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HYGROSHELL – In Situ Self-shaping of Curved Timber Shells

Abstract: Curved, surface-active, shell structures are known for material efficiency and slenderness but typically require complex manufacturing and formwork in combination with intricate on-site construction processes. The presented research proposes an alternative approach: a self-shaping building system for deploying lightweight, curved surface structures made from timber. The system uses the inherent hygromorphic properties of wood which naturally shrinks through drying. This anisotropic shape change is embedded into large-scale bilayer sheets – produced, machined, and shingle clad in a flat state with their later curved shape and connection detailing physically programmed within the material build-ups. When placed on-site, these sheets actuate through air drying to a final curved and interlocked geometry. Geometrically the structure is integratively designed from variable single curved surfaces using key material parameters (end grain angle and moisture content change) within a material stock, in relation to both the self-shaping and the final structural configuration. Each surface is modeled in the curved state using a board specific algorithmic calculation of curvature potential in parallel to a flat fabrication model. Emphasis is placed on investment in early-stage planning and intelligent material arrangement as a method to produce useful curvature. As a result, the curved shell shapes and interlocks without formwork or external mechanical force, with little onsite work. The outcome is a lightweight, long-span roof structure built from single curved wood surfaces with a thin cross-laminated build up. The project demonstrates a tangible new method of low impact, light touch self-construction and an ecologically effective use of material and geometry.

1 Introduction

1.1 Surface-active structures

The high ecological impact of the building industry urgently calls for the reduction of the carbon emissions in construction processes (United Nations Environment Programme 2022). In architecture and engineering this challenge requires innovation in integrating material and manufacturing with structure and geometry as well as development of new ways of working with bio-based, natural materials. Curved, surface-active structures, in which the geometry is used to reduce bending in favor of membrane action, offer elegant solutions for the construction of lightweight building structures (Engel 2013; Adriaenssens 2014). Historic and recent advances in engineering and design have

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opened a range of applications for these types of geometries as long span, lightweight, material efficient roof structures. While designable and efficient in their final form, it is difficult to physically construct curved surface-active geometry. Most surfaces are made by first producing a laborious and material consuming formwork and support structure, or through complex three dimensional, high-precision manufacturing of the elemental parts (Sasaki 2014). Alternatively, many attempts have been made to design deployable structures that are pulled or lifted into shape, but most are made from linear elements that lack surface continuity and require secondary systems for enclosure (Lienhard et al. 2013; Burkhardt and Otto 1978; Rihaczek et al. 2022). Fundamentally, structures that transform face an inherent contradiction between weakening the material or surface for compliance and the required overall stability (Hoberman 2004). Similar conflicting constraints limit many "smart" stimuli responsive shape-changing materials to small scale applications, due to low actuation force, overall stiffness and availability (Tibbits and Cheung 2012).

1.2 Hygromorphic self-shaping

Many regenerative, natural, fibrous composite materials have the ability to change their shape passively based on external stimuli such as moisture. Wood is one of such materials, which exhibits hygromorphic self-shaping behavior, naturally shrinking and swelling anisotropically in response to changes in moisture (Hoadley 2000). Favorably for self-shaping, wood is also a viscoelastic material, its stiffness is lower when wet and increases during drying. When deployed in a bilayer cross-ply board configuration, the shrinking in one "active" layer of boards can be used to generate curved surfaces from flat sheets (Wood et al. 2018). Self-shaping wood has been implemented for predictably shaping bilayers through kiln drying for manufacturing large scale curved cross laminated timber (CLT) and for self-shaping flat pack furniture in ambient conditions (Grönquist et al. 2019; Aldinger et al. 2020; Bechert et al. 2021; Wood et al. 2020; Wood 2021; ICD - University of Stuttgart 2022).

1.3 Research objectives and implementation project

The current research implements self-shaping wood bilayers for on-site shaping of curved surface-active structures. Through this we develop a first of its kind approach to on-site construction, in which flat-pack components, including structure, cladding and connections, can be produced in thin wood layups – physically programmed to deform and interlock into to high curvature surface geometries. To achieve this, the research addresses two objectives. (1) How can specific material information be gathered and included in the computational design and fabrication process to generate structural curved geometries informed and enabled by the hygromorphic and mechanical qualities of wood? (2) How does the self-shaping method reveal a new type of building system for lightweight form active, deployable structures made from regenerative materials and without formwork or supporting structure? The research is investigated through the integrative design, development, and implementation of a research pavilion, the HygroShell (Fig. 1). The geometry of the HygroShell is comprised of three prefabricated, flat-packed components (packages), each containing two self-shaping bilayer surfaces (wings), connected along a shared lower edge (Fig. 2A–C). Through air drying the wings of each package transform from flat to curved. Collectively, the single curved wings interconnect – forming a roof supported at three points (Fig. 2D–F). The system is tested by prefabricating the packages and deploying them in a mock site to evaluate the functional and architectural potential at full scale.

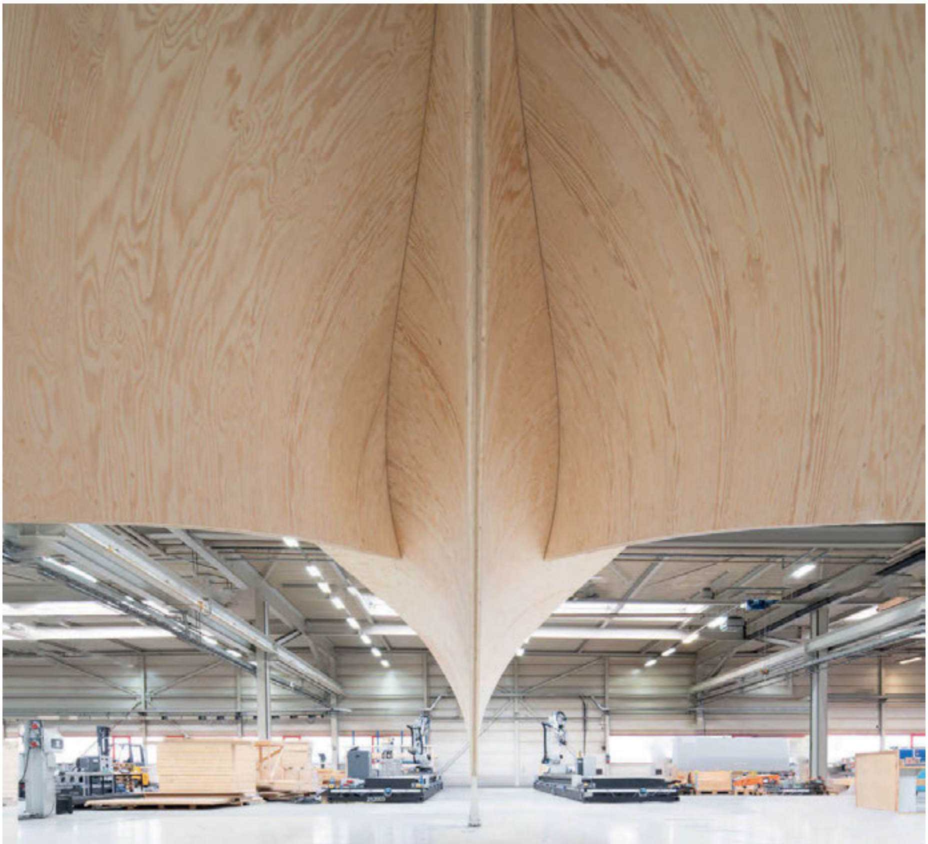

Fig. 1: Interior view of the lightweight curved wood shell, constructed from intersected single curved surfaces.

2 Material driven computational design and fabrication

2.1 Programming self-shaping wood bilayers

Using a natural material such as wood in this context relies heavily on understanding the specific properties of the material and their relationship as both actuator and structure. A bilayer wood structure is used as the self-shaping mechanism and as the primary cross-ply buildup of the larger structure (Wood 2021). The bilayer consists of a thicker 'active' layer which serves as the hygromorphic actuator and a thinner 'restrictive' layer (Fig. 2A). As the moisture content (MC) of the active layer changes the mechanics of the bilayer cause the surface to curve. Curvature in the bilayer can be designed through controlling key parameters: the thickness ratio of the layers, orientation of the wood's fibrous structure in the end grain, described by the angle of the radial and tangential axis in relation to the board (R/T angle), and the change in MC. Material thickness can be defined precisely during the sawing process. The R/T angle in each board is defined by a combination of the sawing pattern, the concentric circular morphology of the log, and natural variation in the growth rings (Fig. 3A–B). When harvested, wood contains a high MC as a result of its living functions and starts to dry out as it equalizes with the relative humidity of the surrounding environment. Thus, the MC can be controlled by defining the point in the natural drying process at which the bilayers are constructed in relation to the desired service conditions. Methods for designing and predicting curvature in bilayers work well using generalized mechanical characteristics from literature and measurement, mainly material stiffness, and the coefficient of expansion but do not account more specifically for variation in the MC

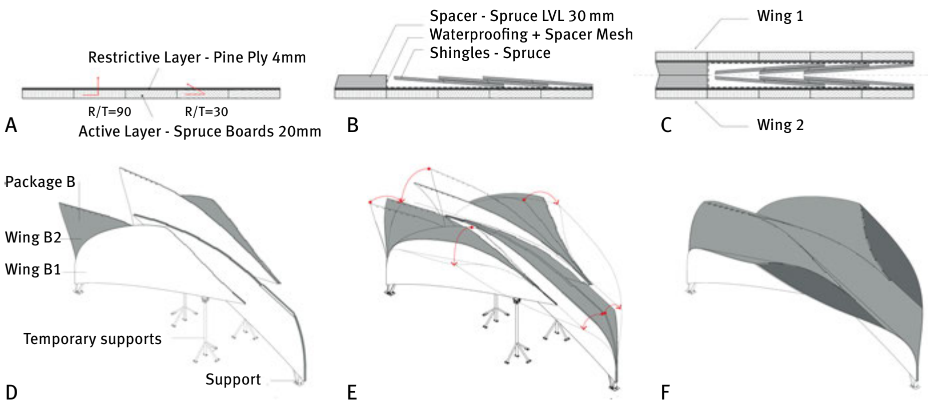

Fig. 2: Self-shaping and geometric concept for the HygroShell. A–C The prefabrication steps of wood bilayer to flat package in section. D The flat packages vertically placed on site. E Self-shaping of the wings. F The completed, interlocked structure.

and R/T angle per board in larger layouts (Rueggeberg and Burgert 2015; Grönquist et al. 2019). Given the natural variation in these parameters, the geometric usefulness of the models is directly limited by the coarseness of the available material input data.

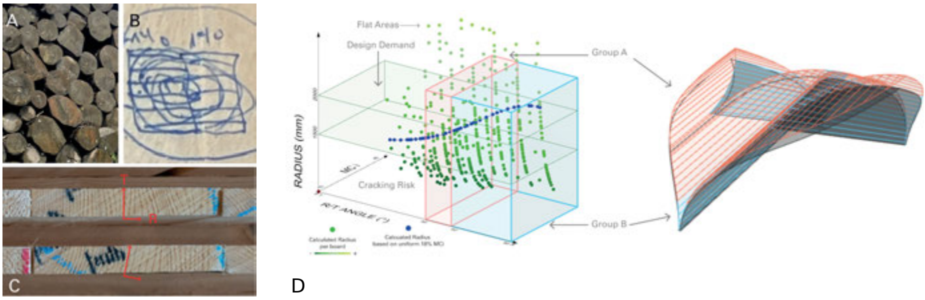

Fig. 3: The data driven approach to utilizing material and curvature. A-C Practical gathering of data in consultation with the existing resource stream. D The graph shows the calculated curvature potentials of each board at delivery (green), the ideal curvatures without variation in MC (dark blue), the global design demand (green box) derived from the ideal 3D design geometry. The sorting groups (red and blue) and optimized distribution of the groups in relation to the 3D design.

2.2 A practical data-driven approach relating material to curvature design and global geometry

As the basis for curvature design, a known analytical model for predicting curvature in wood bilayers is used (Rueggeberg and Burgert 2015). Rather than targeting one specific bilayer configuration and generalizing the natural material properties, a data driven approach was used to simultaneously understand the variation in stock material and its relation to variable curvature in the surface design. To evaluate the feasible surface curvatures, a design space was established using literature values for locally available materials and an estimated range of variation in the R/T and MC parameters. This design space was used to study architectural and structural aspects of the global design configurations, testing different wood species and build ups in relation to geometry. Working with a local sawmill, the species and distribution of R/T angles was refined in relation to a standard sawing pattern that was economical, materially efficient, and fast (Fig. 3C). At this stage, the thickness ratio, specifically, the thickness of the active layer, was fixed and the design space refined. The logs were selected, and the boards cut in 16 minutes, just in time, a week before production (empirical research shows speed is a critical parameter in working with partners from the timber industry).

2.3 Optimizing real word material and geometry

With the thickness ratio selected, the curvature potentials associated with each board depended on the combination of their R/T angle and MC. The R/T angles were not adjustable after cutting, while the MC slowly reduces and can be modulated by the storage conditions. Upon delivery, board specific data was gathered using manual measurements of the end grains and a moisture meter. Due to a high variation in the MC, the boards were stored in a climate chamber at 85 % relative humidity to equalize towards 18 % MC. The MC and R/T angle data was fed into the computational design model to calculate the curvature potential for each board and then compared with the curvature demand from the design geometry (Fig. 3D). Given the variation in MC and the physical space required for sorting, an initial grouping was required in place of board specific arrangement. Boards with low MC and or low curvature potential were sorted out for use in the flat connection areas. Similarly, boards with high MC and extreme tangential orientations were removed due to risk of cracking and used for transport packaging. The remaining boards were sorted into two groups – each representing two target curvatures from the design. A multi-objective optimization algorithm, RBFMOpt, was used to calculate the distribution of the two curvatures in relation to the design geometry while respecting the quantity and range of boards in each group (Wortmann 2017). This step determines the number boards from each group in each wing, and the boards for each wing are chosen at random from the groups to ensure an even distribution of variation. A final smoothing sequence assignment within the wing was made just before fabrication based on a final curvature prediction of each board at the time of the 2D layout (Figure 4A-B). Key to this process was that the global 3D design can be digitally updated and verified throughout the process, ensuring that the specific arrangement was within an acceptable range for the design and structural performance.

3 Development of prefabricated self-shaping wood building components

3.1 Prefabrication

The base elements of the building system are the bilayer wood plates (ca. 10 m × 3 m) of each wing, The wings are manufactured flat by laminating the 'restrictive' layer of 4 mm 3 ply pine veneer plywood (ZEG Zentraleinkauf Holz + Kunststoff eG) with a layer of 'active', 20 mm spruce wood boards with an high MC (Sägewerk Kolb GmbH) using a PUR adhesive (HBS 709, Henkel AG) (Fig. 6A). With a width of 140 mm the boards offer a fine resolution to grade curvature in the active layer. After lamination the bilayer surface is immediately machined on the worktable in the flat position using a 7-axis

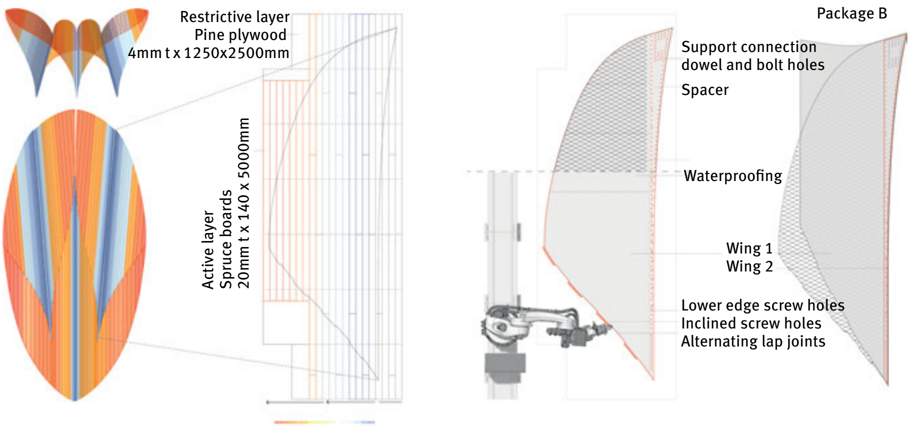

Fig. 4: Prefabrication steps. A, B Gradient in curvature on group distribution (blue/red) and sequence smoothing. B Bilayer lamination. C Machining of edge details, adding of waterproofing and wood shingles. D Completed flat package.

milling setup. The connections along the curved wing to wing intersections use an elongated finger joint with sheer blocks in each finger to compensate for tolerances in the lateral direction. The geometry of the curved connection is calculated from the 3D, curved geometry and translated to the flat geometry, considering the change in angle during shrinkage. Predrilled, angled screw holes are placed along the connection edges and shared lower edges. A waterproofing layer including a spacer mesh (Dörken Delta Trela-plus) is added to the bilayer followed by spruce wood shingles (Schindelzentrum Allgäu). The triangular tipped shingles, common for traditional buildings in South Germany, are applied along the ruling lines (zero curvature), allowing the self-shaping while the angled edges allow for directional water drainage. Sets of two wings are then connected along the lower edge with a softwood LVL spacer forming a package. The packages were wrapped to prevent further drying and, thus, shaping, nested in a single truck and transported to the simulated building site.

3.2 In Situ shaping through air drying

On site the packages were positioned vertically with one end on the ground support and one resting on an elevated temporary support. Once all three packages were in place, the wrapping was removed from the active layer and the shaping began (Fig. 5A). Iterative 3D laser scanning (Leica BLK360 G1) and inertial measurement unit (IMU) sensors embedded in the tip of each wing were used to monitor the curvature of the structure over time. Over 96 hours the components self-shaped in the unconditioned but enclosed environment of ca. 40–65 % RH, decreasing in MC ca. 8–10 % through air drying (Fig. 5).

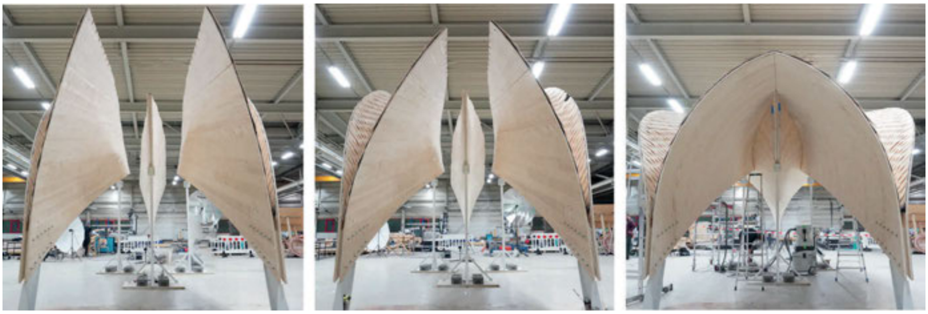

Fig. 5: In situ self-shaping of the bilayer timber building components. Starting flat in a vertical configuration with high MC in the active layer, during shaping, and after full shaping and interlocking.

As the intended curvatures for each wing approached, the longitudinal connections were nudged into alignment and shear blocks and screws were installed. In parallel, two smaller edge components were self-shaped on the ground, lifted into place and attached to the structure connecting the open edges. Lastly, a 4 mm plywood "locking" layer was screw press laminated to the interior surface locking the curvature and stabilizing the structure from further deformation.

4 Geometric synthesis of self-shaping, structure, and architecture

While the self-shaping system can produce high curvature and is valuable for on-site assembly it is constrained geometrically to single curved surfaces and structurally to thin cross sections. The challenge structurally involved designing a geometric arrangement that functions structurally during shaping and, more critically, performs effectively in its final form. To address shaping stability, the packages were oriented vertically so as the self-shaping is assisted, rather than hindered by the self-weight as the wings cantilever out. Additionally, the partially symmetric packages balance along their shared axis reducing load on the supports during shaping. This stabilizes the larger thin sheets during transformation and favorably loads the asymmetric cross section of the bilayer with the outer restrictive layer in tension along the longitudinal fiber direction. The shaped structural geometry was designed through calculated intersection of the single curved surfaces of each package (Fig. 6). Where the surfaces intersect, one curved plate provides out-of-plane support to the adjacent plate. This intersection, combined with the resulting curved seam, effectively restricts flexural deformation of the surface and ensures sound structural behavior. The angle, pitch and spacing of the intersections was modeled parametrically using Rhinoceros and Grasshopper (Robert McNeel & Associates) and the structure studied extensively using

Finite Element Modeling (SOFiSTiK) throughout the design and manufacturing process ensuring its relation to the material and producible curvatures. Architecturally, the geometric system was designed to cover a wide spanning area with the least amount of material. Using a balanced tripod design on hinged supports maximizes the coverage area and reduces the need for bounding supports or walls. This feature was further enabled by the gradient curvature allowing the surfaces to flatten and act as columns as they approach the ground (increasing head height) while smoothly transitioning to curved overhead (increasing the span within the limited sheet width) (Fig. 7).

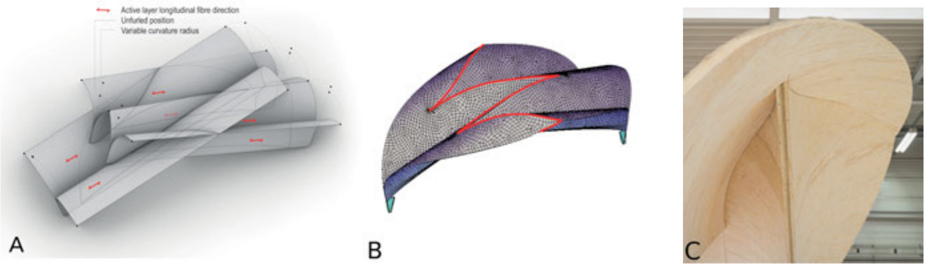

Fig. 6: Geometry of the surface-active structure. A Generation of connections from single curved surfaces of the unfurling packages. B FE model with curved connection seams between wings. C Hidden curved connection from interior.

Fig. 7: The completed HygroShell.

5 Results and discussion

Through the presented integrative, material driven design approach a single curved roof structure spanning 9.5 m longitudinally, 2.8 m between the transverse supports and 4.5 m at the widest cross section is achieved using a 28 mm laminate made from medium grade soft wood. Wood is used as the primary material, including structure (2.58 cbm) and the cladding (0.98 cbm) with the majority sourced directly from a local sawmill. Covering an area of 40 m^2 the building system including cladding weights 39 kg/m^2 of floor area (28 kg/m^2 structural) and 18 kg/m^2 of shell surface (13 kg/m^2 structural), required only three temporary point supports for assembly. Variable curvature in the single curved elements was achieved transitioning from flat areas through radii between 1400 and 2100 mm. The designed curvature gradient was possible, through careful distribution and ordering of the natural variation in the R/T grain angles.

As a prefabrication method, the self-shaping building system performed well. The shaping itself happened relatively fast and geometric deviations were manageable by alignment of curved connection between wings and designed lateral tolerances. The primary shaping was achieved autonomously through air drying. Adding functional layers to the bilayers for weather protection and cladding in the flat state replaces on-site construction labor and assembly steps that are difficult on curved geometries. This approach has the advantage of finished modular prefabrication with the reduced complexity and lower transport volumes of panel-based prefabrication. Compared to even the lightest curved formwork systems, the unfurling self-shaping package concept requires no formwork, no heavy boundary conditions on site and no mechanical or pneumatic actuators, which are time and material intensive (Popescu et al. 2021). In a true exterior environment, actuation conditions would vary more and be harder to predict, but the vertical orientations of the components could protect from the most direct weather. It is further planned to study the long-term durability and form stability of the structure in outdoor conditions and further development will focus on including additional on-site steps, such as the locking layer application, as part of the self-shaping packages.

6 Conclusions and future potentials

The research investigates specific design challenges associated with prefabricated self-shaping building systems which are overcome through integrated exploration of material, geometry, and structure. The resulting form is enabled by in-depth material understanding and by utilizing curvature, material anisotropy, and hygromorphic actuation, showcasing a path towards a new class of lightweight, sustainably produced, surface-active structures. Considering the negative ecological and social impacts of on-site construction, as well as costs and complexity of on-site assembly, future forms of self-shaping system have a high potential impact through their simple embedded logics and on-site autonomy. The approach of programing geometry though material demonstrates how investment in the integration of material intrinsic properties of a low-tech and low-resolution material system can lead to an incredible reduction in complexity throughout the construction process. By learning to work with the, forces, forms, and intricacies of natural materials we chart a path towards intriguing new architectures derived computationally from regenerative and sustainable resources.

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