Bi-stable hybrid composite laminates containing metallic strips: an experimental and numerical investigation

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Abstract
This study scrutinizes the static characteristics of a new category of bi-stable hybrid composite laminates (BHCLs) that contain multiple metallic strips (aluminum) distributed along the middle layer of a carbon fiber reinforced epoxy laminate. With this new class of BHCLs, the direction of curvature of the laminates does not change during the snap-through between the two stable states, unlike the conventional bi-stable cross-ply laminates. The laminates were modeled using finite element analysis and were experimentally validated. BHCLs with two to five metallic strips were fabricated for this purpose. The effect of the number, width, and thickness of the metallic strips on the static characteristics of the laminate were numerically investigated using ABAQUS. Further, the curvatures, out-of-plane displacement, and static snap-through load of the laminates were determined experimentally. The results showed a strong relationship between the residual curvature and the load-carrying capability of the laminate and the number, width, and thickness of the metallic strips, as well as the laminate geometry. Knowledge of this characteristic will allow designers to tune the parameters for a given application and to achieve the desired performance. Good qualitative and quantitative agreement was observed between the numerical and the experimental results.

Keywords: bi-stable, snap-through load, residual curvatures, hybrid composite laminate, metallic strips, finite element method

(Some figures may appear in colour only in the online journal)

1. Introduction

Shape-adaptable and deployable structures are increasingly being considered as a solution to address conflicting requirements of flexibility and stiffness while providing a better performance and versatility in many aerospace applications. Substantial research effort has recently focused on using bi-stable mechanisms in shape-adaptable and morphing structures, due to their multiple equilibrium configurations that is maintained without the need for continuous energy supply. Bi-stable composite laminates are a special type of composite lay-up characterized by a specific unsymmetrical lay-up sequence and exhibits two stable static configurations after the curing cycle is completed. This bi-stability behavior is associated with the internal residual stress that develops via a variety or a combination of methods such as thermal stress [1] and mechanical pre-stressed fibers [2]. The unsymmetrical...
cross-ply composite laminates can exhibit an unequal saddle shape or two cylindrical shapes at room temperature (see figure 1(a)), with the cylindrical axes of both stable configurations positioned perpendicular to each other that is not predicted using classical lamination theory (CLT) [3]. Hyer [4] developed a nonlinear extension of CLT to predict the two cylindrical shapes of square and rectangular cross-ply laminates by applying the Rayleigh–Ritz method based on the principle of minimum total potential energy. Following that work, a number of researchers contributed to the improvement of Hyer’s theory and studied the effects of various parameters on the static response of bi-stable composite laminates including the laminate geometry, layer composition [5, 6], fiber orientation [7], viscoelastic material properties [8], temperature dependency of material properties [9], curved tool plates [10], manufacturing imperfections [11], slippage [12], temperature variations [13], and moisture [14, 15]. The prominent characterization method of bi-stable composite laminates is the snap-through phenomenon associated with rapid deformation from the first stable configuration (FSC) to the second stable configuration (SSC) or vice versa. The snap-through excitation is activated using several methods, such as mechanical loading [16], a temperature gradient [17], or the use of smart actuation techniques such as shape memory alloys [18], and piezoelectric materials or piezoelectric macro-fiber composite [19, 20].

Recently, interest has extended to study the dynamic and vibration behavior of bi-stable laminates [21–24]. The characteristics of bi-stable composite structures, such as low mass and their ability to maintain in their stable configurations without demanding any external energy source, have encouraged designers of composite structures to explore their use in deployable and shape-adaptable structures and anti-icing/de-icing systems [25–27]. However, hygrothermal variability with environmental conditions, low stiffness, low snap-through load, and restrictive geometries of bi-stable pure composite laminates (BPCLs) limits their application. To address some of these limitations, Dyness et al [2] presented a new type of bi-stable laminate that had a symmetric lay-up. They induced bi-stable behavior in the laminates with lay-up of \(0/90/90/0\) by pre-stressing selected fibers prior to curing. The main benefit of the pre-stressed bi-stable symmetric laminates over conventional BPCLs is that two edges of the laminate remain flat in both bi-stable configurations, as shown in figure 1(b), and the laminate is much less prone to hygrothermal variability. Later, Li et al [28] proposed a bi-stable hybrid composite laminate (BHCL) that included two aluminum strips in the middle layer of the symmetrical laminate and showed that the hybridization of the bi-stable composite laminates with the metallic layer led to an increase in the curvatures and the load-carrying capability. The curvature direction of the proposed BHCLs did not change during snap-through between the stable states as it did in the

**Figure 1.** The two stable configurations of (a) conventional BPCLs or BHCLs with inner metallic layer (b) BHCLs with metallic strips in the middle layer or pre-stressed bi-stable symmetrical laminates.
pre-stressed bi-stable symmetric laminates. The simple manufacturing procedure and the large load-carrying capability of the BHCLs provide a major advantage over pre-stressed bi-stable symmetric laminates. In this regard, Dai et al [29] proposed an unsymmetrical carbon fiber reinforced plastic (CFRP) laminate with an inner isotropic metallic layer, [0/metal/90]T, and an external isotropic metallic layer, [0/90/metal]T [30]. They investigated the influence of the metallic layer on the static response of the laminates. Further, Daynes and Weaver [31] extended the analytical technique of Hyer’s model to handle static parametric studies of [0/metal/90]T BHCLs. The shear interaction between the composite lamina and the metallic layer, prior to curing, was accounted for in the developed model by defining a slippage coefficient. Eckstein et al [32] introduced a new laminate which utilizes a low thermal expansion unidirectional (UD) composite layer bonded to a high-expansion isotropic metallic layer. The laminate showed highly nonlinear displacement response to thermal loading and can be used as thermal bimorph structure. The BHCLs was found to have more potential for use in real applications because of its enhanced static characteristics in comparison to BPCCLs. In this paper, inspired by Li’s studies, a new lay-up of BHCLs is introduced. Generally, this lay-up consists of composite laminas in the upper and lower layers and 2, 3, 4, or 5 metallic strips in the middle layer, as shown in figure 2. The orientation of UD carbon fiber-epoxy prepreg in the upper and lower layers is 90°. In the middle layer, metallic strips are evenly distributed between the UD fibers with 0° orientation. The materials of the strips are of higher thermal expansion coefficient than the UD carbon fiber prepreg, and may include aluminum, copper, or steel. The number of 0° laminas through the laminate thickness is related to the thickness of the strips, so that the final thickness of the laminate should be uniform. For simplicity in the expression of the stacking sequence of the newly introduced laminates, the following naming system [90m/x1 Matk-x2 CF0n-1/90m]T are adopted and detailed in table 1.

After this type of bi-stable laminate has been cured and cooled to ambient temperatures, the residual thermal stresses are formed in the laminate such that the metallic strips are in tension and the prepregs with 0° orientation are in compression (in the middle layer). This is due to the large difference in the thermal expansion coefficients between the zero-degree composite laminas (0.37 × 10^-6 °C^-1) and the metallic strips (18.8 × 10^-6 °C^-1). The residual thermal stresses result in a laminate with two stable states and large out-of-plane displacement at room temperature. The stable configurations of the newly introduced laminate are similar to the configuration

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**Figure 2.** Lay-up schematic of a typical BHCL of [90m/x1 Matk-x2 CF0n-1/90m]T including three metallic strips in the middle layer.

**Table 1.** Parameters used for the naming system of bi-stable hybrid composite laminates with metallic strips.

| Parameter | Description |
|-----------|-------------|
| m         | Number of 90° carbon fiber prepregs through the laminate thickness |
| x1        | Width of the metallic strip |
| x2        | Width of the 0° carbon fiber prepreg in the middle layer |
| n         | Number of 0° carbon fiber prepregs through the laminate thickness |
| k         | Number of metallic strips in the width of the laminate |
| mat       | Material of the metallic strips (AL for aluminum) |
| CF0       | 0° carbon fiber prepreg in the middle layer |
of conventional bi-stable composites or hybrid laminates that consist of a metal layer in the middle or outer layers; a major difference, however, is that the direction of the productive axis in both stable states is the same and only its sign changes, see figure 1(b). An advantage of such behavior is that the stable states have greater potential for practical applications, especially in morphing wings.

2. Numerical modeling using ABAQUS

This section describes the numerical model developed to study the effect of various parameters on the characteristics of BHCLs of width, thickness and number of metallic strips, side length, and thickness of the laminate. The impacts of these parameters on the curvatures, maximum out-of-plane displacement, and static snap-through load are investigated. For this purpose, various samples with different dimensions and lay-ups were simulated using ABAQUS. The samples were made of carbon fiber/epoxy T300/5222 A and 2024-T3 aluminum strips with the mechanical properties shown in table 2. The laminates were modeled using 2D shell elements, S8R with eight nodes and reduced integration using hourglass control. Each node had six degrees of freedom, three translational and three rotational degrees of freedom. An approximate global mesh size of 5 mm × 5 mm was used for laminates with the side length of 250 mm based on the convergence criteria. For laminates with side lengths other than 250 mm, the mesh size was scaled. For instance, for a side length of 100 mm, the mesh size was scaled by 100/250.

The static characterization of the laminates was obtained based on general static analysis and by defining the following two steps:

(a) Stable configurations:

(i) In step 1, the laminate was fully fixed at the center and the initial temperature loading of 180 °C was applied on the laminate matching the autoclave temperature when the specimens were manufactured. An artificial imperfection was applied to the structure to allow for the convergence of the model to one of the stable configurations. Therefore, when the temperature range was between 175 °C and 180 °C, a small force was applied at the four corners of the laminate, as indicated in figure 3.

(ii) In step 2, the forces applied in step 1 were removed and the temperature was reduced from 175 °C to 25 °C (room temperature). At the end of this step, the laminate converged to one of the stable states, which was dependent on the direction of the forces applied in step 1. It should be noted that the longitudinal and transverse curvatures were not constant throughout the laminate; therefore, the curvatures were averaged at all nodes of the laminates and then the averaged values were compared with the experimental results.

(b) Static snap-through:

To simulate the snap-through phenomenon, first, one of the stable states of the laminate was modeled as described earlier and then the following steps were defined.

(i) In the first step, four focused transverse forces were applied at the four corners of the laminate. The magnitude of the forces increased in small steps until the snap-through occurred. During this step, in order to observe the snap-through phenomenon, an artificial damping factor was applied to the structure.

(ii) In the second step, to ensure that the snap-through had occurred in the previous step and the new state of the laminate was stable, the applied forces were removed. If the new configuration of the laminate was stable, the laminate would not deform and would maintain the new configuration. The shape of the laminate at the end of this step was called the second stable state.

Table 2. Material properties of the carbon fiber-epoxy T300/5222 A and the aluminum strips.

| Lamina properties | | | | | | |
|--------------------|----------------|----------------|----------------|----------------|----------------|
| $E_{11}$ (GPa)      | $E_{22}$ (GPa) | $G_{12}$ (GPa) | $v_{12}$       | $\alpha_{11}$ (°C$^{-1}$) | $\alpha_{22}$ (°C$^{-1}$) |
| 137.47              | 10.07          | 4.4            | 0.23           | $3.7 \times 10^{-6}$        | $24.91 \times 10^{-6}$ |

Al 2024-T3 properties

| $E_m$ (GPa) | $\nu_m$ | $\alpha_m$ (°C$^{-1}$) |
|-------------|---------|------------------------|
| 79          | 0.3     | $18.8 \times 10^{-6}$  |

Figure 3. Boundary and loading conditions for studying stable configurations.
3. Results—based on the finite element analysis

3.1. Effect of width and number of strips

The effects of the number and width of the strips on the static response of the BHCLs, in the form $[90_2/x_1\ AL^{k-250-k}\ CF0^{k-1}/90_2]_T$, consisting of 2, 3, 4, and 5 aluminum strips were investigated by changing the width of aluminum strips $x_1$ through a range defined in Table 3. Within the studied range, the laminate shows bi-stable behavior, it should be noted that beyond this range, the metallic or $0^\circ$ composite strips will be very narrow which is not realistic and practical. The side length and total thickness of the laminate were assumed to be 250 mm and 0.75 mm, respectively. If the total width of the aluminum strips was zero i.e. $[90_2/0_2/90_2]_T$ or equal to the side length of laminate i.e. $[90_2/AL/90_2]_T$, the residual internal stresses cannot exhibit bending because extension-bending coupling matrix is zero so the laminate will not show bi-stability and therefore remains flat after the curing process is completed. The results are summarized in Figure 4. When two metal strips were considered, the curvature and the snap-through load fluctuated as the total width of the strips increased (see Figure 4(a), (b)). On the other hand, when there were more than two strips, the curvature and the snap-through followed a parabolic shape as the total width of the aluminum strips increased. Thus, the increase in behavior reached a peak before starting to drop again.

It should be noted that in the BHCLs with metallic strips, the maximum snap-through load (see Figure 4(b)) did not occur simultaneously at the maximum curvature (see Figure 4(a)). The maximum curvatures (and the corresponding total width of the strips) of the samples consisting of 3, 4, and 5 aluminum strips were 2.9 m$^{-1}$ (180 mm), 3.6 m$^{-1}$ (160 mm), and 4 m$^{-1}$ (150 mm), respectively. The major curvature and the maximum out-of-plane displacement increased significantly with the increase in the number of strips for a given total width of aluminum strips. The maximum snap-through load (and the corresponding total width of the strips) in the samples consisting of 3, 4, and 5 aluminum strips were 17.2 N (105 mm), 16.6 N (120 mm), and 10.2 N (100 mm). The snap-through load increased with the increase in the number of aluminum strips from 2 to 3 and

| Sample | Lower limit of $x_1$ (mm) | Upper limit of $x_1$ (mm) | Increment (mm) |
|--------|---------------------------|---------------------------|----------------|
| 2 Strips | 5                         | 110                       | 5              |
| 3 Strips | 5                         | 70                        | 5              |
| 4 Strips | 5                         | 55                        | 5              |
| 5 Strips | 5                         | 45                        | 5              |

Figure 5. The effect of side length on the major curvature of the studied BHCLs.
then decreased when the number of strips further increased to 4 and 5.

3.2. Effect of laminate side length

The effect of the side length on the major curvature of the square laminates $[90^\circ_2/(0.48 \text{ side length AL})^k - \frac{0.52 \text{ side length CF}}{k-1} - 90^\circ_2]_T$ consisting of 2, 3, 4, and 5 aluminum strips was investigated. The total thickness of the laminates was 0.75 mm and the ratio of the total width of the aluminum strips to the side length in all samples was taken to be 0.48. The results are shown in figure 5. It was observed that an increase in the side length results in a rapid increase in the major curvature and then a decrease after the peak value. When compared to the conventional BPCLs and BHCLs, by increasing the side length, the curvature asymptotically converges to a constant value. The changing trend of the major curvature with number of strips and side length of laminate shows that the stiffness of the studied structure are nonlinear function of these parameters. The side lengths corresponding to the maximum curvature of the samples with 3, 4, and 5 aluminum strips are 150 mm, 225 mm and 275 mm, respectively. For side lengths less than 150 mm, the curvature of the laminate with 3 aluminum strips is higher than that of the other models. For side lengths greater than 250 mm, the curvature of the laminate increases dramatically by increasing the number of strips.

![Image: Graphs showing the effect of thickness on the static characterization of the laminate with 5 AL strips.](image)

**Figure 6.** The effect of thickness on the static characterization of the laminate with 5 AL strips.
3.3. Effect of thickness of 90° layers and Al strips

In practice, the total thickness of the laminate could be adjusted by changing the number of plies. The effects of the thickness of 90° layers, $T_{90}$, and aluminum strips, $T_{AL}$, on the static characteristics of BHCLs consisting of 2, 3, 4, and 5 aluminum strips were investigated. This was achieved by varying the number of 0° plies in the middle layer and the number of 90° plies in the upper and the lower layers (from 1 to 8 layers). In the analysis, the side length of the laminates was 250 mm and the thickness of each composite ply was 0.125 mm; the thickness of the aluminum strips was considered to be equal to the total thickness of the 0° plies in the middle layer. The results obtained for each model are presented in the following subsections.

(I) Five aluminum strips

The results for the square laminates [90n/24AL5-32.5CF 02m//90n]T consisting of 5 aluminum strips with width of 24 mm are shown in figure 6. As is evident, the longitudinal curvature and the maximum out-of-plane displacement increases when the numbers of 0° and 90° plies decrease. The characteristics of the laminates depend more on the thickness of the 90° layer than the 0° layer. For the specific range of $T_{90}$ and $T_{AL}$, the laminate does not maintain the two stable states. This range is marked in the dark blue region in figure 6(c).

The thickness range corresponding to the maximum longitudinal curvature, $\kappa_{xx}$, differs from the thickness range corresponding to the maximum snap-through load. The maximum longitudinal curvature (6.1 m⁻¹) and out-of-plane
displacement (47.8 mm) correspond to the minimum achievable thickness i.e. $T_{90} = T_{AL} = 0.125$ mm, whereas the maximum snap-through load (29.4 N) occurs in $T_{90} = 0.125$ mm and $T_{AL} = 0.625$ mm. The load-carrying capability decreases dramatically with the increase in the thickness of $T_{90}$. The transverse curvature changes in a more nonlinear fashion than that of the other quantities. The transverse curvature, $\kappa_{yy}$, reaches its maximum ($0.31 \text{ m}^{-1}$) when $T_{90} = 0.125$ mm and $T_{AL} = 1$ mm.

(I) Four aluminum strips

The results for the square laminates of $[90_n/30AL^4-43.3CF0^3/90_n]_T$ consisting of 4 aluminum strips with width of 30 mm are shown in figure 7. Generally, similar behavior (the pattern of contour lines, the area corresponding to the maximum longitudinal curvature, and the out-of-plane displacement) to that in the laminate with 5 aluminum strips is observed. However, the thickness range corresponding to the bi-stable zone is expanded and the maximum achievable longitudinal curvature and out-of-plane displacement decreased to $4.8 \text{ m}^{-1}$ and 39.5 mm, respectively. On the other hand, the maximum achievable snap-through increased to 45.2 N. The maximum snap-through occurs when $T_{90} = 0.125$ mm and $T_{AL} = 0.75$ mm. The snap-through load decreases with the increase in the thickness of $T_{90}$ for a specified total thickness. Further, the transverse curvature reaches its maximum ($0.27 \text{ m}^{-1}$) when $T_{90} = 0.125$ mm and $T_{AL} = 1$ mm.

(I) Three aluminum strips

![Figure 8. The effect of thickness on the static characterizations of the laminate with 3 AL strips.](image)
The results for the square plate with the side length of 250 mm, consisting of 3 aluminum strips with a width of 40 mm, and a $[90_n/40\text{AL}5-65\text{CF0}_m/90_0]_T$ arrangement are shown in figure 8. The maximum longitudinal and transverse curvatures, the out-of-plane displacement, and the snap-through load are determined to be $4 \text{ m}^{-1}$, $0.21 \text{ m}^{-1}$, $33.2 \text{ mm}$, and $75.6 \text{ N}$, respectively. The pattern of contour lines, the area corresponding to the maximum longitudinal curvature, and out-of-plane displacement are similar to those of the laminates with 4 and 5 strips, but the pattern of contour lines in the snap-through load is different. Furthermore, the maximum snap-through occurs when $T_{90} = 0.125 \text{ mm}$ and $T_{\text{AL}} = 1.0 \text{ mm}$.

(I) Two aluminum strips

The results for the square plate with the side length of 250 mm, consisting of 2 aluminum strips with a width of 60 mm, and a $[90_n/60\text{AL}5-130\text{CF0}_m/90_0]_T$ stacking sequence are shown in figure 9. This laminate has the widest range of bi-stability and the highest load-carrying capability but it has the lowest major curvature in comparison with other laminates. Generally, the pattern of the contour lines and the location of the maximum value in the longitudinal curvature and out-of-plane displacement contour maps are the same as for the other models, but the pattern of contour lines in the snap-through load graph is more similar to that of the laminate with 3 metal strips. The snap-through load has a non-linear relation with $T_{90}$, as it increases to reach a peak before starting to decrease. The maximum longitudinal and transverse curvatures, the out-of-plane displacement, and the snap-
through load are found to be $3 \text{ m}^{-1}$, $0.22 \text{ m}^{-1}$, $26.2 \text{ mm}$, and $107.4 \text{ N}$, respectively. The snap-through load variations are also more dependent on $T_{\text{AL}}$ than the $T_{90}$. The maximum snap-through load occurs when $T_{90} = 0.5 \text{ mm}$ and $T_{\text{AL}} = 1 \text{ mm}$.

The thickness range corresponding to the bi-stable zone was expanded by decreasing the number of strips from 5 to 2. Further, the thickness range corresponding to the maximum longitudinal and transverse curvatures and the out-of-plane displacement were approximately the same in all the models investigated, whereas those corresponding to the maximum snap-through were totally different in all the models.

It was also observed that the maximum achievable longitudinal curvature and out-of-plane displacement increased when the number of strips was increased. On the other hand, the static snap-through load decreased with the

| Sample | Lay-up             | Dimensions (mm) | AL. thickness (mm) | Total thickness (mm) |
|--------|--------------------|-----------------|--------------------|---------------------|
| 1      | [902/60AL2-130CF01/902]T | $250 \times 250$ | 0.25               | 0.75                |
| 2      | [902/40AL2-65CF02/902]T | $250 \times 250$ | 0.25               | 0.75                |
| 3      | [902/30AL2-43.3CF01/902]T | $250 \times 250$ | 0.25               | 0.75                |
| 4      | [902/24AL2-32.5CF01/902]T | $250 \times 250$ | 0.25               | 0.75                |
| 5      | [90/60AL2-130CF01/901]T | $250 \times 250$ | 0.25               | 0.5                 |
| 6      | [90/40AL2-65CF02/901]T | $250 \times 250$ | 0.25               | 0.5                 |
| 7      | [90/30AL2-43.3CF01/901]T | $250 \times 250$ | 0.25               | 0.5                 |
| 8      | [90/24AL2-32.5CF01/901]T | $250 \times 250$ | 0.25               | 0.5                 |
| 9      | [902/36AL2-78CF02/902]T | $150 \times 150$ | 0.25               | 0.75                |
| 10     | [902/24AL2-39CF02/902]T | $150 \times 150$ | 0.25               | 0.75                |
| 11     | [902/18AL2-26CF02/902]T | $150 \times 150$ | 0.25               | 0.75                |
| 12     | [902/14AL2-19.5CF02/902]T | $150 \times 150$ | 0.25               | 0.75                |
increase in the number of strips. The patterns of the contour lines in the longitudinal curvatures graph, for all models, were similar. However, their load-carrying capabilities were different. Moreover, the contour lines in the longitudinal graphs were more identical when the number of aluminum strips was increased, emphasizing that the effect of thickness was more noticeable for the laminate with 5 strips.

4. Experimental validation

4.1. Experiment set-up

A selection of the FE results were validated experimentally. Several BHCLs with aluminum strips were fabricated from T300/5222A prepreg and 2024 aluminum sheet. The laminas were cut from the prepreg or aluminum sheet with the desired dimensions and then oriented with the arbitrary lay-up shown in figure 10.

After the lay-up was completed and the vacuum bag prepared, the curing process of the resin was carried out in an autoclave using the temperature of 180 °C and the pressure of 7 bars. It should be noted that, to enhance the bonding between the composite plies and the aluminum strips, the surface of the aluminum strips was roughened using 320 grit sandpaper and then carefully cleaned using ethanol. A description of the fabricated samples is presented in table 4. All the samples had the total aluminum width of 120 mm and therefore the ratio of the metal width to the entire specimen was 0.48. Figure 11 shows the two stable configurations of samples 6–8. As observed, both stable configurations of all the samples have significant curvature in the same direction but in the opposite sign.

Samples 1–4 had the same dimensions (250 × 250 × 0.75) and total width of aluminum (120 mm), but the number of strips was varied. Samples 5–8 were the same as samples 1–4 with the main difference being that the number of 90° laminas in the upper and bottom parts of the laminate were one instead of two. Further, samples 9–12 were similar to samples 1–4, with a change in the side length to 150 mm.

4.2. Experimental results and comparison

The BHCLs with metallic strips had two stable configurations at room temperature. The shapes were a portion of a right circular cylinder. The major curvatures of the FSC and the SSC were in the same direction but had the opposite sign. The laminates profile were measured experimentally using measurement machine Optacom LC 10 with speed of 0.1 mm s−1 and accuracy of 4 μm (figure 12). The Optacom contour software module was used for extracting the major curvature. The results are summarized in table 5. It should be noted that the transverse curvature is nearly zero for the fabricated structures (which were not focused on in this study).

The deformation between the two stable states was investigated experimentally and the static load that resulted in the snap-through between the two stable configurations was measured. A special fixture was designed to restrict the out of plane displacement at the four corners of the specimen while the load is applied at the center, as shown in figure 13. The fixture was placed in the testing area on a universal testing machine and a 100 N load cell was used. A controlled displacement was applied at the center of the laminate at the rate of 20 mm min−1. During the loading, the load–displacement curves were recorded. The snap-through load was identified as the load at which a sudden drop appears in the load–displacement curve. Because of the laminate’s symmetry, the force necessary to change the laminate from the first stable state to the second stable state (snap-through load) and vice versa (snap-back load) was the same, so only the snap-through load was measured. Table 5 compares the numerical and experimental results for the curvature and the snap-through load. Samples 4 and 2 have the maximum curvature and the greatest load-carrying capability, respectively, among the first four samples. This finding confirms the FEM results.
where the major curvature and the maximum out-of-plane displacement increase as the number of strips increases for the side length of 250 mm and the total width of aluminum strips of 120 mm.

Further, the experimental results obtained for samples 5–8 confirm the FEM results regarding the effect of thickness on the laminate behavior. Samples 10, 11, 12, and 9 respectively have the highest curvature, findings that confirm the behavior of the laminate with the side length below 150 mm. For all the tested cases, the maximum error does not exceed 8%. The difference between the FE and experiment results increases with the increase in the number of strips. This may be referred to the slippage effect between the Al strips and the composite layers, which was not considered in the FE simulation. That result may be improved by adjusting the slippage coefficient.

### Table 5. Snap-through load and longitudinal curvature of the fabricated laminate at ambient temperature.

| Sample | Lay-up | Longitudinal curvature (m⁻¹) | Snap-through load (N) |
|--------|--------|-------------------------------|-----------------------|
|        |        | FEM | EXP | Error* | FEM | EXP | Error* |
| 1      | [90₂/60AL₂−130CF₁₀₂/90₂₁₀₂] | 1.75 | 1.69 | 3.55 | 6.13 | 5.87 | 4.43 |
| 2      | [90₂/40AL₂−65CF₁₀₂/90₂₁₀₂] | 2.63 | 2.51 | 4.78 | 16.5 | 15.64 | 5.5 |
| 3      | [90₂/30AL₂−43.3CF₁₀₂/90₂₁₀₂] | 3.39 | 3.21 | 5.61 | 16.59 | 15.6 | 6.35 |
| 4      | [90₂/24AL₂−32.5CF₁₀₂/90₂₁₀₂] | 3.75 | 3.53 | 6.23 | 9.9 | 9.25 | 7.03 |
| 5      | [90₂/60AL₂−130CF₁₀₂/90₂₁₀₂] | 2.24 | 2.14 | 4.67 | 1.87 | 1.78 | 5.06 |
| 6      | [90₂/40AL₂−65CF₁₀₂/90₂₁₀₂] | 3.07 | 2.91 | 5.5 | 9.22 | 8.71 | 8.56 |
| 7      | [90₂/30AL₂−43.3CF₁₀₂/90₂₁₀₂] | 3.93 | 3.73 | 6.22 | 13.64 | 12.78 | 6.73 |
| 8      | [90₂/24AL₂−32.5CF₁₀₂/90₂₁₀₂] | 4.77 | 4.6 | 6.95 | 13.56 | 12.62 | 7.45 |
| 9      | [90₂/60AL₂−130CF₁₀₂/90₂₁₀₂] | 1.59 | 1.54 | 3.25 | 14.82 | 14.2 | 4.37 |
| 10     | [90₂/40AL₂−65CF₁₀₂/90₂₁₀₂] | 2.71 | 2.59 | 4.63 | 9.21 | 8.75 | 5.26 |
| 11     | [90₂/30AL₂−43.3CF₁₀₂/90₂₁₀₂] | 2.58 | 2.45 | 5.31 | 3.09 | 2.91 | 6.19 |
| 12     | [90₂/24AL₂−32.5CF₁₀₂/90₂₁₀₂] | 1.9 | 1.79 | 6.15 | 4.06 | 3.8 | 6.84 |

### Figure 13. Special fixture for measuring snap-through load of the fabricated laminates.

5. Conclusions

This paper presents a new category of BHCLs that consists of CFRP layers in the upper and lower layers and aluminum strips and CFRP in the middle layer. The laminates were numerically modeled and parametric studies of the number, width, and thickness of the metallic strips were performed using ABAQUS to complete the static characterization of the laminates. The results showed that when the number of strips was increased beyond two, both the curvature and the snap-through followed a parabolic shape when the total width of the aluminum strips was increased. The major curvature and the maximum out-of-plane displacement increased significantly with the increase in the number of strips for a specified total width of aluminum strips. The snap-through load increased with the increase in the number of aluminum strips from 2–3, and then decreased when the number of strips was increased to 4 and 5. The maximum achievable curvature for the studied BHCLs with 2, 3, 4, and 5 aluminum strips was 3, 4, 4.8, and 6.1 m⁻¹ respectively and the maximum achievable snap-through load was 29.4, 45.2, 75.6, and 107.4 N respectively. It should be noted that, in the BHCLs with metallic strips, the maximum snap-through load did not occur simultaneously with the maximum curvature and also the major curvature did not asymptotically converge to a constant value by increasing the side length of the laminate unlike conventional BPCLs and BHCLs. The curvatures, the out-of-plane displacement, and the static snap-through load of a sequence of laminates were measured experimentally and compared with the FEM results, where very good agreement was observed. The results revealed that the laminates have bistability for wide ranges of geometry and lay-ups and it was possible to adjust the residual curvature and load-carrying capability of the laminate by adjusting the number, width, and thickness of the metallic strips and the laminate geometry. The BHCLs presented were more designable and variable than conventional BPCLs for the purpose of tailoring responses.
References

[1] Kim K S and Hahn H T 1989 Residual stress development during processing of graphite/epoxy composites Compos. Sci. Technol. 36 121–32
[2] Daynes S, Potter K D and Weaver P M 2008 Bistable prestressed buckled laminates Compos. Sci. Technol. 68 3431–7
[3] Hyer M W 1981 Some observations on the cured shape of thin unsymmetric laminates J. Compos. Mater. 15 175–94
[4] Hyer M W 1981 Calculations of the room-temperature shapes of unsymmetric laminates J. Compos. Mater. 15 296–310
[5] Hyer M W 1982 The room-temperature shapes of four-layer unsymmetric cross-ply laminates J. Compos. Mater. 16 318–40
[6] Dano M-L and Hyer M W 1998 Thermally-induced deformation behavior of unsymmetric laminates Int. J. Solids Struct. 35 2101–20
[7] Giddings P F, Bowen C R, Sala A I T, Kim H A and Iye A 2010 Bistable composite laminates: effects of laminate composition on cured shape and response to thermal load Compos. Sci. Technol. 92 2220–5
[8] Zhang Z, Li Y, Wu H, Chen D, Yang J, Wu H, Jiang S and Chai G 2018 Viscoelastic bistable behaviour of antisymmetric laminated composite shells with time-temperature dependent properties Thin-Walled Struct. 122 403–15
[9] Akira H and Hyer M W 1987 Non-linear temperature-curvature relationships for unsymmetric graphite-epoxy laminates Int. J. Solids Struct. 23 919–35
[10] Ryu J, Kong J-P, Kim S-W, Koh J-S, Cho K-J and Cho M 2013 Curvature tailoring of unsymmetric laminates with an initial curvature J. Compos. Mater. 47 3163–74
[11] Moore M, Ziaei-Rad S and Firouzian-Nejad A 2014 Temperature-curvature relationships in asymmetric angle ply laminates by considering the effects of resin layers and temperature dependency of material properties J. Compos. Mater. 48 1071–89
[12] Cho M and Roh H Y 2003 Non-linear analysis of the curved shapes of unsymmetric laminates accounting for slippage effects Compos. Sci. Technol. 63 2265–75
[13] Zhang Z, Wu H, Ye G, Yang J, Kitipornchai S and Chai G 2016 Experimental study on bistable behaviour of anti-symmetric laminated cylindrical shells in thermal environments Compos. Struct. 144 24–32
[14] Harper B D 1987 The effects of moisture induced swelling upon the shapes of anti-symmetric cross-ply laminates J. Compos. Mater. 21 36–48
[15] Telford R, Katnam K B and Young T M 2014 Analysing thermally induced macro-scale residual stresses in tailored morphing composite laminates Compos. Struct. 117 40–50
[16] Dano M-L and Hyer M W 2002 Snap-through of unsymmetric fiber-reinforced composite laminates Int. J. Solids Struct. 39 175–98
[17] Eckstein E, Pirre A and Weaver P M 2013 Morphing high-temperature composite plates utilizing thermal gradients Compos. Struct. 100 363–72
[18] Hernandez E A P, Kiefer B, Hartl D J, Menzel A and Lagoudas D C 2015 Analytical investigation of structurally stable configurations in shape memory alloy-actuated plates Int. J. Solids Struct. 69 442–58
[19] Taki M S, Tikani R, Ziaei-Rad S and Firouzian-Nejad A 2016 Dynamic responses of cross-ply bi-stable composite laminates with piezoelectric layers Arch. Appl. Mech. 86 1003–18
[20] Lee A J, Moosavian A and Inman D J 2017 Control and characterization of a bistable laminate generated with piezoelectricity Smart Mater. Struct. 26 85007
[21] Firouzian-Nejad A, Ziaei-Rad S and Moore M 2017 Vibration analysis of bi-stable composite cross-ply laminates using refined shape functions J. Compos. Mater. 51 1135–48
[22] Arrieta A F, van Gemmeren V, Anderson A J and Weaver P M 2018 Dynamics and control of twisting bi-stable structures Smart Mater. Struct. 27 25006
[23] Pan D, Ma B and Dai F 2017 Experimental investigation of broadband energy harvesting of a bi-stable composite piezoelectric plate Smart Mater. Struct. 26 35045
[24] Firouzian-Nejad A, Mustapha S, Ziaei-Rad S and Ghayour M 2019 Characterization of bi-stable pure and hybrid composite laminates—an experimental investigation of the static and dynamic responses J. Compos. Mater. 53 653–67
[25] Daynes S, Lachenal X and Weaver P M 2015 Concept for morphing airfoil with zero torsional stiffness Thin-Walled Struct. 94 129–34
[26] Wu Z and Li H 2017 A novel adaptive sun tracker for spacecraft solar panel based on hybrid unsymmetric composite laminates Smart Mater. Struct. 26 115020
[27] Zhang Z, Chen B, Lu C, Wu H, Wu H, Jiang S and Chai G 2017 A novel thermo-mechanical anti-icing/de-icing system using bi-stable laminate composite structures with superhydrophobic surface Compos. Struct. 180 933–43
[28] Li H, Dai F, Weaver P M and Du S 2014 Bistable symmetric laminates Compos. Struct. 116 782–92
[29] Dai F, Zhang B and Du S 2009 A novel bistable hybrid composite laminate 17th Int. Conf. Compos. Mater. [ICCM] http://iccm-central.org/Proceedings/ICCM17proceedings/Themes/Applications/SMART%20COMPOSITES%20%20APPLI/B7.11%20Dai.pdf
[30] Dai F, Li H and Du S 2013 Cured shape and snap-through of bistable twisting hybrid [0/90]_s metal laminates Compos. Sci. Technol. 86 76–81
[31] Daynes S and Weaver P 2010 Analysis of unsymmetric CFRP-metal hybrid laminates for use in adaptive structures Composites A 41 1712–8
[32] Eckstein E N, Pirre A and Weaver P M 2016 Thermally driven morphing and snap-through behavior of hybrid laminate shells AIAA J. 54 1778–88