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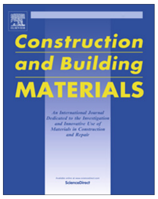

Hygroscopically actuated wood elements for weather responsive and self-forming building parts – Facilitating upscaling and complex shape changes

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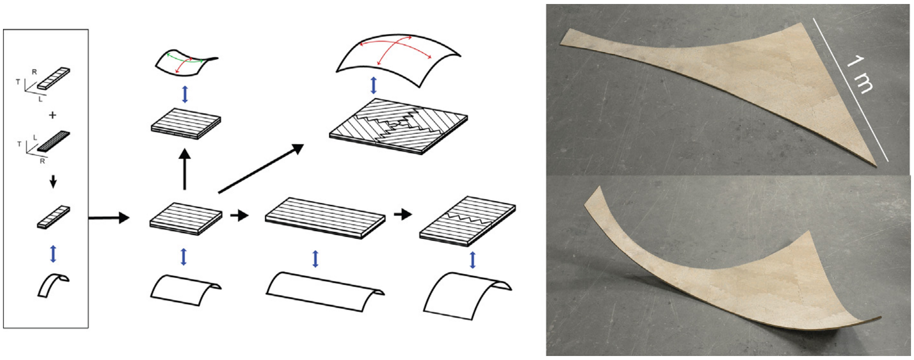
HIGHLIGHTS

- 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



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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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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