Chapter 10
Material Driven Adaptive Design Model for Environmentally-Responsive Envelopes

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Abstract This chapter discusses material-driven adaptive design (MDAD) as an emerging interdisciplinary in material science and design disciplines. The authors define MDAD as a design system with a dynamic interrelationship with its environmental context. They evaluate prospects and challenges associated with MDAD, along with some of the shifts in the design model that it necessitates. Examples as research prototypes are provided to demonstrate the potential of integrated development processes that combine materials with geometry. Drawing from their research on the use of shape-memory polymers authors explore the use of "smart" materials in adaptive design to produce self-responsive and flexible surfaces. The design process includes correlating the micro-scale behavior of materials with macro-scale needs in architecture to create surfaces with the ability to change their geometries in response to temperature. This design process can pave a path to move beyond what is currently used as the primary means of adaptation such as complex mechanical systems (sensors, circuitry, motors, etc.) in architecture. Leading toward a more sustainable and more responsive built environment, this approach also can produce synergistic effects by bringing together expertise in two fields of study—design, and materials science—that are currently divided by differences in terminology, methods, and research practices.

Keywords Material driven adaptive design · Smart materials in architectural design · Environmentally responsive architecture · Shape memory behavior · Shape memory polymer

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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_10

10.1 Introduction

This chapter will address the concept of material-driven adaptive design (MDAD) by defining its principles and qualities. To better understand, MDAD and its prospects and challenges design prototypes have been designed fabricated and tested. The first half of the chapter provides a theoretical framework, while the second half presents specific processes and methods to create self-transformable surfaces. These surfaces have the ability to change their geometries in response to temperature.

Adaptive architecture in this study can be defined as constructed geometries that change in response to environmental stimuli. Such adaptive approaches have primarily been used in architectural skins, for example, façade elements that adjust to the position of the sun (Persiani, 2019; Yilmaz, 2017). Similar to biological skins, these surfaces are well-positioned to interact with a changing environment. While often modeled on natural systems, adaptive architecture has primarily used mechanical means (sensors, circuitry, motors, etc.) to respond to environmental changes. In recent years, however, designers have started to consider alternative ways to implement adaptive designs. The current state of the field can be characterized as being in transition from a purely mechanical approach toward more "passive" environmental response strategies, including material-driven adaption (Kretzer & Hovestadt, 2014; Menges, 2015; Hensel et al., 2006).

Advancements in materials science have been crucial for instigating this transition, particularly with the increasing availability and fundamental research into "smart" materials. These materials are designed at a molecular level to respond to environmental stimuli such as moisture, heat, or light by changing their physical qualities (such as form, transparency, or flexibility). Smart materials can offer significant potential advantages in adaptive architecture due to the ability to reduce mechanical components, lower construction and maintenance costs, decrease weight, and improve reliability (Barozzi et al., 2016; Lopez et al., 2015; Menges, 2015). Essentially, molecular properties in these materials can act as a substitute for the more expensive and less reliable sensors, wiring, and actuators that characterize mechanical-based adaptive architecture. New computational design tools are also making an important contribution to this paradigm shift, as readily-available software now allows designers to analyze material performance, simulate material responses to dynamic environmental conditions, and directly control fabrication tools to implement materials-based design solutions (Kretzer, 2016; Lopez et al., 2015; Sunguroğlu Hensel and Vincent, 2016).

As has historically been the case in architecture, these new innovations are being driven not only by new technologies but also by new concepts, most especially in our understandings of nature as a creative inspiration and model for innovation. The concept of the natural world as being composed of static, conflicting, individual components—an outlook that predominated in earlier centuries—has now been replaced by views that emphasize the flexibility and interconnectedness of biological structures. Many of today's adaptive designs are biomimetic—they mirror the functions, and sometimes the design, of biological systems (Kadri, 2012; Persiani, 2019).

For example, Achim Menges referred to the conifer cone and its repetitive opening and closing cycles in response to humidity changes as an inspiration for the adaptive qualities of his "HygroSkin Pavilion" (Menges, 2015). Similarly, Doris Sung's design of "Bloom" was inspired by leaf stomata (Sung, 2012), Skylar Tibbet's and Nery Oxman's projects (Totems, Silk Pavilion for example) mimics natural processes of organic growth and expansion (Tibbits, 2021; Oxman, 2015).

The HygroSkin and Bloom projects mostly make use of materials that have the ability to deform and then return to their original shape when a particular stimulus is applied. These are generally called shape memory materials (SMMs). Like other types of smart materials, their potential applications in architecture are novel, and we are only beginning to explore their potential uses. The Hygroskin Pavilion relies primarily on the hygroscopic behavior of wood, demonstrating that SMMs do not necessarily have to be manufactured in a lab. By carefully designing bi-layer wooden components, Menges was able to take full advantage of wood's tendency to expand when it is wet. Since the expansion of the inner layers is less severe than the outer layers, the overall bi-layer wood material bends in response to changes in humidity (Menges, 2015; Ugolev et al., 1986; Hensel et al., 2006). The more recent direction through which researchers are exploring wood's responsiveness to humidity. In 3D printed wood project Correa and others use 3D-printing technologies to create specially formulated wood–plastic composite materials and direct the response behavior. The 3D-printed composite materials also require a complicated analysis and technological fabrication process to be effective for intended purpose.

The "Bloom" project takes a similar approach to use material for adaptive design. Sung uses metal materials and takes advantage of their different responses to temperature. Using more than 400 parabolic-shaped panels made of laminated sheets of two metals with different coefficients of thermal expansion, the shell "opens" and "closes" in response to the heat produced by direct sunlight (Sung, 2012).

As these examples demonstrate, architects and designers have been experimenting with SMMs for some time. Experiments to precisely measure shape-memory behaviors for specific combinations of materials and architectural geometries are few, and as a result, the prototype structures that have been created are limited in terms of their response time, strength, range of curvature, and ability to repeatedly change shape without incurring damage.

There are significant challenges in this area mainly due to the current disciplinary split that exists between the design field and the materials science field—pedagogies, practices, and research literature in these disciplines are almost entirely separate from one another, which makes it difficult to establish an integrated method or workflow that considers both material design and structural design. Often designers lack even rudimentary knowledge of current research developments in materials science, let alone more sophisticated understandings of current directions in smart-materials research. On the other side of the split, material developers typically study transformations that occur at a scale of one-billionth of a meter. The application of novel materials to solve design problems and the integration of materials with larger structural geometries is often well beyond the research scope of the scientists who create these materials (Kretzer, 2016; Carolina Ramirez-Figueroa & Dade-Robertson, 2013).

To address these challenges, we propose that we recognize a specific research area called “material-driven adaptive design” (MDAD), which will stake out a unique place in the overall architecture and design firmament. MDAD can be considered as a particular process or system for designing, characterized by an integration of materials science research into design process. Designers who take this approach are likely to focus on inspiration from adaptive features found in natural systems that are difficult to mimic in conventional architectural practice, and they will pursue new materials development that can make such functionalities possible in the built environment. They are also likely to emphasize direct involvement of designers in the fabrication process and its parameters. By combining the two fields in this fashion, we can expect a synergistic outcome in which large-scale design needs contribute more strongly and directly to the direction of materials development, and in which a more robust and precise knowledge of new materials informs the possibilities and horizons of design.

10.2 Material Driven Adaptation as a Design System

Adaptive systems are dynamic. This quality may appear self-evident, but when applied to architectural discourses that have long privileged stability, it can entail significant cognitive shifts to perceive the ever-changing building/environment dynamic as intrinsic to design. This section will discuss some notable aspects of that cognitive shift and how they are relevant to materials-oriented thinking. Most importantly, since environmental features are dynamic and often unpredictable, a truly fluid system has better ability to respond to them in real-time. The building skin may need to open or close at varied times or change its transparency or a surface may need to transform to another shape when exposed to a specific level of heat or humidity. MDAD designers must therefore have a detailed and precise knowledge of material response parameters within specific structural geometries, which can be developed through prototyping and tested through empirical experimentations.

10.2.1 Decentralized Control

MDAD thinking diverges from the centralized perspectives of mechanical adaptive systems. Such systems typically operate through the interaction of their three main parts: (a) the sensor, which transmits input data, (b) the controller, which processes the input and selects a structural activation, and (c) the actuator, which generates a change, for example, a physical change in the built environment. This model replicates cognitive decision-making in the biological realm, in which an input is processed the brain, leading to a decisive response action. An MDAD approach is based on a more decentralized or distributed control. The control is based on materials-intrinsic, and usually continuous function of environmental response,

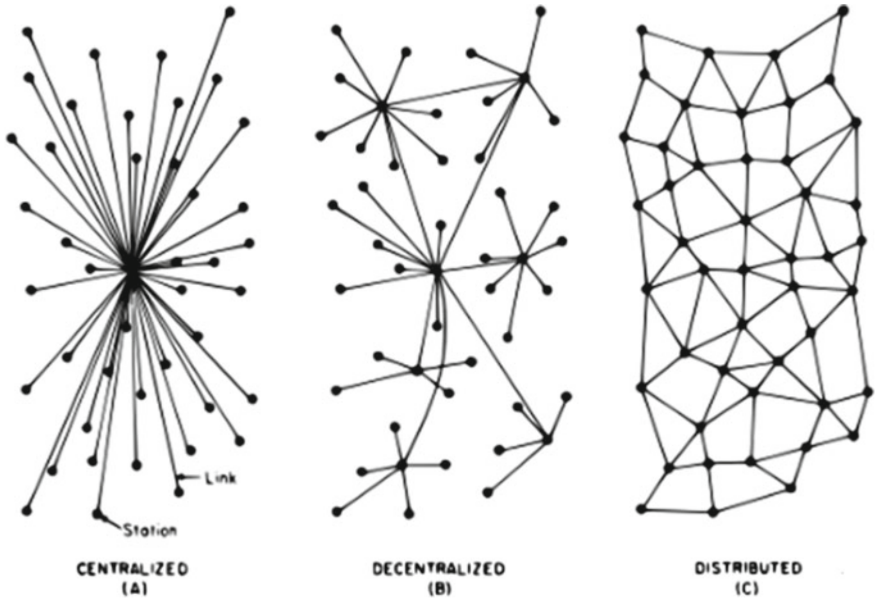

Fig. 10.1 Decentralized control versus Centralized control, illustrated by Paul Baran for network typologies

which can be compared to autonomous biological functions such as sweating in warm temperatures or opening and closing in plant stoma to survive environmental stress. Such intrinsic functions comprise the majority of the ways in which organic materials adapt to environmental changes (Grumezescu, 2016; Rehm, 2013; Tibbits, 2016). Rather than relying on distinct mechanical components and lines of communication between them, the parts of an MDAD system are based on decentralized, self-responsive, and self-sufficient design (Fig. 10.1).

10.2.2 Self-Responsiveness

All biological systems contain self-responsive components, and many parts of the natural world (such as plants) rely exclusively on such responses. A flower may gradually turn to follow the position of the sun; a rise in humidity can trigger pine cones to curl up their scales to prevent ineffective seed dispersal in wet weather. An MDAD approach embraces this model, leading to designs in which materials, structural elements, and/or entire building programs respond to external stimuli in a continuous and dynamic way (Menges, 2015; Hensel et al., 2006). The design process as well as outcomes adjust to accommodate a range of environmental conditions, rather than being bound to the static stand-or-fail dichotomy of unresponsive structures.

10.2.3 Self-Sufficiency

The self-sufficiency of MDAD projects is most notable in terms of energy sources. The adaptations have been defined as "passive" in the sense that they do not or have minimum rely on external energy inputs, beyond what the materials themselves can harness from the immediate environment (Barozzi et al., 2016). Transformations in geometry and other structural characteristics are carried out through internal material reactions (a process of adaptation or self-adjustment), and both the original and altered forms are internally stable.

10.2.4 Micro–macro Effect

The properties of the various materials used in an MDAD project can create a complex, interrelated network that results in overall system-wide behavior. This is often referred to as the micro–macro effect, and it is a vital part of bridging the gap between materials science research and architectural-scale applications. The self-sufficiency of parts and the absence of a top-down governing mechanism in MDAD projects does not mean that the parts operate in isolation from one another. Designers should be aware of this, and they should generally not expect to use smart materials in a monolithic, building-wide fashion. Instead, they should consider the synergies that can be created through the interaction of diverse material components. Like other aspects of the MDAD approach, this can entail significant shifts in perspective as designers learn to think in terms of complex organic development and emergent properties at various scales (Steiner et al., 2020). One strong advantage of this approach is that it can lead to flaw-tolerant designs, in which the system continues to adapt and function even when some individual components become damaged or impaired.

10.2.5 Strength and Flexibility

In architecture, flexibility has often been perceived as disruptive to the strength of a structure and to the designer's control over the behavior of its elements. While architecture often favor impermanence, adjustability, and in some cases transportability in different scales, it is more common to focus only on the rigid structures and define architecture as collections of elements that cannot alter their shape without being destroyed. This continues to be true with mechanical-based adaptive approaches, in which component mobility is obtained through assemblies of rigid parts (hinges, bearings, gears), and in which the failure of a single rigid part can break the entire system. The MDAD approach de-emphasizes rigidity and encourages a productive dialectic between flexible and rigid elements. In other words, while some rigid elements are needed to ensure the stability of the structure, there is less dependency on the survival of such elements. Instead, stability is established through the flexible interconnection of many supporting components, as can be seen in natural phenomena such as wood, bones, shells, and scales.

10.2.6 Free-Form Transformation

Architectural geometries are primarily flat, rectilinear, and orthogonal. There are many reasons for this right-angle-centric design, including the standardization of mass-produced components; ease of shipping, storage, and construction; and simplicity in force calculations. When it comes to adaptive architecture, this has resulted in transformations that are mostly based on the sliding and folding of rectilinear components. However, as Antoni Gaudí famously observed, "there are no straight lines or sharp corners in nature" (Crippa et al., 2003).

Similarly, the transformations that occur in natural structures rarely take place along right-angles but are instead smooth and continuous. Such natural forms and transformations have evolved to be efficient, stable, and resilient, often resulting in various geometries including curved outcomes. MDAD approaches are motivated by similar concerns of efficiency and resilience, and they emphasize materials' capabilities to exhibit smooth and continuous transformation behavior. To better understate the physics and design possibilities of free-form transformation, MDAD designers can benefit from an understanding of curvilinear surfaces and their common techniques in architectural design.

10.3 Experiments

The use of prototyping and scientific experimentation is fundamental in MDAD, as a crucial means of understanding and developing the synergetic relationship between materials and geometry. In our lab we have primarily examined the use of SMMs, focusing on their ability to: (a) respond to environmental changes without using a distinct sensor component, (b) self-adjust into pre-defined forms without the use of an external/artificial energy source, (c) embody both flexibility and strength to produce stable surfaces, and (d) transform geometrically without tearing or cutting. While other adaptive designers have embraced the shape-changing properties of commonly used materials in architecture such as metal or wood, we have focused on exploring the potential of shape-memory polymers (SMPs) that are currently not widely used in architectural research. The research process in our lab begins with tests to evaluate the environmental response properties of a particular SMP when fabricated into specific geometries. We use a variety of fabrication techniques, ranging from conventional SMP mixing and hardening methods to novel 3D-printing approaches. We then evaluate possibilities for combining the SMPs with other materials to create hybrid self-transforming surfaces.

10.3.1 Shape Memory Polymers

There are a variety of shape-memory material options that currently exist, ranging from the aforementioned traditional options of wood and metal to more recently developed shape-memory alloys and polymers. Among these options, SMPs demonstrate the greatest ease of formability and workability, and they are usually lower in cost compared to other shape-changing materials. Another important aspect of SMPs is their ability to readily bond with diverse conventional materials to produce hybrid structures (Wei et al., 1998).

Our investigation into the behavior of SMPs led us to select a temperature-responsive polyurethane epoxy resin-based polymer, which has been widely used as an independent structure, as a coating, and as an adhesive material. Epoxies can effectively bond with other materials as a resin, and the temperature required for stimulating their shape-memory behavior is within the range that we desired. The materials needed to make this type of SMP typically begin their life cycle as liquid mixtures and are solidified through an initial application of heat. This means that they are very easy to shape; the process is pouring the mixture into a mold or applying it with a brush prior to hardening. Once they have gone through the initial hardening process, temperature responsive SMPs remain in a rigid state as long as they are below their “glass transition temperature” (Tg). When the temperature rises above Tg, they become flexible and can be reshaped through the application of force. They then retain the new shape after cooling. However, if the temperature rises above Tg, the material will rapidly self-transform back into its original manufactured shape and no external force is present. Thus, if a flat sheet of SMP is manufactured, it can be heated and pressed into, for example, a double-curved dome shape, and then cooled in order to retain that shape. Reheating the material in the absence of force will lead it to rapidly revert back to its original flat position (Figs. 10.2 and 10.3). These transformations between different shapes can be repeated nearly indefinitely (Wei et al., 1998).

The formula used in the experiments reported here was based on an epoxy called Epon 826, which was mixed with a curing agent (Jeffamine D-230) along with a strengthening agent (neopentyl glycol diglycol ether, NGDE). The general temperature-mediated shape-memory effect of the resulting material has been widely documented in prior materials science literature (Xiao et al., 2012), so we could begin our investigation with confidence that its parameters would be similar to the material effects that we wished to pursue.

The self-transformation properties of this material are a result of a reorientation of the molecular chains in SMP. The Jeffamine D-230 bonds and hardens the epoxy materials to create the shape-memory behavior. The NGDE dilutes the polymer and helps to strengthen it against cracking and brittleness. The relative proportions of these material components in the mixture determine its specific Tg, the extent of flexibility, and other material properties.

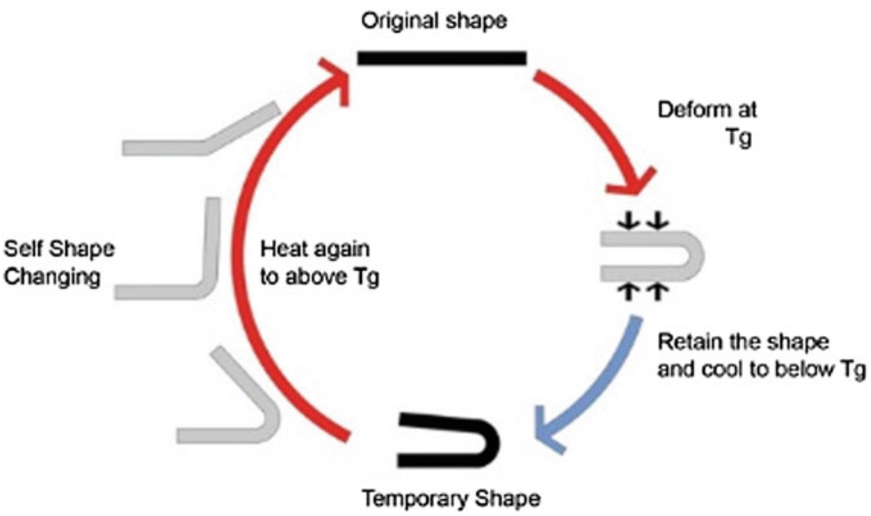

Fig. 10.2 The SMP shape-changing cycle. Illustrated by author

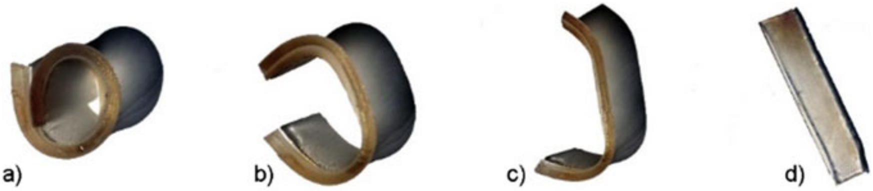

Fig. 10.3 Prototype A:Initial test of SMP responsiveness: **a** the deformed shape of a fabricated sample after applying heat and pressure, and the shape recovery process when re-applying heat for **b** 2 s, **c** 6 s, and **d** 8 s (Mansoori et al., 2019)

10.3.2 Testing SMP Surfaces

Some of our initial experiments and fabrication processes have been discussed at length in our previous publications (Mansoori et al., 2019). In short, to fabricate the SMP surfaces we combined various amounts of the three components in a plastic cup; stirred vigorously with a wooden stick for about 10 s; used a vacuum process during the initial heating to reduce air bubbles; and cured the material in an oven at 100 °C, using a silicone rubber mold to shape the resulting form (Fig. 10.4). For these prototypes, we wanted to achieve a Tg of approximately 40°–60 °C. This range allows the material to remain fully rigid at room temperature, while not requiring overly excessive heating to reach a flexible/shapable state. Tailoring the Tg is vital for design applications, as it directly impacts the range of functional temperatures in accordance with the design goals and the intended operating environment. We tested multiple samples of the polymer to evaluate this behavior, and determined that for

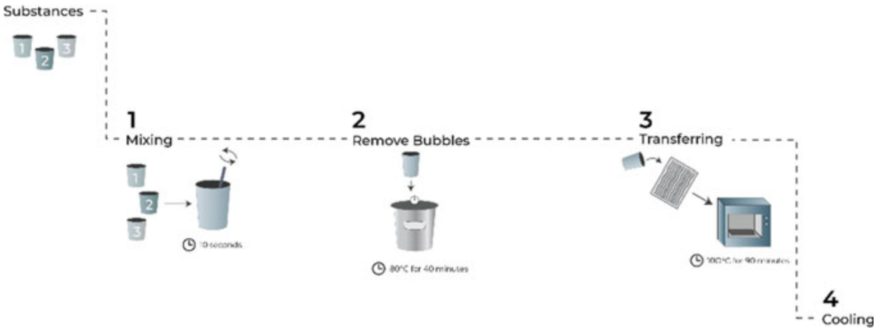

Fig. 10.4 SMP fabrication process in the lab. Illustrated by the author

our purposes a desirable Tg could be obtained with a combination of 1.00 part Epon 826, 0.63 parts Jeffamine D-230, and 0.60 parts NGDE.

The resulting material exhibited full rigidity at 20–25 °C (room temperature), and a significant ability to deform when above 40 °C. To test the shape-memory behavior, a flat sample was heated to 40 °C using a heat-lamp. Pressure was applied to push the sample into a curved shape and hold it in that shape after the heat lamp was removed. After few seconds at room temperature, the composite material cooled sufficiently to become rigid again and retain the new curved form. When once again heated to 40 °C in the absence of force, the material "remembered" its original flat shape and returned to it within 8 s. These initial experiments confirmed the functionality of our material mixture and laid the groundwork for subsequent research into using the SMP as part of hybrid materials and geometric forms.

10.3.3 SMP and EcoFlex Composite

One of our prototyping experiments conducted with the SMP mixture was called "SMP + Flex." In this project we laminated a stretchable silicone material known as "EcoFlex" to a structural framework made of SMP. The goal was to leverage the shape-memory capacities of the composite to produce a surface that could reversibly transform between flat and double-curvature shapes. The stretchable nature of the silicone material allowed it to accommodate these transformations, while the SMP provided the shape-memory effect and room-temperature rigidity.

An Archimedean spiral geometry was used in the SMP to assist the shaping process and encourage a smooth double curvature (Fig. 10.5). This form gives the composite plane surface a desired flexibility and kinematic properties that allow it to transform into a dome-like geometry. The spiral-cut SMP was created first and was placed into a flat mold. The EcoFlex silicone precursors, which also begin in a liquid state, were then mixed together and poured into the mold over the cut SMP. After curing at room temperature for 3 h the composite surface was ready for testing. As we had hoped, the

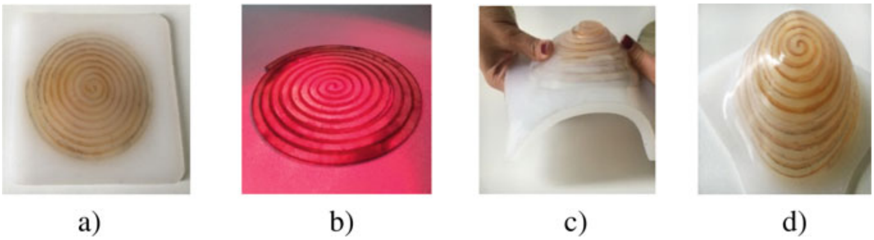

Fig. 10.5. Prototype B. **a** The "SMP + Flex" project began with (**a**) SMP cut into an Archimedean spiral pattern to encourage smooth transitions between flat and dome-like forms. This SMP component was then "cooked into" a surface comprised of EcoFlex silicone. **b** The resulting composite integrated shape-memory behavior into the silicone surface. The composite is in its flexible state when heated above (40 °C). **c** The composite can be deformed to double curvature in its flexible state. **d** The doubled curve surface is cooled and fixed in its new position. The double curvature can self-transform to the flat surface when heated again to (40 °C). We used infra red lamp to heat the surface

inclusion of the SMP base provided greater rigidity to the resulting material at room temperature (compared to EcoFlex alone). The composite regained its full flexibility when the environmental temperature was above the SMP's Tg range (40 °C). In its elastomeric state, force was applied and the material deformed smoothly into a dome geometry. When cooled again to room temperature it retained this shape. It is difficult to fix the composite in its cured position; the material has the tendency to get flat when is heated. After being heated once again to Tg, the composite "remembered" its original flat form and returned to it within 6 s. This cycle could be continuously repeated with no discernable material degradation.

One outcome that we noted in this project was that the stretching of the EcoFlex material in the dome geometry resulted in a latent force that limited the flexibility of the SMP in its glass state. It took additional pressure to form the material into a dome compared to shaping the SMP alone, and the resulting transformation was somewhat less extensive after the material was cooled and the force removed. Correspondingly, however, this latent force resulted in the SMP more quickly returning to its original flat shape when re-heated in the absence of external force. The experiment demonstrated that in pursuing these types of composites, particular attention should be given to the interface regions where the SMP bonds to the silicone material, as this interaction will be very significant in determining the overall geometric properties of the composite as well as being likely points of structural weakness.

10.3.4 Using SMP with Wood Veneers

For this experiment we laminated a veneer made of red oak with a layer of SMP. The veneer, which is often used for patching, repairing, and restoring common items such as doors or shelving, consisted of a very thin (1 mm) sheet of authentic wood.

It is quite flexible and can be readily cut by hand using scissors. The SMP coating was also relatively thin at 0.5 mm for both sides. The combination produced a strong bond, especially in comparison to the SMP–silicone composite from the previous experiment. We heated the wood–SMP composite to Tg (40 °C), and shaped it into a gentle curvature in accordance with the range of flexibility allowed by the wood component (Fig. 10.6).

The hybrid material was quite rigid at room temperature (more so than the wood veneer in isolation, and also more so than the SMP–silicone composite from the previous experiment). Unsurprisingly, the flexibility range of the wood composite at Tg was somewhat less than that of the silicone composite; however the wood was still able to form and hold a significant curvature. No cracking or structural deterioration of the wood veneer was noted after multiple deformation cycles, though this integrity is undoubtedly related to the extent of curvature obtained.

We created two veneer-SMP prototypes. In prototype C-1 the original shape was a flat surface. We used this prototype to test self-transformation from double curved surface to a flat surface. The original shape for in prototype C-2 was double curved surface. The test for this prototype shows how the surface retunes to its curved shape from flat against gravity (Figs. 10.6 and 10.7).

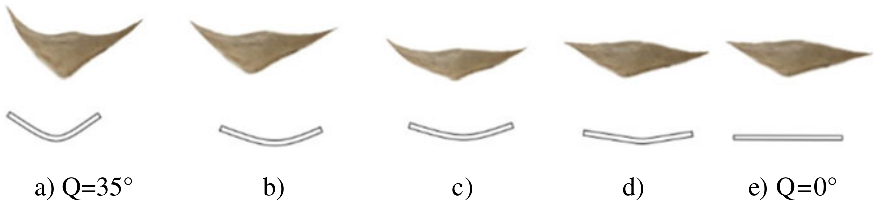

Fig. 10.6 Prototype C-1. Self-transformation from double curved surface ($Q = 35°$) to flat surface ($Q = 0°$). **a** the deformed shape of a composite after applying heat and pressure, the other images show self-transformation to flat surfaces when re-applying heat for **b** 2 s, **c** 4 s, **d** 6 s **e** 7 s

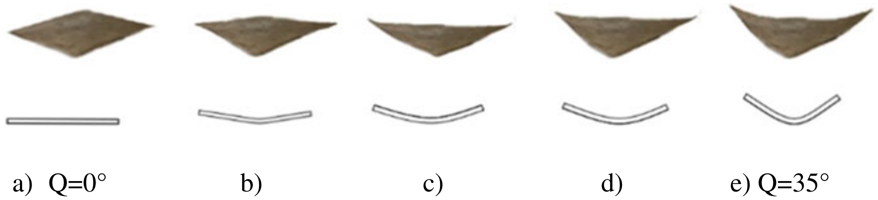

Fig. 10.7 Prototype C-2. Self-transformation flat surface ($Q = 0°$) to curved surface. **a** the flat shape of a composite after applying heat and pressure, the other images show self-transformation to double curvature surfaces when re-applying heat for **b** 2 s, **c** 5 s, **d** 7 s **e** 11 s

10.4 Conclusion

The experiments explained in this chapter were generative exploratory modes of the design process that demonstrate the potential of combining design (in this case, geometry) with materiality. While the study has not exhausted all possibilities but shows how MDAD makes it possible to (1) achieve predefined self-responsiveness without distorting the material, using electrical or mechanical sources, (2) combine contradictory properties of flexibility and rigidity and adopt the combination as an alternative design solution, (3) employ the dynamism in micro-scale to adaptation needed in macro-scale.

We showed how SMP and hybrid materials based on SMP can morph between a flat geometry—useful for ease of manufacturing, shipping, and storage—and curved surfaces, which may be useful in a variety of architectural applications such as shell surfaces. The use of particular SMP, however, was only one of the potential uses of “smart” materials for future adaptive design. More systematic with precise measurements of transformations are needed to continue the research which should address hybrid material and mechanical properties. Other functionalities are increasingly available for integration into our adaptive design repertoire, ranging from two-way polymers to other types of smart materials. While the transformation to the intended form as a result of environmental stimuli, its reversal to the previous condition required external force in our current experiment. Future studies on two-way polymers for example allow us to make the whole cycle automatic. There are tremendous and diverse research opportunities under the MDAD umbrella, particularly when it comes to scaling-up the applications of material-driven design, rigorously measuring the functionality of specific materials/geometry combinations and integrating environmental changes into design.

The MDAD approach can serve as a means for facilitating knowledge-transfer between the materials science and design disciplines. To embrace this process, architects and designers must recognize that it will entail adjustments to our established research and design practices which might need shifting toward different design processes such as an open-ended paradigm of prototyping and testing: the design process to include innovative ways not only form or the material but their behavior.

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