TOWARD ADAPTIVE ARCHITECTURAL SKINS

Designing Temperature-Responsive Curvilinear Surfaces

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Abstract. This research investigated the possibility of creating adaptable and precise curvilinear surfaces through the deformation of flat wooden surfaces. A prototype design system was developed to accomplish this task. The goal was to take a commonly-used architectural material, which is valued for its environmental sustainability and its aesthetic qualities, and to re-conceptualize it for use in cutting-edge adaptive digital designs. We therefore sought to develop a way to create wooden surfaces that could predictably transform in response to environmental stimuli. We successfully developed and tested the reversible deformation of a wooden surface by laminating a shape-memory polymer onto a kerfed wooden plane. The composite obtains its responsiveness from the shape-memory polymer, and its curvature direction and structural stability from the kerfed wood. The composite is able to deform to a defined curvilinear surface when heated to 40-60 degrees Celsius, and then self-transform back to the original flat surface when cooled. In addition to demonstrating kinetic behavior for a wood-based composite, the prototype offers a practical technique that can be used by designers to create flexible, inexpensive fabrication and packaging strategies.

Keywords. Environmental-Responsive Architecture; Shape Memory Polymer; Wood Fabrication; Continuous Curvilinear Surfaces.

1. INTRODUCTION

Advances in computational design are leading toward new possibilities for adaptive and nontraditional architectural forms. However, limitations associated with conventional manufacturing methods still remain a great challenge for the constructability of these free-form geometries (Raviv, Zhao et al. 2014). The contemporary movement toward geometrically complex architectural surfaces calls for a new approach in customized formation and fabrication. By being more involved in direct physical prototyping, architects can become more active agents in designing the construction system's processes, as well as its products (Oxman and Rosenberg 2007).

T. Fukuda, W. Huang, P. Janssen, K. Crolla, S. Alhadidi (eds.), *Learning, Adapting and Prototyping, Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018*, Volume 2, 329-338.

One of the most challenging developments in this area is the creation of self-adapting and self-transforming architecture. Such an approach offers a more flexible and energy-efficient design, in which the final product can transform in response to human and environmental needs without using complex mechanical parts. The products of this approach to design are becoming closer to natural systems, both in terms of their geometry and in their complex responses to dynamic environmental conditions. To create such possibilities, designers have to be fluent both in the possibilities of cutting-edge computational design and in the world of materials, fabrication, and mechanical engineering.

The current research project applied the principles of adaptive design to the commonly-used and aesthetically attractive material of wood. Although wood is often viewed as one of the more traditional and static architectural components, it can in fact be re-conceptualized as an adaptive and flexible material. Digital design has facilitated the use of process such as penalizing and kerfing to create innovative and free form wooden surfaces. However, these processes often come at the expense of a loss in material firmness, and current techniques lack precise control over the outcome of the reshaping (Raviv, Zhao et al. 2014). If the panels have irregular shapes, for examples, it will be harder to pack efficiently and it will increase the shipping costs. Our prototype design system addresses these issues by offering a widely-applicable solution to the common challenges of customized wood fabrication.

1.1. FROM 2D TO 3D SURFACES

The fundamental goal of the research was to create precise, three-dimensional wooden surfaces that can predictably change their shape in response to environmental stimuli. The first part of the incentive for this project was to develop more complex curved wooden surfaces. Continuous curvilinear surfaces have been featured prominently in contemporary architecture, especially with advances in computational design and the related growth of free-from digital modeling (Pottmann, Schiftner, and Wallner 2008). Curvilinear surfaces can offer lightweight, yet sturdy structural forms that are aesthetically pleasing and make efficient use of space. However, the movement toward these forms in architecture has been somewhat hampered by conventional fabrication systems that rely on plane surfaces and sheet materials. Using these traditional fabrication approaches makes curvilinear forms extremely difficult to construct. Sheet materials can only be bent/curved in particular directions, and existing construction methods require complicated tools and extensive assembly procedures to create complex curves (Branko 2005). To address this situation, we wanted to develop greater possibilities for creating curvilinear surfaces from flat wooden surfaces (Figures 1 and 2).

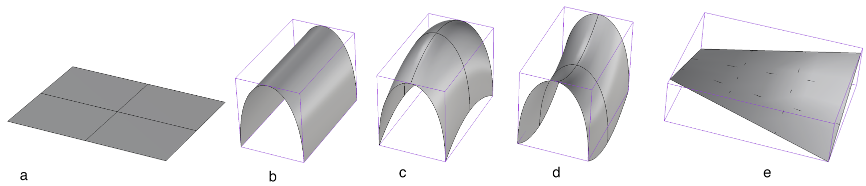

Figure 1. From a flat surface to a curvilinear surface: (a) original flat surface, (b) zero curvature bent surface, (c) positive curvature surface, (d) negative curvature surface (e) negative curvature on a saddle-like surface. Zero curvature surfaces (b) can be made by simply folding a plane surface, while positive or negative curvature (c, d, e) cannot transform into a two-dimensional plane without some degree of surface distortion. .

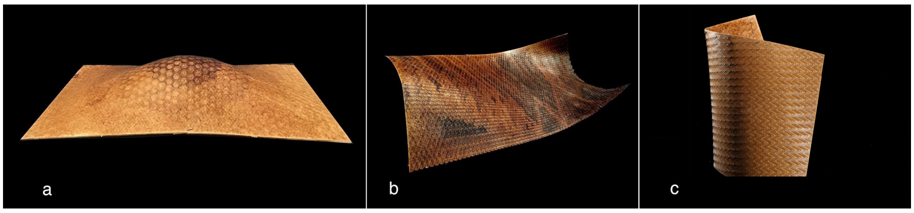

Figure 2. Wooden curvilinear surfaces generated by kerfing a flat sheet: (a) positive curvature, (b) negative curvature, and (c) zero curvature. Projects done in the studio of prof. Alireza Borhani by Chandler Fleming (a), Rotana Hok (b) and Joseph Verd (c). .

1.2. SMART MATERIALS IN ARCHITECTURE

The second part of the incentive for this project was to demonstrate how traditional and sustainable materials such as wood can become a vital part of cutting-edge adaptive design. Advanced research in architectural design have promoted the idea of responsive architectural skins that have the capacity to react to external stimuli (for example moisture, heat, light, and pressure) by exchanging energy in ways that affect qualities such as their size, density, shape, or color (López et al. 2017). While the revolution in “smart materials” has contributed greatly to this direction in design, it does not mean that we have to abandon traditional, inexpensive, and cherished ingredients.

A handful of studies have examined self-deformation possibilities by either superimposing smart materials onto traditional architectural systems, or embedding smart materials within traditional materials (for example, through fused filament fabrication or multi-material 3D printing). One of the biggest challenges in this research area is designing the composite system in such a way that a predictable/desired response to environmental stimuli can be achieved (Beites 2013)

Studies on wood’s responsiveness for adaptive design were primarily introduced to the filed of architecture by Achim Menges and his colleagues

(Menges 2012; Correa et al. 2015). Their work examined wood's natural capacity to react to humidity through reversible shape-changing, a phenomenon that was also explored in a more rudimentary way by B. N. Ugolev in the late 1970s (Ugolev 1986). Wood absorbs and releases moisture in exchange with the environment, which results in dimensional changes and bending that designers can exploit on architectural scales. At the MIT self-assembly lab, Menges and others used 3D printing technologies to create specially formulated wood-plastic composites in which warping caused by humidity could be partially controlled to create reversible curvilinear surfaces. This allowed the design to respond to an environmental stimulus (water) and change shape in a predictable way without additional electronic or mechanical control. So far, however, these efforts have been limited in terms of the materials' response time, range of curvature, and continuous reversibility over time without incurring damage. The materials are also limited in responding only to the stimulus of humidity, and they require a complicated technological fabrication process to be effective.

This study proposes an alternative approach that is quicker and uses less expensive materials and tools, and that we believe will provide for greater material durability over time. We have shifted the environmental focus from humidity to heat, and have used a polymer that can generate predetermined shapes while also functioning as a resin to enhance the durability of the wood. The shape-memory polymer used in this research has been previous studied in a variety of small-scale, self-transforming systems, but it has not yet seen a broader application to curvilinear surfaces at architectural scales. Part of the difficulty is that the structural instability of the polymer makes it hard to achieve sturdy forms. In this research, the combination of the polymer with a kerfed wooden structure is mutually beneficial, as the shape-memory polymer provides the possibility of transformation, while the wooden component provides structural strength.

2. METHOD

2.1. LAMINATING TECHNIQUE

The wood-polymer composite created in this research is formed through a laminating technique, in other words by combining a flexible wooden surface with a shape-memory polymer. The former acts as a fibrous material while the shape-memory polymer offers a resin matrix for the composite. Similar to other laminated composites, the properties of the resulting material are superior to the individual materials from which it is constructed. The composite obtains its responsiveness from the shape-memory polymer, and its shape-changing direction and structural stability from the wooden framework. The individual materials do not dissolve or merge completely in the composite, but rather act together as one (F.A.A. 2012). The two components can still be physically identified even as they interface with one another.

2.2. SHAPE MEMORY POLYMER

As a type of "smart material," shape memory materials (SMMs) are able to deform and then return to their original shape when a particular stimulus is applied. Shape

Memory Alloys (SMAs) and Shape Memory Polymers (SMPs) are the two main types of shape memory materials (F.A.A. 2012). A few conventional materials can also be designed to de achieve similar functions; these are generally referred to as Shape Memory Hybrids (SMHs).

Among all these various options, SMPs demonstrate the greatest ease of formability and workability, and they are also lower in cost compared to other shape-changing materials. Our investigation into the behavior of SMPs led us to select a polyurethane epoxy resin-based polymer to combine with a wooden surface. This type of polymer has been widely used as an independent structure, as a coating, and as an adhesive material. Epoxies can effectively bond with wood as a resin, and the temperature required for stimulating the epoxy-based shape memory polymer is within the range that we desired. The material starts to become flexible as it reaches to its "glass transition temperature" (Tg). SMP can be deformed effortlessly in its elastic state above Tg, and then returns back to its original rigid state when cooled below Tg (Figure 3). This deformation is a result of the reorientation of the polyurethane molecular chains that encourage crystallization (Z. G. Wei and Miazaki 1998). For this study, the SMP was fabricated locally in our labs, which gave us the ability to modify its Tg and to readily combine it with a wooden surface.

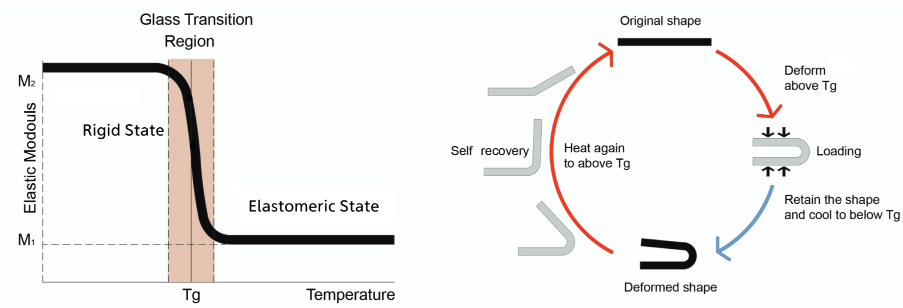

Figure 3. (Left) the general temperature response pattern of SMP. (Right) the SMP shape-changing cycle (Images created by the authors; adapted from Beites 2013).

2.3. MATERIAL PREPARATION

To turn the rigid plywood surface into a flexible material we used a relief-cutting method called kerfing. This technique offers a high level of flexibility in a rigid wood material through cutting or removing parts of the material surface (Figure 4). The specific cutting pattern determines the kind of shape-changing behavior that the wood obtains (Zarrinmehr et al. 2017). Using a laser cutting machine, we applied a diamond pattern drawn in rhino cores to a sheet of 20x18x0.2 cm plywood. The shape-memory polymer then fills the parts of the surface where wooden material had been cut and removed.

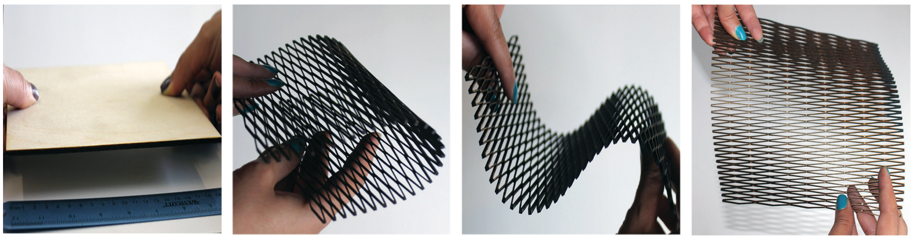

Figure 4. Turning plywood into a more flexible material using the kerfing method. The plywood becomes a very flexible wooden surface with the ability to bend or become double-curved.

The epoxy resin-based shape-memory polymer that we used for this research requires mixing three liquid materials: Epon 826, Jeffamine D230, and Neopentyl glycol diglycidyl ether (NGDE). Epon resin 826 is one of the common resins used as a base material for making epoxy-based polymers. Jeffamine D230 hardens this resin and increases its mechanical and adhesive properties. It also facilitates the bonding of the molecular components of the polymer surface. Neopentyl glycol diglycidyl ether (NGDE) dilutes and strengthens the polymer against cracking and brittleness. The mix ratios for these substances determines the final shape-memory polymer's glass transition temperature, which for our purposes we wanted to be between 40°C and 60°C. The resulting polymer attains its highest possible flexibility at 40-60°C, and is rigid at room temperature.

The composite fabrication follows three simple steps:(1) Mix appropriate amounts of the three substances in a plastic cup and stir vigorously with wooden stick for about 10 seconds. In this research we mixed 73.6 g Epon 826, 46.5 g Jeffamine D230 and 43.7 NGDE. (2) Remove bubbles by placing the mixture in a heat-resistant container, heating to 80 °C, and vacuuming to expel all air entrapped in the mixture.(3) Place the wooden surface in a latex mold, then fill the mold with the polymer mixture and heat it in an oven at 100 °C for 90 minutes. Then cool the material, and the laminated composite is complete (Xiao 2012).

3. RESULTS

We first tested the SMP mixture (without the addition of wood) to verify its expected responsiveness. As expected, the polymer could be deformed through heating to 40-60°C and applying pressure, and it retained its deformed state after being cooled. Then, after being heated again in the absence of external force, it quickly returned to its original shape (Figure 5).

We then tested the combined SMP-wood laminate. As shown in Figure 6, the composite is rigid at room temperature (unlike the isolated kerfed word component). Since the polymer is in its rigid state, the whole composite loses its flexibility. However, the composite regained its flexibility when the environmental temperature was raised above its Tg range (Figures 7, 8, and 9). In its elastomeric state, force was applied and the material deformed. After maximum bending along a single curvature, the composite was cooled below the Tg, by simply removing the heat source. After 20 seconds at room temperature the composite material had cooled sufficiently to return to its glassy state and become rigid. When heated again to above Tg, the material “remembered” its original flat shape and returned to it within 8 seconds. This cycle could be continuously repeated.

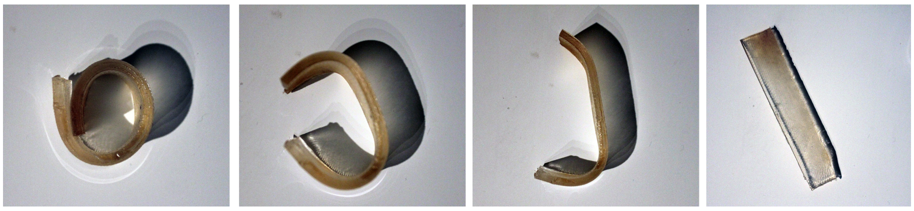

Figure 5. Initial test of SMP responsiveness: (a) the deformed shape of a fabricated polymer sample after applying heat and pressure, and (b, c, d) the shape recovery process at 2 seconds, 6 seconds, and 8 seconds.

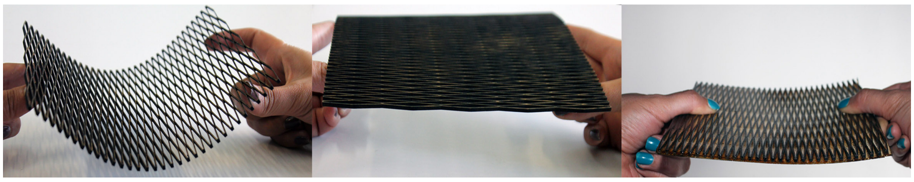

Figure 6. Comparing the Flexibility of the Kerfed Wood and Composite in Room Temperature.

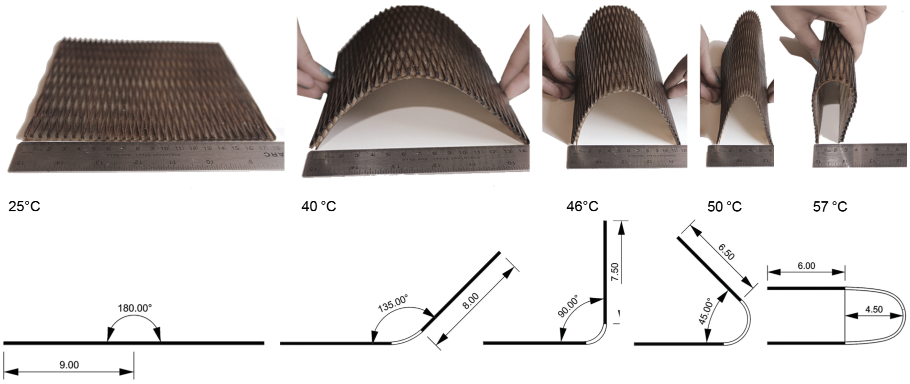

Figure 7. The process of surface deformation by heating with external force, then cooling to get a rigid surface.

The composite regained flexibility when the environmental temperature was above its Tg range, as it is shown in Figure 7 and Figure 8 and Figure 9. In its elastomeric state, force was applied and the material deformed. After maximum bending along a single curvature, the composite was cooled below Tg. The infrared light that served as source heating in this experiment was turned off. It took 20 seconds to return to its glassy state when the composite was rigid. When heated again to above Tg, the designed material eventually remembered its original flat shape and returned to it within 8 seconds. This cycle could be continuously repeated.

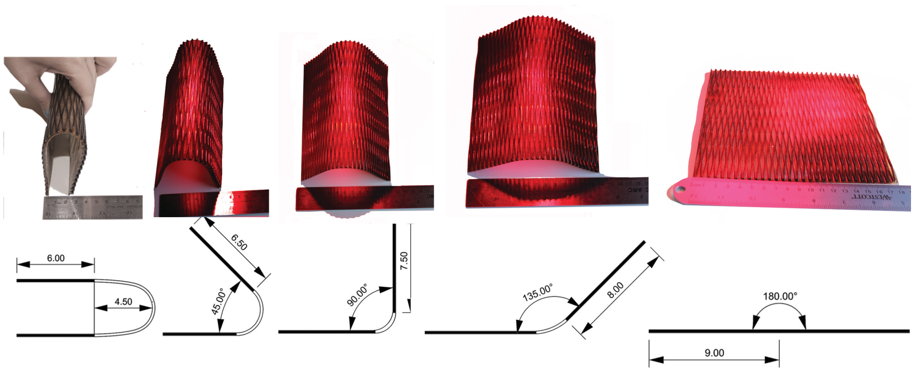

Figure 8. The process of shape recovery by heating without an external force.

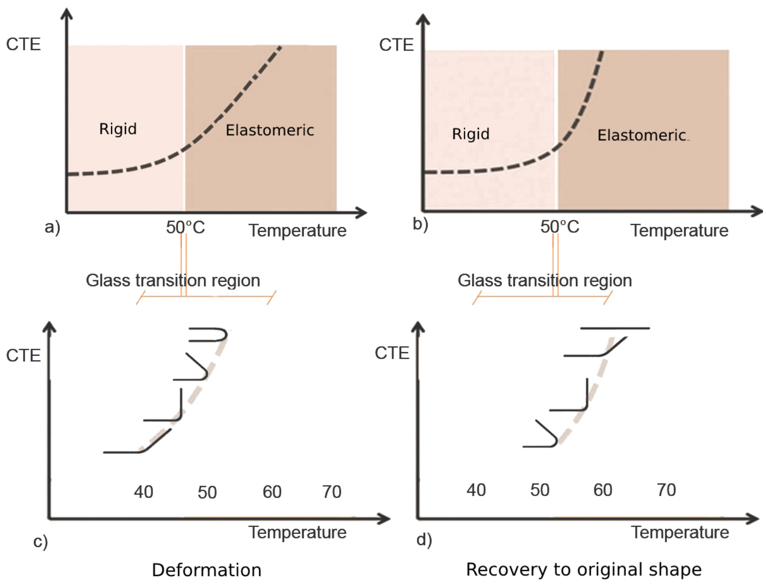

Figure 9. Coefficient of thermal expansion (CTE) vs. temperature for: (a) deformation by loading and (b) recovery without loading. The composite exhibits a significant ability to deform between 40 °C and 60 °C.

4. Conclusion and Future Work

This research project developed a new method to produce responsiveness and reversible shape-changing characteristics in wooden surfaces. By laminating an epoxy resin-based polymer with a kerfed wooden surface, we combined the "shape memory" qualities of the polymer with the structural rigidity and aesthetic properties of wood. The outcome is a wooden surface that can take on attractive and complex geometries and is capable of changing shape in response to the environmental stimulus of heat (Figure 10). The composite surface has the ability to be transformed into a variety of curvilinear shapes through the application of heat and pressure, followed by cooling. Upon being heated again in the absence of external pressures, it will rapidly revert to its original shape (within just a few seconds). This composite offers designers an opportunity to re-conceptualize the use of wood in contemporary architecture. As a kinetic and responsive architectural skin this method can allow wooden surface to interact and adapt itself to environmental temperature. It is also possible to ship these composites in flat planar pieces that can efficiently be packed. The flat composites can be formed again effortlessly when is needed in a construction site.

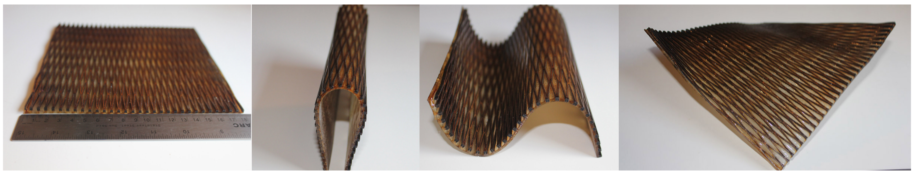

Figure 10. The wood-polymer composite can be used to create a variety of curvilinear surfaces, such as: (a) simple zero curvature surface, (b) Double-curvature surface, and (c) saddle-like surface with negative curvature.

In future projects, we plan to continue the study the composite's performance by using different relief cutting patterns that will encourage alternative curvatures and degrees of flexibility. In addition, however, ongoing work in this area can focus on improving the wood-composite interface, and analyzing the recovery time and temperature range for specific shape deformations. While there is available research literature that discusses the properties of wood and the properties of SMP separately, the mechanical characteristics of this new composite as a whole (which behaves differently from either of its two components) needs further investigation. This investigation will help us to examine the proposed technique for different architectural scales. The inherent brittleness of polymers, for example, often limits their applications, and additional work will need to be carried out to determine if there are similar concerns with the structural properties of this new composite. The relationship between strain on the composite surface and failure/deformation at various temperatures still needs to be evaluated.

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