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Fabrication and Testing of Kirigami-Inspired Multi-Stable Composites

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ABSTRACT

This paper aims at highlighting the fabrication procedures and proof-of-concept tests of a Kirigami inspired multi-stable composite laminate. Bistable composites consisting of asymmetric fiber layout have shown great potentials for shape morphing and energy harvesting applications. However, a patch of such a bistable composite is limited to very simple deformation when being snapped between its two stable equilibria (or states). To address this issue, this study investigates the idea of utilizing Kirigami, the ancient art of paper cutting, into the design and fabrication of bistable composite laminates. Via combining multiple patches of laminates and cutting according to prescribed Kirigami pattern, one can create a structure with multiple stable states and sophisticated deformation paths between them. This can significantly expand the application potentials of the multi-stable composites. This paper details the fabrication procedures for an elementary unit cell in the envisioned Kirigami composite and the results of proof-of-concept experiments, which measure the force required to switch the Kirigami composite between its different stable states. Preliminary results confirm that the Kirigami unit cell possesses multiple stable states depending on the underlying fiber layout. Each patch in the Kirigami composite could be snapped independently between stable states without triggering any undesired snapping in other patches. Moreover, a transient propagation of curvature change is observed when a patch in the Kirigami composite is snapped between its stable states. Such a phenomenon has not been reported in the bistable composite studies before. Results of this paper indicate that Kirigami is a powerful approach for designing and fabricating multi-stable composites with a strong appeal for morphing and adaptive systems. This paper highlights the feasibility and novelty of combining Kirigami art and bistable adaptive composites.

1. INTRODUCTION

A fiber reinforced polymer composite consists of the matrix and reinforcements. The matrix material is typically thermoset polymers like epoxy, vinyl esters, and phenolics etc.; while the reinforcements are either synthetic fibers like carbon, glass, aramid or natural fibers like sisal, jute, and choir. Based on the fiber arrangement, composites can be classified either as fibrous composites or as laminated composites. The reinforcing fibers in the fibrous composites are orientated randomly, and fibers in the laminated composite are arranged in layers with uniform orientations [1]. Fiber composites exhibit high strength and stiffness-to-weight ratios and strong corrosion resistance, which make them favorable for the usage in aerospace, automobile, petroleum, and many other industries [2].

Laminated composites that are symmetric in both geometry and fiber orientations about its middle surface through thickness are referred as symmetric laminates. This symmetry eliminates bending-extension coupling and the associated internal stress during curing. Therefore, symmetric laminates are widely used in applications that require strong structural rigidity and strength. The asymmetric laminates, on the other hand, are not symmetric about its middle surface in terms of the fiber arrangements. As a result, they show a significant bending-extension coupling and exhibit curved shapes after curing. Moreover, if this asymmetry is strong enough, the overall laminate can possess two different stable equilibria (or states) [3]. Such bistable asymmetric laminates can settle into any states even without external stimuli, and they can experience large deflections moving from one state to another with small energy input [4–7]. These unique characteristics have opened up exciting opportunities of creating adaptive and multi-functional structures [8,9].

Shape morphing is a well-studied application. Bistable composites have several advantages that make them uniquely attractive for such a purpose: They do not require a constant power supply for maintaining shapes at a stable state; the snap-through

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motion typically features a large deformation range and short response time; and fiber composites inherently have high stiffness and strength-to-density ratios. Therefore, bistable composites have been investigated for use in adaptive airframes, wind turbine blades, automotive structures, and robots [10–12]. Moreover, it is possible to autonomously activate these bistable composite by embedding active components such as piezoelectric actuators [13] and shape memory alloy wires [14]. In addition to morphing, vibration isolation [15] and energy harvesting [16] were also achieved with the bistable composites. Compared to the equivalent linear systems that work ideally only at near resonance frequencies, bistable composite performed well in a wider frequency band. Such broadband advantage is especially evident when the laminates vibrate between their two stable states (aka. inter-well responses via snap-through) [17].

Despite its bright potentials, the implementation of bistable composite is significantly constrained by some of their most fundamental properties: These composites are essentially 2D sheet materials with external shapes that are close to simple cylindrical surfaces at the stable states. Thus, a single patch of bistable laminate is usually too simple to be used for practical applications that require complicated shape and deformation. To solve this issue, two different strategies of combining multiple patches of bistable laminates were investigated: One involves assembly [18,19] and the other uses varying fiber orientation within a single patch [20]. However, neither of the two solutions is capable of programming multi-stability and enable sophisticated shape changes, and at the same time reliable enough for relatively simple and scalable fabrication.

Based on the arguments above, we investigate a novel approach of incorporating *Kirigami* principles into the design of multi-stable composites. Kirigami is a variation of origami, which involves the cutting of paper in addition to folding [21]. The idea is that after slitting and folding operations, a thin 2D sheet material can be developed into sophisticated 3D shapes [22]. The Kirigami concept is originally used to make "pop-up" books, however, it is employed recently to design and build various engineering structures. For example, a honeycomb metamaterial fabricated via cutting and folding principle can provide shape morphing capability [23]. Kirigami is also being utilized to create simple and efficient solar tracking device: an elegant cut-pattern is made in thin film gallium-arsenide solar cells, which are then stretched to adjust its orientation according to the sun position [24].

We envision that via combining multiple patches of asymmetric laminates and then applying carefully designed slit cuts. A thin composite sheet can be developed in to a multi-functional structure that has multiple stable states (Figure 1). We will refer such structure as "Kirigami composite" hereafter. Via snapping the different elementary units, or cells, of the Kirigami composite between its stable states, one can create sophisticated shape morphing and mechanical property programming functions. Moreover, the Kirigami cutting is a relatively simple procedure for fabrication, and would not negate the inherent light-weight advantages of the composites.

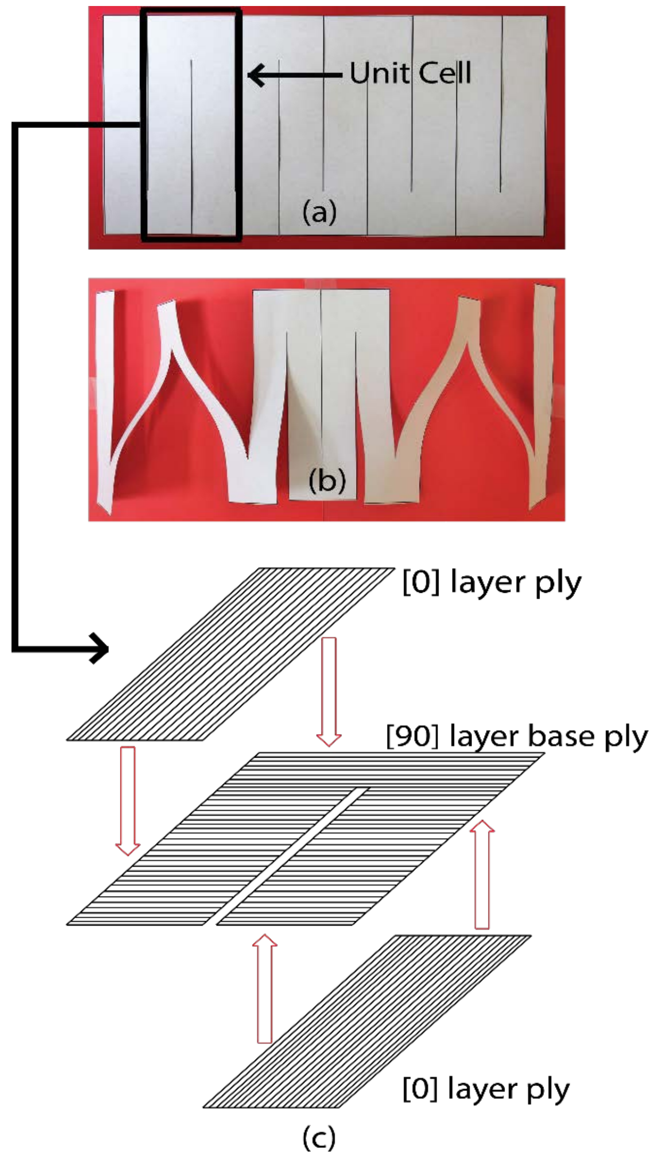

Figure 1. The multi-stable Kirigami composite concept illustrated based on the simple parallel cut pattern. (a) The underlying Kirigami geometry (undeformed). (b) Deformed Kirigami paper to demonstrate the envisioned snapping between stable states. (c) The fiber layout designs of the unit cell in Kirigami composite.

This paper aims to detail the fabrication procedures and present proof-of-concept test results of the simplified Kirigami composite. Here we focus on a unit cell of the simple parallel cutting pattern to illustrate the concept without unnecessary complexities. The preliminary tests aim to validate the multi-stability in the Kirigami unit cell composite, and measure the required force to induce snap-through response. It is observed that, due to the unique boundary conditions in the Kirigami geometry, the bistable patches snap between its stable states via a "propagation" of surface curvature changes. Such a transient behavior has never been carefully examined in the bistable composite

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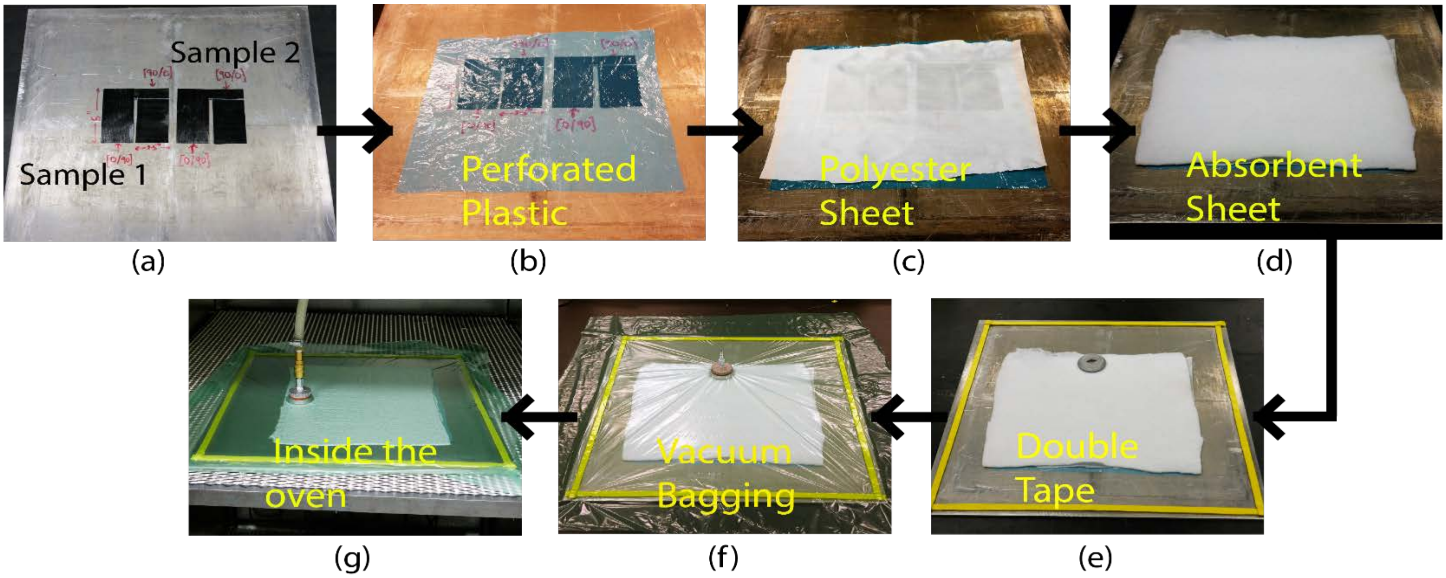

Figure 2. The steps of setting up the vacuum bagged packet for curing. We first put uncured Kirigami samples on the aluminum plate (a). Then we apply perforated Plastic sheet (b), polyester sheet (c), and absorbent sheet material (d) on top of the sample. Then double-sided tape (e) and vacuum bagging plastic (f) are used to seal everything. The finished packet is vacuumed and placed in the oven (g) for curing.

studies before, however, it plays a crucial role in the overall structural behavior.

It is worth highlighting that the envisioned Kirigami composite structure (Figure 1) consists of many unit cells that are examined in this paper. However, the multi-stability and snap-through behaviors of the unit cells are directly applicable to such a larger scale multi-cell structure. This is because the individual patches in unit cells can maintain their bi-stability independently even though they are structurally connected. Therefore, results of this paper elucidate the feasibility and novelty of combining the Kirigami cutting art and bistable composites, which has never been done before.

The rest of this paper is organized as follows. Section 2 discusses the fabrication procedures of the Kirigami composite in detail. Section 3 presents the experimental results, particularly regarding the reaction force-deformation relationship and the transient behaviors during snap through. Section 4 concludes the paper with summary and discussions.

2. FABRICATION OF KIRIGAMI COMPOSITE

The Kirigami samples discussed in this paper are fabricated using AS4 carbon fiber prepregs embedded in HexPly 8552 resin, and vacuum based oven curing method is used [25]. The first step of fabrication is freezing and cutting. The prepregs are cooled in a freezer to a temperature between 0°C to 4°C, and then they are cut according to the Kirigami geometry using a paper cutter board or scissors. Freezing maintains the rigidity of the matrix resin so that the fibers in prepregs would not be distorted during cutting. Otherwise excessive distortions in fiber plies can eliminate the desired multi-stability in finished prototypes. The Kirigami pattern described in this paper consists of a base ply in

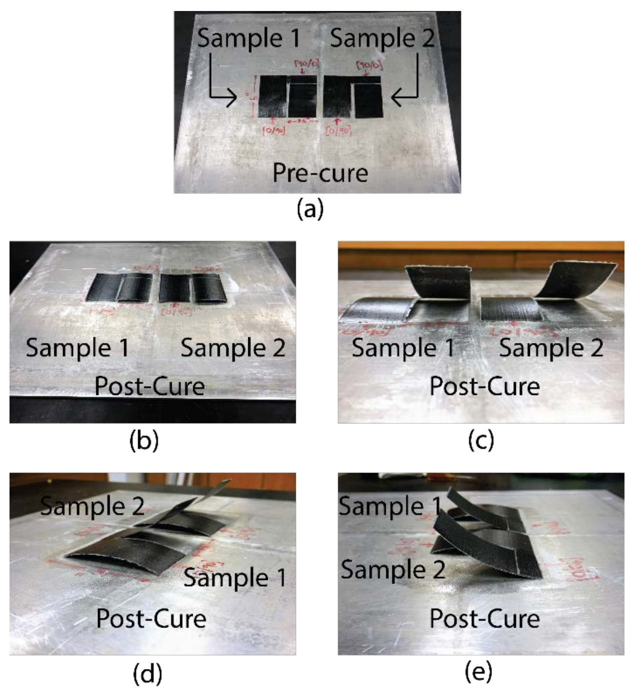

Figure 3. The cured Kirigami composite unit cell sample. (a) The two samples before the curing process. (b) The shape of the cured unit cell sample immediately after the removal of vacuum bagging. The two patches in the unit cell exhibit independent bistability. The multiple views in (c-e) shows the shape of the unit cell when its two patches are manually switched to the other stable state.

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the [90°] direction with dimensions of 133mm x 127mm (Figure 1). A 100mm long, 6mm wide slit cut is made at the center of this base ply. Two additional plies of 127mm x 64mm and [0°] fiber direction are added to the base ply. One of the [0°] plies is attached on the upper side of the base layer and the other on the lower side (Figure 1(c)). This forms the basic structure of the unit cell of a Kirigami prototype.

The second step of the fabrication is to set up a vacuum bagged packet (Figure 2). A 0.6m x 0.6m x 4mm aluminum plate is used as the platform for this packet. This plate is covered with mold releasing agent, and the uncured Kirigami unit cell samples are placed on its top. Then a layer of perforated plastic sheet (10 LYD 3015-PERF-D - Release Ply - High Temp 450F – Perforated Film) is placed on top of the Kirigami sample followed by a polyester sheet (10 LYD 3000-D - Econo Ply J Polyester Peel Ply). These layers are then covered with a sheet of absorbent material (10 LYD 3011-D - Breather Fabric). A nozzle is placed on top of this assembly and it is sealed by vacuum bag films (10 LYD 3014-D - Stretchlon SL200 Vacuum Bag Film) and double-sided tapes. This entire assembly is then connected to a vacuum pump (1 EA. VacuMaster 5 CFM Vacuum Pump) via the nozzle and it forms the vacuum packet. All the material required for making the vacuum packet was procured from RockWest Composites.

The final step of the fabrication is curing. The vacuum bagged packet is placed inside a heated oven at 135°C for an hour. The oven is 1.219 m x 1.219 m in dimensions and has a thermostat for controlling its internal temperature. Then it is cooled down to the room temperature by shutting down the oven. This heat up and cool down procedure induces internal thermal stresses in the laminates, which eventually result in the generation of bistability (Figure 3). Once fully cured, the vacuum packet is taken out of the oven and the samples are retrieved by removing the vacuum packet. On opening the vacuum packet, it is found that the two patches in each Kirigami unit cell sample have already settled to one of the stable states as shown in Figure 3(b). We refer these configuration as their first stable state. Figures 3(c-e) represent the profile of the laminates when their two patches are manually switched to the other stable state. We refer these as the second stable state. When the patches are snapped from the first stable state to the second stable state, the process is called as "snap-through" process. Similarly, when the patches are snapped from the second stable state to the first stable state, the process is referred as "snap-back" process. Using these terms as the basis, we conduct "snap-through" and "snap-back" test on every single patch of the two fabricated Kirigami unit cell samples as detailed in the following section.

3. EXPERIMENTAL TESTING

In order to examine the multi-stability of the fabricated Kirigami composite samples, we perform proof-of-concept tests to understand their nonlinear elastic behaviors. To this end, we use a universal tester machine to measure the transverse force-displacement relationship of the two patches in the Kirigami unit cell (ADMET Expert 5601 with MTESTQuattro controller). The objective of this test is to validate the desired independence of the two patches in a unit cell. That is, each patch can be snapped between its stable states without inducing any snap-through in the other patch even though they are structurally connected. In this test, one end of a patch is fixed via a bolt to a custom-designed fixture, and the external force is applied to the other end of this patch by a thin rod connected to the load cell (model number: SM-25-38). Meanwhile, the other patch of the Kirigami unit cell is completely free (Figure 4). To accurately measure the force-displacement relationship, the thin rod is controlled to move down slowly at 0.1mm/sec, and the corresponding reaction force magnitude is recorded by the load cell. It is worth highlighting that the thin rod is simply contacting the Kirigami composite during the loading process. Therefore, when the thin rod displacement is large enough to trigger the snap response, the rod

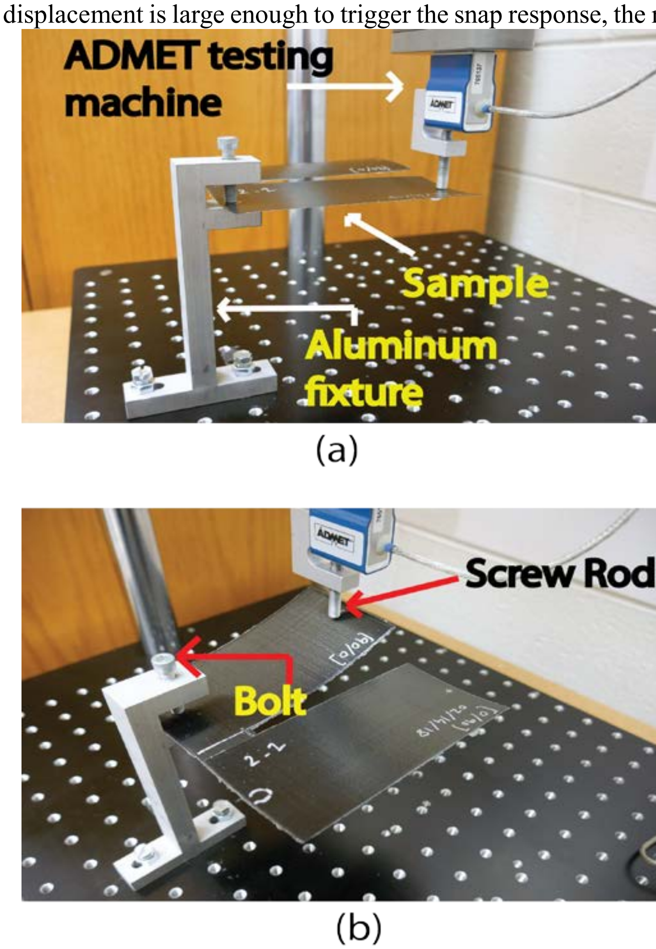

Figure 4. Experimental setup for the Kirigami composites. Depending on the configuration of tested patch prior to loading, two tests are conducted, one is called "snap-through" test (a) and the other "snap-back" (b).

would lose contact with the composite patch and the test would end accordingly. The load applied is a coercive load as the rod experiences a small translation along the length of the unit cell as the unit cell deforms.

The measured reaction force-displacement curve of the snap-through tests are summarized in Figure 5. In these tests we observe that: 1) the bistability of patches are indeed independent

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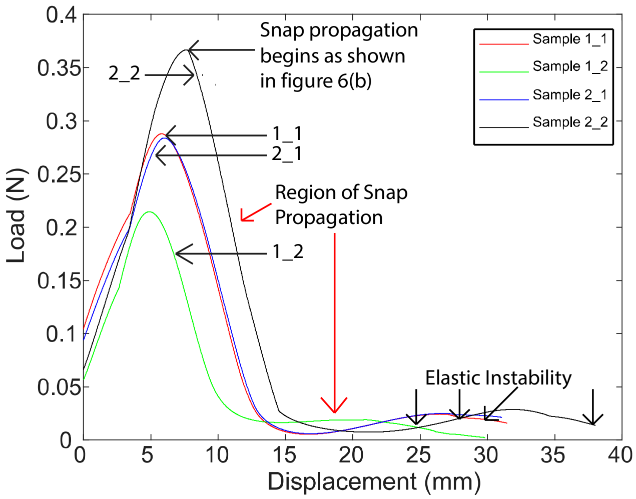

Figure 5. The reaction force vs. displacement curves from the snap-through tests.

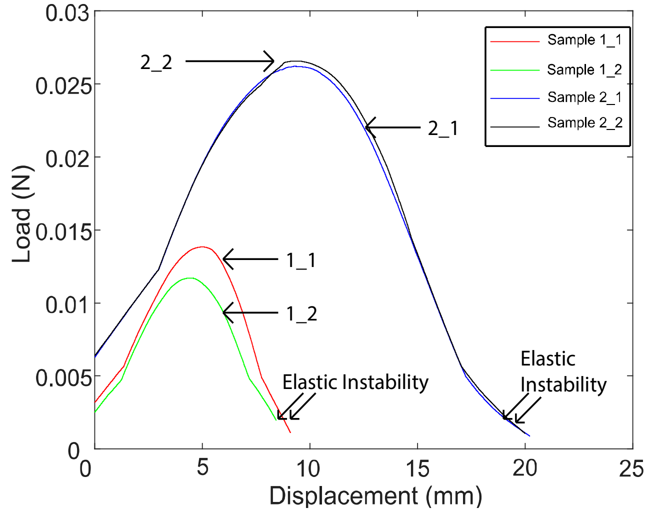

Figure 7. The reaction force vs. displacement curves from the snap-back tests.

from each other; 2) the magnitudes of the reaction force show notable variations between different patches; and 3) despite the differences in magnitude, all the force-displacement curves rise quickly to a relatively high value first, and then drop down to close zero for a significant amount of end displacement before the snap-through finally occurs. Such a drop in the reaction force is against the current consensus that bistable composite should be snapped to the other stable state immediately when the external load reaches the threshold to induce the elastic instability. That is, the snap-through in Kirigami composite is not an instantaneous response but rather a process with some transient behaviors. To further examine the drop in reaction force before snap-though, we mark a Kirigami path by a grid pattern and carefully observe its shape change during the snap-through test (Figure 6). At the start of the experiment when no end displacement is applied, the gridlines along the length (x-direction) of the patch are straight, while the gridlines along the width (y-direction) have a concave shape (aka. positive curvature in the z-direction, Figure 6a). When end displacement is applied, the snap-through response does not occur uniformly throughout the patch, but rather originates *locally* from the fixed end. This can be observed in Figure 6(b), where the y-direction grid lines near the fixed end deform from a concave shape into straight lines, and the x-direction grid lines start to show bending near the fixed end. As the end displacement increases further, more y-direction grid lines change from curved to straight, and the bending deformation along the x-direction grid lines continue to progress (Figure 6c). When end displacement reaches a critical level, elastic instability finally occurs and the aforementioned propagation of gridline deformation accelerates until the snap-through is complete (Figure 6d). At this point, the composite patch and the end rod lose contact. Note that the maximum reaction force observed in the

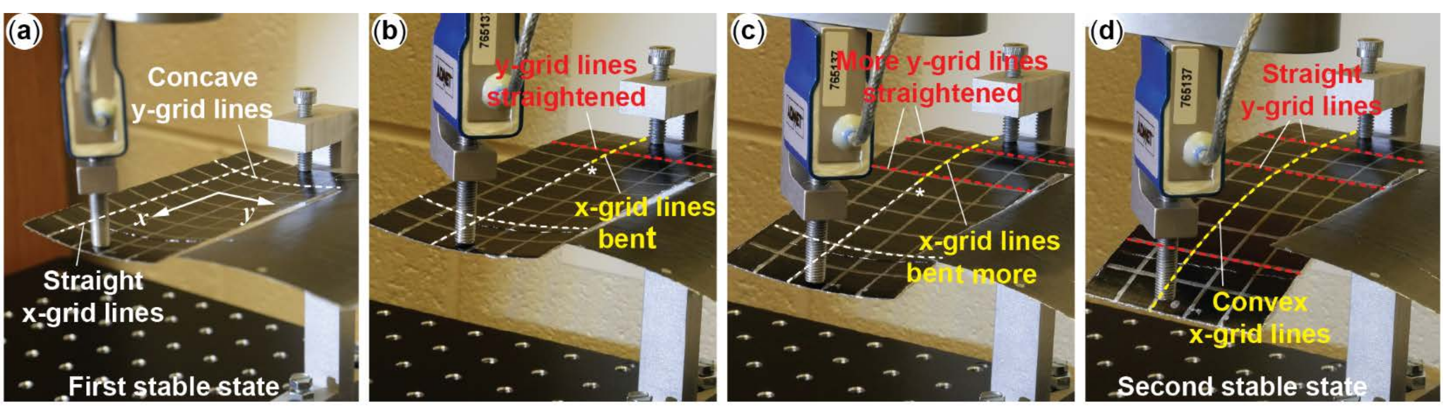

Figure 6. The snap-propagation phenomenon. (a) The shape of grid lines before any end displacement is applied. (b) When the end displacement is applied, the gridlines begin to show curvature changes from the fixed end. The marker “X” indicates the transition region between deformed and un-deformed grid lines. (c) The grid line curvature changes propagate toward the free end as the end-displacement increases. (d) The Kirigami patch after the elastic instability occurs, showing a completed grid line curvature change.

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snap-through test corresponds to the moment when the change in gridline curvatures initiates near the fixed end of the patch.

Results of the snap-back tests shows a qualitatively similar behavior as in the snap-through tests (Figure 7). The reaction force of the patches in Kirigami composite reaches a peak value initially, and then quickly drops to a very low value as the aforementioned changes in curvature starts to propagate through the patch. At some critical end displacement, the elastic instability occurs and completes the snapping process. However, the instability occurs earlier than the snap-through tests thus the transient behavior of snapping is not as significant. That is, the changes in gridlines curvatures propagate faster in the snap-back tests compared to the snap-through tests.

It is worth noting that, although all the Kirigami composite patches show the same *qualitative* behaviors, the magnitudes of reaction force vary significantly between tests. This is probably due to the inconsistency in our manual fabrication, and documenting these variations will be the topic of future work. It is also worth noting that the samples 1 and 2 that were subjected to the experiments were not of the same age, that is, they were fabricated on different dates. The effect of the age of the samples on the results obtained in the experiments will also be one of the topics of our future work.

4. SUMMARY AND CONCLUSION

This paper highlights the fabrication procedures and the proof-of-concept test results of a Kirigami-inspired multi-stable composite laminate. Such a composite laminate consists of multiple bistable patches fabricated in a form of a Kirigami inspired pattern, and each patch features a prescribed asymmetric fiber layout. This paper covers the fabrication process involved in the fabrication of a unit cell of the Kirigami composite. Vacuum bagging techniques are used to ensure repeatability in terms of the desired multi-stable behavior. A universal tester machine was used to examine the transverse force-displacement relationship of the two patches of a Kirigami unit cell. It is observed that the patches of could be snapped independently without triggering any undesired snaps in other patches. Moreover, it is found that the patch does not snap immediately when the external force reaches the critical level based on the current consensus. Instead, we observe a transient process by which the change of curvatures propagates from the fixed end of the bistable patch to the other end. Such a phenomenon was never reported in bistable composite studies before and it will be the subject of study in our future research. Also, the future work involves the finite element analysis of the Kirigami bistable laminates to understand the linkage between the cutting geometry and the overall multi-stable behavior. Results of this study elucidate that the principle of Kirigami can be a powerful tool to create multi-stable composites with sophisticated shape and deformation pattern.

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