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Design and manufacturing of highly tailorable pre-bent bi-stable composites

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ABSTRACT

A composite bi-stable structure can deform and maintain its stable states without the need for constant energy inputs. In this paper we describe a class of composite bi-stable shells that makes use of ad-hoc stacking sequences and pre-bending to modify the curvature of the plate. These composite structures possess two types of bi-stability (same direction and opposite direction). The same-direction bi-stable structure is characterized by the presence of two stable states that face the same direction. The same-direction bi-stable configuration can produce a final shape of the shell that effectively minimises the overall volume of the structure and can therefore be used in reconfigurable and stowable antennas. We also describe a procedure to extend the duration of the transition process between the stable states from ~ 1 s to ~ 5 s. This slow transition process can effectively reduce the potential damage to components attached to the bi-stable structure. The slow transition process described here is also relevant to further develop the technology readiness level of engineering applications involving multi-stable composites.

1. Introduction

The continuing development of the aviation and aerospace industry leads to increasing requirements on the performance of airframe structures. Smart materials and structures [1], morphing [2–4], composite bi-stable [5,6] and origami configurations [7–9] are all examples of deployable and deformable structures that have attracted increasing interest within the community of aerospace designers. Although the materials and structures cited above possess fairly high deformation capabilities, they feature however a poor load bearing capacity and are therefore not suitable for primary structural elements. Composite bi-stable structures possess deformation capability and can maintain a stable state without continuous energy input [10–12]. Bi-stable composites have also the advantage of providing large structural deformations and good fatigue resistance, which makes them a potential candidate to develop deformable wings [13–20], deployment mechanisms [21–26] and deployable solar panels [27,28].

Traditional bi-stable structures are generally prepared using asymmetric layers. The design principle of traditional bi-stable composites is shown in Fig. 1. Because of the asymmetric layers and the temperature difference, the thermal residual stresses in the composite layers are asymmetrically distributed along the thickness direction (Z direction). Therefore, two bending moments occur around the X and Y directions. Those bending moments provide two types of possible deformations for the composite plate. When the bi-stable structure bends around one direction (such as the Y direction), it will form an arch in the XZ plane. The arch makes the bending stiffness about the X axis very large, can resist the bending moment around that axis and the bi-stable structure shows stability. Under the action of an external load, the height of the arch decreases continuously. The bending stiffness along the Y direction depends on the height of the arch and will therefore decrease continuously. When the bending stiffness in the Y direction cannot resist the bending moment around Y, the bi-stable structure snaps and changes its shape.

Although traditional bi-stable structures feature many advantages, they also show some drawbacks: 1) traditional bi-stable structures can only attain opposite-direction bi-stable states; 2) the curvature of a traditional bi-stable structure cannot be designed without changing the layers or the architecture of the composite; 3) traditional bi-stable structures with asymmetric layers are significantly affected by environmental factors, especially cold and heat cycles; 4) traditional bi-stable structures deform suddenly and can therefore generate impul-

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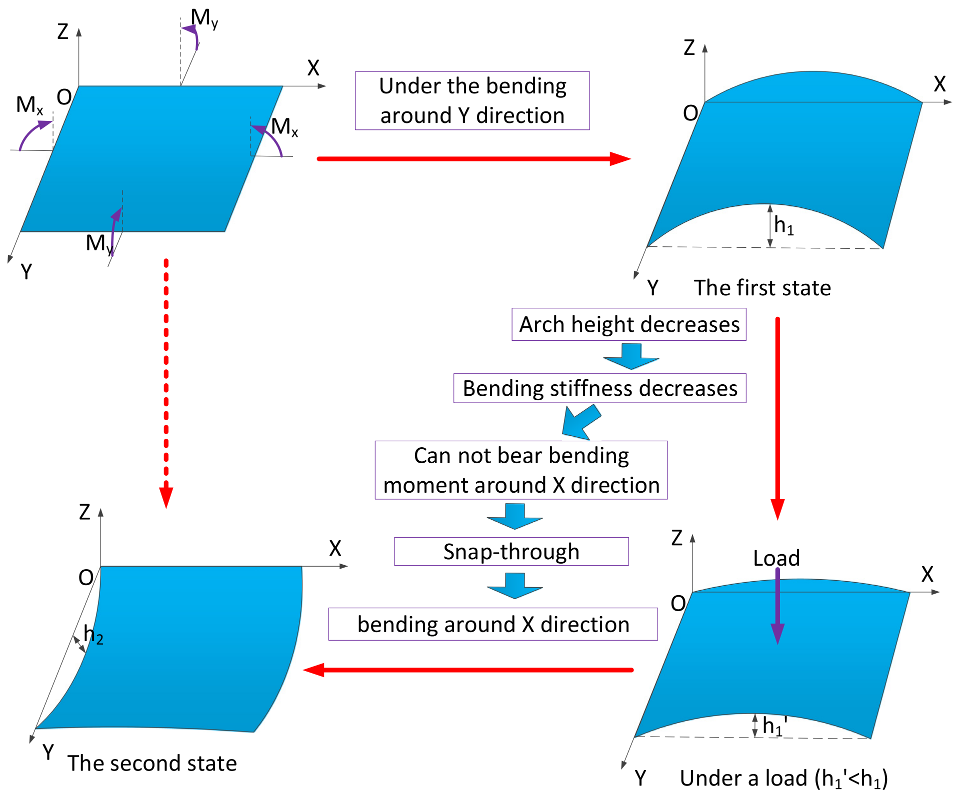

Fig. 1. The principle of a bi-stable structure.

sive loads detrimental to the structural integrity of the components. Although bi-stable structures made of viscoelastic materials can deform slowly, they have however a limited load carrying capacity [29–31]. Introducing damping actively into bi-stable structure also can makes bi-stable structure to deform slowly, however, this method costs a lot and has a complex process [32,33].

In this paper we propose a new type of bi-stable composite based on applying a pre-bent state to the overall structure. By introducing pre-bending into each layer and then gluing them together, the pre-bending bi-stable structure possesses the following advantages: 1) it can be designed as a same- direction bi-stable structure or 2) as a bi-stable structure with symmetrical layers; 3) the curvature can be designed without changing the layers or the properties of the composite; 4) the configuration can feature a slow multi-stable deformation and provides an increased load bearing capacity compared to bi-stable structures made of viscoelastic materials. It should be emphasized that the new bi-stable structure proposed in this work can not only feature the above characteristics, but also exhibit them all at the same time.

2. Pre-bent bi-stable structure and its manufacturing

The basic deformation principle of the pre-bent bi-stable structure is similar to the one of a traditional bi-stable composite plate. However, unlike traditional bi-stable composites whose design envelop is rather constrained, the two bending moments related to the pre-bent configuration are provided by imposing pre-bending deformations that are independent of the layers and thickness of the laminas; this makes possible to tailor the architecture and geometry of the composite. The manufacturing procedure of the pre-bent bi-stable structure is as follows:

1) Prepregs are laid on a cylindrical mold. Different from the traditional bi-stable structure, which must be made of anisotropic prepregs, the pre-bent bi-stable structure can be made of any types of prepregs. The radius of the mold can be in theory arbitrary. In practice, the size of the composite plate should also be considered. Thin plates with a very small curvature cannot provide bi-stability.
2) The assembly of the prepreg rolled around mold is vacuum bagged with a technical vacuum that reaches -1 atm. Curing in autoclave is adopted in this paper to produce two curved thermoset composite thin plates. In reality, any other method suitable to produce a thin plate with a curved surface in a free state also can be used.
3) The two composite curved plates are flattened and then stuck together along the orthogonal direction, or on the same direction using double-sided and/or strong single layer adhesives, silica gel, Z-pin, adhesive film, or secondary curing with resin. Same-direction bi-stability can be obtained by bonding the layers along the same path. More details about the different pre-bent multi-stable topology architectures and principles are explained in section 3.

3. Same/opposite-directions bi-stable structures

The concepts of same and opposite-direction bi-stable are here described. The geometric center of the composite plate is defined as point A (Fig. 2a). The normal lines of the two deformation states pass through point A. It is possible to observe that the normal direction from the geometric center in the first deformation state is the same as the Z-axis direction; the normal direction from the geometric center in the second deformation state is however opposite to the positive Z-

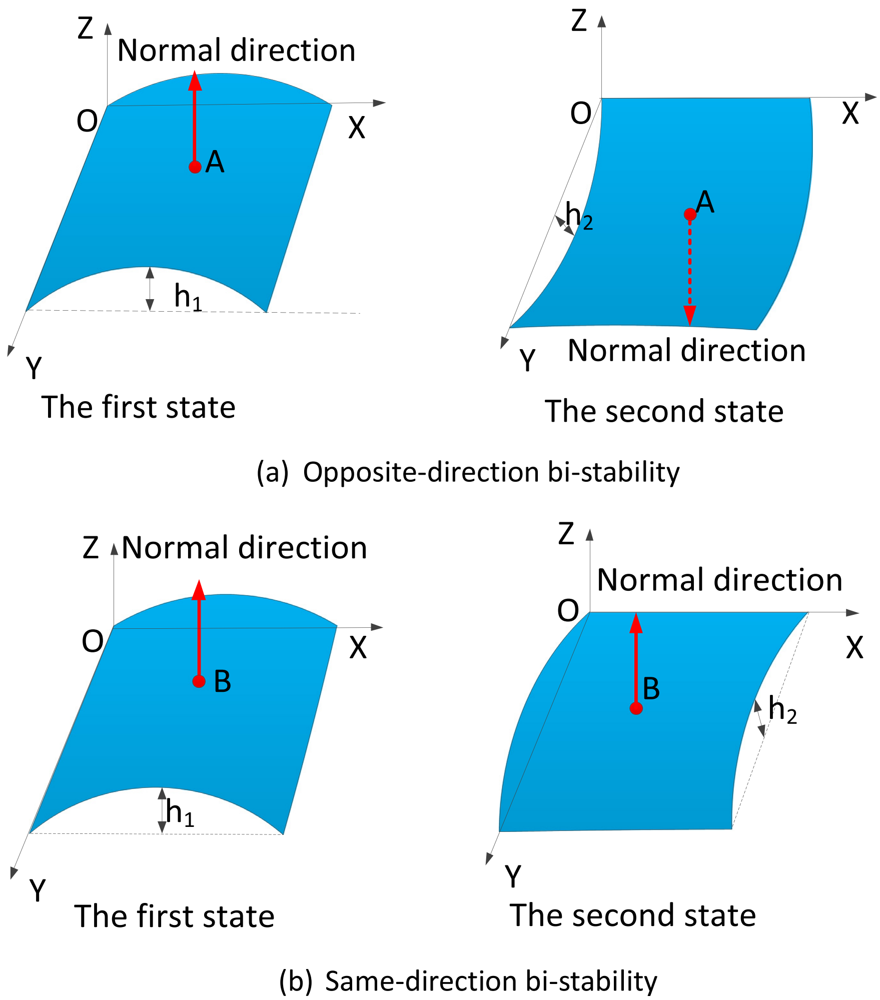

Fig. 2. Same-direction bi-stability or opposite-direction bi-stability.

axis direction. This bi-stable structure is called opposite-direction bi-stable. To date, traditional bi-stable structures mostly belong to this particular opposite-direction bi-stability [5,6,10–12].

In another type of composite plate, the geometric center is defined as point B (Fig. 2(b)). The normal lines of the two deformation states pass through point B. In this case the normal directions through the geometric center in both deformation states are the same as the Z-axis direction. This particular multi-stable architecture will be called here as same-direction bi-stable structure. A pre-bent bi-stable structure can deform either into a same-direction bi-stability, or an opposite-direction bi-stability.

In this work traditional, same-direction and opposite-direction bi-stable structures, as well as pre-bent bi-stable configurations with slow-snapping process have been prepared at a curing temperature of 120 ˚C and curing time of 120 min. The sizes of all the specimens are 20 cm × 20 cm. The materials used are unidirectional TC35/7901 composite and AS4/8552 woven composite. The material parameters provided by the manufacturer are shown in Table 1. The two traditional bi-stable structures are denominated as S-1 and S-2. Cylinder molds with diameters of 20 cm are chosen to make 12 thin composite plates (denoted as C-1, C-2…C-12). These thin composite plates are made using TC35/7901. The pre-bent bi-stable structures (S3-S8) were produced by sticking two thin composite plates together using silica gel along the orthogonal direction. The S-3 and S-4 are the same-direction bi-stable structures with asymmetrical layers, S-5 and S-6 are the opposite-direction ones with asymmetrical layers. The specimens S-7 and S-8 are related to opposite-direction bi-stable structures with symmetrical layers. Details of layers of composite plates and pre-bent bi-stable members are shown in Table 2. The bi-stable structures with asymmetrical and symmetrical layers are shown in Fig. 3.

Fig. 4 shows all the deformed states of the bi-stable structures S1-S6. Compared with S-1 and S-2, the normal directions of the two deformed states have the same directions of the specimens S-3 and S-4; the normal directions of the two deformed states in S-5 and S-6 are along the opposite directions. The specimens S-3 and S-4 are therefore same-direction bi-stable structures, while S-5 and S-6 are exam-

Table 1
Material parameters for the composites.

composite	E_{11} (GPa)	E_{22} (GPa)	ν_{12}	V_f	Thickness (mm)	Curing temperature (℃)	Curing time (minutes)
TC35/7901	115.00	12.00	0.23	0.67	0.030	120	90
AS4/8552	68	66	0.20	0.55	0.425	180	90

Table 2
The layers of pre-bending bi-stable and composite plates.

Bi-stable structures	Deformation direction	Stacking sequences	Composite plates	Layers	Radius of curvature (mm)
S-1	\	[0/0/0/0/90/90/90/90]	\	\	100
S-2	\	[45/45/45/45/−45/−45/−45/−45]	\	\	100
S-3	Same	[0/0/0/0/90/90/90/90]	C-1	[0/0/0/0]	100
			C-2	[0/0/0/0]	100
S-4	Same	[45/45/45/45/−45/−45/−45/−45]	C-3	[45/45/45/45]	100
			C-4	[45/45/45/45]	100
S-5	Opposite	[0/0/0/0/90/90/90/90]	C-5	[0/0/0/0]	100
			C-6	[0/0/0/0]	100
S-6	Opposite	[45/45/45/45/−45/−45/−45/−45]	C-7	[45/45/45/45]	100
			C-8	[45/45/45/45]	100
S-7	Opposite	$[0/90/90/0]_s$	C-9	[0/90/90/0]	50
			C-10	[90/0/0/90]	50
S-8	Opposite	$[45/-45/-45/45]_s$	C-11	[45/−45/−45/45]	150
			C-12	[−45/45/45/−45]	150

ples of opposite-direction bi-stable plates. Those features demonstrate that pre-bent bi-stable structures can realize either a same-direction bi-stability, or an opposite-direction bi-stability.

The bending deformation of plates C-1 and C-2 is along the side length direction, while the bending deformation of structures S-3 occurs along the diagonal direction. The bending deformation of plates C-3 and C-4 occurs along the diagonal direction, but the bending deformation of structure S-4 is only along the side length. This means that the angle between the bending deformation of the same-direction bi-stable structures and the bending deformation of the composite plates is 45 degrees. The bending deformation of the opposite-direction bi-stable structure and the bending deformation of the composite plates are along the same direction.

The engineering significance of same-direction bi-stable structure is to effectively reduce the total volume of deployed/stowed structures. As shown in Fig. 5, the height of the opposite-direction bi-stable composite along the Z-direction should be $h_1 + h_2$, while the height of the same-direction bi-stable structure along the Z-direction is the maximum value between h_1 and h_2 ($h_1 > 0$, $h_2 > 0$). When the dimensions of opposite-direction and same-direction bi-stable structures in the X-Y plane are basically the same, the volume of the same-direction bi-stable structure becomes smaller, and this has some implications to engineer deployable structures.

Another advantage of the same-direction bi-stable structures lies in potential applications for reconfigurable antennas. By designing the size of the plate and the curvature, the frequency of the signal received by the reconfigurable antenna can even be tuned. As shown in Fig. 6 (a), the concave surface related to the first state becomes (i.e., the signal receiving surface) the convex surface after snap-through for the opposite-direction bi-stable structure. In the case of snap-through, signal cannot be received as the feed source must be positioned on the

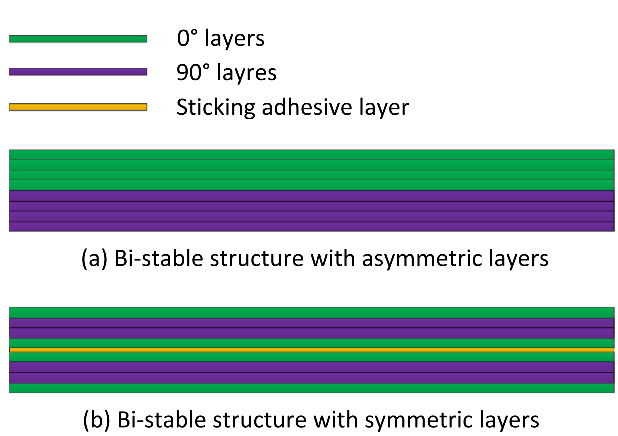

Fig. 3. The bi-stable structures with asymmetrical and symmetrical layers.

concave side which causes the frequency of the signal to remain unchanged [34]. For the same-direction bi-stable structure of Fig. 6 (b), the concave surfaces of the two deformed states can always face the signal receiving direction. At this time, signals of another frequency can also be received.

4. Design envelope of layers and curvature

As pointed out above, the bending moment of the conventional bi-stable structure is generated by thermal residual stresses asymmetrically distributed along the thickness direction. When symmetrical layers are used the bending moment becomes zero, therefore bi-stability cannot be obtained. The bending moment of pre-bent bi-stable structure is provided by the pre-bending deformation in curved composite plates. The curvature is related to the pre-bending curvature of the composite plate and it is independent of the thickness and architecture of the layers. Therefore, the curvature of the pre-bend bi-stable structure can be easily manipulated by changing the curvature of the mold.

In order to verify this, two other opposite-direction bi-stable structures (S-7, S-8) shown in Fig. 7 have been produced using four composite plates (C-9 to C-12). The composites are TC35/7901. The performance parameters of composites are shown in Table 3. Mainly provided by the manufacturer.

In the sticking process of composite laminates, the first composite plate is curved and assumes its radius as κ_0. The second composite plate is straight, which means that its radius of curvature is 0. After sticking, the two composite plates affect each other, bending occurs and deformation coordination is maintained. Assuming that the bending moment of the first composite plate is M, while the second must be -M. Then the change of the radius of curvature of these two composite plates are:

$$\begin{cases} \Delta\kappa_1 = \frac{M}{D_1} \\ \Delta\kappa_2 = -\frac{M}{D_2} \end{cases} \tag{1}$$

Where D_1 and D_2 are the bending stiffness of the first and second composite plates, respectively.

Under the action of bending moments, the curvature change directions of the two composite plates are opposite to the initial curvature of the first composite plate. Therefore:

$$\begin{aligned} &\kappa_0 - \Delta\kappa_1 + \Delta\kappa_2 = 0 \\ &\Rightarrow M\left(\frac{1}{D_1} + \frac{1}{D_2}\right) = \rho_0 \\ &\Rightarrow M = \frac{D_1 D_2}{D_2 + D_1}\rho_0 \end{aligned} \tag{2}$$

For symmetrically laminated composite plates, $D_1 = D_2$. Therefore:

$$\begin{cases} M = \frac{D_1}{2_1}\rho_0 \\ \Delta\kappa_1 = -\Delta\kappa_2 = \frac{\kappa_0}{2} \end{cases} \tag{3}$$

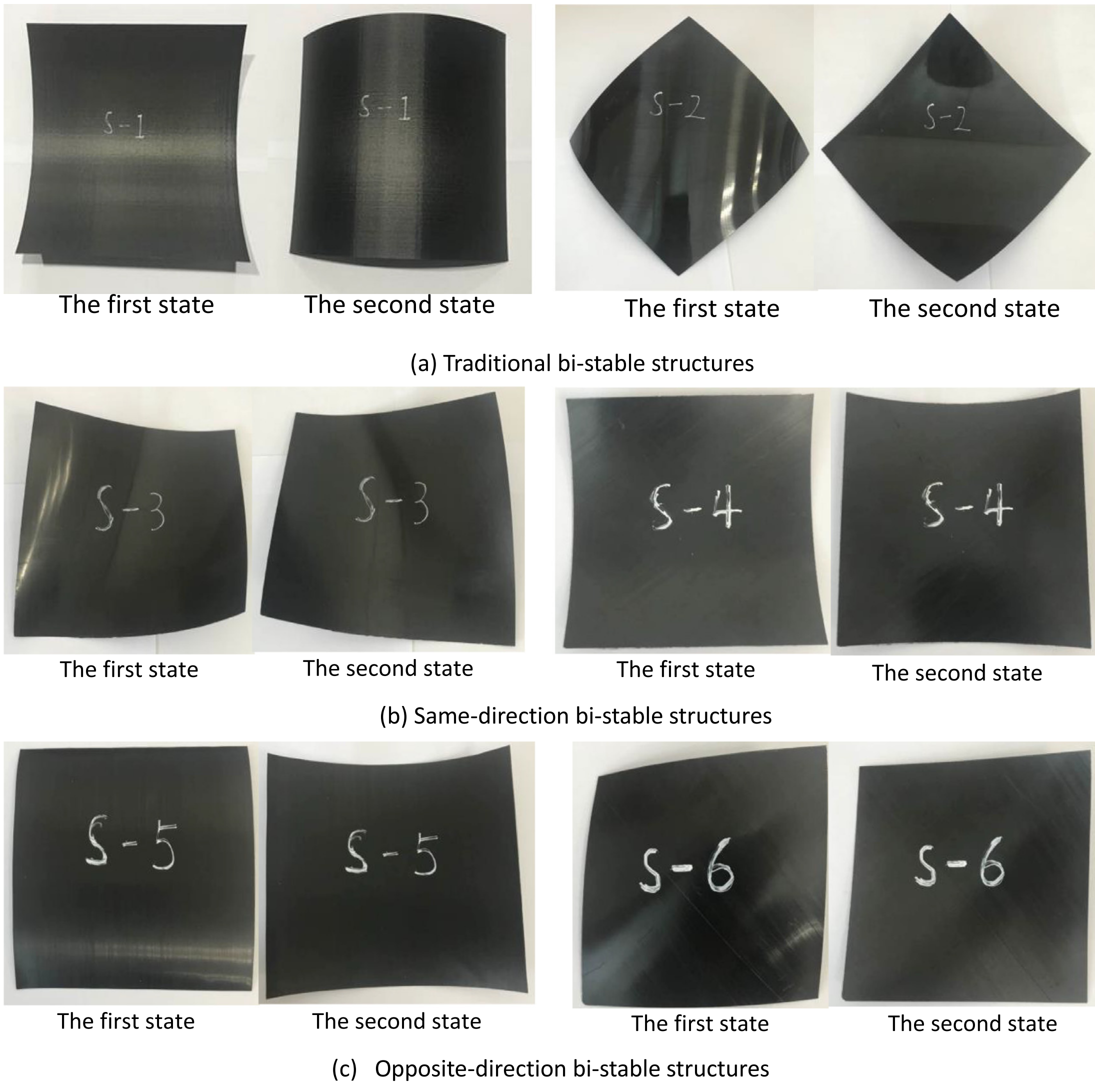

Fig. 4. The various shapes of bi-stable structures (S-1 ~ S-6).

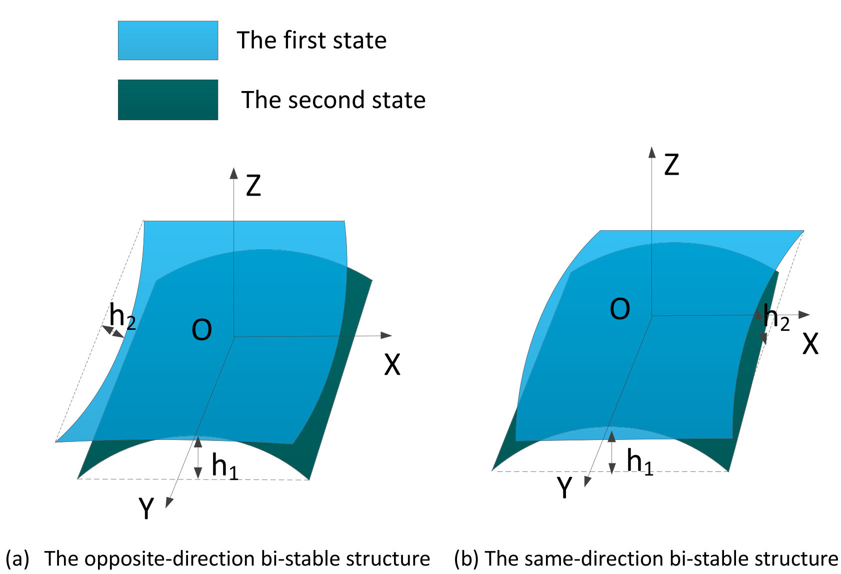

Fig. 5. Comparison of opposite-direction and same-direction bi-stable structures.

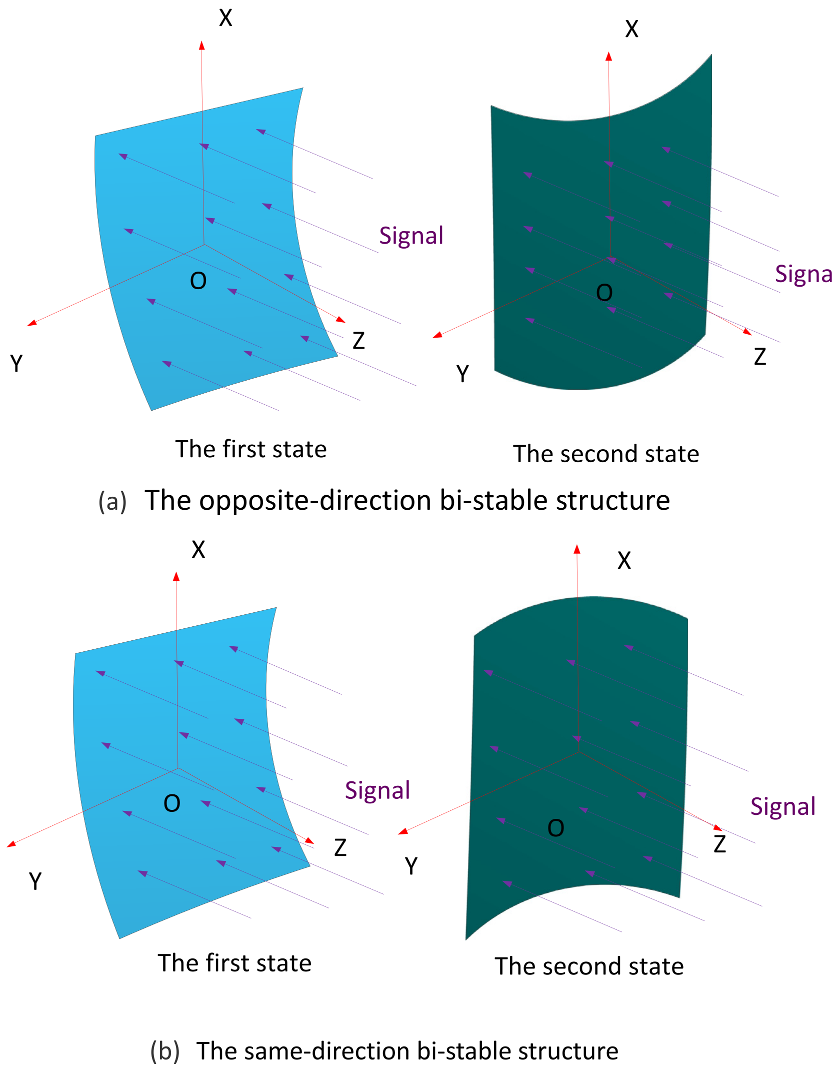

Fig. 6. The application of opposite-direction and same-direction bi-stable structure in reconfigurable antenna.

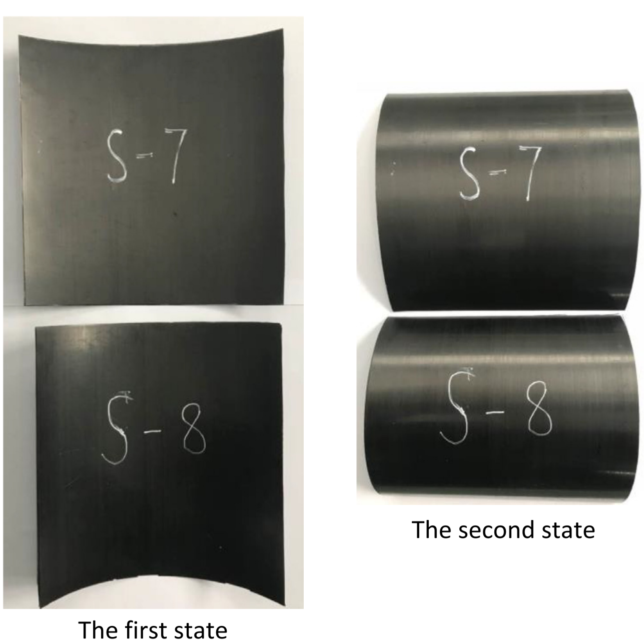

Fig. 7. The shapes of S-7 and S-8.

The calculation shows that the initial curvatures of C-9 and C-10 are 20 μm^{-1}. The initial curvatures of C-11 and C-12 are 6.67 μm^{-1}. According to Eq. (3), the curvatures of S-7 and S-8 are 10 μm^{-1} and 3.34 μm^{-1} after stacking. In the experiment, the curvature radii of S-7 and S-8 measured are 9.12 μm^{-1} and 2.88 μm^{-1}, respectively, and the deviations are 8.80% and 13.77%, respectively. There are two reasons for the deviations: the first reason is that the uneven heating during the curing process of composite plate leads to the change of initial curvature. The second reason is that silicone rubber has certain thickness and bending rigidity. However, they are ignored for the convenience of calculation.

According to micromechanics theory of composite materials [35], the bending stiffnesses and the bending moments of C-9 ~ C-12 after sticking are shown in Table 4. The stress distribution in the stuck composite plates are shown in the Fig. 8. It is worth noting that for S-7, the layer in the X direction is $[0/90/90/0]_s$ and $[90/0/0/90]_s$ in the Y direction. The σ_{22} in X and Y of the pre-bent bi-stable composites are 0. Therefore, only σ_{11} are show in Fig. 8. Meanwhile for S-8, the plies and the stress distributions in the X and Y directions are antisymmetric. There, only the stresses in X direction, including σ_{11} and σ_{22}, are show in Fig. 8.

Comparison of the deformation states of the structures S-5 to S-8 show that the pre-bent bi-stable structures can have either symmetrical layers or asymmetrical layers with varying curvatures. Considering

Table 3
The mechanical parameters of the composites.

composites	E_{11} (GPa)	E_{22} (GPa)	μ_{12}	G_{12} (GPa)
TC35/7901	135.50	10.40	0.230	3.56

Table 4
The bending stiffnesses and the bending moments.

Composites	Bending Stiffness (N.mm^2)	Bending moment (N.mm)
C-9	3472.22	34.72
C-10	750.75	7.51
C-11	443.26	4.43
C-12	443.26	4.43

that asymmetrical layer will affect the curvature because of the asymmetrical distribution of the thermal residual stresses along the thickness, symmetrical layers are generally recommended for better control of the curvature and deformation. The significance of using symmetrical layers also lies in the fact that the deformation is less affected by environmental factors, especially temperature; this is important to ensure a normal operational mode of the structure even in harsh environment (space, for example). Although thermal residual stresses change, the overall bending moment is zero because of the presence of the symmetric layers. When using a traditional bi-stable asymmetric layers composite the temperature change will however affect the asymmetrically distributed thermal residual stresses and cause the bending moment to change, therefore ultimately affecting the curvature of the structure.

5. Slow-deformation process of the pre-bent bi-stable structures

The use of a sticking adhesive layer in pre-bent bi-stable structures provides the possibility to realize some special features. Silicon rubber with a thickness of 0.1 mm has been used to mitigate the snap-through process. In the experiment, Thin plates with sizes of 20 cm × 20 cm are made using AS4/8552 woven composite. When the displacement load is applied at 5 cm/s, the traditional bi-stable and pre-bent bi-stable structures will reach the lowest point in about 1 s. The traditional bi-stability will jump when it is close to the lowest point, the snap-through process of traditional bi-stable states is usually lower than 1 s, almost instantaneous. While the pre-bent bi-stable structure will hysteresis and deform slowly when it reaches the lowest point. This makes the transient deformation of bi-stable structures lasting approximately 5 s (see Fig. 9). In applications such as reconfigurable antennas, the sharp snap-through process may adversely damage the components attached to the bi-stable structure. By using a pre-bent bi-stable structure with a slow transition time damage to components attached to the composite can be effectively reduced.

6. Conclusions

This paper has presented the design and manufacturing of pre-bent composite bi-stable structures. Compared to traditional bi-stable composites whose orthogonal bending moments are generated through asymmetrically distributed thermal residual stresses along the thickness direction, the bending moments of pre-bent bi-stable structures are provided by applying a deformation caused by bending. This feature offers a significant freedom to use and obtain different layers and curvatures.

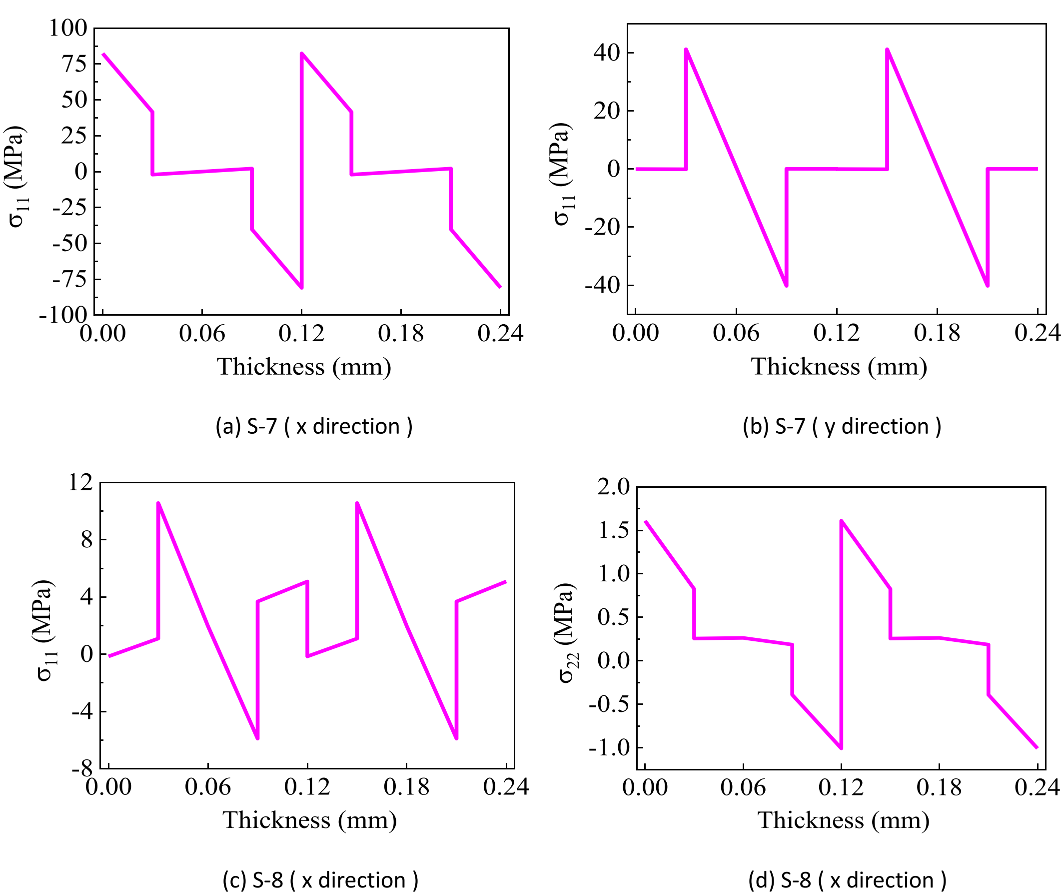

Fig. 8. The stresses distribution in the stucked composite plates.

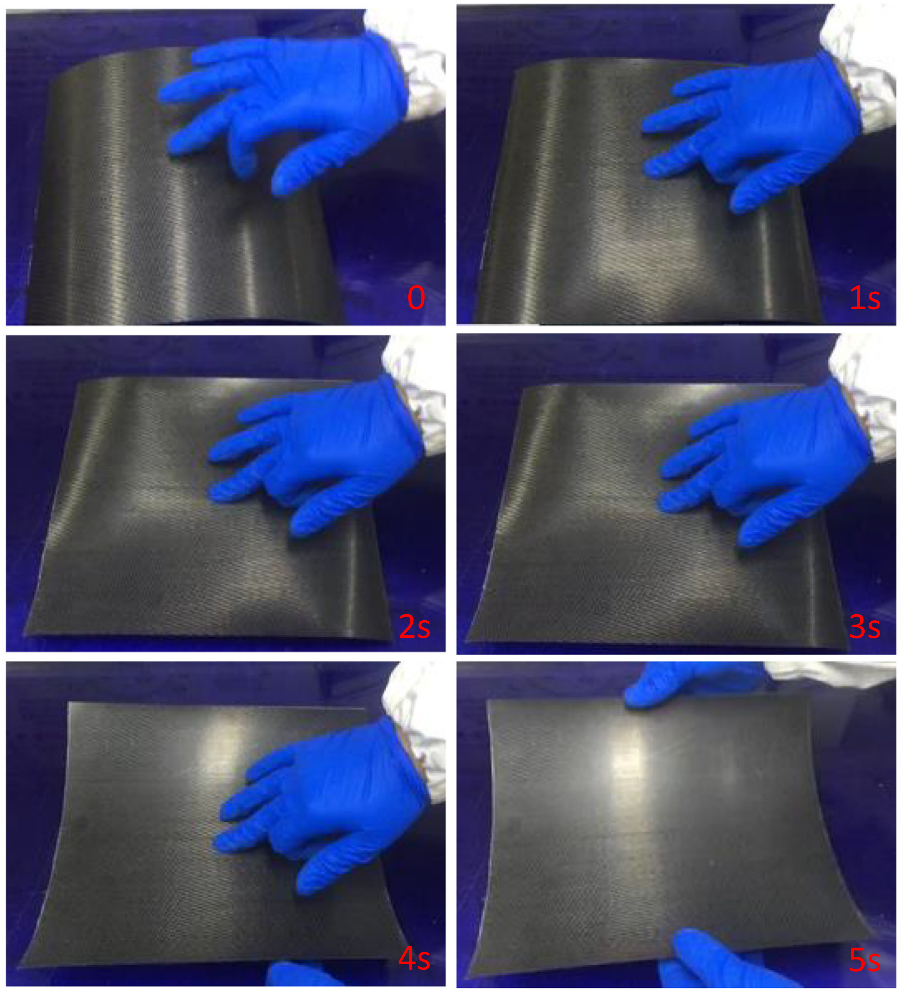

Fig. 9. Pre-bending bi-stable structure with slow-deformation process.

While traditional bi-stable structures can only realize opposite-direction bi-stabillity, same-direction bi-stable composites are possible and have been here described and manufactured. The fact that the two states of the same-direction bi-stable structure face the same direction enables concave surfaces of any reconfigurable surface (antenna) to receive signal in all geometrical configurations. The frequency of signals received by the reconfigurable antenna can also be changed through an appropriate selection of the curvatures and sizes. In addition, a same-direction bi-stable structure can effectively reduce the total volume of the structure with beneficial effects for deployable structures.

While traditional bi-stable structures can only be designed with asymmetric layers, the layers of the pre-bent bi-stable structures can also be symmetric. The significance of using symmetrical layers is that it they offer a mechanical performance less sensitive to environmental factors like temperature, which can ensure a normal service state for the structural element itself. For the pre-bent bi-stable structures developed in this work, the deformation process (snap-through) between two stable states can be extended from 1 s to 5 s circa. This fairly slow transition process between two states would cause less damage to the components attached to the bi-stable structure, and to the global structure itself.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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