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# Structural design and construction of a self-shaping single curved timber structure HygroShell

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## Abstract

This research introduces a novel structural typology for single-curved, interlocked laminated timber structure, leveraging natural shrinking property and material heterogeneity of wood to produce high curvature in timber plates. The developed demonstrator HygroShell is a long-spanning, lightweight shell made from flat-packed components shaped on-site, demonstrating stable in situ deployment of large scale self-shaping wood. The structure spans approximately 10 meters with components only 28 mm thick, exploring the potential for broader structural applications of single-curved timber structures. Intrinsic properties of wood with digital fabrication and contemporary engineering are integrated to propose a new class of timber structures.

**Keywords**: Self-shaping wood, timber structures, shell structures, structural typology, digital fabrication, material programming.

## 1. Introduction

### 1.1. Motivation

Timber construction plays a major role in the inevitable shift towards a sustainable future in the building industries. Advances in forest management, wood processing industrialization along with the standardization of timber, adhesive and fastening have made engineered mass timber more accessible and reliable. Particularly, cross laminated timber (CLT) gained an unprecedented demand in the current construction market due to its lower carbon footprint [1], extreme degree of prefabrication, light weight and associated ease in transport and rapid assembly. Dimensional stability, predictable fire resistance, and reliable structural behavior are the promising formula that led to a wide adoption of engineered mass timber as faithful structural component. While CLT succeeds in replacing the conventional construction elements such as in-situ and prefab concrete slabs, its structural typology remains unaltered; a flat and nearly homogeneous panel of constant depth (Fig. 1a). The conventional CLT manufacturing restricts the applicable geometry to straight or flat shapes and thus unwantedly defines the range of its structural typology, inherently limiting the range of economical span. Ultimately, the use of flat elements restricts the boundary in which architecture can be conceived.

This predetermined set of structural systems aligns closely with linear design thinking common in engineering practice, where a plan is drawn, materials are allocated, and dimensions are determined, resulting in a disassociation of the geometric meaning from the inherent structural property. Shell structure, in contrast, leverages geometry as a primary mechanical principle, often achieving an extreme structural efficiency [2]. This efficiency owes particularly to the presence of surface curvature, which enables membrane action in various loading conditions [3]. While contemporary shells, notably gridshells, tend towards increased complexity in surface definitions, such as freeform and double curvature, the simpler forms of the early 20th century shells have proven that even singly curved surfaces can result in sound structural behavior when well-conceived (Fig. 1b). The development of modern shells heavily relied on concrete, an ideal material for creating continuous surfaces that can transfer the internal forces in all directions. However, concrete shells have declined over time, which may be attributed to rising labor cost and the extensive use of formwork, rendering this construction method economically unviable.


Figure 1: (a: left) Typical CLT construction. Source: adapted from https://www.siga.swiss. (b: middle) Single curved shell for Salto bus terminal by Eladio Dieste. Source https://www.fadu.edu.uy/eladio-dieste/obras/terminal-municipal-de-omnibus. (c: right) Morphing property of conifer cones, in which change in volume due to moisture condition is translated into motion. Source [4].

The material of wood may offer a unique opportunity to revitalize surface-active structures, addressing the challenges in conventional timber and shell structures. Wood is a material that naturally swells and shrinks in response to the change of ambient moisture conditions (Fig. 1c). This shrinking property and the material heterogeneity, which often cause undesired deformation and cracking, are commonly considered as drawback and thus rather suppressed in construction. Conversely, self-shaping wood utilizes these very properties to reliably produce high single curvature in laminated timber plates, or namely bilayers. This process contrasts to a conventional forming process of wood that forces lamellas into a prescribed curvature, a process which is heavily assisted by mechanical equipment. A bilayer consists of cross ply laminates with one thicker ‘active’ layer starting with a high moisture content and one thinner ‘restrictive’ layer. This amplified sectional asymmetry, along with the orthogonality of stiffness and shrinking property between the two layers, induces a pronounced curvature in one direction when the wood dries as a result of internal stress equilibrium (Fig. 2a). This controlled curvature formation through the self-shaping principle has been applied to the Urbach Tower, which combined multiple curved CLT components of 90mm thick total buildup to create a 14m high, globally hyperbolic hollow structure [5]. Despite its success in this large scale demonstrator, the potential for structural application of self-shaping wood remains unexplored, especially for long span, lightweight, load bearing structures.

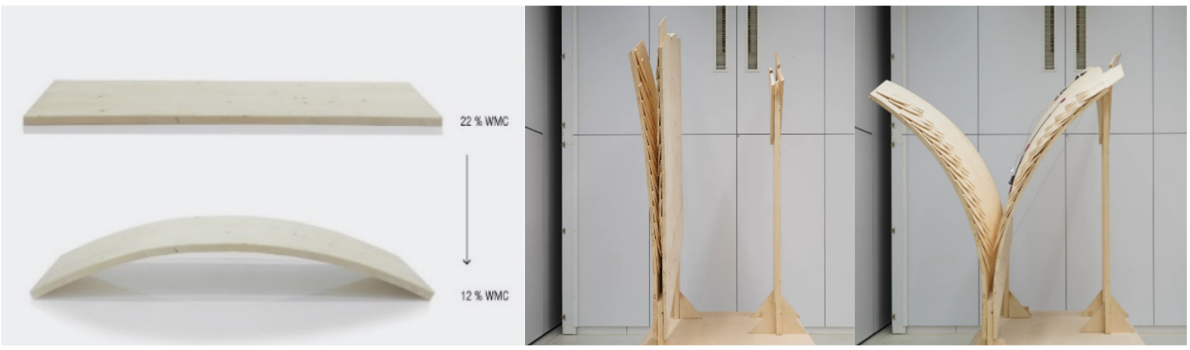


Figure 2: (a: left) Self-shaping of a single board Source [5]. (b: right) self-shaping of a test package developed for HygroShell.

### 1.2. Research demonstrator for an in situ self-shaping timber shell

In the lineage of research pavilions at the University of Stuttgart, the demonstrator - HygroShell ITECH Research Pavilion 2023 - was developed to explore the use of self-shaping wood for construction, in attempt to address four research questions:

a) How can we employ the natural hygroscopic and structural properties of wood to create large-scale, high curvature building components?
b) In what ways can self-shaping wood mechanisms be deployed as methods of in-situ forming and construction?
c) What new architectural tectonics and structural typologies can be generated through computational design and fabrication methods for self-shaping wood?
d) How can we utilize the geometric and material properties specific in self-shaping curved laminated timber plates for the development of long span, lightweight timber shell structures?

The developed demonstrator features robotically machined, shingle-clad, flat-packed, prefabricated bilayer components that curve in situ (Fig. 2b). Each component embeds curvature potentials in function of naturally varying wood moisture content (WMC) and grain angles across different boards, actuating on site through air drying to produce predicted curvatures. Six of these components in total, approximately 8 by 4 meters in size, are paired to form three ‘packages’ that sit on temporary punctual supports in the final position and stably self-shape despite under self-weight (Fig.4). The resulting curved geometry is then interlocked with the adjacent components to provide the final structural rigidity. An additional 4mm thick ‘locking’ layer, identical thickness to the ‘restrictive’ layer, is then applied to the interior surfaces, ensuring cross-sectional symmetry and dimensional stability (Fig. 3). The interlocked shell made of variable single curvature resulted in a delicately arched canopy spanning 10 meters yet only 28 mm thin (Fig. 12).

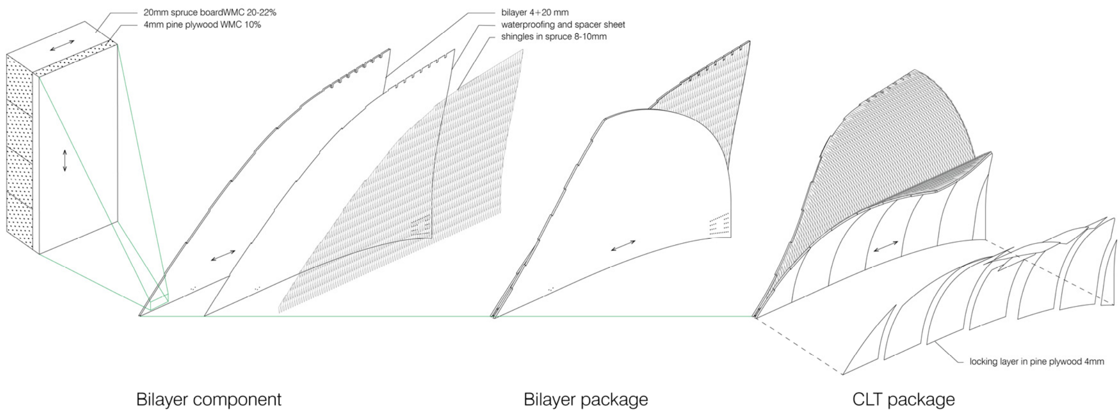


Figure 3: Anatomy of the HygroShell component

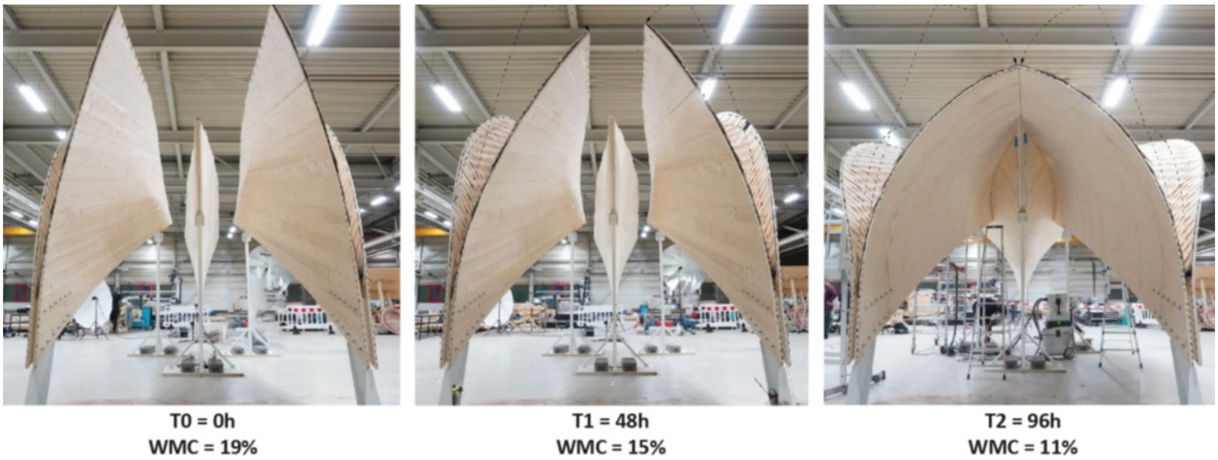


Figure 4: Self-shaping process of  the research demonstrator HygroShell: source adapted from [6]

### 1.3. Scope

This paper focuses on engineering aspects specific in self-shaping wood as well as structural design of the HygroShell. Chapter 2 examines the design research development of HygroShell, covering sectional buildup, component design, global stability, structural analysis and detailing specifically developed for the project. Chapter 3 briefly discusses and evaluates the result of the demonstrator.

This pavilion project also embodies other research area which are not covered in this paper, including digital fabrication methods for the bilayer components, detailed analysis of the material behavior and the curvature prediction, and in-depth analysis of large scale self-shaping mechanism. The literature by Wood et al 2023 [6] discusses the computational design methods used for synthesizing the material and geometry of the demonstrator. Detailed analysis and discussion on self-forming wood and bilayer are provided in the article by Grönquist [7]

## 2. Design research development

### 2.1. Synthesis of curvature potential, mechanical properties and sectional design

Self-shaping offers a broader geometric possibility for wood as construction product. While a conventional curvature forming process relies uniquely on elastic bending, limiting the radius empirically to 200 times the lamella thickness, self-shaping allows active layers to achieve as small as three or four times tighter radii. The definition of the layer buildup is important in the design of self-shaping wood structures: the buildup simultaneously determines the curvature and the material arrangement within the section, thus coupling the resulting geometry and the cross sectional mechanical properties.

The curvature of a bilayer is known to follow analytical mechanical expression called Timoshenko formula [8] and is described in function of the material properties such as elastic modulus, swelling coefficient as well as layer thickness and change of WMC. Figure 5 plots this analytical expression for a set of certain material properties, visualizing achievable radii with respect to the active and passive layer thicknesses. The graph provides a useful indication of the desirable thickness configuration for an aimed curvature, despite the reported minor deviation between the curvature prediction and the observed curvature [9]. The actual curvature range is much broader when the variations in species, log, and plank cut angle are considered.

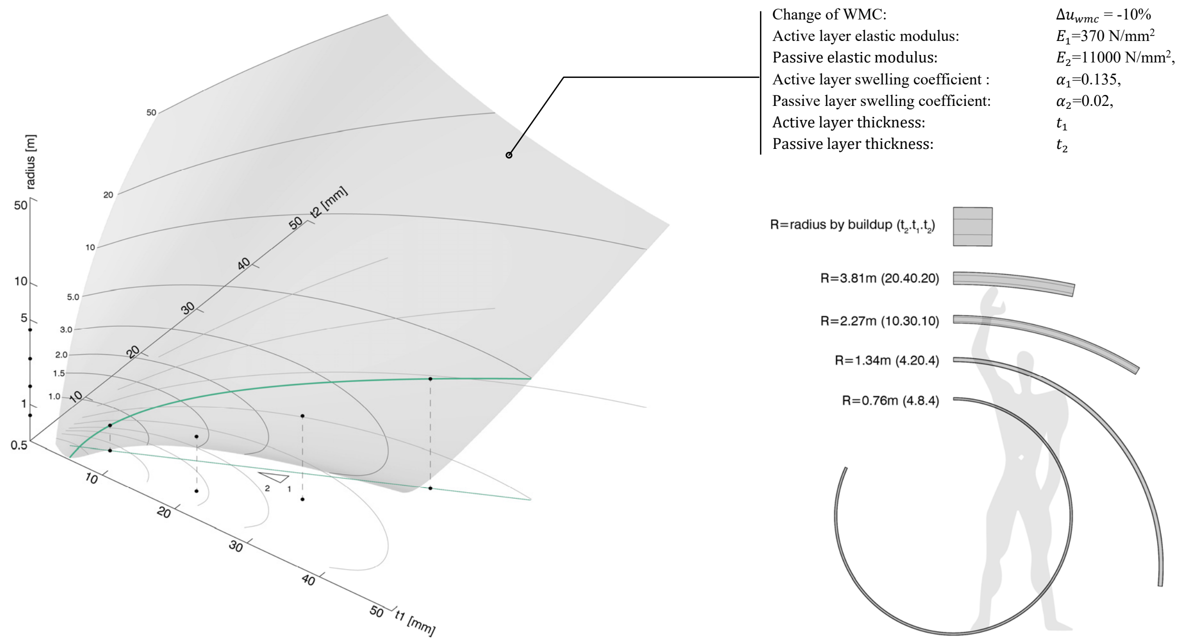


Figure 5: (a: left) 3D plot of the Timoshenko formula for fixed material parameter. Green line highlights the 1:2 thickness ratio which is most predictable according to Grönquist et al [9] (b: right) curvature of different buildup (locking layer included) out of the same volume resulting in various radii and length.

The mechanical properties of laminated plates follow the classical lamination theory. The theory stacks multiple layers of different fiber orientations with respect to the neutral axis, describing the constitutive law of the composite section. Figure 6 presents the stiffness variations in composite sections composed of three layers arranged in 0-90-0 degree orientations, whose total thickness is identical. Expectedly, the 4-20-4 millimeter composite (red), the buildup that generates the highest curvature, renders remarkable orthotropy between axial and bending stiffness, as opposed to the 28 millimeter thick single plank (orange, magenta) that exhibits unidirectional stiffnesses.

Generally in self-shaping plates composed of three layers, the axial stiffness is higher in 90 degree direction, whereas the bending stiffness remains substantial at 0 degrees. This pronounced orthotropy provides design guidance, suggesting the alignment of the major axial stiffness - the active layer's longitudinal grain direction - with the spanning direction of the structure. Consequently, this alignment dictates the curvature's orientation in the transverse direction.

The cross section buildup 4-20-4 is chosen for the HygroShell, resulting in the total 28mm thickness and variable radii between ca. 1.4 m to 2.0 m which are derived from the varying material properties and WMC of the used load. This buildup is then used for all six bilayer components that self-shapes in situ.

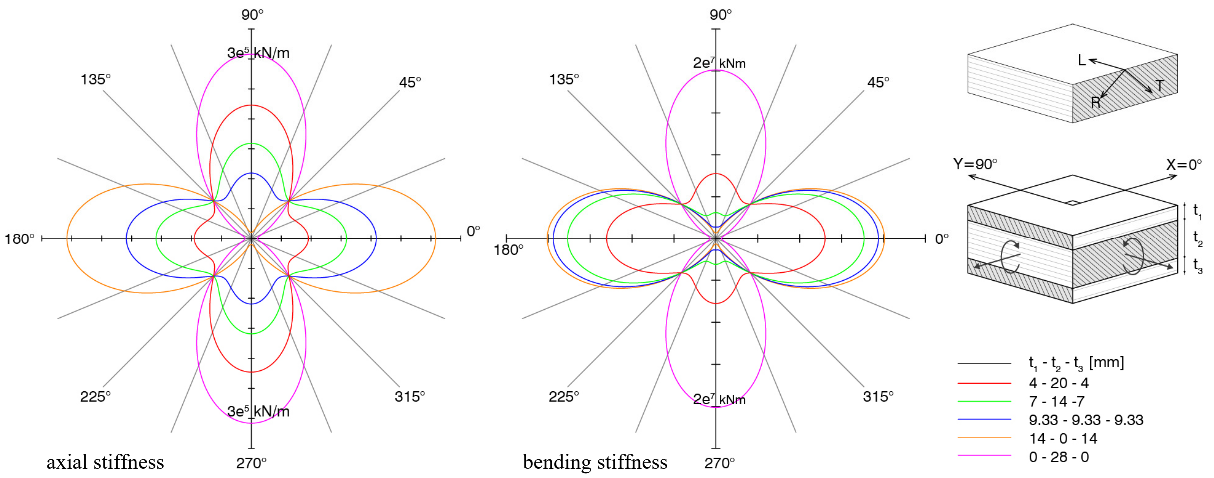


Figure 6: Axial (left) and bending (right) stiffness mapped along angle according to classical laminate theory and material property of the standard C24 timber defined in EC5.

### 2.2. Bilayer components for stable deployment and interlocked shell from

The bilayer components were developed to enable stable, large scale self-shaping, while also producing a load bearing structure in the final state. This challenge is characterized by transitioning supporting conditions from a transient state of self-shaping to a permanent, stable state once the self-shaping process is complete.

The developed component consists of a pair of two bilayers, oriented to curve out in opposing directions (Fig. 7a). Three of these packages are positioned in a staggered arrangement, creating longitudinal, curved intersections between the surfaces (Fig. 7b). These intersections play a central role in static behavior in the permanent state, as they interlock the surfaces that are individually unstable, thus eliminating the need for additional structural stiffeners.

Furthermore, this paired component creates a rigid edge where two bilayers meet, providing fixation points for supporting elements. The initial vertical orientation of the package provides sufficient structural height to span longitudinally between two supporting points, one steel foot on the ground and another temporary column (Fig. 7e). Each set of two bilayers comprising a package is developed to have approximately the same weight and surface area, resulting in a symmetric weight distribution between the two opposing plates, which helps balancing during self-shaping process (Fig. 7f).

These various considerations were integrated to develop 8 meters long self-shaping wood components, which stably deploys in situ while forming a rigid, interlocked surface structure.

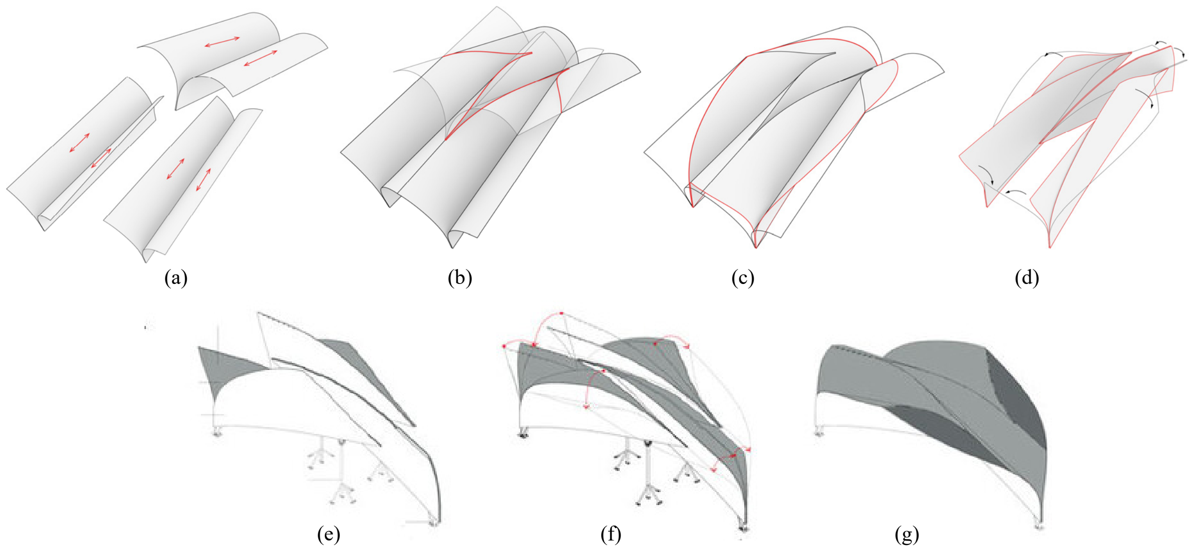


Figure 7: (a) three paired bilayer components with curvature derived from Section 2.1. (b) Three packages are positioned in a staggered manner, creating curved intersections. (c) These basic shapes are then cut off to form the final geometry (d) The pre-shaping flat geometry of the components is computed back from the curved geometry. (e) initial vertical position of the self-shaping components (f) stable self-shaping with the aid of temporary supports. (g) final state, where the surfaces are interlocked and temporary supports removed. Source of e-g adapted from [6]

### 2.3. Global structural behavior

The HygroShell structure forms an arch-like vault, touching the ground on three articulated supports (Fig. 8a). The supports are hinged in longitudinal rotations, a detail that reduces static indeterminacy and eliminates parasitic moment reactions to the substructure. The same detail is made transversally moment-rigid to enhance the support boundary condition of the shell. Figure 8b compares the horizontal and vertical eigenmode under two support conditions, highlighting a notable decrease in out-of-plane deformation under the rigid condition.

At the surface intersection, a curved plate stiffens the adjacent plate, restraining the flexural deformation along the edge. Furthermore, the intersection enables structural joinery between multiple components in span direction without creating material discontinuity in the whole cross section. Parametric studies of surface intersection have informed the final geometry, with the optimized arrangement of the curved seams that enhances the structural behavior under various loading conditions.

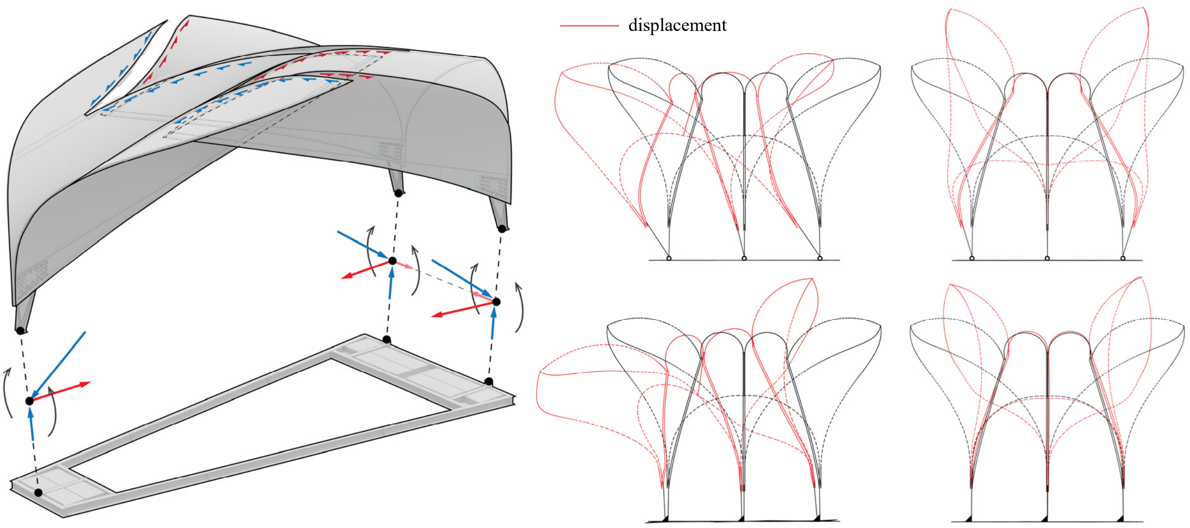

Figure 8: (a: left) Support condition and statical scheme. (b: right) Horizontal and vertical eigenmodes in two transverse support conditions: moment free (top) and moment rigid (bottom).

### 2.4. Structural analysis and verification

Finite element analysis (Fig. 9a) using the software package Sofistik 2022 is performed for the analysis of internal forces, deformation and reactions and for the design of details and foundation under various loading conditions. The design hypothesis and verification are made conforming the relevant Eurocode. Timber plates are modelled using quad shell elements with material stiffness calculated based on the laminate theory. The standard C24 timber grade is considered for spruce wood. Steel members in S235 are modelled using beam elements.

In the modelling of complex timber structures, the primary challenge lies in the evaluation of connection stiffnesses. For realistic stiffness and load transfer, timber-to-timber and timber-to-steel connections are modelled using springs with 6 DOF and evaluated according to EC5 and ETA technical specifications of the used screws (Spax). Complex shape of the curved seam and variable screw-to-grain angles necessitated the use of parametric modelling for the spring definitions.

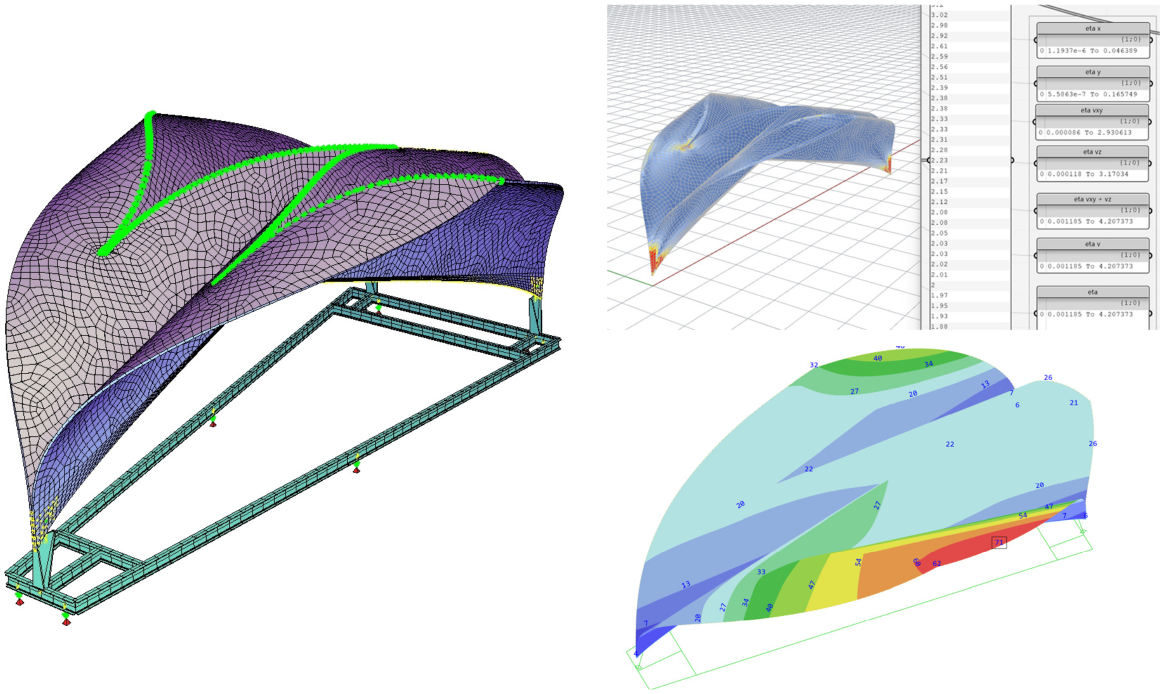

Figure 9: (a: left) Finite element model used for structural analysis. (b: right top) ULS utilization factor in various actions in the CLT plate, calculated in the parametric modeling environment. (c: right bottom) The maximal deformation in SLS characteristic wind load [mm].

The self-weight of the structure consists of 28mm structural wood as well as waterproofing membrane and 8 millimeter spruce shingles, which make up to 30% of the total dead weight in high WMC condition. Wind load is calculated with peak velocity pressure 240 Pa, a value in German urban environment with reduction for temporary duration, to which varying force coefficient between 0.6 and 1.8 are applied in symmetric and asymmetric manner. ULS and SLS load combinations are applied according to the EC1.

Figure 9b illustrates the verification setup for the internal force, where maximum ULS utilization factor are displayed by color. The maximum deformation under characteristic asymmetric wind gust was 7cm at the tip of the cantilevering wing (Fig. 9c). The steel foundation with counterweight was designed to spread symmetric and asymmetric reaction from the superstructure with resulting ground pressure lower than 50 kPa, preventing the structure from turnover.

### 2.5. Structural detailing of timber component

An alternating screwed butt joint was developed for connections on the curved seam between two components (Fig. 10a). The joint facilitates alignment of two components with tolerance while transferring shear force between two fingers. Screws (D6x80), placed in the center plane of the plate thickness, provide pullout resistance and additional shear capacity. The curved seam led to variations in the angle $\alpha$ of screw insertion as well as edge preparation, which are realized using robotic 7-axis milling on the flat bilayer plate before self-shaping. Although such screw-pressed timber connections typically offer moment rigidity, this rotational stiffness was neglected in the structural analysis due to its insignificant value. Importantly, the rotation along the seam is inherently restrained due to its curvature. It is the curved seam derived from the global geometry that allows for simpler detailing, reducing the dependence of the overall structural integrity on the stiffness of the detail.

Footing details are realized using 15mm thick steel plates, rigidly connecting the timber components with inserted steel dowels (D10mm) (Fig. 10b). These details are dimensioned to provide sufficient space above the ground, isolating the timber from moisture. The designed detail can resist a moment of 25kNm, while the solicitated ultimate limit state moment is 12kNm. The transverse moment rigidity is achieved through the bending stiffness of the 15mm steel plate, which contributes to the global stability as discussed in Section 2.3.

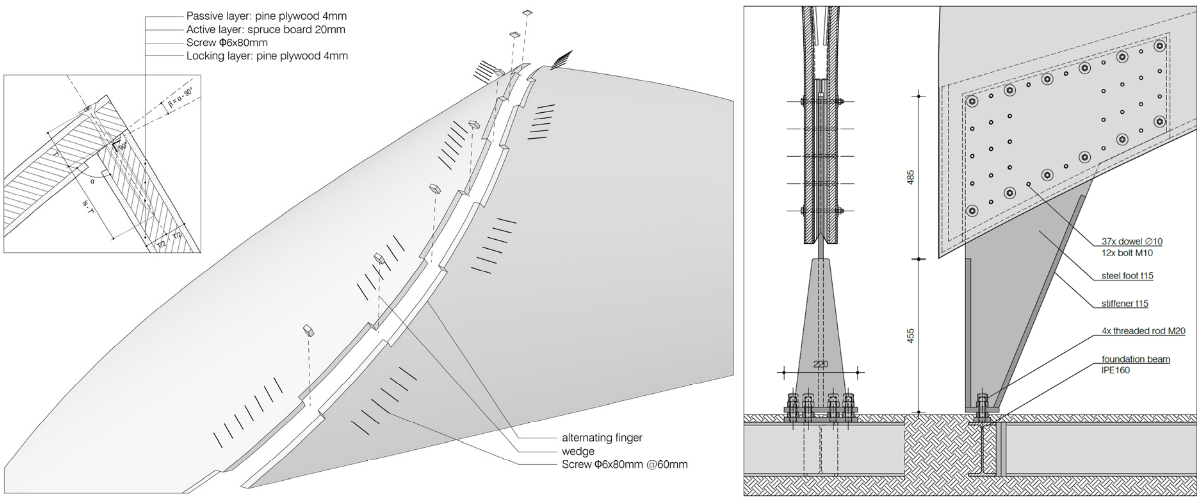


Figure 10: (a: left) Alternating butt joint for timber-to-timber connection. (b: right) Timber-to-steel connection in dowels.

## 3. Result

### 3.1. Realization

The HygroShell demonstrator was constructed all in house at the University of Stuttgart (Fig. 12a). The spruce log was regionally sourced within 100 km away from Stuttgart, and selected in close collaboration with the local sawmill. The resulting structure spans 9.3m between the supports, covering a total projected area of 40 $m^2$. The components consist of 1400kg structural timber and 400kg shingle roofing, totaling 3 $m^3$ wood. Due to practical limitation, 3-ply pine plywood was used for the 4mm thick passive and locking layers, which were laminated using 1K PUR structural glue. Spax screws in 6mm diameter were used for package assembly and butt joint on the curved seam. The bilayers were laminated and machined flat using 7-axis robotic arm on the same custom vacuum-lamination-milling bed. The waterproofing and shingles were applied and then transported to the mounting site on the flat state. The packages, positioned on temporary supports, shaped to the expected radii between 1.4 to 2.0 meters after 4 days of air drying. All details are designed to enable disassembly; the structure was demounted, shipped, and successfully reassembled at the Chicago Architectural Biennial 5 in the United States (Fig. 12b).

### 3.2. Evaluation

The design constraint derived from onsite deployment of self-shaping bilayers resulted in geometric situation of the surface, which are generally unfavorable to shell structures; the exterior edges are open and unstiffened, and the interior edge intersects with another surface on a point. The adverse effect of this singular point is observed in the resulting high utilization factor of out-of-plane actions in the surrounding area as seen in Figure 11a. Figure 11b evaluates the demonstrator's structural behavior "as shell" using structural analysis with modified element stiffness, where the flexural stiffness (the part D of the constitutive ABD matrix) is reduced to 25% of the full stiffness. As opposed to the model I with full stiffness, the flexural stiffness is reduced around the singular point in the model II, and reduced entirely in the model III. The model II illustrates the negligible differences in eigenfrequencies, indicating that the stiffness around the singular points have little contribution to the overall stiffness. The model III exhibits the decrease in eigenfrequencies by approximately 35%, implying the decrease of overall stiffness to 40% of the original. Although this suggests that the structure relies on the bending stiffness to some extent, Figure 11c shows that the interlocked edges of the surfaces successfully prevents the out-of-plane action and the dependency on the bending stiffness is concentrated along the unrestrained open edges.

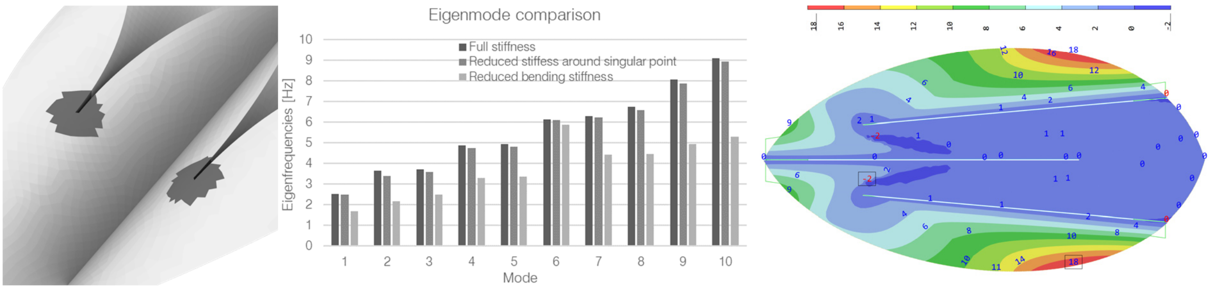


Figure 11: (a: left) Finite elements around the singular point of which the flexural stiffness is reduced in Model II. (b: middle) Comparison of the eigenfrequencies from $1^{st}$ to $10^{th}$ mode, illustrating negligible difference between Model I and II, and approximately 35% decrease in Model III. (c: right) Difference of the deflection between Model I and III under vertical load, illustrating little difference in interior surfaces and large difference on unstiffened edge.

## 4. Conclusion and outlook

The research has examined the structural use of highly single-curved laminated timber made of self-shaping wood through the realization of a lightweight, interlocked shell structure, representing the first of its kind in using self-shaping wood for a horizontally spanning structure. The entire design to fabrication process went successfully from stock sorting, vacuum lamination, machining to shipping, in situ self-shaping, and joint interlocking in the predicted position, meeting the ambitious objectives of onsite shaping under self-weight, air drying in ambient conditions, and the use of non-homogeneous material arrangement to achieve variable curvature.

Figure 12: (a: left) After shaping and assembly at the LCRL, Waiblingen, Germany. (b: right) After reassembly at James R. Thompson Center, Chicago, USA.

The demonstrator also did render some drawbacks associated to the specific goals of the project, including the need of manual effort for laminating locking layers on site after self-shaping, and the complexity in the stock management requiring meticulous logistics to deliver the specific board in the right location. Moreover, the implication of self-shaping requires further investigation, as the material undergoes significant eigenstress, which may influence the final mechanical property and sectional resistance in dry condition.

The research presents new possibilities in timber construction to leverage geometry to create sustainable, lightweight structures, exemplifying an integral approach to developing a novel structural typology that emerges from intrinsic material properties and informed fabrication.

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