% RH and the spruce samples into 50% RH climate for drying. Curvature and weight were measured over 900 hours of acclimatization time on eight samples per configuration. Curvature was calculated as $\kappa = \psi''(1 + \psi'^2)^{-3/2}$ by image analysis. Second-order polynomials ψ were fitted to thresholded edge segments obtained by applying a Canny edge detector algorithm. WMCs ω were determined using reference samples cut from the bilayer samples before climate relocation (details in section S3).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/9/eaax1311/DC1

Movie S1. Time-lapse video of large-scale wood bilayer actuation.

Section S1. Sensitivity analysis

Section S2. The sensitivity parameter S_i^{tot}

Section S3. Statistical analysis of shrinkage coefficient in active layer

Fig. S1. Results of sensitivity analyses.

Fig. S2. Statistical analysis of shrinkage coefficient.

Table S1. Input and output of uncertainty quantification.

Table S2. Statistical test results on differential swelling coefficient measurements.

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Acknowledgments: We thank A. Wick, T. Schnider, K. Kovacs, E. Trachsel, T. Keplinger, and I. Burgert for help and discussion. **Funding:** This work was supported by Innosuisse-Swiss Innovation Agency (grant number 25114.2), Swiss National Science Foundation (grant number 140002), and the GETTYLAB. **Author contributions:** P.G. designed and performed the analysis and experiments and wrote the paper. M.R. and F.K.W. contributed to the conception and design of the analysis and experiments. M.M.H. contributed to the numerical analysis. D.W. and A.M. contributed to the conception of application. All authors discussed and commented on the manuscript. **Competing interests:** P.G., D.W., A.M., and M.R. are inventors on a patent application (PCT/EP2019/056817) related to this work. The authors declare no other competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 1 March 2019
Accepted 12 August 2019
Published 13 September 2019
10.1126/sciadv.aax1311

Citation: P. Grönquist, D. Wood, M. M. Hassani, F. K. Wittel, A. Menges, M. Rüggeberg, Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures. *Sci. Adv.* **5**, eaax1311 (2019).

Science Advances

Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures

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Sci Adv **5** (9), eaax1311.
DOI: 10.1126/sciadv.aax1311

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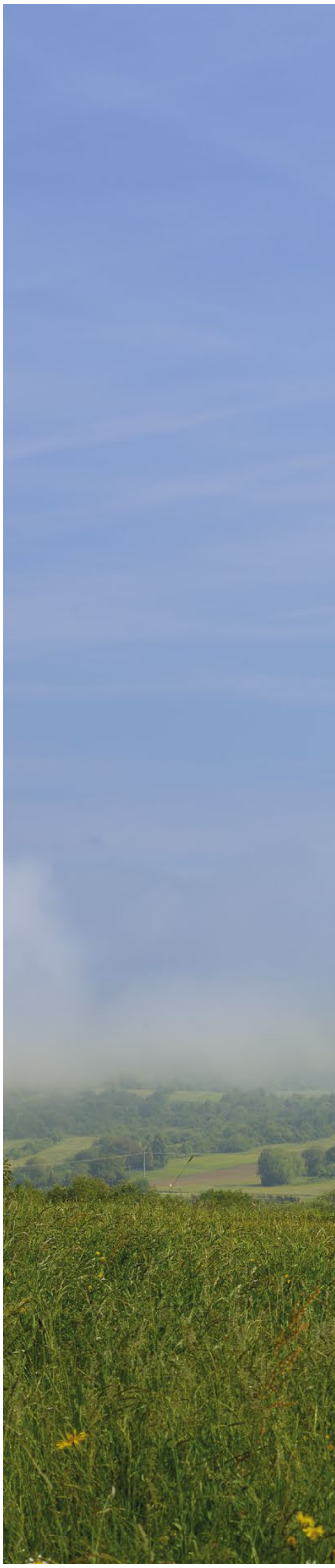
Article D
From machine control to material programming: Self-shaping timber manufacturing of a high performance curved CLT structure – Urbach Tower

12 Article D
From machine control to material programming: Self-shaping timber manufacturing of a high performance curved CLT structure – Urbach Tower

Wood, D., Grönquist, P., Bechert, S., Aldinger, L., Riggenbach, D., Lehmann K., Rüggeberg, M., Burgert, I., Knippers, J. and Menges, A. (2020), **From machine control to material programming: Self-shaping timber manufacturing of a high performance curved CLT structure – Urbach Tower**, in J. Burry, J. Sabin, B. Sheil and M. Skavara (eds.), FABRICATE 2020: Making Resilient Architecture. UCL Press London, pp. 50–57. DOI: 10.2307/j.ctv13xpsvw.11

This short article presents an overview of the material programming approach and self-shaping manufacturing approach for the Urbach Tower building demonstrator in the context of architecture and digital fabrication. The work is framed as an alternative approach to digital design and construction methods highlighting the architectural and structural performance achieved through the novel design and manufacturing approach. It describes the architecture, design process, geometry and engineering of the Urbach Tower and how low-level material parameters are accessed as part of the material programming. The article briefly describes the results of the full manufacturing run for producing the large curved CLT components and how these compare to a form-bending method. It concludes by discussing the potentials of the approach as a major shift towards the digital production of material-driven ecological and evocative architecture.

D. Wood is the lead author of this work and developed the overall concept and contextualisation in architecture and construction in conversation with A. Menges and I. Burgert. D. Wood served as the project leader and construction manager for the demonstrator building and the fabrication of the self-shaping components. D. Wood, M. Rüggeberg and P. Grönquist designed the industry integration concept and experiments in consultation experts from the industry partner D. Riggenbach and K. Lehmann. Integration of the self-shaped components in the demonstrator and FE analysis of the overall structure including the structural engineering and planning was carried out by S. Bechert, L. Aldinger and J. Knippers. Structural testing and verification was conducted by P. Grönquist. The manuscript was written and revised by D. Wood and presented by D. Wood and P. Grönquist.



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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

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.

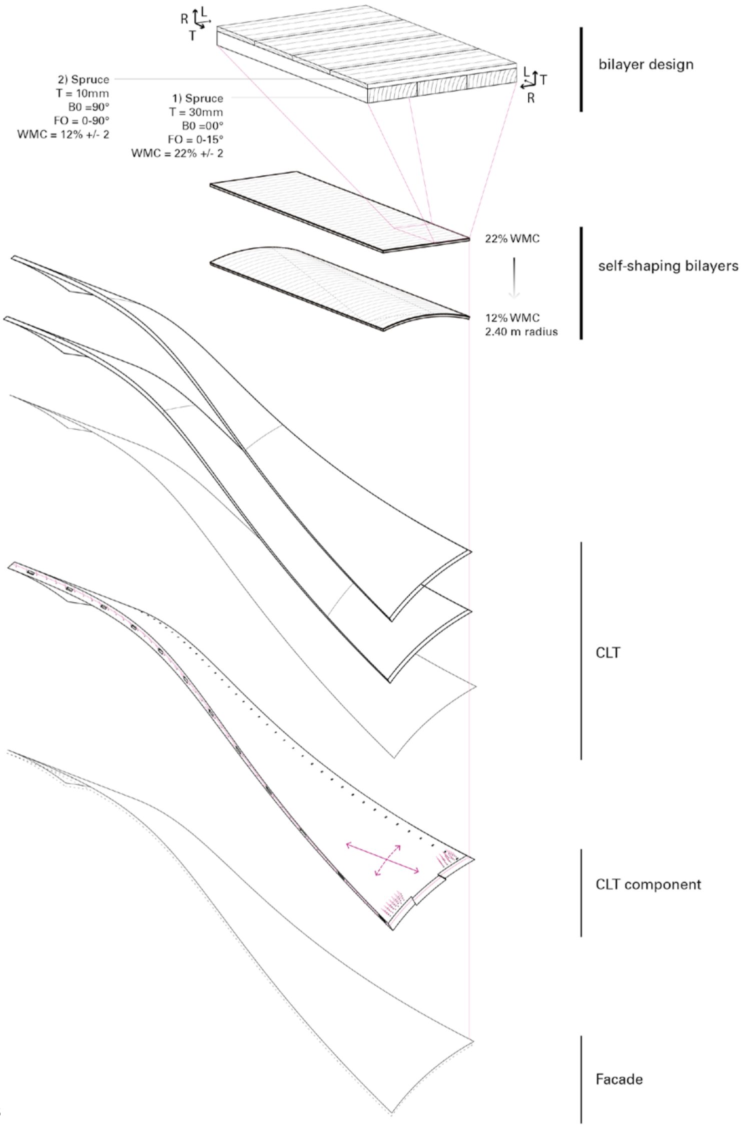
Research Questions

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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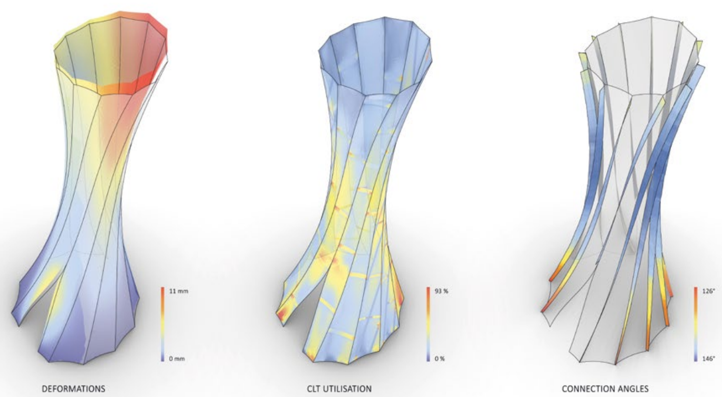
Research Evaluation

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.

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).



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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.

Acknowledgments

The research was funded by: The Swiss Innovation Agency – InnoSuisse (grant number 25114.2), GETTYLAB, The Deutsche Bundesstiftung Umwelt DBU (German Federal Environmental Foundation) (grant number DBU Az. 34714/01), Blumer Lehmann AG, the University of Stuttgart, Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2120/1 – 390831618, Gemeinde Urbach, Remstal Gartenschau 2019 GmbH, Carlisle-CCM Europe, and Scanntronik Mugrauer GmbH. The demonstrator with completed with the support of Ramon Weber, Robert Faulkner, Christo van der Hoven, Denista Kolvea, Monika Monika Göbel , Urs Basalla,Stefan Bischof, Markus Fitzi, Peter Trittenbass, Josua Preisig ,Kai Strehlke, Martin Antemann, Urban Jung, Richard Jussel, and Huizhang Guo.

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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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A

Supporting Publications with Contribution by the Author

Appendix A includes topic-relevant research papers with notable contributions by the author.

A.1 Appendix A – Publication 1

Wood, D., Brütting, J. and Menges, A. (2018), **Self-forming curved timber plates: Initial design modeling for shape-changing material buildups**, in C. Mueller and S. Andriaenssens (eds.), Proceedings of the International Association of Shell and Spatial Structures (IASS) Annual Symposium 2018 – Creativity in Structural Design, July 16–20, MIT, Boston, Massachusetts

Abstract
This research shows an initial investigation into digital modeling of designed active material behaviors for shape-changing and self-forming timber plates based on hygroscopic actuation applicable for environmentally responsive structures and actuators. By explicitly defining fibre orientation layouts and layups within the plate, different curved movements can be designed. This design space of self-forming movements, combined with the stiffness and high actuation forces in wood, can be applied to larger self-supporting building components compared to other smart materials. This paper presents a process-specific digital design and simulation workflow to design large self-forming timber plates. Using this tool, the designer can modify upstream material information, which is translated into a FE model to simulate deformation patterns. The designer can fine-tune the input conditions to achieve desired deformed geometries. Case studies are shown for multiple movement patterns based on combinations and variations of single curvature within a standard plate geometry. The research expands the design space for self-forming plates by allowing methods for adaptations of curvatures. The included FE simulation gives a quick and reliable estimate of the physically achieved deformation patterns given the

material uncertainties of wood and the simplification of material properties. The workflow shows the possible design control and simplicity of the system, which can be applied to structural applications such as large-scale actuators or responsive surfaces as well as parts for self-forming or shape-shifting structures.

Relevance
This conference publication describes an initial computational approach to material programming and presents a lightweight digital workflow using a 3D-modelling environment and FE modelling software.

Contributions
D. Wood is the main author of the work and designed the concept and experiments in discussion with A. Menges. J. Brütting implemented the workflow in the FE modelling environment and provided the structural modelling expertise. D. Wood and J. Brütting prepared the manuscript and D. Wood presented the work at the IASS conference.

A.2 Appendix A – Publication 2

*Aldinger, L., *Bechert, S., *Wood, D., Knippers, J. and Menges, A. (2020), **Design and structural modelling of surface-active timber structures made from curved CLT – Urbach Tower, Remstal Gartenschau 2019**, in C. Gengnagel, O, Baverel, J. Burry, M. Ramsgaard Thomsen and S. Weinzierl (eds.), Impact: Design With All Senses [Proceedings of the Design Modelling Symposium 2019], Springer International Publishing, pp. 419–32. Doi: 10.1007/978-3-030-29829-6 33
*Authors contributed equally

Abstract
Recent advancements in structural engineering, 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 favorable elastic properties allow bending of timber for use in free-form curved beam structures. Such complex geometries necessitate a high degree of prefabrication enabled by the machinability of timber and established digital fabrication methods. In parallel, cross-laminated timber (CLT) offers high dimensional stability and biaxial load-bearing behavior; however, it has predominantly found use in standardized, rectilinear geometries. Only recently, has curved CLT drawn interest in the building industry as it provides advantageous structural performance due to its inherent curvature in combination with surface-active typologies. These properties add to the formal and structural potential for the design of slender and lightweight structures. Further, curved plates structures made from CLT offer high structural performance and present an alternative for free-form structures typically constructed from less sustainable

building materials. This research presents an integrated design and modelling framework for the use of single curved CLT components in multi-component, surface-active structures. The inherent geometric complexity of curved parts leads to a challenge on three interdependent levels: 1. Global design and interplay of components. 2. Curvature and material build-up of components. 3. Adaptive connection strategies for structural connections of multiple curved components. Architectural requirements, structural feedback and fabrication constraints inform these interdependencies. Thus, a sophisticated process is shown that integrates the parametric adaption of the design parameters. The modelling approach and construction system were validated through the design and construction of a 14 m tall tower structure serving as landmark and hiking shelter.

Relevance
This research paper describes the design and structural modelling of the Urbach Tower demonstrator building. This includes the integration of the unique characteristics and constraints of the self-shaping manufacturing process. Relevant to this thesis, the paper describes the details of the architectural tectonic in relation to the structural engineering, structural detailing and constructional aspects of assembly and building systems.

Contributions
D. Wood, L. Aldinger, and S. Bechert conceived of the concepts under the supervision and direction of J. Knippers and A. Menges. The geometric and parametric and fabrication modelling strategies were investigated by D. Wood and the structural modelling investigations were designed and tested by L. Aldinger and S. Bechert. Construction management and on-site coordination

of the project was supervised by S. Bechert and D. Wood. L. Aldinger and D. Wood prepared and revised the manuscript with input from S. Bechert. The research was presented by the co-authors at the Design Modelling Symposium Berlin in 2019.

A.3 Appendix A – Publication 3

Grönquist, P., Panchadcharam, P., Wood, D., Menges, A., Rüggeberg, M. and Wittel, F. K. (2020), **Computational analysis of hygromorphic self-shaping wood gridshell structures**, Royal Society Open Science, Vol. 7 (7), DOI: 10.1098/rsos.192210

Abstract

Bi-layered composites capable of self-shaping are of increasing relevance to science and engineering. They can be made out of anisotropic materials that are responsive to changes in a state variable, e.g. wood, which swells and shrinks by changes in moisture. When extensive bending is desired, such bilayers are usually designed as cross-ply structures. However, the nature of cross-ply laminates tends to prevent changes of the Gaussian curvature so that a plate-like geometry of the composite will be partly restricted from shaping. Therefore, an effective approach for maximizing bending is to keep the composite in a narrow strip configuration so that Gaussian curvature can remain constant during shaping. This represents a fundamental limitation for many applications where self-shaped double-curved structures could be beneficial, e.g. in timber architecture. In this study, we propose to achieve double-curvature by gridshell configurations of narrow self-shaping wood bilayer strips. Using numerical mechanical simulations, we investigate a parametric phase-space of shaping. Our results show that double curvature can be achieved and that the change in Gaussian curvature is dependent on the system's geometry. Furthermore, we discuss a novel architectural application potential in the form of self-erecting timber gridshells.

Relevance

This research article describes a computational method for modelling self-shaping curved gridshells made from wood bilayers. The paper presents an additional novel application of self-shaping wood as a potential on-site self-forming method for mechanisms made from multiple bilayer parts. The critical contribution of the work is in the identification of a material and geometric configuration that works in the mechanism of both the bilayer and the gridshell.

Contributions

P. Grönquist, D. Wood, A. Menges and M. Rüggeberg developed the concept for implementing the bilayers in a self-shaping gridshell. D. Wood provided expertise in the architectural and technical design of wood lath gridshells. F. Wittel, P. Grönquist and P. Panchadcharam designed the computational approach and experiments, and analysed the results. P. Panchadcharam conducted her Bachelor's thesis on the topic and contributed to the results and manuscript. P. Grönquist prepared and revised the manuscript.

A.4 Appendix A – Publication 4

Forestiero, F., Xenos, N., Wood, D. and Baharlou, E. (2018), **Low-tech shape-shifting space frames**, in C. Mueller and S. Andriaenssens (eds.), Proceedings of the International Association of Shell and Spatial Structures (IASS) Annual Symposium 2018 – Creativity in Structural Design, July 16–20, MIT, Boston, Massachusetts

Abstract
This research demonstrates a system for low-tech shape-shifting space frame structures, passively responding to environmental conditions. The focus is designing simple lightweight structures that are capable of large geometrical transformations with high activation speed. The shape-shifting relies on the combination of passive wooden actuators and compliant nodes. In the proposed system, global geometrical transformations are obtained by strategically integrating passive actuators and nodes with designed compliance to create space frames that change in shape. The actuator is a hygroscopically actuated wood bilayer, that passively curves in response to the Relative Humidity (RH) fluctuation. The nodes are 3D printed with specific complaint geometries to accommodate the specific local and global transformations. Geometrical transformations are investigated through an interactive physics-based simulation and tested on physical prototypes.

Relevance
This research article presents an additional large-scale application for self-shaping wood bilayers as responsive members in shape-morphing space-truss structures. The work is influential in two

ways. First it shows larger structures can be transformed into complex configurations using only a limited number of self-shaping parts. Second it shows that self-shaping wood systems can be upscaled as lightweight structures with relatively fast response times.

Contributions

D. Wood, F. Forestiero and N. Xenos developed the concept and application of self-shaping wood bilayers in space-frame structures. E. Baharlou contributed to the computational design and modelling methods. D. Wood and F. Forestiero revised the manuscript. F. Forestiero and N. Xenos developed the work as part of the Master's thesis C.2, and wrote and presented the manuscript.

A.5 Appendix A – Publication 5

Cheng, T., Wood, D., Kiesewetter, L., Özdemir, E., Antorveza, K. and Menges, A. (2021), **Programming material compliance and actuation: hybrid additive fabrication of biocomposite structures for large-scale self-shaping**, Bioinspiration & Biomimetics. DOI: 10.1088/1748-3190/ac10af

Abstract
We present a hybrid approach to manufacturing a new class of large-scale self-shaping structures through a method of additive fabrication combining fused granular fabrication (FGF) and integrated hygroscopic wood actuators (HWAs). Wood materials naturally change shape with high forces in response to moisture stimuli. The strength and simplicity of this actuation make the material suitable for self-shaping architectural-scale components. However, the anisotropic composition of wood, which enables this inherent behavior, cannot be fully customized within existing stock. On the other hand, FGF allows for the design of large physical parts with multi-functional interior substructures as inspired by many biological materials. We propose to encode passively actuated movement into physical structures by integrating HWAs within 3D-printed meta-structures with functionally graded stiffnesses. By leveraging robotic manufacturing platforms, self-shaping biocomposite material systems can be upscaled with variable resolutions and at high volumes, resulting in large-scale structures capable of transforming from flat to curved simply through changes in relative humidity.

Relevance
This research article presents an additional approach to upscaling

self-shaping wood bilayers and expanding the possible geometric configurations. This is achieved through the combination of large-scale additive manufacturing (robotic 3D printing), where meso-structuring of the component can be designed in high resolution and used to connect multiple bilayer actuators.

Contributions
D. Wood and A. Menges developed the concept for hybrid robotic additive manufacturing in discussion with T. Cheng. The production process was prototyped through a workshop hosted by X. Wang and P.F Yuan and further implemented by T. Cheng. T. Cheng wrote and presented the manuscript. D. Wood and T. Cheng revised the manuscript and have further developed a concept based on the publication C1.

A.6 Appendix A – Publication 6

Dierichs, K., Wood, D., Correa, D. and Menges, A. (2017), **Smart granular materials: prototypes for hygroscopically actuated shape-changing particles**, in T. Nagakura, S. Tibbits, M. Ibañez and C. Mueller (eds.), ACADIA 2017 Disciplines & Disruptions: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), pp. 222–31. Cambridge, Massachusetts

Abstract
Hygroscopically Actuated Granular Materials are a new class of designed granular materials in architecture. Granular materials are large numbers of particles that are only in loose contact with each other. If the individual particle in such a granular material is defined in its geometry and material make-up, one can speak of a designed granular material. In recent years these designed granular materials have been explored as architectural construction systems. Since the particles are not bound to each other, granular materials are rapidly reconfigurable and recyclable. Yet one of the biggest assets of designed granular materials is the fact that their overall behavior can be designed by altering the geometry or material make-up of the individual composing particles. Up until now mainly non-actuated granular materials have been investigated. These are designed granular materials in which the geometry of the particle stays the same over time. The proposed Hygroscopically Actuated Granular Materials are systems consisting of time-variable particle geometries. Their potential lies in the fact that one and the same granular system can be designed to display different mechanical behaviors over the course of time. The research presented here encompasses three

case studies, which complement each other both with regard to the development of the particle system and the applied construction processes. All three cases are described both with regard to the methods used and the eventual outcome aiming at a potential design system for Hygroscopically Actuated Granular Materials. To conclude, these results are compared and directions of further research are indicated.

Relevance

This research article presents an alternative unstructured and distributed use of self-shaping wood bilayers in macro-scale aggregate systems. The work shows an entirely different application of self-shaping as a binding element to hold together loose granular particles. This is shown through the computational design and mass-production of standardised self-shaping particles and physical testing in a variety of structural configurations.

Contributions

K. Dierichs, D. Wood and D. Correa developed the smart granular materials concept in discussion with A. Menges. D. Wood was responsible for the design and computational modelling of the hygroscopic particles and the fabrication procedures for production. K. Dierichs, D. Wood and D. Correa advised the students whose work is described C.4. K. Dierich designed and conducted the experiments, and prepared and revised the manuscript. D. Wood presented the work at the ACADIA conference.

A.7 Appendix A – Publication 7

Tahouni, Y., Cheng, T., Wood, D., Sachse, R., Thierer, R., Bischoff, M. and Menges, A. (2020), **Self-shaping curved folding**, in Symposium on Computational Fabrication (SCF), ACM, New York, pp. 1–11. DOI: 10.1145/3424630.3425416

Abstract

Curved folding, a method to create curved 3D structures from a flat sheet, can be used to produce material and manufacturing efficient, static or dynamic structures. However, the complex assembly and folding sequence of curved crease patterns is the bottleneck in their fabrication process. This paper presents Self-shaping Curved Folding: a material programming approach to create curved crease origami structures that self-assemble from flat into 3D folded state upon exposure to external stimuli. We propose a digital fabrication process via the 3D-printing of shape-changing materials, accompanied by a computational design workflow in which the geometry of a crease pattern is correlated with the printing toolpaths and the layup of stimuli-responsive and passive materials to achieve a target shape-change. We demonstrate our method by producing multiple prototypes and documenting their shape-change upon actuation. Lastly, we explore the functional and performance benefits of self-shaping curved folding under three application scenarios relevant to the field of industrial design and architecture.

Relevance

This work describes a material programming approach and digital fabrication workflow for the design and production of self-shaping curved crease folding surfaces. While the work is presented through additive manufacturing at a smaller scale, the approach is based on that described in Article A. Especially relevant is the use of coordinated self-shaping in multiple sub-parts to produce a complex change in shape from a very thin flat sheet to a rigid beam capable of carrying a larger load. This displays an additional geometric and tectonic application of self-shaping with possible application in manufacturing and structural design.

Contributions

Y. Tahouni, D. Wood and T. Cheng developed the concept for self-shaping curved folding in 3D-printed parts. A. Menges contributed to the development of the computational design approach and architectural applications. Y. Tahouni designed and carried out the physical experiments and implemented the design-to-fabrication workflow with the input of T. Cheng. R. Sachse and R. Thierer, and M. Bischoff designed and carried out a parametric simulation of a basic curved folding mechanism to understand the relationship between the self-shaping mechanism and the geometric mechanism. Y. Tahouni and D. Wood wrote and revised the manuscript. Y. Tahouni presented the paper at the SCF symposium.

A.8 Appendix A – Publication 8

Bechert, S., Aldinger, L., Wood, D., Knippers, J., Menges, A. (2021), **Urbach Tower: Integrative structural design of a lightweight structure made of self-shaped curved cross-laminated timber**, Structures, 33, pp. 3667–3681. Elsevier. DOI: 10.1016/j.istruc.2021.06.073

Abstract
Recent development in research and practice for curved cross-laminated timber (CLT) opens up novel and interesting possibilities for applications of slender surface-active shell structures in architecture. Such typologies provide advantageous structural behaviour allowing for efficient and lightweight structures while simultaneously determine the envelope and space of a building. The high degree of prefabrication combined with a sustainable and renewable building material makes CLT an ecological and economic solution for future construction. This paper presents the design development and construction of the Urbach Tower for the Remstal Gartenschau 2019: a structure made from high curvature CLT components on a building scale. This research contribution illustrates a sophisticated integrative design to construction process emphasizing computational and structural design, fabrication and detailing for curved timber components in complex spatial structures. The authors further explore the structural potential of self-shaped curved CLT investigating the influence of curvature radius on the load-bearing behaviour of the tower structure. The Urbach Tower translates these technical developments into practice arising at the intersection of digital innovation and scientific research.

Relevance
This research article provides an in-depth analysis of the structural design and engineering of the Urbach Tower demonstrator building and the associated construction systems developed by the engineers and architects.

Contributions
D. Wood contributed to the design experiments for the curved structure optimisation and the development of the projects construction systems and detailing. S. Bechert wrote the manuscript and conducted all experiments related to the structural engineering. L. Aldinger contributed to the structural design concept and overall modelling. D. Wood developed the parametric design and production models and revised the manuscript. A. Menges and J. Knippers supervised the research.

A.8 Appendix A – Publication 8

B
Supporting Patent Applications

Appendix B includes topic-relevant research patent applications submitted by the author during the period of the research.

B.1 Appendix B – Patent Application 1

Wood, D., Menges, A., Rüggeberg, M., Grönquist, P. and Burgert, I, **Manufacturing process for shaped, stacked, multilayer, wood-based building components (herstellungsverfahren für geformte, gestapelte, Mehrschichtige, holzbasierte baukomponenten)** 2020. PCT/WO 2019/180006 A1, EP3543000 A1, DE 11 2019 001 411.0, CH 01189/20, A 9119/2019

Summary

The disclosed invention comprises a manufacturing process for complex shaped laminated, multilayered, plant fiber-based components (4') of isotropic or anisotropic plant fiber based plant fiber-based elements (0, 0'), which is less expensive and more resource efficient, as it produces less waste. This is achieved by,that plant fiber based elements (0, 0') are formed by a deformed by a self-forming step (II), which produces shape-changed plant fiber based components (3') by applying an input stimulus (2) change from initial condition with initial wood moisture content (U1) and initial temperature (T1) to final state with final wood moisture content (U2) and final temperature (T2) for a moisture change ΔU between 1 % and 20 % and/or a temperature change between 0 °C and 70 °C before the shape-changed plant fiber-based building components (3') in a stacking and fixing step (III) and fastening step (III), the shaped, laminated stacked and bonded in a stacking and bonding step (III), which includes shaped, laminated multilayer plant fiber-based building components (4) for further treatment.

This patent application describes the invention of a self-shaping manufacturing process for the production of curved wood-based components. The invention is presented in comparison to the current state of technology for self-shaping materials and the shaping of curved wood. The process of selection, arranging, self-shaping and stacking to mechanically lock the components is introduced in the technical description. Critical parameters are identified and an example case using wood materials is shown.

Contributions
D. Wood is a co-inventor of the patent. The concept was identified by D. Wood and M. Rüggeberg in conversation regarding the upscaling and mechanical stability of wood bilayers. D. Wood prepared the initial physical proof of concepts and M. Rüggeberg the initial material and structural sketches. The concept was further discussed and adapted in discussion with A. Menges and I. Burgert. Technical detail and proof of concept was developed by D. Wood, P. Grönquist and M. Rüggeberg. The underlying invention disclosures and evaluation of the current technology were prepared by M. Rüggeberg and D. Wood. The initial applications were prepared in English and translated into German for national submission.

B.2 Appendix B – Patent Application 2

Wood, D., Menges, A., Kiesewetter, L., Rüggeberg, M., Grönquist, P. and Burgert, I, **Manufacturing method of a multi-layer component of layered elements and a multi-layer component of layered elements as such** 2021. EP20216959.5

Summary

The present invention relates to a manufacturing method of a multi-layer component (1) of layered elements (0, 0') and to a multi-layer component of layered elements (1) as such. The multi-layer component (1) is manufactured such that it self-transforms through actuation from an external stimulus such as heat or humidity into a shape-changed multilayer component (2) forming, for example, a furniture piece. The shape-changed multilayer component (2) stays in the shape-changed configuration unless it is exposed to an extended amount of time to the first climatic condition of manufacturing, which condition is preferably different from normal ambient and indoor climatic conditions.

Contributions

D. Wood is a co-inventor of the patent and the lead developer of the invention. D. Wood outlined and revised the initial patent application.

B.2 Appendix B – Patent Application 2

C
Supporting Thesis Projects Advised by the Author

Appendix C includes a list of relevant thesis projects on which the author was an advisor during the research period.

C.1 Project 1

Antorveza, K., Kiesewetter, L. and Özdemir, E. (2020), **Hybrid additive manufacturing of self-shaping building components**, MSc. Thesis, University of Stuttgart. Supervisors: A. Menges and J. Knippers. Advisors: T. Cheng, S, Leder and D. Wood (thesis preparation).

C.2 Project 2

Forestiero, F. and Xenos, N. (2018), **Hygroscopic shape-changing networks: Hierarchical programming of large scale responsive structures**, MSc. Thesis, University of Stuttgart. Supervisors: A. Menges and J. Knippers. Advisors: D. Wood and E. Baharlou.

C.3 Project 3

Giachini, Pedro A. G. S. and Gupta, S. (2018), **Fluid formations: Design and fabrication of soft matter structures with functional stiffness gradients**, MSc. Thesis, University of Stuttgart. Supervisors: A. Menges and J. Knippers.. Advisors: D. Wood, E. Baharlou and W. Wang.

C.4 Project 4

Wolkow, A. (2016), **Selectively self-reinforcing aggregates: A two particle-type granular system for performance in tension**, MSc. Thesis, University of Stuttgart. Supervisors: A. Menges and J. Knippers. Advisors: K Dierichs and D. Wood.

C.5 Project 5

Lago, A. (2015), **Adaptive wood plates: Hygroscopic responsive elements in architectural plate systems**, MSc. Thesis, University of Stuttgart. Supervisors: A. Menges and J. Knippers. Advisors: D. Wood and D. Correa.

C.6 Project 6

Panchadcharam, P. (2018), **4D Holzstrukturen: Holzbilayer als Streben von Gitterschalenstrukturen [4D wood structures: wood bilayers as lamellas in lattice grid shell structures]**, Bachelorarbeit im Bereich Werkstoffe und Mechanik [Bachelors in field of materials and mechanics], Institut für Baustoffe (IfB), ETH Zurich. Supervisors: I. Burgert, H. Herrmann, F. Wittel, M. Rüggeberg, P. Grönquist and D. Wood.

C.7 Project 7

Schnell, L. (2018), **4D Holzstrukturen: Keile aus verdichtetem Holz [4D wood structures: wedges of mechanically densified wood]**, Bachelorarbeit im Bereich Werkstoffe und Mechanik [Bachelors in field of materials and mechanics], Institut für Baustoffe (IfB), ETH Zurich. Supervisors: I. Burgert, F. Wittel, M. Rüggeberg, P. Grönquist and D. Wood.

D
Project Credit List

Appendix D includes the project credits for the Urbach Tower building demonstrator.

D.1 Urbach Tower

PROJECT TEAM

ICD – Institute for Computational Design and Construction, University of Stuttgart
Prof. Achim Menges, Dylan Wood
Architectural design Self-forming curved wood components research and development

ITKE – Institute of Building Structures and Structural Design, University of Stuttgart
Prof. Jan Knippers, Lotte Aldinger, Simon Bechert
Structural design and engineering

Scientific collaboration:

Laboratory of Cellulose and Wood Materials, Empa (Swiss Federal Laboratories for Materials Science and Technology), Switzerland
Wood Materials Science, ETH Zurich (Swiss Federal Institute of Technology Zurich), Switzerland
Dr. Markus Rüggeberg, Philippe Grönquist, Prof. I. Burgert
Self-forming curved wood components research and development (PI)

Industry collaboration:

Blumer-Lehmann AG, Gossau, Switzerland
Katharina Lehmann, David Riggenbach
Self-forming curved wood components research and development, wood manufacturing and construction

PROJECT SUPPORT

Gemeinde Urbach
Remstal Gartenschau 2019 GmbH
University of Stuttgart

The Deutsche Bundesstiftung Umwelt DBU (German Federal Environmental Foundation) Design, fabrication and engineering methods for the application of curved wood elements in high-performance, resource-efficient wood construction: Urbach Tower project, Remstal Gartenschau 2019

InnoSuisse – Swiss Innovation Agency Smart, innovative manufacturing of curved wooden components for architecture with complex geometry

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6.13 Urs Basalla, Institute of Engineering Geodesy Stuttgart (IIGS)– University of Stuttgart. **Figure 7.1**: Robert Faulkner, ICD/ITKE – University of Stuttgart. **Figure 7.2**: Dylan Wood, Robert Faulkner, ICD/ITKE – University of Stuttgart. **Figure 7.3-6**: Robert Faulkner, ICD/ITKE – University of Stuttgart. **Figure 7.7**: Philippe Grönquist, ETH Zürich and Dylan Wood, ICD – University of Stuttgart. **Figure 7.8** Urs Basalla, Institute of Engineering Geodesy Stuttgart (IIGS)– University of Stuttgart. **Figure 7.9**:Philippe Grönquist, ETH Zürich and Dylan Wood, ICD – University of Stuttgart. **Figure 8.1** Roland Halbe.

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Curriculum Vitae

Dylan Wood is an American architect, builder and researcher whose work embraces the intersection of design and science. His research focuses on developing intelligent design and fabrication principles for smart shape-changing materials as a form of material robotics that can be applied in building systems, construction, and manufacturing. He has studied at the University of Southern California, completing a Bachelor of Architecture degree, Magma Cum Laude, and graduated from the University of Stuttgart with a Master's of Science with honours. Professionally he has worked as a designer and computational fabrication specialist at Barkow Leibinger Architects in Berlin, Germany and DOSU Studio Architects in Los Angeles, California.

At the Institute for Computational Design and Construction (ICD) at the University of Stuttgart he has worked under the direction of Prof. Achim Menges and in collaboration with researchers from the Max Plank Institute for Physical Systems, ETH Zurich and EMPA, Dübendorf. Most recently he has established and leads the Material Programming Research Group at the ICD, which works on developing and deploying methods of material programming as form generation techniques for high-performance building components and in weather-responsive building envelopes. Increasingly his work focuses on the use of computational design approaches for the utilisation of sustainable natural materials in new forms of light touch construction and passive building systems.

Abstract

Form and structure play critical roles in architecture yet the processes required to produce performative geometries often require tremendous resources and physical effort. Advances in computational design and the programming of digital fabrication machines have increased variety, precision and automation in the production of building components. However, the underlying processes of generating material form still rely predominantly on brute-force methods of shaping. This research presents an alternative, material programming approach to the fabrication of building components in which shape is generated by activating the material's inherent capacity to change in relation to external stimuli. The concept is investigated through the development of an innovative method of self-shaping manufacturing for load-bearing curved wood building components. The dissertation introduces material programming in the context of architectural design, fabrication processes, wood materials and existing self-shaping technology. The self-shaping method is investigated first through physical experiments and development of a computational design-to-fabrication approach. In parallel the challenges of upscaling and predictability are addressed through computational mechanics and physical prototyping. The concept is then adapted and implemented through the design and production of components for a building demonstrator, the Urbach Tower highlighting both the technical efficiencies and architectural performance of the material system. The material programming approach is therefore shown as a simple yet sophisticated method of fabrication for a novel, ecological and effective architecture.

Cover image:
Image The Urbach Tower a high performace structure constructed from self-shaped curved wood. ICD/ITKE-University of Stuttgart I 2019

Submitted to the

University of Stuttgart
Institute for Computational
Design and Construction

ISBN 978-3-9819457-6-8