Chapter 4
Material Programming for Bio-inspired and Bio-based Hygromorphic Building Envelopes

Dylan Wood, Tiffany Cheng, Yasaman Tahouni, and Achim Menges

Abstract Building skins play a decisive role in maintaining occupant comfort. Adaptive building skins have been proposed to adjust to the weather, with mechanically complex multi-component solutions that require operating energy. Nature and its materials exhibit a fundamentally different strategy for environmental responsiveness; motile plant systems show entirely passive, integrative, hygroscopic actuation due to their cellulose-based material structure. Through a design and fabrication process we refer to as material programming, a bio-inspired and bio-based functional integration of actuator, sensor, and controller can be achieved. We present an overview of related research on weather responsive building components. Wood-based composite elements that respond to relative humidity without operational energy have been demonstrated at architectural-scale. This research was recently expanded through the additive manufacturing of custom-made natural fiber composites, allowing 4D-printed self-shaping compliant mechanisms based on highly differentiated and multifunctional plant movements with varying mechanical stiffnesses and actuation speeds. The application of 4D-printing to weather responsive shading systems still necessitates the codesign of materials, mechanism, and façade system as well as matching stimuli-responsiveness to ambient weather conditions and mass production at the scale of buildings. Overcoming these challenges will enable a more reliable, sustainable, and zero-energy solution for regulating comfort in the built environment.

Keywords Computational design · Additive manufacturing · Responsive materials · Hygroscopic actuation · Adaptive architecture · Building Skins · Hygromorphic · 4D-printing · Bio-based materials

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J. Wang et al. (eds.), *Advanced Materials in Smart Building Skins for Sustainability*,
https://doi.org/10.1007/978-3-031-09695-2_4

4.1 Introduction

In nature, many materials exhibit shape-changing characteristics in response to stimuli such as temperature or moisture. In many plants, shape-change is used as functional, motile movements without living biological or electrical energy. The awns of the Erodium and Pelargonium seeds, for example, self-drill into the ground by reversibly coiling and uncoiling in response to the fluctuations of environmental humidity (Burgert & Fratzl, 2009; Jung et al., 2014). Another example, the standard spruce cone, can open up and release its seeds in response to a loss of moisture and resultant drying of the fibrous composite material in each and every scale in mass quantity (Dawson et al., 1997; Harlow et al., 1964; Reyssat & Mahadevan, 2009). Such a transformation is remarkable, given that it occurs passively as the material equalizes with the humidity of the surrounding air, after the cones are separated from the living biological functions of the tree (Poppinga et al., 2017). In the spruce cones, the variations in the morphology of cellular structure and layout of fibers within the scales have evolved over time to suit the specialized function of each type of cone, the environment in which the species grows, and the kinds of seeds they release.

Similar to the tissue of the spruce cones, a handful of well-known natural fibrous materials exhibit hygromorphic behavior, in that they dramatically expand or contract as they absorb and desorb moisture from the surrounding environment and can be engineered into a responsive system (Carneiro et al., 2013; Le Duigou et al., 2020). Common examples that can be found in our daily lives include cellulose-based materials such cotton, paper, and wood. In the context of adaptable building systems, three aspects of these natural hygromorphic materials are particularly interesting. First, many of these materials can naturally actuate with stimuli ranges found in daily and seasonal weather patterns. Second, the shape-changing characteristics are inherent or well-integrated into the material structure, giving them unmatched hygromorphic performance with a fraction of the processing and engineering required for synthetic "smart materials (Erb et al., 2013). Third, the materials are available in large quantities, at low costs, and in regenerative life cycles that can be considered viable and sustainable solutions at the scale of building facades. These qualities are advantageous for the development of ecologically constructed building envelopes explicitly designed to adapt with the natural ebbs and flows of weather on Earth.

Working with natural materials comes with unique challenges and opportunities concerning design, engineering, and manufacturing. We develop new types of bio-inspired and bio-based prototypes of passively adaptive building envelopes through careful decoding, re-programming, and re-packaging these natural materials—a design and fabrication process that we refer to as *material programming*. In this context, computational design and fabrication provide the key to the critical understanding and unitizing of the unique functional aspects of natural materials and systems, from the analysis of movement patterns to the physical programming of simple yet novel shape-changing structures. More specifically, material programming can be viewed here as arranging natural materials within larger systems and in higher function hygromorphic structures. The approach can be applied at various scales, resolutions, and specific material combinations but fundamentally involves developing a technical understanding of the materials themselves as well as a precise method of their arrangement in physical space.

Considering that building systems and construction have a substantial impact globally in terms of both carbon footprint and energy consumption, the question of how to more effectively regulate the interior climate of buildings is of increasing relevance across a range of cultures and climates (United Nations Environment Programme, 2020). Contrary to the pursuit of increased efficiency often at the expense of complexity in active systems for heating and cooling, passively adaptive building envelopes offer a potentially low-cost, reliable solution for regulating human comfort in both interior conditions and exterior public spaces (Grondzik & Kwok, 2020; Poppinga et al., 2018; Tabadkani et al., 2021). Starting with wood as well-known hygromorphic building material, we have developed principles for material programming with natural, plant-based materials with existing shapeshifting behaviors. From these principles, we explore this concept through the combination of additive manufacturing and the development of custom cellulose-based printing filaments that enable the 3D internal arrangement of material strands to design and fabricate intricate mesotructuring within each piece. Paired with computational methods for designing high resolution structuring, this approach to material programming opens up new functionalities including the choreography of actuation speed, tuning of response ranges and architecting of movement patterns.

4.2 Understanding and Deploying Wood as Pre-constructed Natural Hygromorphic Smart Material

Wood in its living and harvested state is inherently a hygromorphic material, adapting both its shape and its mechanical properties in response to changes in moisture. The hygroscopicity of wood comes from the complex material arrangement of cellulose microfibrils inside the tube-shaped cell walls that make up its primary structure. When wet, the cell walls expand volumetrically in the defined anisotropic coordinates of the material and simultaneously soften. When dried, the same wood material naturally contracts in volume and increases in stiffness—a phenomenon known for causing unwanted geometric deformations in wood boards as a result of variation in the natural structuring. As a living organism, the cellular structure of wood serves many purposes, one of which is the transport of water, which means the material by design is able to maintain its overall structure even when the cells are in a fully saturated state. Once harvested, wood materials continuously desorb and absorb moisture to maintain an equilibrium with the relative humidity of the surrounding air (Hoadley & Barbara, 2000). This constant, passive equalization and resulting form adaptation makes it a near-ideal material for the development of adaptive building systems intended by design to fluctuate with changes in the environment.

To implement wood in adaptive systems, first, the hygromorphic behaviors must be understood and quantified, an aspect which has for centuries been studied and quantified scientifically for the purpose of preventing unwanted movements in fields ranging from timber construction to art preservation. Beyond understanding the basic shape-changing principle, the directional change in volume can be translated into a change in curvature using a bilayer mechanism, a principle in which one layer of active material is connected to a perpendicular, resistive layer. Changes in the volume of the active layer results in a translational bending of the bilayer, a geometric movement significantly larger than the volume change of the active layer alone. Bilayer mechanisms have been studied extensively in both structural mechanics and in thermally responsive material in which isotropic shape change further limits the possible movement patterns in larger arrangements. Critically, the curvature of a bilayer system can be predicted with relatively high accuracy using an analytical model developed by Timoshenko in 1925 and more recently adapted for use with the anisotropic properties of wood (Grönquist et al., 2018; Rüggeberg & Burgert, 2015; Timoshenko, 1925).

Through a careful selection of the wood species and adjustment of controllable design parameters, the relatively untamed deformation in wood can be programmed into reliable movement patterns that respond to daily and seasonal fluctuations in relative humidity (Fig. 4.1). More specifically, European Maple (*Acer platanoides*) is chosen as it combines good values for the shrinking and swelling coefficient, structural integrity, and can be sourced with straight, even grains. Additionally, maple is known to exhibit a natural resistance to fungus and weather-related deterioration due to water and UV exposure. While the swelling coefficient and stiffness are ingrained within the material, the thickness of the veneers and the orientations of the fibers/grains can be used to further design the direction and magnitude of curvature within the bilayer build-up. In parallel, the moisture content of the active boards is used to embed the geometric configuration assigned to a specific corresponding relative humidity. Similarly, the restrictive bending layer made from wood can be used to further tune the curvature through a selection of the species and thickness. Alternatively, composite materials such as glass fiber reinforced plastic (GFRP) or natural fiber reinforced plastic textiles can be implemented for different mechanical properties. In the demonstrator projects HygroScope and HygroSkin from the ICD (Fig. 4.2), a thin 0.5 mm maple veneer is combined with lightweight GFRP textile to give an added mechanical spring back in the restrictive layer and counteract the long term effects of creep found in wood (Menges & Reichert, 2015; Reichert et al., 2015). Through the design of these simple parameters, responsive wood and wood composite parts can be tuned to curve cyclically, from flat to curved and vice versa, in a matter of seconds, in a relative humidity range of 20–95% or through direct exposure to water.

Despite the promising material qualities and relatively easy to construct mechanisms, hygromorphic climate-responsive wood systems have been implemented only in limited architectural scenarios. Weather responsive wood composite bilayers were designed and tested by the ICD prototypically in the project HygroScope, which used artificially accelerated simulation of real-world fluctuations in relative

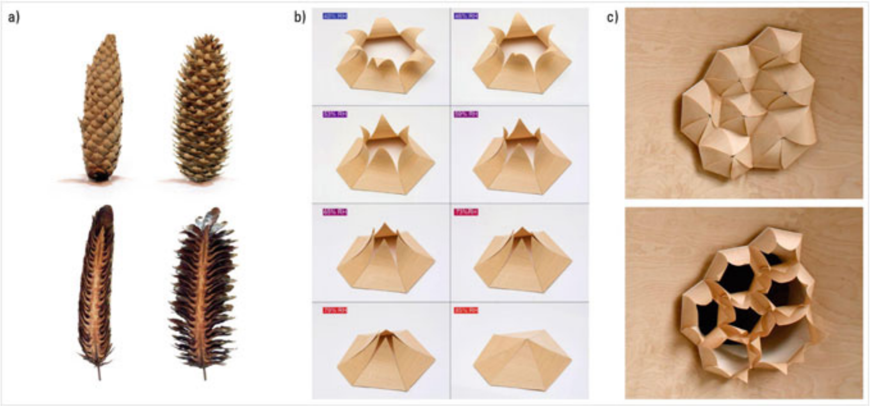

Fig. 4.1 Research at the ICD investigated the transfer of the pine scale actuation (**a**) to a hygroscopic veneer-composite bilayer system (**b**) for humidity-responsive apertures for architectural applications (**c**)

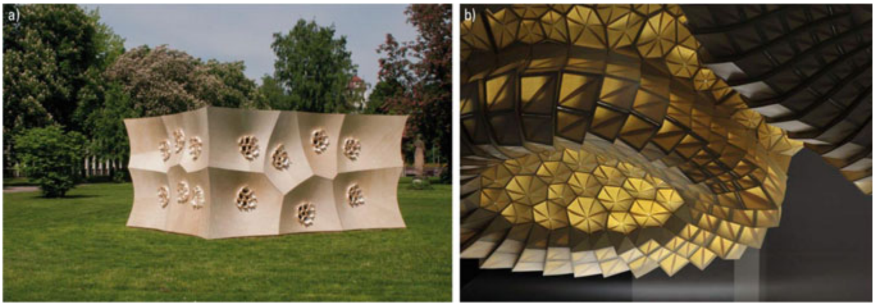

Fig. 4.2 The wood veneer-based bilayer system has been instrumentalized in full-scale architectural prototypes, demonstrating the hygroscopic response in outdoor conditions in HygroSkin Pavilion (**a**) as well as in controlled and accelerated humidity cycles from past weather data (**b**)

humidity to demonstrate the concept. Similar responsive parts are implemented as weather responsive apertures in the HygoSkin pavilion, designed to open to light and air in hot, dry, sunny conditions and close up in humid, rainy weather (Krieg et al., 2017). Wood bilayers have also been studied extensively for adaptive shading devices such as horizontal louvers that use a change in curvature to adjust the angle between their surface and the sun (Holstov et al., 2017; Vailati et al., 2018). When cleverly implemented, even single monolayers of wood can be used as self-ventilating adaptive building systems similar to the wood shingle cladding used historically in the Nordic regions and in recent studies (Davidova, 2016). While wood is unique in its ability to change shape naturally within a suitable range of relative humidity on earth and requires little to no extra process to implement in responsive systems, the scale of its structuring presents limitations in the fine-tuning and design. The speed of actuation, for example is strictly governed by the thickness and depth/width of the active boards, which cannot be independent of the mechanical performance. Similarly, wood suffers from creep due to the realignment of the microfibers when bent over longer periods of time. While exhibiting natural variation, both the bending orientation and structural characteristics are typologically hardcoded into the material itself, presenting constraints for further architecting the material at the mesoscale. Simply put, the overwhelming power of the natural structuring means that intentional tuning is practically governed in lower resolution by the width of the board (typically 25–50% of the tree diameter).

4.3 Computational Design and 3D Printing as Tools for Constructing Natural Material Systems

In contrast to the material constraints of solid wood materials, advances in computational design and digital manufacturing enable the modeling and production of features in increasingly fine resolution and accuracy. Hierarchical structuring of materials for higher-level functionality is common in many adaptive motile plant structures but has historically been difficult to emulate in man-made engineered structures, even at an abstracted level. Digital design of material gradients and differentiation has advanced considerably faster than the physical production methods, allowing designers to turn structures at the incredible resolution but typically abstract from the resolution allowed by the physical production methods (Duro-Royo et al., 2015; Oxman, 2010). 3D printing, on the other hand, enables the fabrication of intricate structures through a differentiated layering of material to form larger three-dimensional objects.

More specifically, Fused Filament Fabrication (FFF) is an ideal method for producing macro-scale parts (ca. 10+ cm) with mesoscale variation (0.5 m–1 mm resolution) from combinations of filament-based materials (Correa & Menges, 2017). Using FFF, strand based, multi-layer mesostructures can be constructed using low-cost, generic, 3D printing technology (Correa & Menges, 2017). An integrated computational design framework has been developed at the ICD for FFF-based 4D printing taking into account the material programming and processing parameters specific to the printing method, such as the anisotropy and stiffness that results from the sequence and quality of material deposition (Cheng et al., 2020). The developed design approach simplifies the complexity of considering highly differentiated structures into a networked assembly of functional regions defined using the intuitive geometric descriptors from existing CAD workflows. This workflow allows the assignment and tuning of material properties and bending behavior—including the direction, magnitude, and orientation or curvature—to be directly translated into the necessary fabrication data for producing the desired hygromorphic response (Fig. 4.3). Parameters in the strand spacing, strand thickness, layer height, and functional patterning can additionally be defined in each sub-millimeter printing layer for constructing varying levels of directional stiffness, time scale of hygro-responsiveness, and elasticity in the overall composite build-ups.

Incorporating this functional mesostructure allows for extending and augmenting the hygromorphic characteristics of wood materials using both wood bilayer actuators and hygromorphic printing filaments. The project HygroFold demonstrates the use of 3D printing through the development of a custom mesostructure with multi-directional bending and an integrated folding hinge integrated with a wood bilayer actuator (Fig. 4.4). A parallel approach displays how meso structural design principles can be used to emulate the sophisticated structuring and transformations found in biological examples of passive movements such as the pine cone scales (Fig. 4.5). Here, variants of the basic bilayer mechanism are built up using standard thermoplastics for the restrictive layers and commercially available wood fiber-based plastic filaments that respond to moisture change through water submersions and drying (Correa et al., 2015, 2020).

Fundamentally, mesostructural tailoring allows for the decoupling of parameters that are inherently linked in solid wood material, opening up the potential to further architect and choreograph movement. Speed of actuation for example can be designed separately from the desired curvature through adjustment of the spacing and resulting porosity of the structure while at the same time counter adjusting the spacing in the restrictive layer to maintain the magnitude of curvature (Fig. 4.6). Through this approach, similar curvatures can be reached on dramatically different time scales, under the same actuation condition (Tahouni et al., 2021) At the level of the mechanism, 3D printing also enables the design of in-plane pattern variation to combine multiple areas of bilayer effect with alternating directions of curvature, variable orientations of curvature, and compliant hinges. This is exemplified by the construction of self-shaping curved crease folding surfaces in which the actuation comes from inside the curved surfaces rather than an external or localized actuation at the edges or hinge

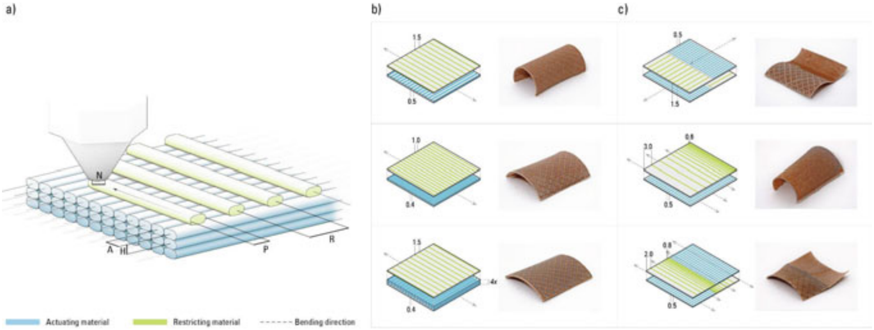

Fig. 4.3 The material programming of functional mesostructures is based on the fabrication parameters of FFF 3D printing (**a**) including the nozzle size N, layer height H, toolpath spacing of the active A and restrictive R filaments, as well as the resulting extrusion paths P. Through the mesostructure design, bending can be tuned, for example in (**b**) the amount of curvature and (**c**) even combined together in different configurations. (Figure adapted with permission from Cheng et al. 2021; p. 5)

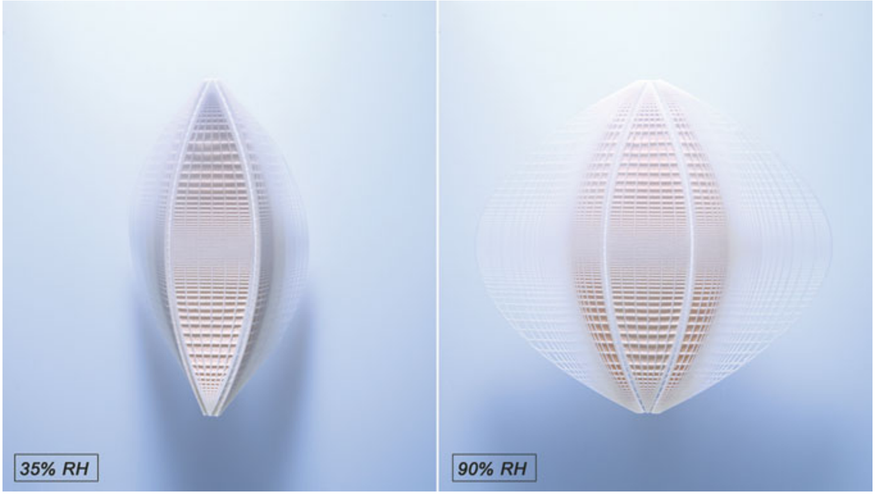

Fig. 4.4 The Hygrofold is a curved folding mechanism combining bio-based 3D-printing and wood actuators, which self-shapes and folds at low RH (left, shown at 35%) and unfolds at high RH (right, shown at 90%)

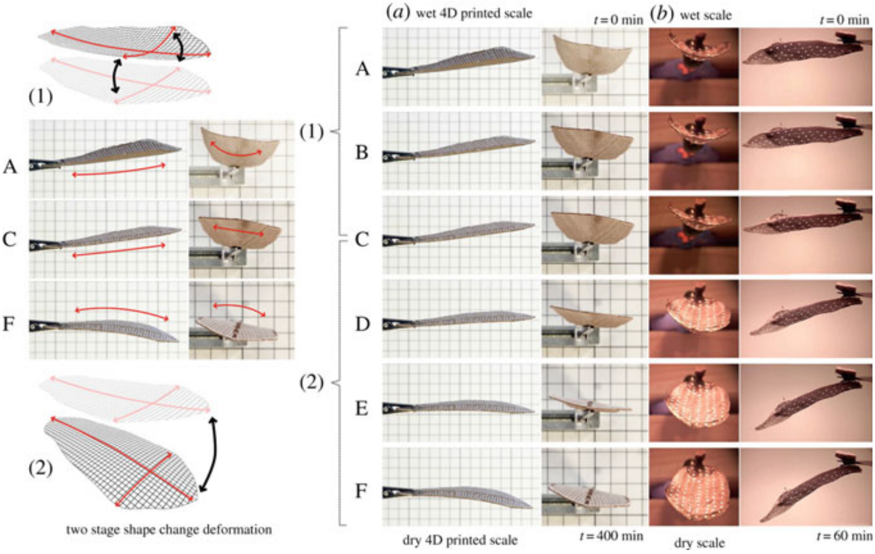

Fig. 4.5 A 4D printed artificial scale with two-phase shape deformation compared with the two-phase movement of the Bhutan pine scale. Starting fully wet (top) both scales show predominantly transversal curvature. The transversal curvature decreases (**a**–**c**) in the first stage of actuation, then the longitudinal curvature increases (**c**–**f**) until the maximum bending angle is reached when fully dry (bottom). (Figure adapted with permission from Correa et al., 2020; p. 13)

zones (Tahouni et al., 2020).Complex folding patterns can be used to geometrical amplify the actuation and/or to dramatically enhance geometric stiffness and depth in larger tessellations (Fig. 4.7), thereby demonstrating the complex movement patterns and functionalities enabled by distributing the actuation throughout the material via 3D printing.

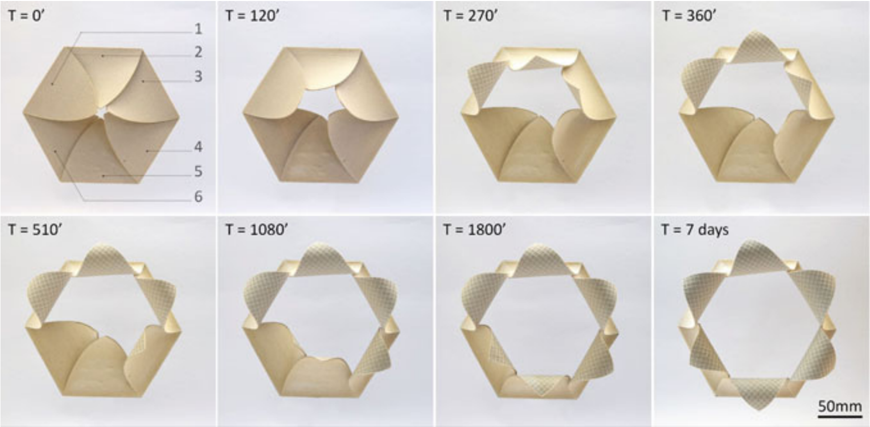

Fig. 4.6 Sequential shape-change in a 4D printed aperture. The timelapse shows six flaps taking turns to bend until the successful opening upon drying in 40% RH. (Figure adapted with permission from Tahouni et al., 2021; p. 16)

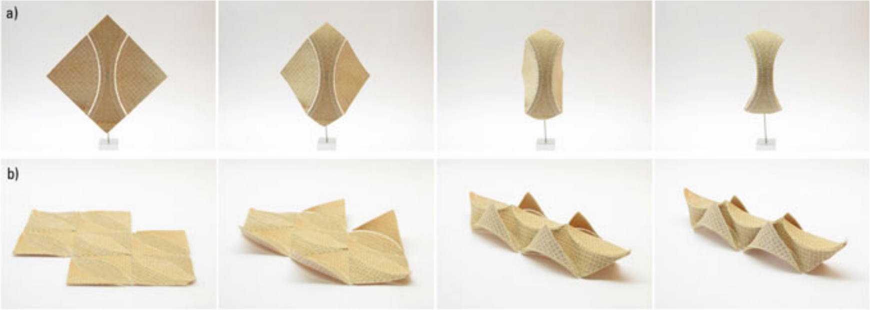

Fig. 4.7 Self-shaping curved folding mechanism (**a**) and lens tessellation design (**b**) and their transformation from flat (left) to folded (right) state. (Figure adapted with permission from Tahouni et al., 2020; p. 1)

4.4 Material Co-design for Bio Based, Hygromorphic Materials and Next-Generation 4D Printed Smart Structures

The next generation of hygromorphic smart structures is based on cooperative development of both material, digital manufacturing, and computational mechanism design. While wood and commercial filaments provide a starting point, the future of engineering or reengineering bio based materials for specific hygromorphic functions will provide for wider application and improved functionality. In our current research, this approach is carried out through the design and engineering of a pallet of cellulose-filled bioplastic printing filaments presenting a range of hygroscopic and stiffness combinations (Fig. 4.8). The basis of these materials is cellulose fibers, a highly hygromorphic, low-cost, plant-based material derived from pulp and refined to a fine powder. The cellulose powder is fine enough that it can be compounded with common thermoplastic polymers with a range of mechanical properties, resulting in filament materials that maintain printability in the latter FFF process (Kliem et al., 2020; Langhansl et al., 2021). While the fibrous structure and anisotropicity of the base material are broken down, the design of the 3D printed mesostructure can be used to reintroduce a new tailored structuring supplementing the natural characteristics. Working at multiple hierarchical levels from the material to the larger mechanism the approach maximizes the potential of the material through targeted design moves at each level. While the properties of the cellulose base material are fixed, the overall hygro response for example can be adjusted by the percentage of cellulose to matrix material in compounding, the stiffness of the matrix material as well as in the design of the bilayer mesostructure. The engineering of the custom filaments is also valuable in ensuring compatibility with materials used in other parts of the mesostructure with no active roles.

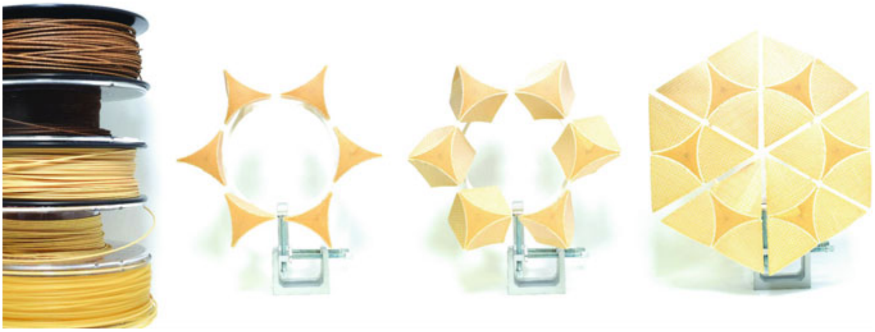

Fig. 4.8 Development of custom hygroscopic printing filaments composed of biobased matrix polymers and cellulose powder for humidity responsive smart structures based on the curved folding mechanism, transforming from fully folded (left) to nearly flat (right)

Through such multi-scale co-development approach, highly functional smart structures and weather-adaptive building envelopes can be created (Fig. 4.9). In the material level, the use of pure cellulose powder and selective matrix polymers results in high responsiveness and large shape-transformations in the printed structures. As a result, the smart structures can fully transform, for example open and close, in response to naturally occurring ranges of relative humidity. An optimized arrangement of mesostructures allows for this transformation to be fast, responding to weather changes in real-time. Furthermore, this shape-change is fully reversible and repeatable in many cycles, allowing for long-term use of such structures in real-world applications. On the mechanism level, the use of bilayer structures and curved folding geometries provides a motion amplification effect that further enhances the shape-change of the smart structures. Such shape-change can be utilized for different functionalities in building skins, such weather-adaptive ventilation or shading. As a result, the zero-energy system can dramatically enhance the performance of the building system, reducing the energy consumption related to heating, cooling and ventilation through utilizing the environment and natural resources.

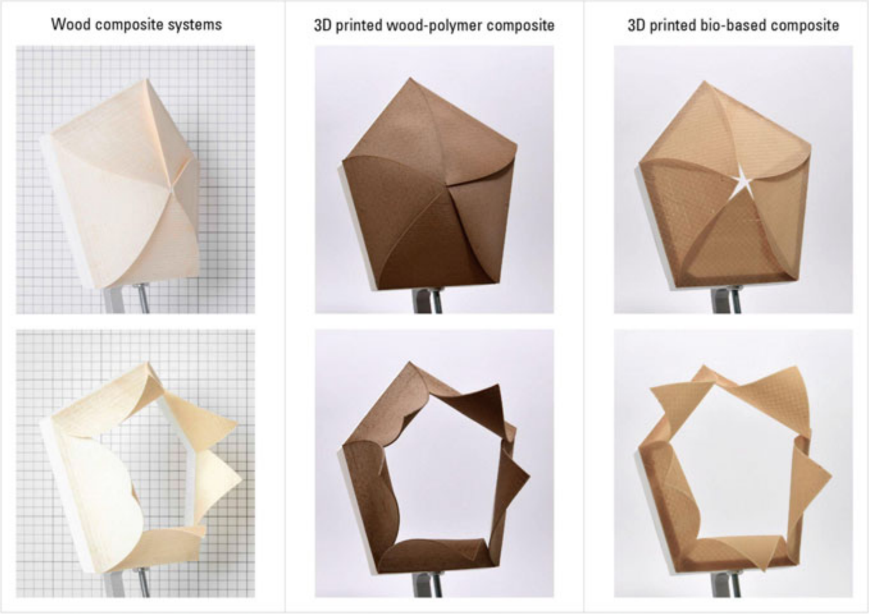

Fig. 4.9 The ICD has developed a series of bio-inspired weather-responsive apertures made from natural materials such as wood composites as well as newly developed bio-based materials for 3D printing

4.5 Future Perspectives—Learning to Build and Live with Biobased Materials for Sustainable Building Systems

Our work shows the value of deploying biobased hygromorphic materials in prototypical, passively responsive systems. However, working with natural materials presents challenges in contemporary design and manufacturing where precision, predictability and repeatability is highly valued. Future work will need to balance the unique natural functionality of these materials with the standards of engineering and design, to best utilize the range of sustainably harvested materials we have to work with (Sanandiya et al., 2020). One approach is to use data driven methods for optimizing the use of materials that come with inherent variation in material properties and structure and consider them advantageously during manufacturing (Morin et al., 2020; Sanandiya et al., 2020; Tamke et al., 2021). Combining advances in machine vision and applied machine learning is especially promising for utilizing hygromorphic functions which are sensitive to variation in natural material structuring and are challenging to solve using classical mechanical or material models (Akbar et al., 2022). The low cost, high availability, and regenerative aspects of naturally responsive materials favors further development in digital design and manufacturing technology to better utilize them in resource intensive applications such as building construction.

Parallel to the technical challenges is the adoption of responsive material systems in our building culture. Passively responsive material systems that exhibit morphing behaviors are common in nature but can be unexpected in the built environment. They tend to operate slowly and silently in the background and with high levels of redundancy. While this adaptation happens efficiently, they cannot be turned on or off with a switch or reprogrammed for different functions. Overcoming the perception of lack of control and visual variations in performance are major social challenges. A shift towards buildings that operate with the cycles of the natural environment is a shift towards the grand challenge of sustainable construction and building operation.

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