Exploring the Impact of Geometry and Fibre Arrangements on Daylight Control in Bistable Kinetic Shades

Elena Vazquez *[1,2], **Jose Duarte** [1]

* Corresponding author
1 The Pennsylvania State University, Department of Architecture, United States of America
2 University of North Carolina at Charlotte, School of Architecture, United States of America, e.vazquez@uncc.edu

Abstract

Bistable laminates are composite structures that exhibit more than one static configuration, showing a "snap-through" behaviour that results from residual stresses generated during the curing process. This study focuses on finding adequate fibre and laminate arrangements for bistable laminates used in functional kinetic shadings. We present a study with a mixed-methods approach, combining experimental prototyping and performance simulation studies. We fabricated and analysed the geometry of a series of prototypes, conducting daylight studies to assess the performance of different laminates and fibre arrangements and showing how specific fibre arrangements can help control daylight throughout the day. We concluded that controlling fibre arrangements of bistable laminates could increase the functionality of bistable kinetic shadings in terms of daylight control, leading to more differentiated shapes between their two stable states, which corresponds to the open and closed positions of the shadings. Increasing such a difference increases the range of system configurations and, therefore, the ability to respond to various external lighting conditions and internal user requirements.

Keywords

kinetic architecture, bistability, snap-through, carbon-fibre laminates, kinetic shading

DOI

http://doi.org/10.47982/jfde.2022.1.03

1 INTRODUCTION

In recent years, there has been an increasing interest in designing more efficient building envelopes. Kinetic shadings adjust their configuration to shifting environmental conditions, thereby improving a building's environmental performance (Fiorito et al., 2016). There are several ways to describe kinetic systems like the one described in this research, including terms such as Adaptive Envelopes and Climate Adaptive F s (Barozzi et al., 2016; Juaristi et al., 2018). For this study, kinetic shades are defined as solar-shading elements that can change their shape configuration. Daylight control is critical for designing energy-efficient buildings, which can be regulated with kinetic shading structures. One of the main obstacles to developing kinetic shading systems is the cost of production and maintenance of sophisticated mechanical systems that these have traditionally relied upon. In this context, bistability—a phenomenon observed in daily life in snap bracelets and measuring tapes—can be considered a promising approach to designing lightweight kinetic shape-morphing shading devices. However, little is known about incorporating bistable laminates in shading devices; therefore, we must first investigate what suitable shapes and forms can be obtained with bistable laminates for functional kinetic shades.

The use of bistable laminates as shape-morphing structures has attracted researchers' attention because they do not require continuous power to remain in either of their states (Emam & Inman, 2015). These laminates can keep their static(s) configuration(s) and transition on demand by supplying a small external force as needed. Bistability has been implemented in shape-morphing structures for multiple functionalities. Still, it has yet to be studied in architectural design as a potential strategy that can be used for developing kinetic façades. An architectural application of such laminates requires the design and study of prototypes with shapes and dimensions suitable for use at the building scale, the analysis of their shape-morphing range and their usefulness for daylight control, and the optimization of their configuration. Bistable systems could be used for automated kinetic systems where the user does not need to operate the shading device, which is particularly important for spaces with multiple users. They could also provide a wide variety of design forms and shapes and increase the granularity of shading devices. This study is motivated by the desire to attend to both performance needs (daylight control) and design needs (aesthetics, flexibility).

The research described in this article is part of a larger research agenda, the goal of which is the design and fabrication of kinetic shading screens that can increase the control of daylight being captured and filtered to interior spaces. This research includes several steps: (1) to identify adequate design forms for bistable laminates used in a kinetic screen, (2) to study suitable actuation mechanisms for bistable laminates using smart materials, and (3) to assess the performance of a bistable kinetic screen in a full-scale test. This paper is focused on the first step, whose goal is to identify configurations of the bistable flaps used in the shading screen with an increased difference between the open and closed positions to improve the capacity of the screen to control the filtering of daylight. In this step of the research, the only performance metric was light intensity. Future steps of the research will be concerned with activating the bistable laminates using smart materials, including glare as an additional lighting requirement, and optimizing daylight capture, considering the lighting requirements for the activities assigned to the space.

This study focuses on finding adequate fibre and laminate arrangements for bistable laminates used in functional kinetic shadings with a mixed-methods approach that combines experimental prototyping and performance simulation studies. In the first step, a set of bistable laminate designs are compared in terms of their curvature and impact on light capture performance, considering a north-facing façade orientation, where diffuse light is prevalent. After this initial evaluation, the selected bistable laminate is used to explore the effects of changing fibre orientation to achieve material configurations that permit increased control over how sunlight enters the building. We show how prototypes with the same base geometry but different fibre arrangements could help maintain a daylight performance target throughout the day. The study shows the potential of bistable systems as an alternative to current shading solutions, showing possible shapes and opening patterns, and manipulating fibre arrangements to control curvature deflections, thereby diversifying kinetic shade design.

2 BACKGROUND

2.1 KINETIC BUILDING ENVELOPES

Kinetic or dynamic building envelopes are hardly a new concept in architectural design, albeit few built examples exist worldwide. Unlike kinetic devices in aviation or automotive industries, Kinetic systems in architecture are usually custom-designed and manufactured for every application, making them very costly. Some well-known icons of kinetic façades are the Institute du Monde Arabe (1987) and the Al-Bahr tower in Abu Dhabi (2012). Barozzi et al. (2016) present a review of several built examples of kinetic façades, classifying the different design approaches based on case studies. Researchers have also sought to characterize kinetic systems' performance by developing building performance simulation workflows that can potentially inform the design of such façades (Loonen et al., 2017)while maintaining high levels of indoor environmental quality. The development of such innovative materials and technologies, as well as their real-world implementation, can be enhanced with the use of building performance simulation (BPS. However, the current trend is to create kinetic systems that do not require mechanical actuation (Fiorito et al., 2016; Yi & Kim, 2021). Research in this area has sought to develop shape-changing mechanisms and study how smart materials can actuate such mechanisms. This paper focuses on finding adequate shape-changing forms of bistable composite laminates for kinetic façades, which can be used in combination with smart materials for actuation. A few studies have focused on developing shape-changing forms, for instance, Flectofin®, an elastic mechanism developed for façade shading systems inspired by the movement of plants (Lienhard et al., 2011).

In addition, there has been increasing interest over the past two decades in developing kinetic systems using smart materials. Recent advances in smart materials and methods have allowed designers to envision lighter and more efficient shape-changing façades that can change according to existing environmental conditions (Addington & Schodek, 2005). A recent review (Vazquez, Duarte, & Randall, 2019) identified different design and fabrication strategies used by researchers and designers over the past twenty years to develop kinetic envelopes using smart materials. There are two main strategies for incorporating smart materials into kinetic façades: passive and active actuation. In passive actuation, kinetic systems rely on changing environmental conditions to change shape, for instance, hygromorphic wood structures (Wood et al., 2016; Vazquez, Gürsoy, & Duarte, 2019), and structures made with thermo-bimetals (Sung, 2016), or Shape Memory Alloys (Denz et al., 2021; Sigmund, 2016). In active actuation, kinetic systems can be activated on demand, for instance, in designs with electroactive materials (Kretzer & Rossi, 2012) or with shape memory alloys activated with joule heating (Khoo, Salim, & Burry, 2012). While passive systems can be highly advantageous, relying only on shifting temperature and humidity to change their shape, active systems are preferred when the system's on-demand user control is required, or specific performance metrics are needed. We argue that bistable composite laminates can be used in combination with smart materials with on-demand actuation to develop novel kinetic architectural façade systems. While actuation is not the focus of this study, a basic diagram of the proposed system is shown in the Conclusions section of the paper. Combining bistable mechanisms with smart materials for shape transformation is not new in fields other than architectural design, as will be discussed in the next section.

2.2 BISTABLE SHAPE-CHANGING SYSTEMS

Bistable mechanisms exhibit more than one static configuration and are a well-established research area with over thirty years of development (Emam & Inman, 2015). Current research trends focus on developing applications for such structures, both for actuation and energy harvesting functionalities. As actuators, studies include morphing aircraft structures (Mattioni et al., 2008) and wind turbine blades (Lachenal, Daynes, & Weaver 2013), allowing them to change shape according to operational or environmental requirements. Thin asymmetric laminates—used in this study—are a bistable mechanism that can assume large deflections from one static configuration to another with only a small input of energy (Emam & Inman, 2015). The low energy use and substantial shape transformation make them particularly promising for architectural applications, where energy efficiency is critical. Table 1 compares measured values for critical loads needed to transition between stable states. These values were obtained through experimental and modelling studies. While critical force values depend on boundary conditions, they estimate the required force to transition between states. The results confirm the practicality of combining bistable carbon fibre laminates with smart materials as actuators for kinetic shading systems. The critical loads are very low (~0.4 N) for the type of carbon-epoxy prepregs utilized in this study. To transition from one state to another, researchers have studied the use of smart materials such as piezoelectrics (PZT) and other smart materials (Schultz & Hyer, 2003). As an example, a study by Kim et al. (2010) presented a flytrap robot combining bistable laminates and shape memory alloy (SMA) springs. Together, these studies indicate two main characteristics of bistable laminates that make them appealing for building applications: a large shape-morphing motion and low energy requirements to snap through different stages.

TABLE 1 Critical force to allow snap-through of bistable laminates

BISTABLE LAMINATE MATERIAL	CRITICAL FORCE – N	SIZE	REFERENCE	NOTE
Carbon-epoxy prepregs	~0.4 N	Modules of 130 x 62 mm	(Lele et al., 2019)	0.075mm thick
Carbon-epoxy prepregs	5.8 N	120x100 mm	(Cantera et al., 2015)	0.44 mm thick
Graphite-epoxy prepreg	2.37 N	152.4 x 152.4 mm	(Tawfik et al., 2007)	0.1 mm thick. The critical force depends on the aspect ratio

Instability is not typically the desired feature in architectural design, primarily associated with structural malfunctions. Nevertheless, some studies utilize bistable principles in designing kinetic architectural elements. Seminal research in the area is the work of Song et al. (2018), who presented a prototype for a snapping façade that exploits instability for a shading device.

The bistable components utilized are snapping beams that offer a mechanical behaviour similar to elastic springs. Polyester membranes are then attached to the snapping beams with a Miura-ori folding pattern, and the device is designed to be operated manually. In a similar approach, Vander Werf (2009) developed a shading system using snapping beams made with carbon fibre plastics, covered with a textile membrane, and actuated with a metallic coil actuated with heat. Both studies rely on snapping beams and secondary materials to develop kinetic shades successfully, demonstrating the potential of using bistability as a design principle for kinetic architecture. Researchers, however, have not yet considered the use of another type of bistable element, bistable laminates, as a material for kinetic architecture. As opposed to bistable beams, bistable laminates present two stable states in the form of surfaces, which can be used as the skin itself in kinetic architecture applications. We argue that bistable laminates—which remain virtually unexplored in architecture—present significant potential for developing kinetic shading systems. Figure 1 shows the schematics of bistable laminates in two stable cylindrical shapes and a diagram showing the potential energy of bistable systems, which have two zero energy states corresponding to the stable shapes.

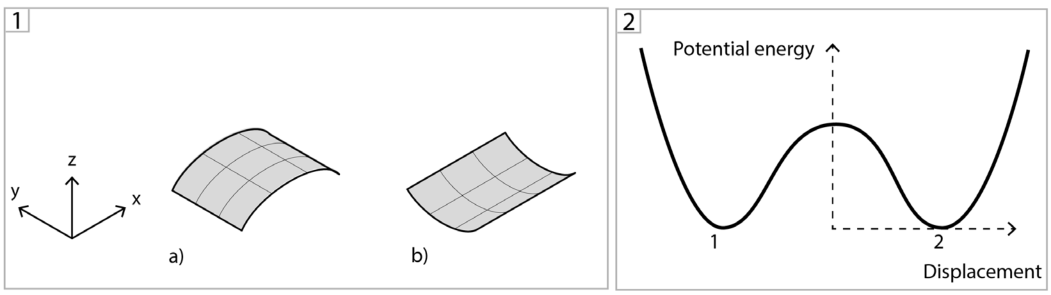

FIG. 1 The two stable states of a bistable composite laminate 2) a diagram depicting the potential energy of bistable systems, redrawn from Noh et al. (2021).

The bistable carbon fibre laminates in this study are fabricated following the method described by Yang et al. (2018) using prepreg carbon fibre sheets and a three-step process are summarized as follows. The first step is freezing and cutting, in which the carbon fibre prepregs are cooled in a freezer to ~0°C and then cut into the desired shapes. The freezing step avoids putting any additional stress on the samples. The next step is to layer the composites and assemble them in a vacuum bag. Two consecutive layers of carbon fibre prepregs are placed on an aluminium plate covered with mould release wax. These layers have fibre arrangements orthogonal to each other, i.e., 90°-180°, 45°-135°, and so on. A layer of perforated plastic sheet, followed by a polyester sheet and a breather fabric layer, goes on top of the uncured carbon prepregs. A vacuum bag film seals all the layers and is fixed to the aluminium plate with high-temperature tape. The entire package is vacuumed using a vacuum pump that is turned on during the whole curing process. The bag is then placed in the oven at 135°C for one hour, then slowly cooled down by turning off the oven until it reaches room temperature. When taken out of the vacuum bag, the prototypes are already settled in one of their two stable states. The authors explain that the prototypes' heating up and cooling down creates internal thermal stresses that generate the laminates' bistable behaviour.

2.3 DAYLIGHT PERFORMANCE AND KINETIC BUILDING SHADES.

Shading devices significantly impact both energy consumption and daylight performance of internal building spaces (Bellia et al., 2014). Static shades, however, present some limitations in terms of daylight and thermal performance in that they cannot adjust to shifting environmental conditions (Al-Masrani et al., 2018). Researchers have recently investigated the potential of kinetic shades in improving daylight performance, radiation, and even natural ventilation (Vazquez et al., 2019). This study focuses on daylight control because it is one of the main performance aspects that can be improved with kinetic shades. In a review by Al-Masrani & Al-Obaidi (2019), eleven out of the twenty studies were concerned with kinetic screen's daylight performance. Therefore, this study adds to the growing body of literature on kinetic building shades interested in daylight performance, with a focus on bistable elements. The study forms part of a larger research agenda aimed at characterizing the performance of bistable kinetic screens, addressing daylight performance in this first step.

3 METHODS AND MATERIALS

In recent studies, researchers have used experimental methods to develop kinetic façade systems, relying mostly on prototyping and testing cycles, aided by digital design and fabrication strategies. Ahlquist et al. (2013) characterize this research model as a material-centred approach, where a sequence of experimentations in increasing levels of complexity inform the introduction of new engineered materials into architectural design. Research into new materials in architecture has mostly relied on such experimental inquiry models. For example, Yoon (2019) develops kinetic façades using shape memory polymers by proposing design solutions and evaluating them through fabrication and performance simulation. Similarly, Sung (2016) argues that her research into smart materials for responsive shading is at the middle point between "scientific reduction and aesthetic expression."

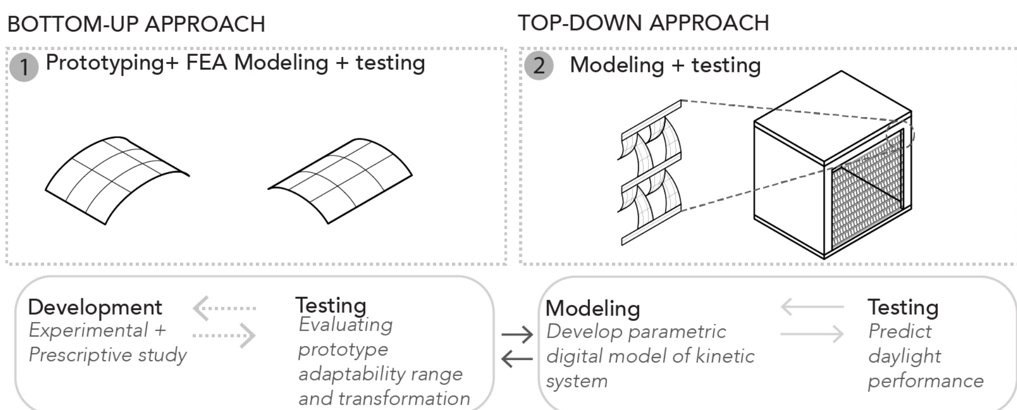

FIG. 2 Methods: A combined bottom-up and top-down approach. The bottom-up approach combines FEA modelling and testing. The obtained forms are then used in the top-down approach to conduct daylight studies.

This research adopts a mixed-methods approach that combines experiments and simulation studies. The methodology implemented is summarized in Figure 2. A bottom-up approach is concerned with prototyping at a smaller scale and evaluating the resulting deflection by measuring physical prototypes and comparing them to FEA modelling results. From the bottom-up explorations, we obtain the geometry of the two stable states. These geometries are tested later in the top-down approach. The iterative development and analysis of prototypes permit the selection of promising configurations. A complementary top-down approach simulates the performance of the fabricated prototypes in terms of daylight. We developed a digital model of the kinetic system to assess the performance and defined a test room for conducting digital simulation studies. From the top-down approach, we obtain daylight performance data. Combining these two approaches aims to find adequate shapes and configurations for bistable laminates that enhance their performance as architectural elements. The prototypes are evaluated on their potential as architectural elements and ranked according to a design decision matrix. The most promising solutions then enter the subsequent rounds of prototyping and simulation studies.

In terms of digital simulations, we developed two different models: a daylight model that simulates the performance of the bistable shading device and an FEA model that simulates the cured state of bistable laminates. The daylight model was developed using the DIVA plugin for Grasshopper, which relies on Radiance as the simulation engine. The simulation was conducted in Rhinoceros. The FEA model was developed in ABAQUS, using the thick shell element SR4. The model uses the Standard/Explicit model, where the geometry is defined as a composite laminate of two plies of 0.12 mm thickness placed at 90 degrees from each other. The development of the FEA model includes two steps. First, defining the mesh geometry of the shell, identifying the composite layup, and setting the boundary conditions —for this experiment, the composite is fixed at the geometric centre, and second, establishing a temperature field to simulate the uniform heating of the samples followed by the cooling down of the samples. The nonlinear behaviour that results in the accurate cylinder shapes instead of saddle shapes (Schultz & Hyer, 2003) is implemented in the model with the NIgeom function. For further details on the FEA model, readers can refer to Pirrera et al. (2010).

In addition, the main material used in the experimental component of this study is the prepreg carbon fibre sheets, which were obtained from Rockwest composites. The prepregs utilized are 0.11684 mm thick with standard modulus and a unidirectional fibre arrangement. Table 2 lists the material properties of the carbon fibre prepregs. Figure 3 shows photos of the fabrication process, including layering carbon fibre prepregs and curing them in the oven under a vacuum.

TABLE 2 Material properties of the carbon fibre prepregs

PROPERTY	VALUE	PROPERTY	VALUE
Thickness	0.11684 mm	Epoxy	Newport 301
Pattern	Unidirectional	Curing temperature	250-300°F
Material	Standard Modulus Carbon (Graftil TR50S)	Tensile strength (0-90) Tensile modulus (0-90)	2950 MPa-79MPa 142 GPa-9GPa

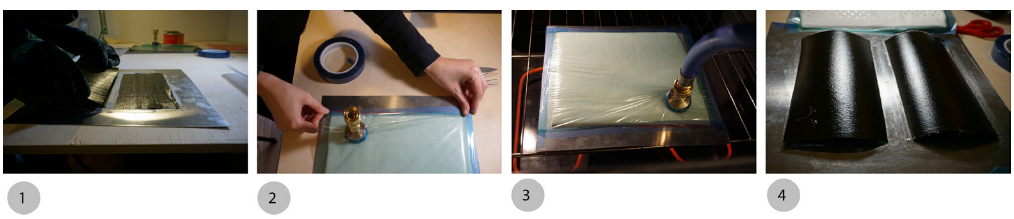

FIG. 3 Fabrication process. From left to right: 1) Placing the two layers of prepreg carbon fibres, 2) arranging the vacuum bag, 3) curing process in the oven, 4) prototypes after cooled in one of the stable states.

Numerous variables need to be considered in the design and fabrication of bistable composite laminates: fabrication variables, material variables, actuation variables, and design variables (Figure 4). Fabrication variables describe the manufacturing conditions, i.e., curing temperature and time, vacuum strength, and so on. Material variables relate to the carbon fibre properties and the resin utilized to layer the laminates. This study uses thin prepreg carbon fibre sheets to achieve a very lightweight structure that does not require much force to transition between states (the thicker the material, the more strength required to change states). Actuation variables refer to the snapping conditions that make the prototypes transition from one state to another. This study focuses only on two bistable laminates' design variables, the geometry of the composite and fibre arrangement, to determine the configurations that lead to their increased daylight functionality as part of a kinetic architectural shading device through experimental prototyping and daylight performance evaluation. These variables are selected because we hypothesize that these could significantly impact the daylight performance of the kinetic bistable screen. As such, the composites' shape and size are considered to determine how different shapes translate into different shading configurations. The fibre arrangement is also considered to explore its potential to enlarge the dynamic systems design's solution space by systematically changing the fibre angle of the prototypes. The layer order is not considered since a preliminary study did not show any significant statistical difference in the resulting bistable states' average curvature when changing the layer order in the prototypes. Layer count is also not considered since the goal is to have thin laminates with only two layers, since increasing the number of layers would decrease the curvature of the two stable states.

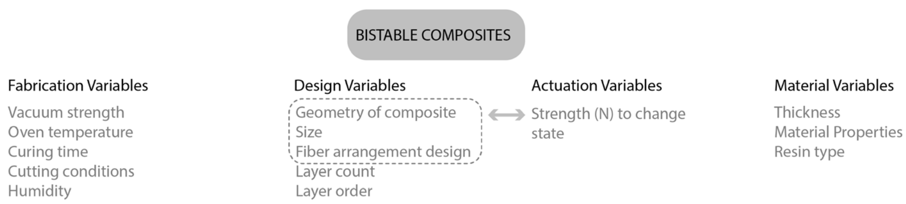

FIG. 4 Bistable laminate variables. The design variables considered for this study are highlighted.

4 RESULTS

4.1 DESIGN AND FABRICATION OF PROTOTYPES

The first set of prototypes was aimed at exploring different kinetic shading designs that could be constructed with three basic units: a rectangle (w, l), a triangle (b, h, a°), and a trapezoid (b1, b2, h). These initial shapes were defined through preliminary design exploration, following examples of other shape-changing architectural skins that rely on quadrilateral shapes (Worre Foged & Pasold, 2015) and triangles (Correa et al., 2015). The quadrilateral shapes also remain inside the 1-3 aspect ratio, over which Tawfik et al. (2007) found that shapes cannot go back to their original position. Figure 5 shows geometric designs A, B, and C, —whose basic shapes are a rectangle, triangle, and trapezoid, respectively, their predicted 'open' and 'closed' positions, and design ideas for overall configuration options. Note that the two stable states are named 'open' and 'closed' due to the predicted morphology that these will adopt. The open state is when the laminates k curvature is transversal to the prototype's longest side, and the closed state is when the laminates k2 curvature is parallel to the longest side. The overall configuration options are shown with their parameters, which can be adjusted according to specific design requirements on a case-by-case basis. Although many other arrangements exist, two possible design configurations are displayed for each prototype. As this study is not focused on the overall configuration design, these are shown to illustrate the potential to create various bistable screen designs from the three basic shapes considered in the study.

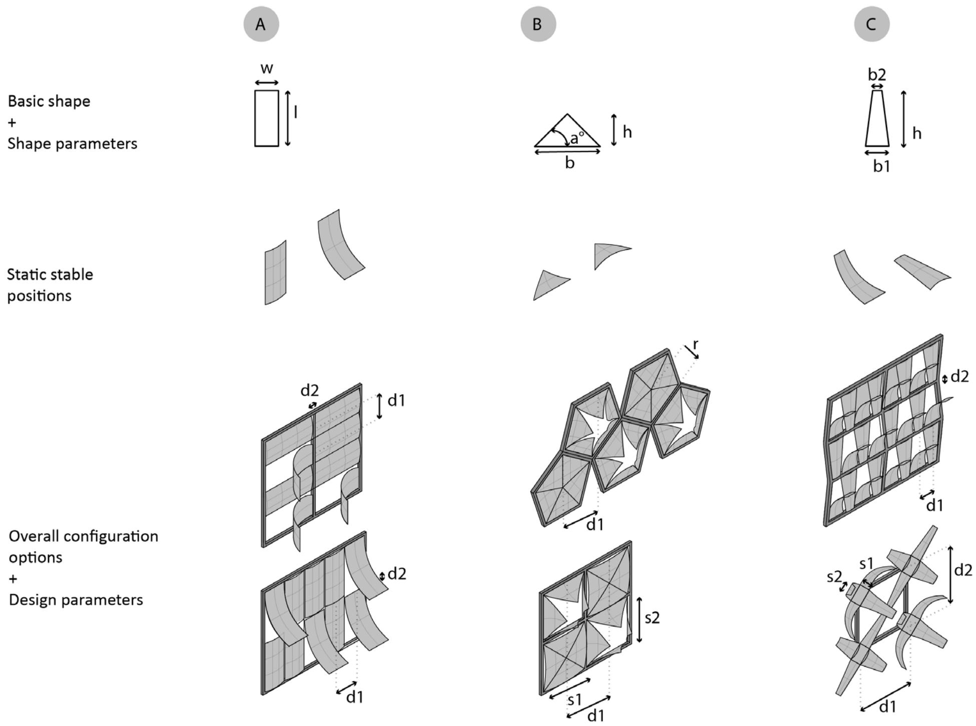

FIG. 5 Designs with basic shape, predicted open and closed positions, and overall configuration options

The three basic prototypes A, B, and C, were fabricated using the manufacturing method described in the previous section. In the initial prototypes, the dimensions were as follows: prototype A, w=7.62 cm l=15.24 cm; prototype B, b=30.5 cm h=15.24 cm a°=45°; and prototype C, b1= 7.62 cm, b2=3.81 cm and h= 15.24 cm. All the prototypes had a 0-90° fibre angle arrangement parallel to the lines that conform to the basic shapes. In prototype A, the two layers had the carbon fibres aligned with the width and length of the rectangle, the triangle had the fibres aligned to its base and height, and the trapezoid had the prepreg fibres aligned with its base and height. After the layering, curing, and cooling procedures, the prototypes were 3D scanned with a 3D Systems SENSE scanner. After scanning the prototypes, the resulting meshes were edited, and the surface was rebuilt to simplify the geometry and obtain the curvature k values. The modelling of the two bistable positions also allowed us to determine the adaptability range of each prototype.

Figure 6 shows the fabricated prototypes and the scanned surfaces corresponding to their open and closed positions. In Figure 6-1, we overlaid pictures of the two positions. Note that in prototype B the two positions are not significantly different. Furthermore, the most significant curvature k is parallel to the longest side, resulting in a configuration different from that initially anticipated, drawn, and shown in Figure 5. Results show that the height must be longer than the base to obtain a unit with a more significant curvature k, parallel to the triangle's height, provided all other variables remain unchanged. In prototypes A and C, the open position is also the one with curvature k parallel to the longest side. However, unlike in prototype B, the difference between the two positions is such that it would work for a shading device, as shown in Figure 6-1. Figure 6-3 compares the FEA model with the 3d scanned prototype. The curvature values from both are within a 10% difference, which can be considered acceptable. The FEA model is used in this study to predict the cured state of different bistable laminates and analyse the deflection shape and curvature of the built prototypes. The FEA model also provides the digital models of the prototypes used in the simulation studies.

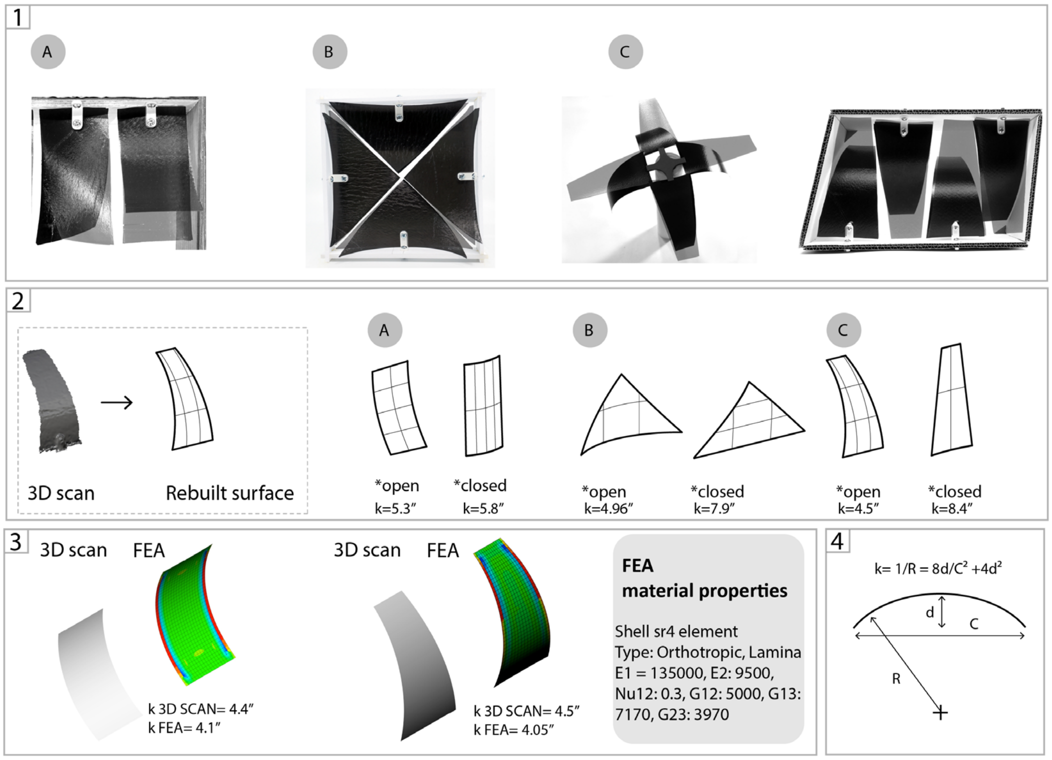

FIG. 6 Prototype fabrication with different geometries. 1) Built prototypes 2) Scanned and rebuilt surfaces with curvature value. 3) Compared curvature values from 3d scans and the FEA model. 4) Curvature formula.

The second set of studies aimed to assess the impact of changing the fibre arrangement on the prototypes. Changing the fibre arrangement made it possible to obtain two stable states that enhanced the units' potential use as shading devices, enriching the design space, and thereby increasing the possibility of achieving aesthetically pleasing architectural skins. The fibres were angled 45-135° with respect to the main lines used to construct the rectangle, triangle, and trapezoid. The manufacturing process mainly remained the same, except that the prototypes needed to be cut with particular attention given to the fibre orientation. The layer order, in which the 45° or 135° carbon fibre laminates are placed first on the aluminium plate, did not seem to affect the stable states' resulting curvature.

Figure 7 shows the prototypes fabricated with a 45-135° fibre arrangement; 7-1 shows the prototypes in their two stable positions by overlaying two photos; and 7-2 shows the scanned and rebuilt digital prototypes. All three basic shapes—rectangle, triangle, and trapezoid—were fabricated with the same initial measurements. The prototypes were also scanned, and the geometries were rebuilt to obtain the curvature k values and study the adaptability range of both stable states. One main difference in this set of prototypes is that instead of having 'open' and 'closed' positions, the stable states can be characterized as position one and position two due to their present geometry, as depicted in Figure 7-2. As seen in Figure 7-1, the two states for Prototypes A and C are distinct and appear promising for a shading device design since they could direct sunlight in two different directions. This hypothesis is tested in the next section of this paper. On the other hand, Prototype B with the 45-135° fibre arrangement does not present distinct positions in its two stable states. Modifying the triangle's boundary condition could yield better results for skin design.

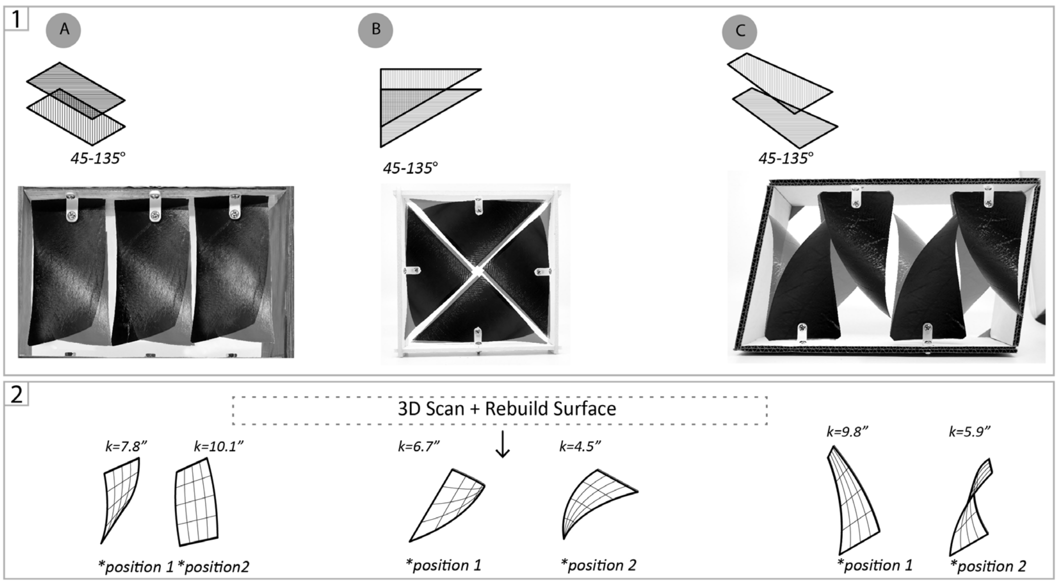

FIG. 7 Prototype fabrication with changing fibre arrangement 45-135°

4.2 DAYLIGHT PERFORMANCE EVALUATION OF FABRICATED PROTOTYPES

As mentioned before, this study combines bottom-up experimental prototyping with top-down studies to simulate the performance of the kinetic shading systems and assess their functionality as environmental control elements. The prototypes described in the previous section were scanned and rebuilt in modelling software. To evaluate the different prototypes' performance, we developed a digital model of the kinetic system and defined a simple test room to perform daylight simulation studies. This study aims to measure the amount of daylight that enters a test room in the screen's open and closed positions. For this study, a larger difference in daylight performance between open and closed positions is better, since this would provide a broader range for daylight needs. In contrast, if there is not much of a difference between the open and closed positions, the kinetic screen is not functional for the purpose of this study. The test room measures 2.1 x 2.5 m, and has a large window opening of 1.7 x 1.86 m. The shading screen is placed 12.7 cm behind the window's glass pane to avoid the bistable flaps colliding with the glass facing north. North-facing windows in the northern hemisphere receive little direct sunlight, so we selected this orientation for the study: To assess the difference between daylight with the screens in their all open and all closed positions. Details of the materials and enclosure are shown in Figure 8-3.

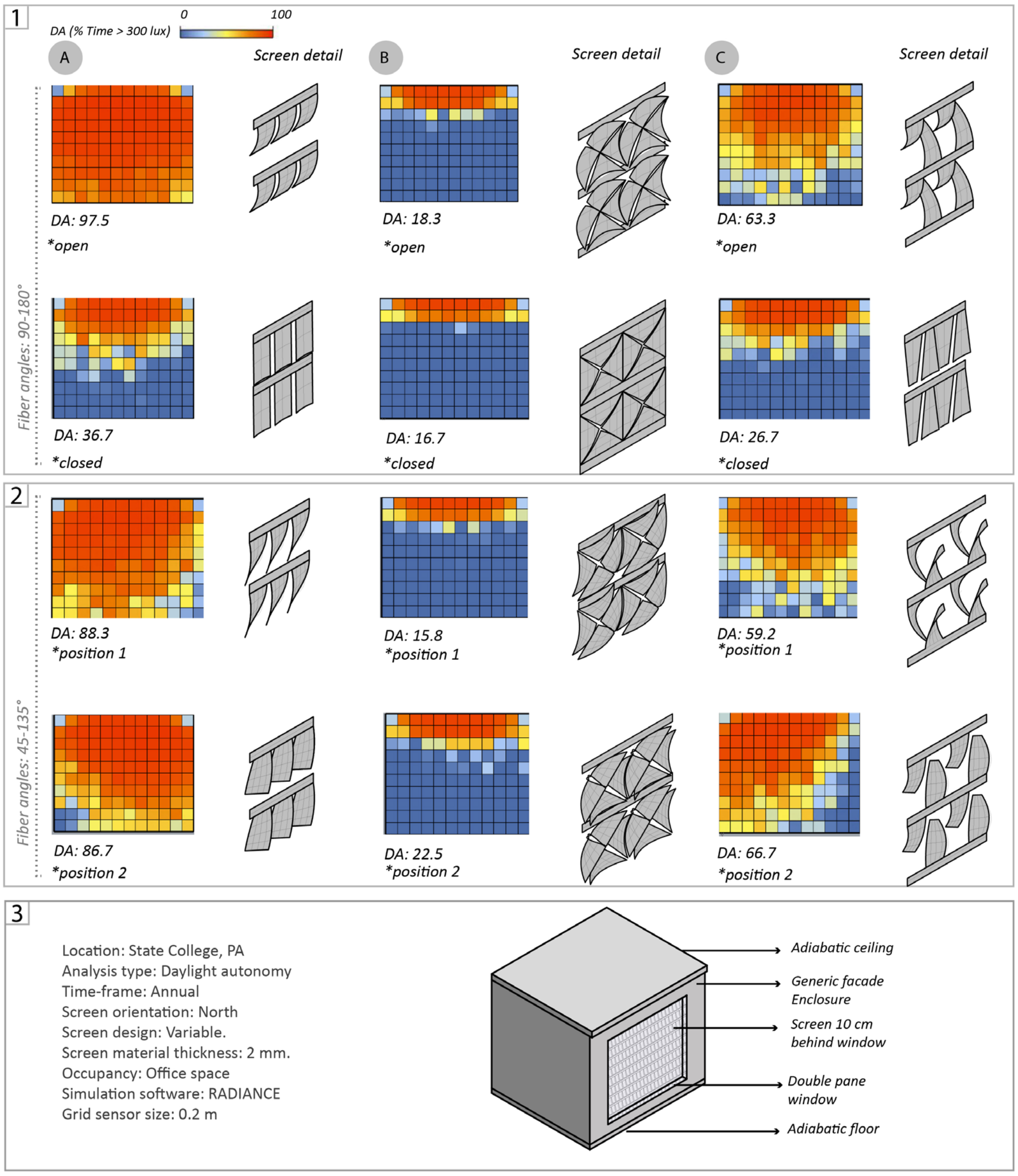

FIG. 8 Daylight simulation studies

Prototypes A, B, and C were simulated with two different fibre arrangements, 90-180°, and 45-135°. Again, it is noted that only prototypes with a 90-180° fibre arrangement have differentiated 'open' and 'closed' positions. Annual daylight autonomy analysis studies were conducted for State College, PA, to compare the screen's performance in its two stable states. The main advantage of kinetic shape-morphing systems is that each unit that forms the screen can adopt different positions during the day to achieve enhanced environmental performance. However, in this first set of simulations, the shading screen was assumed to remain stable for the entire year. This is because this study's goal was to assess where there was a significant difference in daylight performance when the prototypes were in one stable state versus the other, i.e., when screens are open versus closed, position one versus position two. With the second set of simulation studies, we aimed to find optimal screen configurations and states for achieving specific daylight targets throughout the day.

Figure 8-1 shows daylight simulation results for designs with a 90-180° fibre arrangement. Notice how Prototypes A and C present distinct daylight performances in their open and closed positions, decreasing from ~98 % to 36% and from ~63% to 27% daylight autonomy. This result indicates that the two stable states of the bistable laminates are enough to impact daylight performance significantly and could be manipulated to achieve specific daylight requirements. On the other hand, Prototype B does not present significantly different daylight values for its two stable states, changing only from ~18 to 17% annual daylight autonomy. This result indicates that these prototypes need to be redesigned to increase the design's adaptability range and utilize them as units in a functional shading device. Figure 8-2 shows the simulation results of prototypes with a 45-135° fibre arrangement. Visual inspection of the daylight results shows that screen designs A and C direct daylight to either the right or left sides of the room, having distinct daylight performances. Although these results concern annual daylight values, they show the potential of designing different fibre arrangements of bistable laminates to achieve specific functional requirements, such as regulating daylight throughout the day. Prototype B, however, does not show distinct performance metrics for the two stable states. As mentioned above, the basic unit's proportions and design could be rethought to enhance its functionality as a shading device unit in terms of its potential for daylight control.

4.3 RANKING DESIGNS

The results from the experimental prototyping and simulation studies discussed above presented different criteria for evaluating the designs and selecting the most promising ones regarding their functionality as shading screens. While daylight performance was limited in scope, it indicates how distinct the performance that the two states of the prototypes generate is. Prototypes A, B, and C were evaluated according to the following criteria in a design decision matrix shown in Figure 9: 1) ability to easily maintain two states; 2) adaptability range; 3) adaptability range with other fibre arrangements; and 4) daylight performance in different states. The design decision matrix compares design alternatives from multiple points of view, where each attribute is assigned a score based on the scale. The prototypes' ability to maintain their two states was assessed empirically by handling the prototypes and referring to the amount of force needed to transition from one state to another. Since these prototypes are asymmetric, i.e., have one side longer than the other, the stresses in one direction are not the same as the other direction's stresses. Therefore, more considerable forces are needed to transition from position 1 to position 2 than from position 2 to position 1—position 1 being the one in which the curvature is parallel to the longer side. If this difference is too big, it becomes a problem to use them in a shading screen because the actuator would have to be measured up to the largest force, thus decreasing the system's efficiency. These findings are consistent with Tawfik et al. (2007), who found that prototypes required a decreasing force to snap through to position 1 as the length to width ratio got higher until the prototypes stopped exhibiting two stable states. Prototypes B and C required a large force to transition from position 1 to position 2, but a small force to transition back, making them unappealing for kinetic skin applications as any unintended force (air current) might make the laminates transition between states. The adaptability range was assessed by overlaying the pictures of their two stable positions and visually inspecting the two states' differences. The third criterion, fibre arrangement and adaptability range, was also evaluated through visual analysis of the overlaid photos. The last criteria, daylight performance in different states, was assessed through daylight performance studies. Figure 9 shows the design decision matrix with the scores assigned to each prototype. Prototype A was selected as the most promising one. Therefore, the third set of experimental prototyping and the second round of simulation studies focused only on Prototype A.

	Typology A	Typology B	Typology C
Able to maintain states	5	1	1
Adaptability range ON/OFF state	5	1	5
Adaptability range with different fiber arrangements	5	2	5
Daylight performance in different states	5	2	5

Ability to maintain states: 5)Two similar forces are needed to snap from one position to the other to 1) The difference between the forces is so large that the prototype maintain only one position. Adaptability range: 5) There is a large difference in the shape of position 1 versus position 2 assessed visually to 1) There is not much difference in the shape of position 1 versus position 2. Adaptability range with different fiber arrangement (same as previous scale). Daylight performance in different states: 5) There is a 50+ percentage difference in daylight autonomy assessment to 1) There is a 10+ percentage difference in daylight autonomy assessment

FIG. 9 Evaluating the prototypes

4.4 FABRICATING PROTOTYPES WITH MULTIPLE FIBRE ARRANGEMENTS

The third set of studies focused only on Prototype A, as it was selected as the most promising one to use in a kinetic shading device. This study aimed to explore the potential of multiple fibre arrangements to increase the design space of kinetic shading systems while potentially enhancing functionality by tailoring fibre arrangements to targeted performance requirements. The second aim of this study was to characterize the geometry of the two stable states resulting from designed fibre arrangements. Six different prototypes were built with dimensions w=7.62 cm l=15.24 cm. The prototypes had different fibre arrangements, namely, 0-90°, 15-105°, 30-120°, 45-135°, 60-150°, and 75-165°. The angles were selected to test a gradient of options from 0 to 90 degrees. The prototypes were cured in a single aluminium plate to decrease any possible variability derived from different fabrication conditions (temperature, humidity) in multiple rounds.

Figure 10-1 shows the photograph of the prototypes in both states. At first glance, it is apparent that Prototypes 1 through 4 present a significant adaptability range, while prototypes 5 and 6 do not present states that are easily differentiated from each other. Also, the scanning and modelling of the prototypes and comparing them with FEA results gave more accurate information on the adaptability range. Figure 10-1 characterizes the geometry of all six prototypes, regardless of the individual fibre arrangement. The geometry is derived from a straight generatrix l and a curved directrix m. The angles of l and m with the main geometric lines of the prototypes change according to the designated fibre arrangement. Figure 10-3 shows the curvature k1 and k2 of the different prototypes, corresponding to position 1 and 2 states. Curvature k1 (position 1) presents a shorter radius—meaning it is more curved—in all the prototypes. Prototypes 1 through 6 have a shorter curvature radius parallel to the longest side of the rectangle in position 1, which indicates that the curing process generates more stress in that direction due to the fibres being longer in that direction. With both the scanned prototypes and the FEA results, the modelling and geometric characterization allow one to construct accurate digital models that can be used to predict their performance as functional shading devices. In general, the directions of the fibres determine the directrix of the curved states, and the curvature radios appear to be smaller in the direction of the longer fibres.

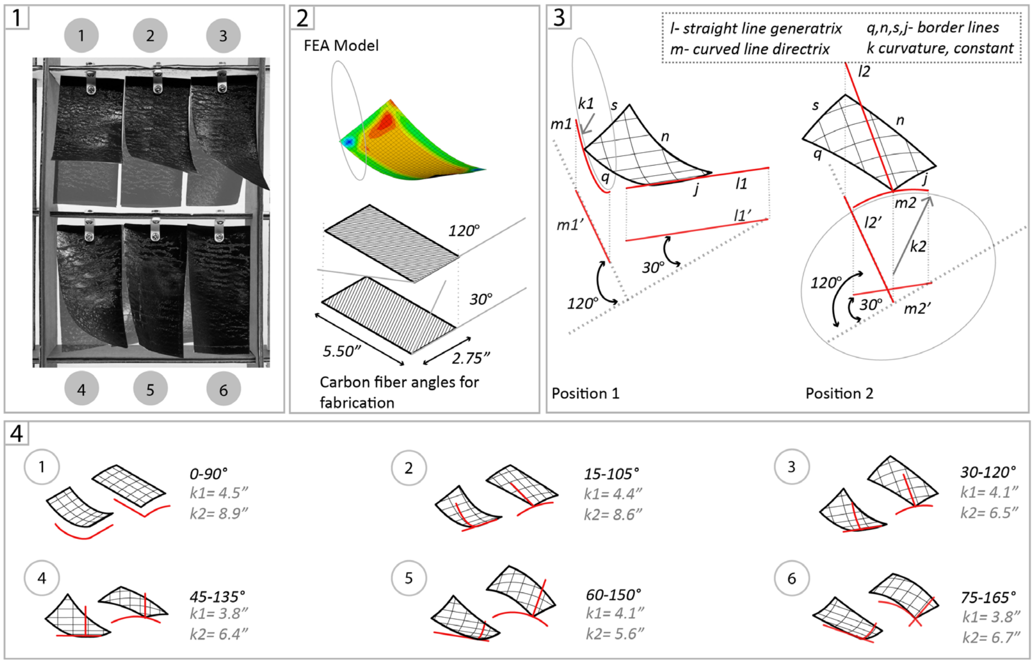

FIG. 10 Impact of fibre arrangement on the two states of the prototypes

4.5 OPTIMIZING KINETIC SHADING CONFIGURATIONS

The advantage of kinetic screens relies on being able to adapt their configuration according to changing environmental conditions. The first simulation studies compared daylight performance between the kinetic shades' different states, disregarding dynamic features. A second simulation study was then conducted to test the efficiency of Prototype A (w=7.62 cm l=15.24 cm), in two variations, in helping to maintain a certain level of daylight throughout the day. Prototype A.1 has fibres at angles of 90-0°, and Prototype A.2 has fibres at angles of 45-135°. The idea is that the kinetic shading system adopts multiple configurations throughout the day to guarantee a targeted performance, which, in this case, was to maintain an average of 500 lux in the space—appropriate for office work. It may be recalled that one of the benefits of having kinetic systems with active actuation is that they can be adjusted on demand to meet functionality requirements. Optimization algorithms were used to find the optimal screen states in two-hour intervals for the year's longest day—June 20. The objective of the study is the average lux value in the space: The algorithms seek to minimize the difference between the obtained average lux and the target average lux of 500. The variables are the values for each row (0: row is open, 1: row is closed). The room settings were the same as those adopted in the first simulation study. They were also conducted using Radiance as the simulation engine, with the DIVA plugin for Grasshopper 3D. The optimization problem was solved using Galapagos, a plugin for Grasshopper that utilizes genetic algorithms to minimize or maximize a function. Each row of the screen could adopt either one of the two stable positions modelled according to the study on fibre arrangement. The selected fibre arrangements to test were 90-0° and 45-135°, which displayed wide adaptability ranges and tight curvature values in both states.

Figure 11-3 shows the performance of the optimized solution, which indicated that the screen with Prototype A.1 (90-0° fibres)—in optimized configurations—can keep a targeted daylight average of 500 lux throughout the day. The optimization algorithm found the best configuration to achieve an average value close to the targeted daylight value. As shown in the graph, prototype A.1 is more successful in maintaining the target daylight due to its shape in both states. For instance, at 2pm, the optimized configuration for the screen with Prototype A.1 is to have all the rows in Position 1, blocking the high sun rays at that time of day. Prototype A.2, on the other hand, can only achieve an average of ~1000 lux even in its optimal configuration at noon. The study showed that between two designs, A.1 and A.2, which only differ in their fibre arrangement, the optimal configuration of one design (A.1) performs better than the optimal configuration of the other. The optimization results suggest that selecting adequate fibre arrangement for kinetic bistable screens yields designs with better daylight performance.

The screen adopts a different configuration every two hours to maintain the targeted daylight. The study was performed every two hours due to the time (~10 hours) that the optimization takes. The possible kinetic shading configurations were also limited; we limited the number of possible screen configurations by establishing that all laminates on the same row must adopt the same position at a given time, which was decided based on the high position of the sun at the selected date, as shown in Figure 11.1. Future studies could allow each screen unit to move independently, enhancing daylight control and creating more complex aesthetic design solutions. Nevertheless, finding optimal screen configurations with such an ample design space and possible individuals in the optimization problem would require other heuristics to reduce computation time. Furthermore, finding the optimal configuration for the kinetic shadings would probably have to be done a priori, since real-time optimization does not seem feasible due to long computation times.

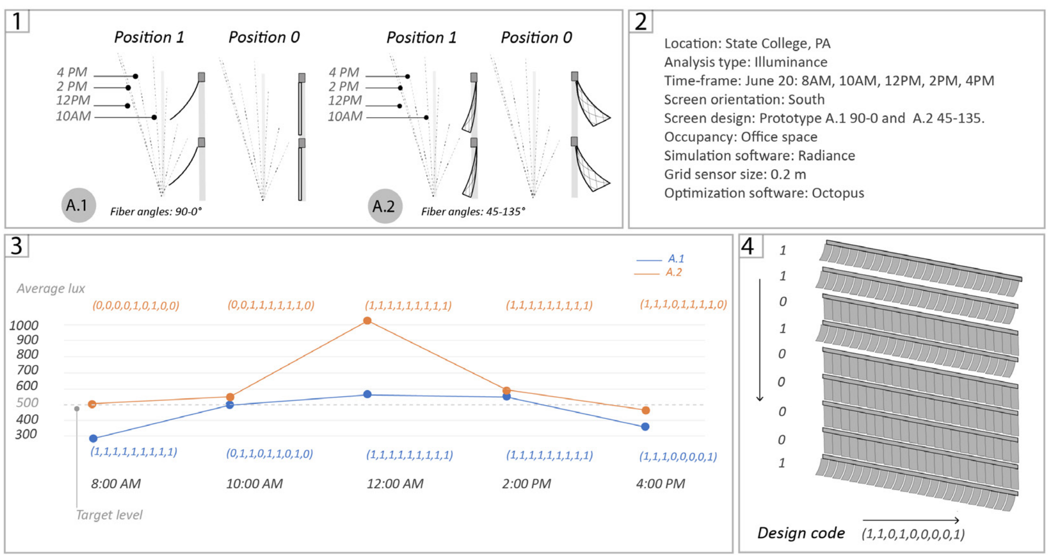

FIG. 11 Daylight simulation studies conducted to optimize screen configuration.1) Sunray angles for both prototypes 2) Optimization settings 3) Optimization results, and 4) Design code for results.

5 CONCLUSION

This paper presents a comprehensive investigation of using bistable composite laminates for kinetic building shading devices. Following experimental prototyping, we analysed a series of bistable units with different geometrical configurations, aiming at different design solutions for kinetic shading devices. The analysis of such prototypes allowed us to identify the most promising units by assessing their adaptability range and studying their forms in the two equilibrium states, using an FEA model and scanned digital models. A series of annual daylight simulation studies were then conducted to compare the performance between the two states. We selected one prototype (Prototype A, a rectangle of w=7.62 cm l=15.24 cm) as the most promising unit to continue the investigation using a design decision matrix. In the second round of experimental studies, we explored the effects of changing fibre arrangement on the resulting stable states and characterized its impact on the units' geometry. The presented strategy for designing the fibre alignment increases the range of possible design configurations of the shading units, thereby increasing their potential as shape-morphing elements. The proposed strategy enhances their functionality as architectural elements by offering designers important insights for designing with bistable materials. Finally, we compared the effectiveness of a kinetic shading system using Prototype A with two fibre arrangements (90-0° and 45-135°) in maintaining target daylight throughout the day.

The first set of simulation studies demonstrated the impact of geometry on the resulting two stable states and its effect on daylight performance. Results show that some base geometries, such as rectangles, have a more distinct open and closed shape configuration and therefore are better suited to use in the design of kinetic shading devices for various daylight needs. The second set of simulation studies shows that the proposed system facilitates keeping daylight within the desired range. Research results indicate that fibre arrangement has an impact on the difference between the open and closed position of the bistable flaps, which is important to improve the daylight performance of the shading screens. Therefore, fibre arrangements and overall geometry are important design variables in achieving specific daylight targets.

This study argues that bistable kinetic systems could be introduced as an alternative to conventional shading solutions, with increased design potential in shape variety and shape morphing range of motions. This system offers increased granularity (resolution) by having smaller shading modules than in conventional systems, thereby allowing increased control of daylighting in terms of level. The main advantage of bistable systems for kinetic applications is their ability to maintain two stable states without additional input energy. Nevertheless, bistable laminates still have some limitations that need to be addressed: the non-manual actuation, the high cost of the carbon fibre prepregs, and the unknown impact carbon fibre has on the environment after its use. The design space of kinetic bistable shades increases when considering fibre arrangements, as shown with the different prototypes of this research.

A limitation of this study is that we only considered geometry, size, and fibre arrangement as design variables for the proposed kinetic shading system using bistable composite laminates. Other variables such as material thickness and mechanical properties, and optical values (reflection, absorption) were not explored. Considering that fatigue, durability, overall robustness, and human factors are critical for building-scale applications. Also, we only considered daylight in evaluating the performance of the shading devices; future research could also consider metrics such as glare, radiation, energy performance, and solar heat gain coefficient. Furthermore, this study assumes that the proposed kinetic systems can be actuated with a smart material actuator. We base that assumption on both the studies that have demonstrated the feasibility of combining bistable materials and smart actuators and the low energy required to transition between states that previous studies, described in the literature review, reported using the same material in this study—carbon fibre prepregs. Future studies will combine bistable composite laminates with smart actuators, as shown in Figure 12. Notwithstanding these limitations, the study suggests that the geometric configurations that bistable composite laminates express render them a promising material for developing novel and functional kinetic systems for buildings.

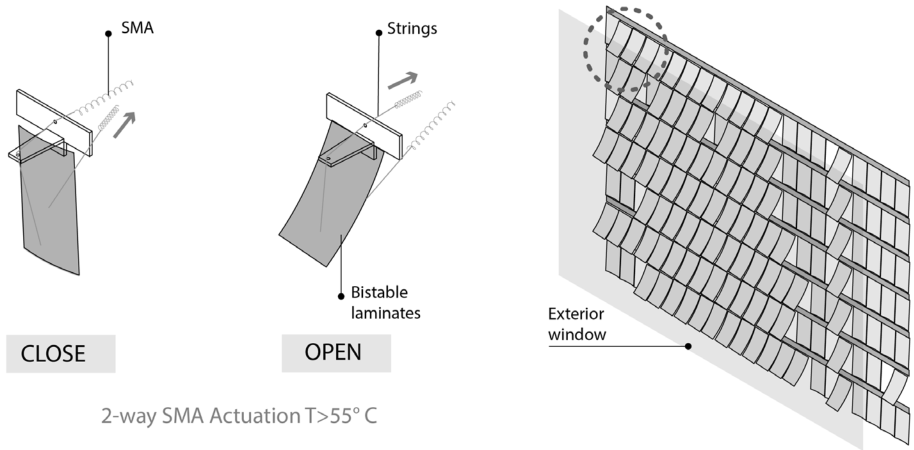

FIG. 12 Actuation mechanism schema, bistable laminates combined with two-way shape memory alloy springs.

Acknowledgments

This work was supported by the American Institute of Architects Upjohn Research Initiative, and the Architectural Research Centers Consortium Research Incentive Award.

References

Addington, M., & Schodek, D. (2005). Smart Materials and New Technologies - For architecture and design professions. In *Elsevier*. Architectural Press.

Ahlquist, S., Thün, G., Newell, C., & Velikov, K. (2013). Toward a Pedagogy of Material Systems Research Toward a Pedagogy of Material Systems Research. *TxA Interactive*, *November 2013*, 22–33.

Al-Masrani, S. M., & Al-Obaidi, K. M. (2019). Dynamic shading systems: A review of design parameters, platforms and evaluation strategies. *Automation in Construction*, *102*, 195–216. https://doi.org/10.1016/j.autcon.2019.01.014

Al-Masrani, S. M., Al-Obaidi, K. M., Zalin, N. A., & Isma, M. I. A. (2018). Design optimisation of solar shading systems for tropical office buildings: Challenges and future trends. *Solar Energy*, *170*, 849–872. https://doi.org/https://doi.org/10.1016/j.solener.2018.04.047.

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture. *Procedia Engineering*, *155*, 275–284. https://doi.org/10.1016/j.proeng.2016.08.029

Bellia, L., Marino, C., Minichiello, F., & Pedace, A. (2014). An overview on solar shading systems for buildings. *Energy Procedia*, *62*, 309–317. https://doi.org/https://doi.org/10.1016/j.egypro.2014.12.392

Cantera, M. A., Romera, J. M., Adarraga, I., & Mujika, F. (2015). Modelling and testing of the snap-through process of bi-stable cross-ply composites. In *Composite Structures* (Vol. 120, pp. 41–52). https://doi.org/10.1016/j.compstruct.2014.09.064

Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Reichert, S., Menges, A., & Tibbits, S. (2015). 3D-Printed Wood: Programming Hygroscopic Material Transformations. *3D Printing and Additive Manufacturing*, *2*(3), 106–116. https://doi.org/10.1089/3dp.2015.0022

Denz, P.-R., Sauer, C., Waldhör, E. F., Schneider, M., & Vongsingha, P. (2021). Smart Textile Sun-Shading: Development of Functional ADAPTEX Prototypes. *Journal of Façade Design and Engineering*, *9*(1), 101–116.

Emam, S. A., & Inman, D. J. (2015). A review on Bistable Composite Laminates for Morphing and Energy Harvesting. *Applied Mechanics Reviews*, *67*(6). https://doi.org/https://doi.org/10.1115/1.4032037

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews*, *55*, 863–884. https://doi.org/10.1016/j.rser.2015.10.086

Khoo, C. K., Salim, F., & Burry, J. (2012). Designing Architectural Morphing Skins with Elastic Modular Systems. *International Journal of Architectural Computing*, *09*(04), 397–419. https://doi.org/10.1260/1478-0771.9.4.397
Kim, S. W., Koh, J. S., Cho, M., & Cho, K. J. (2010). Towards a bio-mimetic flytrap robot based on a snap-through mechanism. *2010 3rd IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics, BioRob 2010*, 534–539. https://doi.org/10.1109/BIOROB.2010.5627994
Kretzer, M., & Rossi, D. (2012). ShapeShift. *Leonardo*, *45*(5), 480–481. https://doi.org/https://doi.org/10.1162/LEON_a_00451
Lachenal, X., Daynes, S., & Weaver, P. M. (2013). Review of morphing concepts and materials for wind turbine blade applications. *Wind Energy*, *16*(2), 283–307. https://doi.org/https://doi.org/10.1002/we.531
Lele, A., Deshpande, V., Myers, O., & Li, S. (2019). Snap-through and stiffness adaptation of a multi-stable Kirigami composite module. *Composites Science and Technology*, *182*(May). https://doi.org/10.1016/j.compscitech.2019.107750
Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: A hingeless flapping mechanism inspired by nature. *Bioinspiration and Biomimetics*, *6*(4). https://doi.org/10.1088/1748-3182/6/4/045001
Loonen, R. C. G. M., Favoino, F., Hensen, J. L. M., & Overend, M. (2017). Review of current status, requirements and opportunities for building performance simulation of adaptive façades†. *Journal of Building Performance Simulation*, *10*(2), 205–223. https://doi.org/10.1080/19401493.2016.1152303
Mattioni, F., Weaver, P. M., Potter, K. D., & Friswell, M. I. (2008). The application of thermally induced multistable composites to morphing aircraft structures. *Industrial and Commercial Applications of Smart Structures Technologies*, *6930*, 693012. https://doi.org/https://doi.org/10.1117/12.776226
Pirrera, A., Avitabile, D., & Weaver, P. M. (2010). Bistable plates for morphing structures: a refined analytical approach with high-order polynomials. *International Journal of Solids and Structures*, *47*(25–26), 3412–3425. https://doi.org/https://doi.org/10.1016/j.ijsolstr.2010.08.019
Schultz, M. R., & Hyer, M. W. (2003). Snap-through of unsymmetric cross-ply laminates using piezoceramic actuators. *Journal of Intelligent Material Systems and Structures*, *14*(12), 795–814. https://doi.org/https://doi.org/10.1177%2F104538903039261
Sigmund, B. (2016). Solar Curtain – Sonnenschutz durch Formgedächtniseffekt (Solar Curtain - sun shading through shape memory effect). *DETAIL Research*.
Song, J. Y., Heo, S., & Shim, J. (2018). Snapping Façades: Exploring Elastic Instability for the Building Envelope. *Technology Architecture and Design*, *2*(1), 45–54. https://doi.org/10.1080/24751448.2018.1420964
Sung, D. (2016). Smart Geometries for Smart Materials : Taming Thermobimetals to Behave Smart Geometries for Smart Materials. *Journal of Architectural Education*, *4883*. https://doi.org/10.1080/10464883.2016.1122479
Tawfik, S., Tan, X., Ozbay, S., & Armanios, E. (2007). Anticlastic stability modeling for cross-ply composites. *Journal of Composite Materials*, *41*(11), 1325–1338. https://doi.org/https://doi.org/10.1177%2F0021998306068073
Vander Werf, B. (2009). *Elastic Systems for Compliant Shading Enclosures*. University of Arizona.
Vazquez, E., Gürsoy, B., & Duarte, J. P. (2019). Formalizing shape-change: Three-dimensional printed shapes and hygroscopic material transformations. *International Journal of Architectural Computing*. https://doi.org/10.1177/1478077119895216
Vazquez, Elena, Randall, C., & Duarte, J. P. (2019). Shape-changing architectural skins: a review on materials, design and fabrication strategies and performance analysis. *Journal of Façade Design and Engineering*, *7*(2), 91–102. https://doi.org/https://doi.org/10.7480/jfde.2019.2.3877
Wood, D., Correa, D., Krieg, O. D., & Menges, A. (2016). Material computation-4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces. *International Journal of Architectural Computing*, *14*(1), 49–62. https://doi.org/10.1177/1478077115625522
Worre Foged, I., & Pasold, A. (2015). Thermal Activated Envelope : Development of a Method and Model for Programming Material Behaviour in a Responsive Envelope. In B. Martens, G. Wurzer, G. T, W. Lorenz, & R. Schaffranek (Eds.), *Proceedings of the 33rd eCAADe Conference - Volume 2, Vienna University of Technology, Vienna, Austria, 16-18 September 2015* (pp. 449–458). Vienna University of Technology.
Yang, Y., Dias, M. A., & Holmes, D. P. (2018). Multistable kirigami for tunable architected materials. *Physical Review Materials*, *2*(11), 1–6. https://doi.org/10.1103/PhysRevMaterials.2.110601
Yi, H., & Kim, Y. (2021). Self-shaping building skin: Comparative environmental performance investigation of shape-memory-alloy (SMA) response and artificial-intelligence (AI) kinetic control. *Journal of Building Engineering*, *35*(October 2020), 102113. https://doi.org/10.1016/j.jobe.2020.102113
Yoon, J. (2019). SMP Prototype Design and Fabrication for Thermo- responsive Façade Elements. *Journal of Façade Design and Engineering*, *7*(1), 41–62. https://doi.org/10.7480/jfde.2019.1.2662