3D-Printed Wood: Programming Hygroscopic Material Transformations

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ORIGINAL ARTICLE

3D-Printed Wood: Programming Hygroscopic Material Transformations

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Abstract

Rapid advances in digital fabrication technologies and new materials development allow for direct control and programmability of physical material transformations. By utilizing multimaterial 3D printing technologies and anisotropic material compositions, we can physically program hygroscopic materials such as wood to precisely sense and self-transform based on fluctuations in the environment. While wood remains one of the most common building materials in use today, it is still predominantly designed to be industrially standardized rather than taking advantage of its inherent anisotropic properties. This research aims to enhance wood's anisotropic and hygroscopic properties by designing and 3D printing custom wood grain structures to promote tunable self-transformation. In this article we present new methods for designing hygroscopic wood transformations and custom techniques for energy activation. A differentiated printing method promotes wood transformation solely through the design of custom-printed wood fibers. Alternatively, a multimaterial printing method allows for greater control and intensified wood transformations through the precise design of multimaterial prints composed of both synthetic wood and polymers. The presented methods, techniques, and material tests demonstrate the first successful results of differentiated printed wood for self-transforming behavior, suggesting a new approach for programmable material and responsive architectures.

Introduction

Programming materials

Recent advances in software and hardware have enabled new digital fabrication tools and greater design freedom of physical structures from CNC machines, multimaterial 3D printing, and robotic fabrication. This has in turn created increasing interest in materials and material behavior across many disciplines. More specifically, research in biomaterials, metamaterials, and soft material robotics has demonstrated that from the nanoscale to large-scale smart components it is now possible to program materials to dynamically change properties, shape, and structure.[1,2] Simultaneously, advances in multimaterial printing capabilities have enabled designers to have a greater agency in creating unique material composite structures, textures, and functionality.

The growing presence of computation in everyday environments has increasingly enabled responsive environments, machines, and processes like automated manufacturing capabilities or smart-home environments. However, most adaptive systems today still operate within a highly electromechanical paradigm and remain energy intensive, highly reliant on failure prone, and expensive mechanisms. Natural systems offer many examples of climate-responsive kinematic structures that are of particular interest for architectural or environmental applications. For example, Conifer (Pinophyta) pine cones reveal intricate bilayer structures that amplify the swelling anisotropic properties of the plant tissue.[3]

By taking advantage of multimaterial 3D printing technologies, we aim to fully integrate dynamic transformations into material structures without the need of complex sensors or traditional forms of actuation. In this article, we present initial methods for programming wood structures by multimaterial printing wood fiber materials to direct their behavior for sensing and actuation capabilities by designing their material composition and environmental interactions.

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Wood printing

While wood is one of the most common materials used in furniture making and architectural construction, it still remains one of the most difficult materials to precisely form and control, due to its hygroscopic and anisotropic behavior originating in wood anatomy.[4] For centuries, architects and designers have been responding to the challenge of wood bending, curling, and custom forming through the labor-intensive and complex techniques of steam bending and lamination. Until now, the differential dimensional change of wood has mainly been understood as a deficiency of the material. This research seeks to present an alternative approach that utilizes dimensional change as the motor for shape change, which can be choreographed and finely tuned through 3D printing.

The presented methods offer alternatives to overcome the existing limitations in utilizing wood for design and manufacturing. We propose wood curling and self-folding methods that take advantage of 3D printing technologies and the material's inherent hygroscopic swelling properties. 3D printing provides unique control over wood transformation and material size while minimizing production labor. Contrary to manipulating natural wood grain, 3D printing technologies also allow us to design specific wood grain patterns, thus enabling the curling direction to be precisely controlled. Moreover, by utilizing multimaterial printing with different materials in combination with wood, we can create custom wood composites that create new macroscale behaviors. These composites take advantage of wood's natural expansion and contraction properties, intensify wood's transformational properties, and offer greater control over the desired curvature.

Wood's moisture content can be affected by local atmospheric changes like ambient temperature, relative humidity, radiation, and so on, or through direct wetting by either surface moistening or submersion. In this article we outline various techniques for moisture-based wood activation and the resultant shape transformations. 3D printing can be used as a new method for producing flat wood sheets that self-transform into 3D preprogrammed shapes and wood composites that rapidly adapt to environmental conditions.

Research context

In this article we position complementary research approaches to programmable material systems developed by the Institute for Computational Design at the University of Stuttgart (ICD) and the Self-Assembly Lab at MIT (SAL) that use 3D-printed synthetic wood composites for hygroscopic transformations. In this research, ICD has focused primarily on responsive and reversible wood transformation behavior driven by printed hygroscopic wood that reacts to changes in relative humidity. SAL has focused on the precise control over geometric transformations through multimaterial programmability and water submersion. This article discusses the common methods as well as distinct approaches that draw upon the research trajectory and background of each institute to realize printed hygroscopic programmable materials.

Over the last seven years, ICD's research into programmable materials has focused on a variety of wood systems due to the material's exceptional structural strength, locally sourced availability, positive carbon footprint, and very low embodied energy.[5,6] Previous research has focused on the instrumentalization of hygroscopic movement through a bilayer veneer composite.[7] The range of curling deformation, environmental operational range, and material programming has been demonstrated through a variety of full-scale architectural prototypes[8,9] (Figs. 1 and 2).

Multilayer fabrication with wood veneer has provided a promising outlook into wood bilayer systems such as hygroscopic

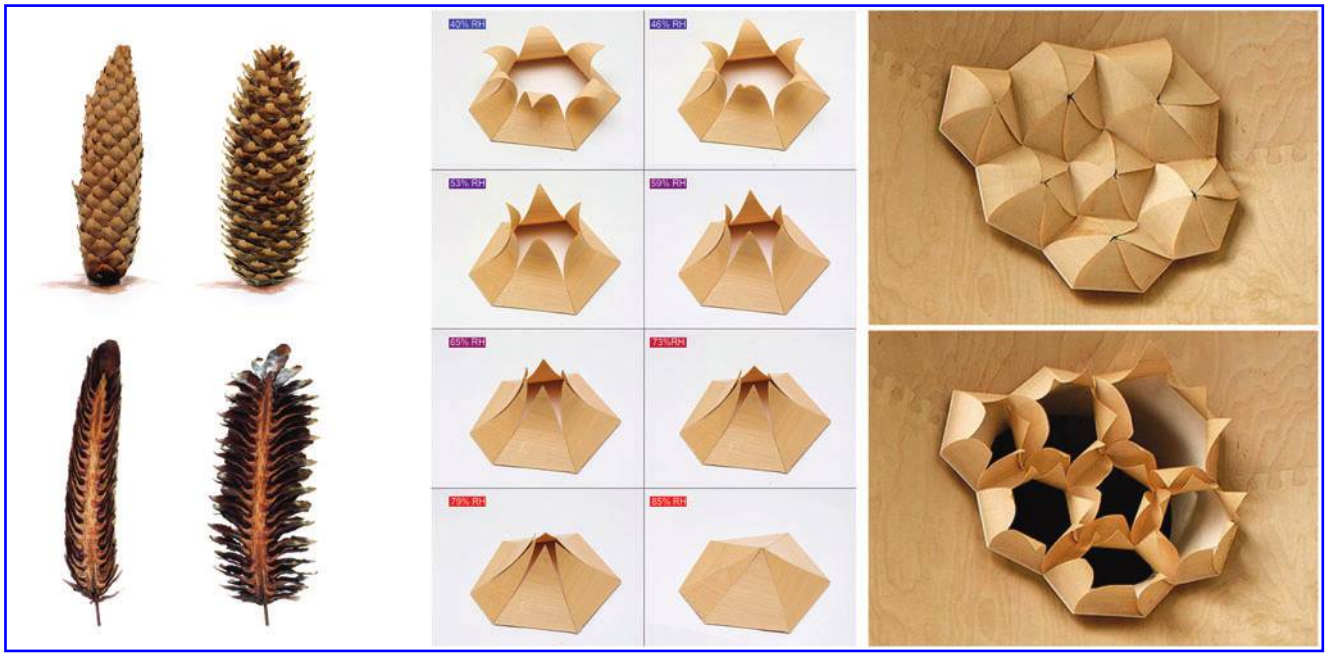


FIG. 1. Previous research at the ICD[8] investigated the transfer of the biological principle of shape change triggered by hygroscopically induced dimensional change to humidity responsive, veneer-composite elements. ICD, Institute for Computational Design at the University of Stuttgart.

FIG. 2. HygroSkin project aperture developed by ICD.[9] Based on the veneer-composite elements (left) employed as a weather-responsive architectural skin on the HygroSkin Pavilion (right), which is closed at high relative humidity (top left) and open at low relative humidity (bottom left).

actuators for large-scale mechanical systems.[10] Assemblies of large-scale hygroscopic surface components have highlighted technical opportunities to augment the material behavior by articulating multidirectional responsive mechanisms.[11] ICD's research into biomimetic 3D-printed hygroscopic material continues this research trajectory by integrating the material behavior, functional principles, and mechanisms while expanding the material scope and fabrication methodology.[12]

Recent research conducted at the SAL includes 4D printing, which consists of 3D-printed multimaterial polymer structures that change shape and physical property over time. These structures include rigid polymers and hydrogels that respond to moisture to transform from any 1D, 2D, or 3D structure into other arbitrary shapes and functions.[13,14] More recently, the SAL introduced a category of programmable materials expanding the pallet of activation energies utilized (water, heat, light, etc.) as well as the range of material compositions (textile, carbon fiber, other polymers, etc.) and industry applications (aviation, automotive, sportswear, furniture, etc.).[15]

Materials and Methods

Printed wood composition

Wood swells and shrinks due to moisture intake and moisture loss. These changes generally occur in response to atmospheric conditions, like relative humidity, radiation from the sun, or direct precipitation. ''Wood'' FDM filaments are developed by combining a suitable 3D printing polymer with microwood fibers. Since the wood fibers remain hygroscopically active, the material swells or shrinks in response to humidity changes. Additionally, a certain amount of shear-induced alignment in the nozzle may arrange some of the fibers longitudinally along the extrusion path. This behavior has been verified in smaller non-FDM 3D printing processes at the microscopic scale,[16] but they have only been visually verified in the context of this research. An example wood filament is a copolyester composite with high cellulose content (approx. 40%) that is commercially available under the name Laywood™. A number of commercial and custom ''wood'' filaments were initially tested; however, due to consistency challenges and material availability, most of the presented samples were developed using off-the-shelf wood filament. While the wood filament responds to moisture, other polymers are used in combination that may be substantially less responsive to moisture or that may be actuated by other stimulus to help amplify the transformation.

Wood activation techniques

To trigger wood transformation, the 3D-printed wood composites (either only wood or multimaterial) must be exposed to moisture. In the presented experiments three controlled climatic conditions were tested: direct water submersion, dry or moist air (R.H.) via a climatic chamber, and heat radiation combined with one of the moisture intake techniques.

Water submersion. The first technique for moisture intake utilizes full water submersion of the printed wood composite. This can be applied for both the wood-only and multimaterial wood composites. The printed samples are placed inside a room-temperature water vessel until the wood composite is fully saturated. The amount of time required depends on the type, density, and thickness of the print. While moisture intake will always induce swelling on the wood composite, water submersion can be used to activate a curling/folding deformation or it can return the curling to the flattened state depending on the desired result.

Water vapor. The second technique for moisture intake utilizes a climate chamber to control the amount of moisture and water vapor in the air. This setup can be used to subject the samples to a full range of relative humidity conditions from very dry (10% RH) in order to remove moisture or very humid (90% RH) in order to increase moisture in the print. This setup can also be used to test target humidity levels that may be desired for a given curvature deformation by setting a specific condition. This setup can also be used to create a dry environment that can accelerate moisture loss without using radiant heat or to maintain precise control of the environmental conditions. High relative humidity can also be created to increase moisture in the samples but this process takes exponentially longer than the water submersion method.

Thermal radiation. Thermal radiation can be combined with either the water vapor or the water submersion technique to activate transformation. Thermoplastics can have large changes in their physical properties due to heat at various temperatures, from dimensional changes to bending stiffness. Thermal radiation is effective when combined with the water vapor technique because increasing the air temperature has a direct impact on relative humidity and can accelerate moisture desorption.

Similarly, thermal radiation is also effective when used after the water submersion technique, when multimaterial prints are tested, to amplify the wood transformation. As further described in Materials and Methods, a wood composite material may be printed with an added thermally shrinking polymer. After being submerged in the water, the multimaterial print can be subject to heat ranging from 70°C to 90°C to help expedite the drying process and enhance shape transformation.

FIG. 3. A photograph showing printed wood grain in precise two-dimensional anisotropic patterns developed by Self-Assembly Lab (SAL) at MIT.

Methods for 3D-printed wood transformation

By taking advantage of current 3D printing technologies, we are able to deposit material in precisely defined grain patterns, controlling the material's anisotropic behavior (Fig. 3). Utilizing such capabilities, we are able to design custom ''wood grain'' specifically to enhance shape change. Building on the bilayer theory of bimetals,[17] it is possible to reach various bending equilibrium states via differential expansion between the two layers.

Nastic plant movement using fibrous motors provides a suitable template to instrumentalize stress deformations across multiple layers in order to generate complex kinematic movements.[18] A wide range of kinematic folding and curling deformations can be programmed in a responsive bilayer composite through the anisotropic properties of both layers. This functional anisotropic principle has been successfully reproduced in hydrogels[19] and a wide range of other soft materials.[20]

Based on the research concluded to date, two key methods have been identified to augment and program wood transformations.

Method A: differentiated printing (wood-only). Differentiated printing of wood relies on customized deposition, through 3D printing, of wood filament over many layers. The transformation is caused by the natural expansion and contraction of the fibers due to water absorption. By designing the pattern and orientation of each layer, the layer height, and the interlayer interaction, it is possible to program the material to produce different curling or folding deformations under controlled moisture and/or heating conditions. For example, one side of the wood composite material may be printed smooth, while the other is printed with ridges to promote curling in one direction (Fig. 4). In this method, control of transformation is achieved through the specific pattern of the wood grain only. As a general principle, the final object's folding direction will be perpendicular to the grain's direction.

Method B: differentiated multimaterial printing. Differentiated multimaterial printing expands on the previous method by using two materials, a re-active material with high hygroscopic swelling capacity (wood fiber composite) and a nonreactive material. The difference in volumetric expansion, bending stiffness, and modulus of elasticity of each layer form the basis for the responsive deformation behavior. This method uses multimaterial 3D printing as a way to create custom-differentiated multilayer composites. For example, a hygroscopic wood composite material may be printed in combination with a stable polymer layer; the various differences in physical properties of the two materials induce the curling deformation (Fig. 5).

For this method, nylon, ABS, PLA, or other commercially available polymer filaments, with low moisture absorption and swelling properties, can be used in addition to wood filament. The purpose of the polymer is to constrain the expansion of wood when exposed to moisture. As a result, it is possible to obtain greater control over the direction of folding, precise angles, and speed of response as compared to Method A, which only uses wood. As is the case in Method A, the grain direction and the height of the print are the two main factors that control the transformation. Given the increased material performance of each layer, this method is highly effective in increasing the response time while producing a narrower radius of curvature.

Results

Differentiated printing (wood-only) results

Controlled folding through differentiated wood printing has been achieved through the control of density and pattern of the printed wood grain (Fig. 6). The grain pattern and the shear-induced alignment of the fibrous fillers (micro wood fibers) along the extrusion path form the basis for transformation. The denser the grain, the smaller the folding angle. Another factor that determines the folding angle is the number and height of the printed layers of the object. With a layer height of 0.8 mm and distance between the printed fibers 0.01 mm, it has been observed that the optimal number of layers is three, with composite height of 2.4 mm. Greater height than the optimal results in decreased folding angle due to the increased material weight and rigidity. Less height than the optimal is insufficient to produce enough force for repeatable transformations. The samples are initially saturated in a controlled state through water submersion inside a room temperature water vessel for an optimal time of 2–3 h. After being soaked in water, the prints can be left to air-dry. The

FIG. 4. A series of photographs showing a differentiated printed wood composite developed by SAL that self-transforms from a flat sheet into curved surface.

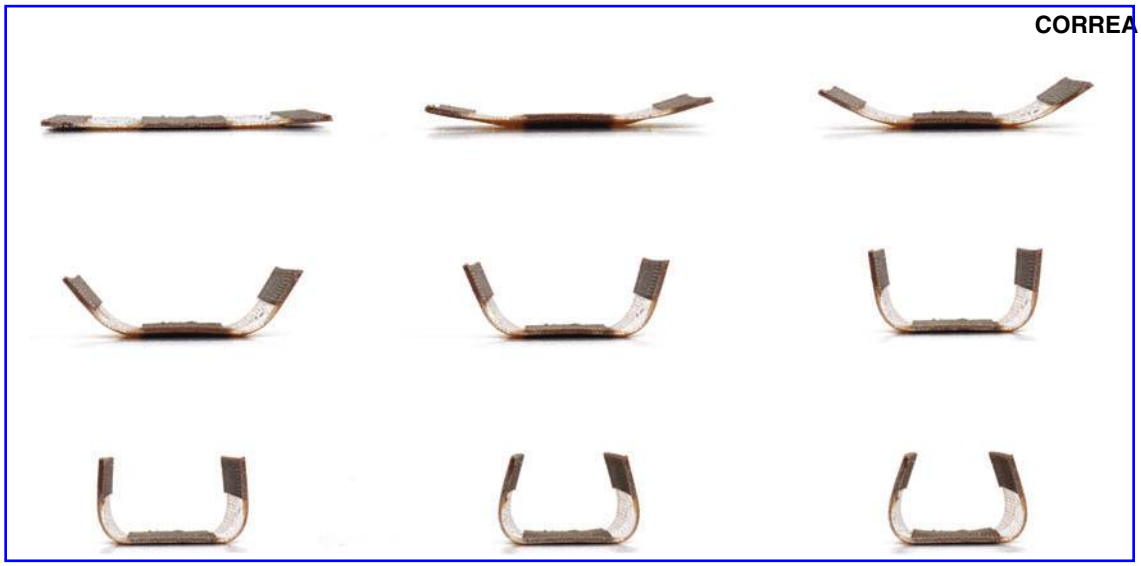


FIG. 5. A series of photographs showing a multimaterial printed wood composite developed by SAL that self-transforms from a flat sheet into a symmetrically folded structure.

average transformation time is approximately 60–120 min for a printed sample of 52 mm by 52 mm size. Orientation of the fibers at 90 or 45 degree angles will result in different types of transformation (Fig. 6).

As an alternative approach, the base (responsive layer) can be printed with a single grain direction, while the subsequent layers have a spaced grid pattern oriented 45 degrees from the base pattern (Fig. 7). This configuration is intended to constrain the base layer while reducing the effect of its own swelling expansion on the system. The sample was tested in both climatic chamber and submersion tank achieving equivalent deformation results under different time scales. A sample of 20 mm by 100 mm will reach full transformation under full submersion after 12 h; the reverse cycle is faster and can range from 15 min to 2 h, depending on the R.H. of the surrounding environment. The deformations follow the programmed wood grain direction and are fully reversible. That is, the sample can reach multiple equilibrium states through curling at various moisture content levels and reverse. These changes can occur cyclically, under ambient temperature by increasing or decreasing the moisture content.

Differentiated multimaterial printing results

The curling deformation in multimaterial printed wood is an equilibrium state resulting from the shear stress between the two material layers. Similar to the previously developed veneer system (Figs. 1 and 2), the responsive layer can also be calibrated to either shrink or expand after printing by careful adjustment of the material properties (prior to fabrication) and the fabrication settings.[12] Therefore, equal thickness samples can be designed to achieve different curling radii or completely inverse transformations (Fig. 8).

In one approach, ABS filament was selected as the nonresponsive material to be used in combination with the wood filament due to the low water absorption (less than 1%), strength, and mild flexibility. Therefore, the mechanism relies solely on moisture intake and desorption (without the need for

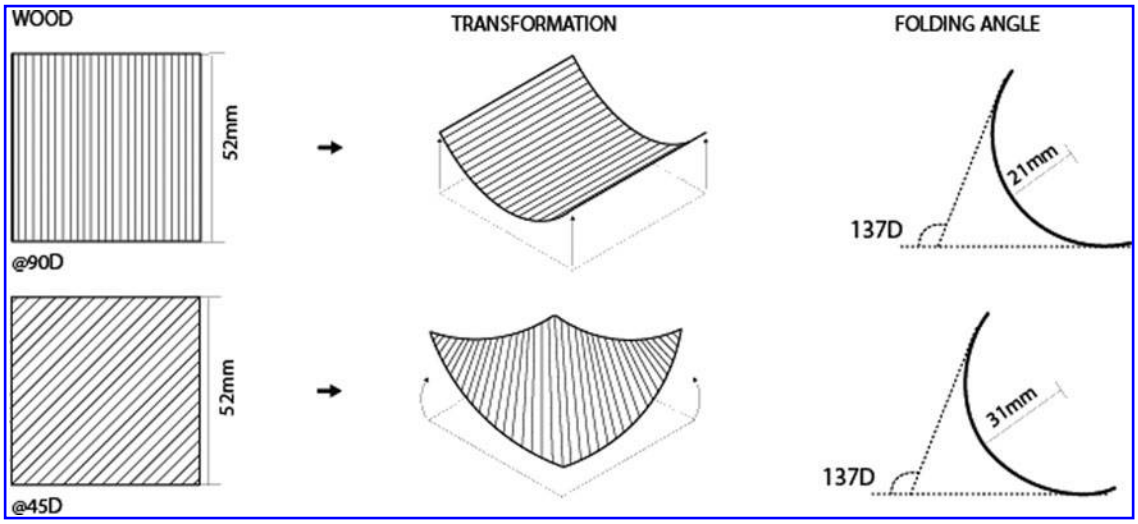


FIG. 6. Diagrams showing various wood transformations and the corresponding curvature after submersion in room-temperature water (20–25°C). The different transformations are caused by the different wood grain direction as depicted in the diagrams. The printed sample's height is 0.6 mm (consisting of 3 printed layers × 0.2 mm).

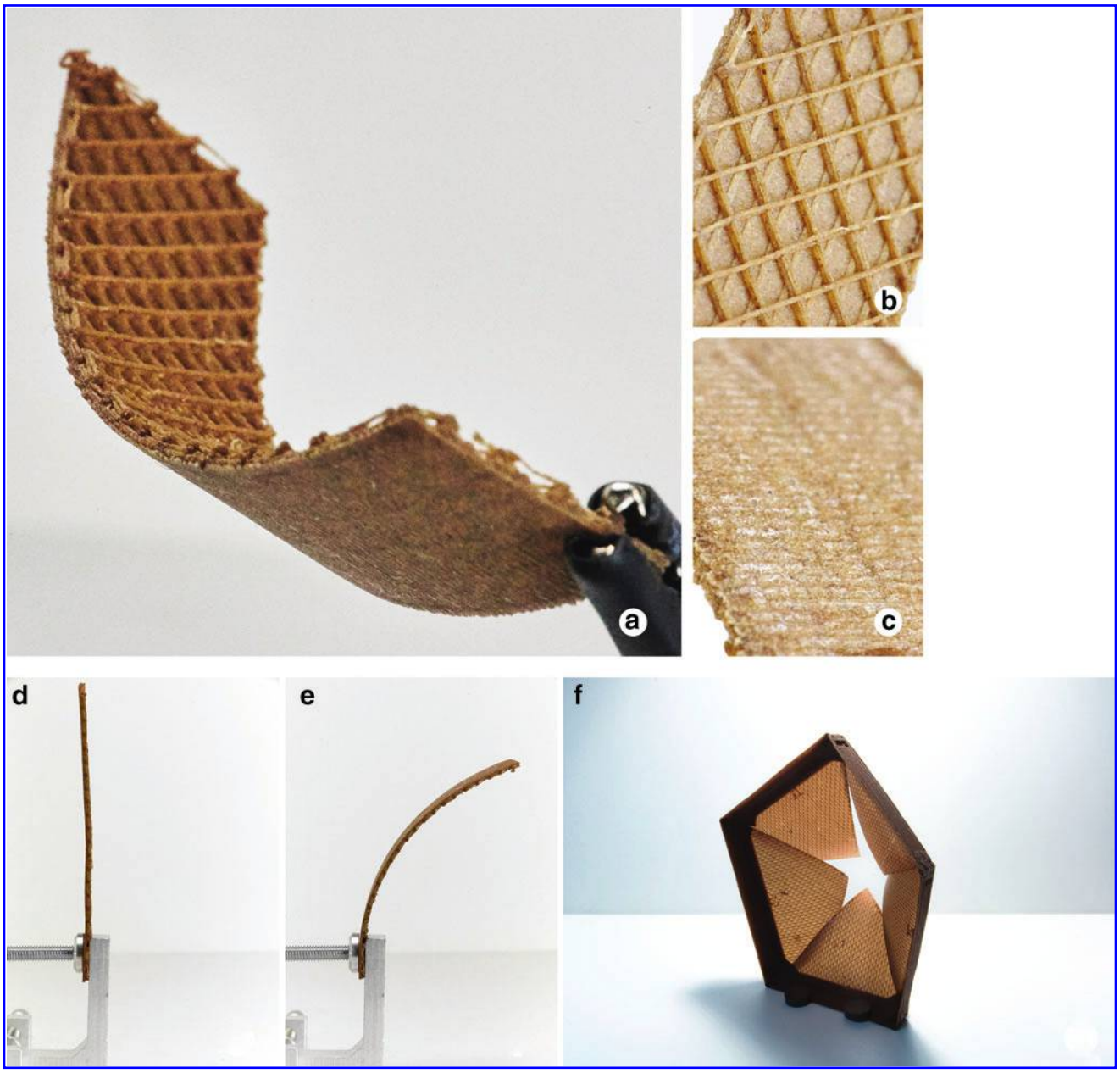


FIG. 7. Photo of single-material 3D-printed test sample developed by ICD **(a)** showing grid pattern and layer details **(b)** and curling wood grain layer detail **(c)**. Curling states under high R.H. **(e)** and low R.H. **(d)**. **(f)** Photo of the single-material 3D-printed aperture previously developed by ICD[12] that shows the functional grading from the static framelike perimeter support to the weather-responsive central region.

heat) to achieve the curling deformation. In order to achieve this, this method relies on two key aspects: good interlayer bonding and a high surface-to-volume ratio. The latter facilitates the exchange of moisture (intake and desorption), while the former prevents delamination. The interwoven pattern is designed to incorporate the nonresponsive polymer in a way that minimally affects the bending stiffness while maximizing restraint of the responsive layer—perpendicular to the grain (Figs. 8 and 9).

Additionally, the net type of structure allows moisture and air to easily access the responsive layer from both sides. Actuation is notably faster during the drying cycle, but due to the slower absorption rate (compared to wood veneer) and reduced amount of wood content in the composite, the system requires between 12 and 24 h in a high-humidity environment in order to reach its maximum saturation. Similar to the approach for Method A, activation and curling of the system start immediately upon moisture intake and it is fully reversible for multiple cycles. Empirical tests have shown repeatability for over 30 cycles without any visible effects of material degradation or changes in curling range. The dual material coupled with the interwoven printing pattern can be functionally graded to incorporate specialized nonresponsive structural supports or assembly mechanisms (Fig. 10).

A second approach was tested utilizing nylon filament as the second material. To result in a controlled transformation,

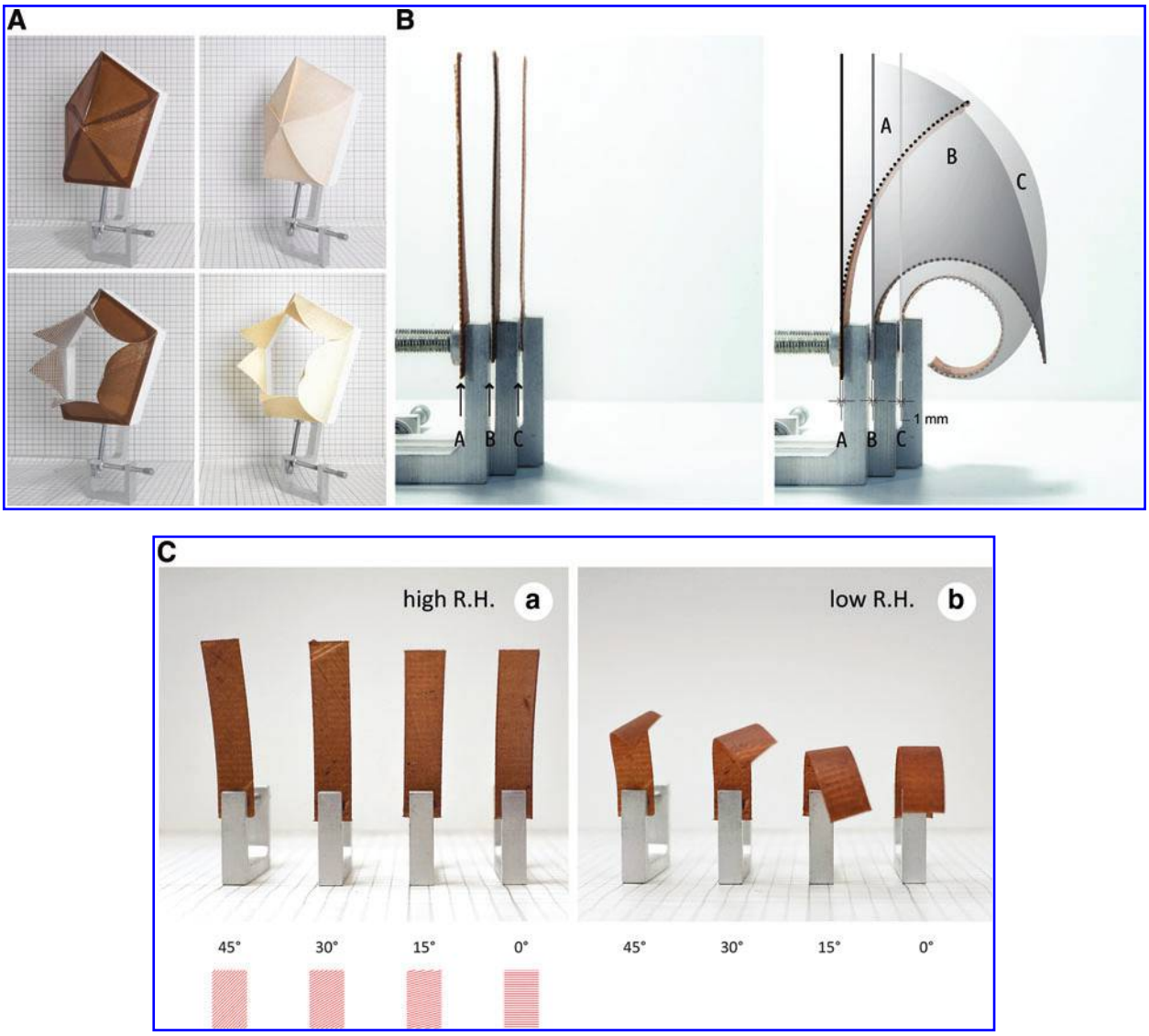


FIG. 8. **(A)** The performance of the responsive 3D printed aperture (left) developed by ICD[12] as compared to the previously ICD-developed veneer-composite system aperture adapting to relative humidity changes: open at low relative humidity (middle) and closed at high relative humidity (right). **(B)** Three 1-mm-thick test samples (left) programmed to respond with different curvature ranges due to an increase/decrease in relative humidity level (right). **(C)** Controlled curling angles based on 3D-printed wood grain on multimaterial samples developed by ICD.[12] Samples with no deformation under high R.H. (left, **a**) and high deformation under low R.H. (right, **b**). Curling and twisting deformation angles are achieved in response to the printed wood grain.

the disposition of printed nylon fibers follows the direction of the printed wood grain as opposed to a net-like structure. The polymers are printed either on the top or on the bottom of the printed wood in order for the two materials to interact, resulting in controlled transformation. For multimaterial composites with nylon, the polymer will remain in the interior of the radius of the curvature, while wood will remain on the outside (Fig. 11). On the contrary, if ABS is used as a polymer, the polymer will remain on the exterior of the curvature. Therefore, as a general principle, nylon and ABS will result in opposite transformations.

In this method, either water submersion or water with heat exposure can be used as activation techniques. However, the process is highly accelerated when heat radiation is used after the moisture intake. While activation follows the same process, as in the case of wood-only composites, the response time is highly accelerated due to the increased drying and differential expansion/contraction of the two materials. The transformation results for air-drying and heat-drying in wood–nylon composites demonstrate that the samples dried with heat radiation exhibit greater curvature and faster transformation as compared to the air-dried samples. For a printed square sample of size 51.5 mm and central deposition of nylon with a width of 21.5 mm, the transformation time with no heat radiation is 1.5–2 min, resulting in a transformation of a 104-degree folding angle. The same sample, when exposed to heat radiation after being submerged in the water, transforms in 10–12 min, resulting in a transformation of a 110-degree folding angle. The accelerated and increased folding appears to be due to the induced flexibility when applied with heat as well as the nylon's slight shrinkage rate. Increasing the nylon width

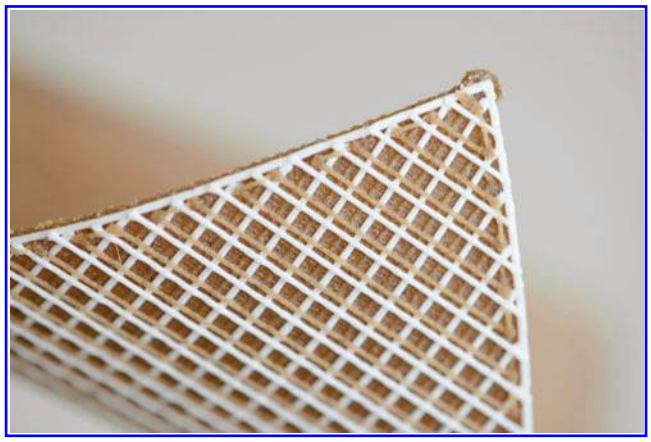


FIG. 9. Interwoven multimaterial 3D printing pattern of the responsive system ABS (clear) and wood filament developed by ICD.[12]

results in increased folding as well as in faster transformation (Fig. 11). In this case, the transformation is reversible only if the printed sample is submerged in the water. After the print returns to its initial flat state, the folding process can be repeated. However, the folding angle gradually decreases with each transformation cycle (Fig. 12). The multimaterial printing method demonstrates greater control and intensity for transformation as compared to wood-only printing methods (Figs. 6 and 13).

Discussion and Next Steps

Integration of various activation techniques

In this article we outlined the processes and results, including various activation techniques conducted for 3D-printed wood transformation. The results from the tests suggest that the same material composition and pattern can lead to different transformations if the environmental conditions vary. Further research aims at testing different transformations under different environmental conditions within hybrid systems that incorporate more than one of the described activation techniques. Such hybrid transformation systems could potentially lead to a greater degree of curvature, response time, and reversibility.

Further material research

Further tests may be conducted to gain a better understanding of the behavior of the wood composites by analyzing their physical and mechanical properties. To this end, long-term cyclical endurance tests may be conducted to test the performance of the wood composites under transformation and ensure efficient and repeatable results for potential applications. Moreover, the possibility of custom wood filament production allows for further experimentation on material composition. The production and testing of different filaments consisting of different wood and polymer compositions can aim at augmented material performance in terms of both transformation speed and reversibility.

Performance and further development

Moisture absorption and volumetric expansion in the synthetic composites may be further developed through the increased content of hygroscopic filler, improved moisture diffusion across the material, or by a more precise calibration of the polymer binder. Further studies can also test the impact of different fiber sizes, as fillers, and their interaction with the thermoplastic binder during filament production, storage, and fabrication.

Further development in this rapidly advancing field will provide additional tools for material adjustments, layer deposition complexity (through multiaxis printing), as well as

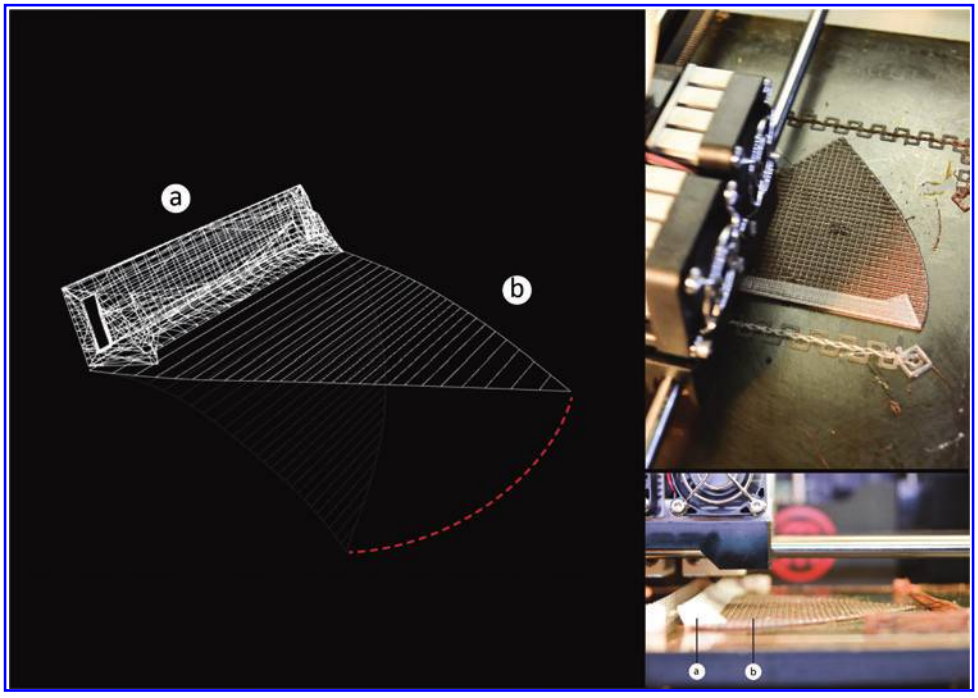
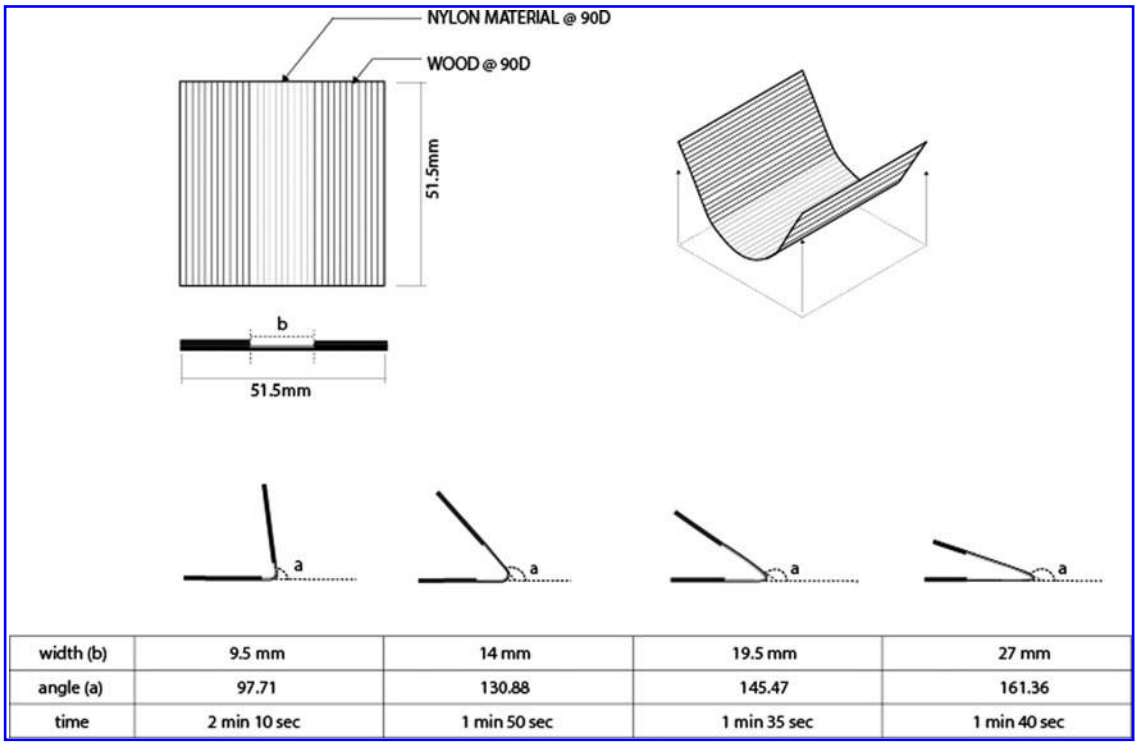
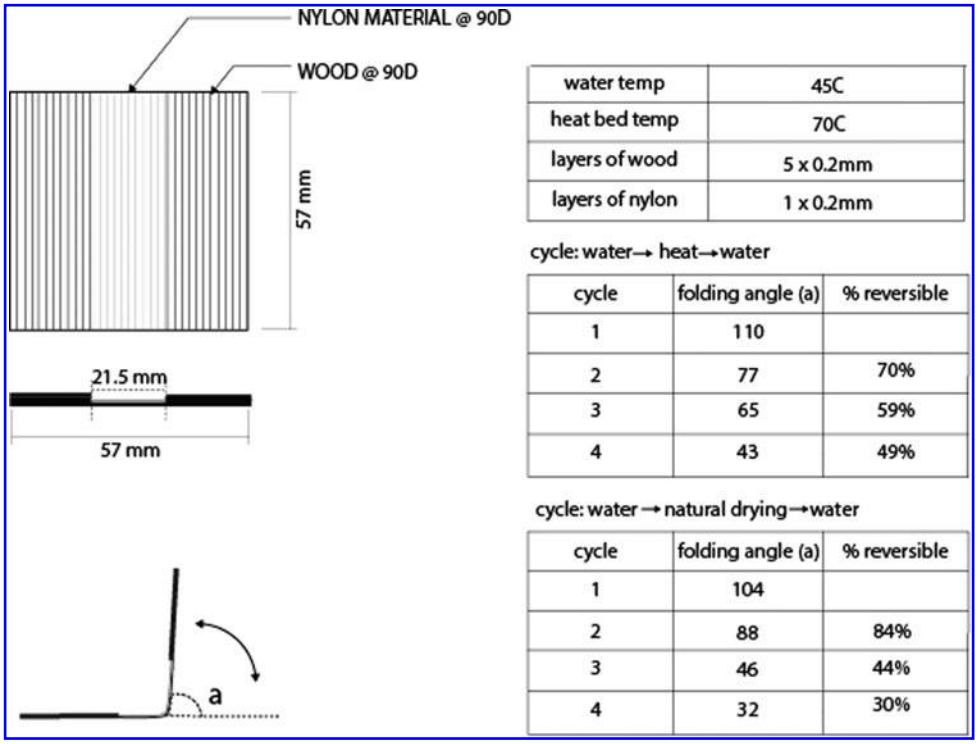


FIG. 10. Multimaterial 3D printing fabrication process showing functional grading: **(a)** structural support perimeter, **(b)** responsive aperture region. Previously published work at ICD.[12]



width (b)	9.5 mm	14 mm	19.5 mm	27 mm
angle (a)	97.71	130.88	145.47	161.36
time	2 min 10 sec	1 min 50 sec	1 min 35 sec	1 min 40 sec

FIG. 11. Data table and section drawings depicting transformations of a multimaterial print consisting of wood (5 printed layers × 0.2 mm height) and various widths of printed nylon (1 printed layer × 0.2 mm height) transformed after being exposed to moisture (full water submersion 20–25°C) and heat (70°C). The diagrams and corresponding measurements depict the values of the corresponding to the nylon width folding angles and the transformation time needed. As depicted in the diagrams, under the same environmental conditions, increasing the nylon width results in increased folding as well as in faster transformation. The nylon remains in the internal side of the curvature.



water temp	45C
heat bed temp	70C
layers of wood	5 x 0.2mm
layers of nylon	1 x 0.2mm

cycle: water→ heat→water

cycle	folding angle (a)	% reversible
1	110	
2	77	70%
3	65	59%
4	43	49%

cycle: water→ natural drying→water

cycle	folding angle (a)	% reversible
1	104	
2	88	84%
3	46	44%
4	32	30%

FIG. 12. Data table and diagrams presenting folding angle measurements and degree of reversibility for repeated transformations of multimaterial samples consisting of wood and nylon after cyclical water submersion and heat exposure. As can be inferred from the measurements, the transformation process is not fully reversible as the folding angle gradually decreases with each cycle.

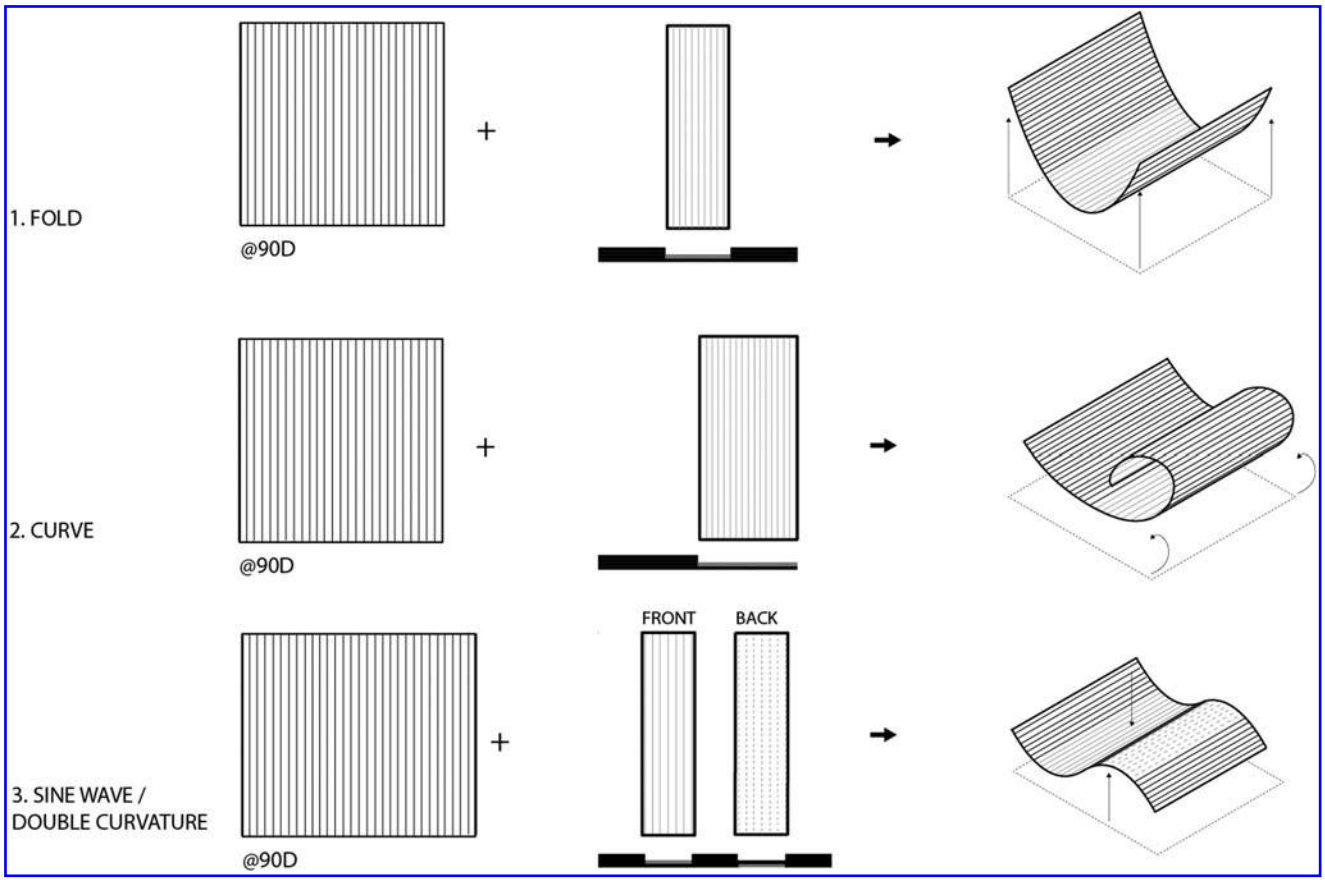


FIG. 13. Diagrams showing various transformations of multimaterial prints consisting of wood and nylon, after submersion in room-temperature water (20–25°C) and heat exposure (70°C). The different transformations are caused by the different wood pattern directions as depicted in the diagrams.

multimaterial workflow support. Adjustments of material composition, number of printed layers, and thickness are some of the parameters that are currently being tested to achieve more precise and consistent results at multiple scales.

Digital tools

The presented projects highlight both the importance of tool path generation and tool path control in order to achieve proper interlayer interaction. However, limited tools are currently available to easily access and manage these variables within a design interface. Direct and real-time access to printing parameters and real-time machine control/feedback (temperature, feed rate, retraction, etc.) are critical for the effective optimization of the multilayer composites.

Similarly, digital simulations are critical in order to facilitate both the integration of 3D-printed transformation methods into a greater research community and the integration of such methods in industry applications. Further development of simulation platforms can offer greater design capabilities for complex geometric transformation and better communication between design and 3D printing production.

Conclusions

In this article, we have outlined limitations with existing wood manufacturing and forming processes due to wood's anisotropic and hygroscopic properties as well as the intense labor and complex forming processes used. This research focuses on customized responsive wood structures that can be easily produced and highly tuned through multimaterial 3D printing. We have developed a series of design and production methods that utilize multimaterial wood printing and hygroscopic activation techniques for programmable material products and responsive architecture.

We have outlined differentiated wood printing and differentiated multimaterial printing as the two main methods for 3D-printed wood and described three main activation techniques (water submersion, water vapor, and thermal radiation) for self-transformation. Through laboratory tests we have been able to gather data for wood transformation using different methods and techniques while comparing the results. Although Method A and Method B offer a similar range of transformations, Method B has been proven to respond to environmental stimuli faster and to result into greater folding angles. Moreover, the testing of both methods has demonstrated that transformation is reversible once the sample is exposed to moisture a second time.

Comparing the different activation techniques within the multimaterial method, we have demonstrated that heat exposure combined with water submersion is more effective regarding transformation speed and intensity of curvature as compared to water submersion alone. Comparative tests using multimaterial printing with ABS, nylon, and other polymers suggest that heat radiation results in expedited drying as well as thermal contraction of the polymer, which in turn

results in increased transformation. Where nylon was used instead of ABS, the transformation was faster with more increased curvature. This conclusion is based on tests conducted with the technique of water submersion and water combined with heat exposure.

Wood's moisture absorption characteristics are affected by the synthetic polymer within the composite filament. While it slows down the moisture absorption and swelling of the material, it also makes the material more elastic and durable. While both methods are effective in instrumentalizing the wood grain as the main driving factor for deformation, both research efforts highlight different strategies to control response time, range of curvature, and input stimulus.

Method A operates by constraining and manipulating the swelling of only wood material through a different material distribution pattern. No significant temperature changes are applied to the systems. As a result, the mechanisms and deformation are simple and reversible but their response time is significantly slower than the Method B presented, which involves multimaterial structures and heat as an additional stimuli. Notably, Methods A and B take very long when subjected to moisture intake via water vapor as opposed to direct submersion.

The presented methods propose a new approach to programming hygroscopic wood material for self-transformation through 3D printing. These methods can lead to more precise and controllable results with reduced labor and the elimination of actuators, sensors, or physical forming/molding processes. Moreover, such methods provide the capacity to enhance design agency by having complete control over grain pattern, material composition, and full customization of the transformation processes.

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