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# Shape Memory Alloy-Actuated Bistable Composites for Morphing Structures

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## ABSTRACT

Laminated composites with orthogonally-applied mechanical prestress have been shown to exhibit two stable shapes where each shape is influenced by only one prestrained lamina. The application of mechanical prestress is associated with an irreversible non-zero stress state; when combined with smart materials with controllable stress-states, this results in multifunctionality in morphing composites. This study presents an experimental characterization of the shape transition or snap-through in mechanically-prestressed bistable laminates. Measurements, conducted using tensile testing and 3D motion capture, show that snap-through in these laminates is a multi-stage phenomenon. An active bistable morphing composite is demonstrated using NiTi shape memory wire actuators in push-pull configuration; activation of one wire resets the second wire as the composite morphs. The set of shape memory actuators not only actuate the composite in both directions, but also act as dampers that enable vibration-free shape transition.

**Keywords:** Bistable, morphing, shape memory alloy, residual stress, fiber-reinforced elastomer

## 1. INTRODUCTION

Morphing structures present opportunities in aircraft<sup>1,2</sup> and automobiles<sup>3</sup> as lightweight structural panels that change shape to optimize performance over a broad range of operating conditions. Curved bistable laminated composites are candidates for morphing as they can hold deformed shapes in the absence of actuation energy and require actuation only for shape transition. Shape transformation can be achieved in bistable composites by incorporating smart laminae that have controllable stress states.

Thermally-cured fiber-reinforced polymeric laminates can exhibit multiple curved shapes that are influenced by fiber-orientation, curing size, and geometry; multi-stability is associated with residual stress arising from a difference in thermal contraction of the matrix and fiber during manufacturing. The stable shapes are strongly coupled because residual stress is a global property and is a function of a single variable, i.e., curing temperature. Therefore, these shapes cannot be designed individually. Chillara et al.<sup>4</sup> developed curved composites by inducing mechanical prestress in select laminae, thereby enabling the design of adaptive features in the stress-free laminae. Prestress was applied using elastomeric matrix composites (EMC). These stretchable EMCs have fibers aligned in the width direction (90° orientation) and therefore exhibit near-zero in-plane Poisson's ratio.<sup>5</sup> Bistability can be achieved by laminating two pre-stretched 90° EMCs on either face of a stress-free layer (Figure 1(a)). When the 90° EMCs are oriented such that the respective fibers in each EMC are at 90° and 0° with respect to the *X* axis, the resulting stable shapes are cylindrical and orthogonal.<sup>6</sup> The stable shapes are weakly coupled when the prestressed laminae are orthogonal to each other; each weakly-coupled shape is influenced by only one prestressed lamina. Further, the bistability regime for such a composite is a function of two sources of residual stress and is therefore different from the regime seen in similar thermally-cured FRP laminates.

Actuation of a bistable composite typically involves switching or snap-through between the stable shapes. The actuation approach for minimal energy consumption depends on the composite's boundary conditions. For

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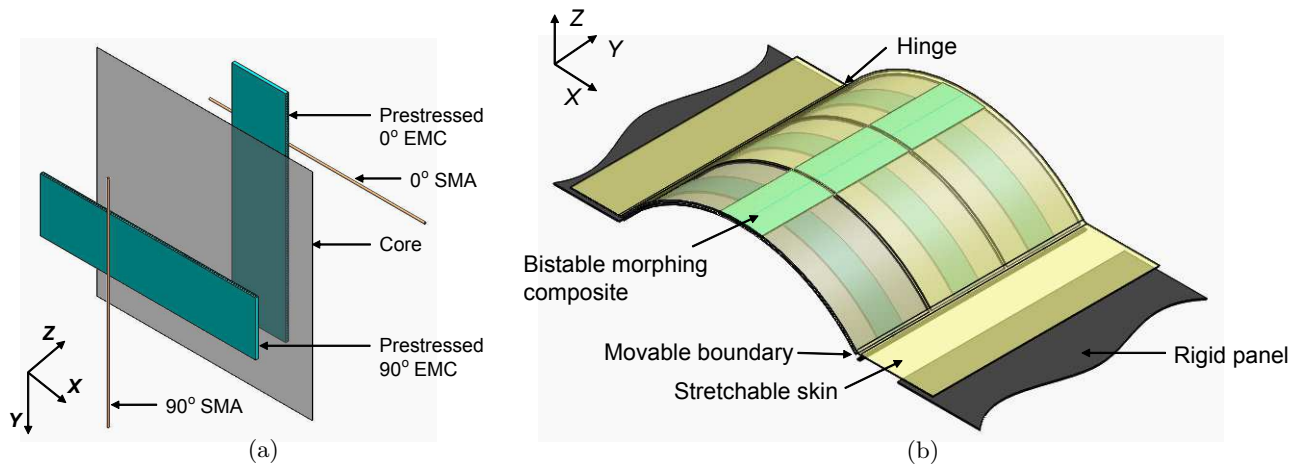


Figure 1: (a) Schematic of a mechanically-prestressed bistable composite actuated by shape-memory alloy wires (SMA) and (b) concept for bistable composites configured in a morphing structure.

instance, a composite element in a larger structure, as in Figure 1(b), can be actuated by a pair of flattening forces in the axial ( $X$ ) direction. Another approach is to apply a transverse point load or pressure in the  $Z$  direction. A third approach is to flatten the composite by applying an in-plane load. Embedded smart material actuators can be a source of in-plane forces. Piezoelectrics and shape memory alloys are attractive because they enable compact and lightweight laminated composites. Piezoelectric actuators have low strain capacity of 0.1 % and are suitable for small deflections.<sup>7,8</sup> For larger curvatures, shape memory alloys are candidates due to their high recoverable strain (up to 6%).<sup>9–11</sup>

This paper presents an experimental procedure to quantify the energy requirements for snap-through in a bistable composite. Tensile tests are conducted on fabricated passive composites and snap-through is recorded using a 3D motion capture system. The energy associated with the measured force-deflection curves is compared with simulations conducted by Chillara and Dapino<sup>12</sup> for the axial loading case. An active bistable composite is demonstrated using shape memory alloy actuators. SMA wires are installed in the 90° and 0° orientations on either face of a composite to create a push-pull actuation system (as in Figure 1(a)). Antagonistic actuation is achieved by installing one Martensitic SMA in the detwinned state and the other in the twinned state; Austenite and Martensite are the respective high and low temperature phases of an SMA. Activation of one SMA resets the other SMA while actuating the composite. Chillara and Dapino<sup>13</sup> modeled the phase transformation of SMAs in a push-pull configuration as a function of composite curvature.

## 2. EXPERIMENTS

The experimental procedure involves flattening a passive curved composite in a uniaxial tensile tester until the composite experiences snap-through (Figure 2). It is sufficient to record actuation from the first shape to the second since the stable shapes are weakly coupled. The composite is hinged at the midpoints of its straight edges  $\overline{AD}$  and  $\overline{BC}$ . The head of the load frame (Test Resources Inc.) moves vertically and measures the force profile using an inline 200 N load cell. Since the frame measures displacement only up to snap-through, composite displacement is also measured by a 3D motion capture system. Hemispherical reflective markers of 3 mm diameter are placed at the center ( $O$ ) and the four vertices ( $A, B, C, D$ ) of the composite. A set of four still cameras (OptiTrack, Natural Point Inc.), with a resolution of 1.3 megapixels, is used to record the position of each marker through coordinate triangulation. The cameras are mounted to have a capture volume of  $1.1 \times 1.1 \times 1.1$  (m). Square test samples, with dimensions listed in Table 1, are fabricated in the 90° EMC/core/0° EMC configurations with equal EMC prestrains of 0.4, 0.6, and 0.8. Quasistatic tensile tests are conducted on each sample by moving the frame head at a rate of 5 mm/min until the composite snaps into its second shape. The load frame and the motion capture system are synchronized to record displacement at 10 frames per second.

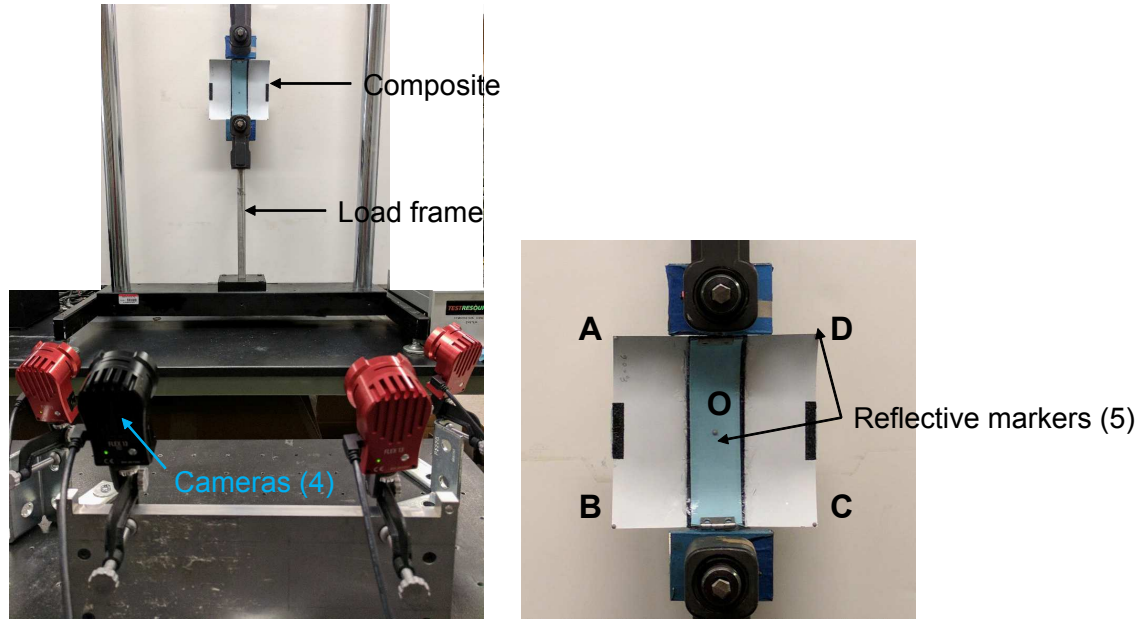


Figure 2: Experimental setup to characterize shape transition in a bistable composite.

Table 1: Measured material properties and dimensions of the fabricated composites.

Lamina	$E_1$ (MPa)	$E_2$ (MPa)	$G_{12}$ (MPa)	$\nu_{12}$	$\nu_{21}$	Lg. (mm)	Wd. (mm)	Ht. (mm)
90° EMC	Nonlinear	0.4	1.2	0	0	152.4	38.1	2.032
Core	200,000	200,000	78,125	0.28	0.28	152.4	152.4	0.127
0° EMC	0.4	Nonlinear	1.2	0	0	38.1	152.4	2.032

### 3. RESULTS AND DISCUSSION

Prestrain in the 90° and 0° EMCs is denoted by  $\epsilon_{90}$  and  $\epsilon_0$  respectively. The initial cylindrical shape of a composite with  $\epsilon_{90} = \epsilon_0 = 0.8$  is such that edges  $\overline{AD}$  and  $\overline{BC}$  are straight (Figure 2). Figure 3 shows the average out-of-plane displacement of  $\overline{AD}$  and  $\overline{BC}$  as a function of time;  $w$  is the out-of-plane displacement of an arbitrary point on the geometric mid-plane of the composite. The first transition corresponds to a switch in the sign of  $w_{AD}$  while  $w_{BC}$  remains positive. Therefore, one half of the composite transitions into the second shape before the other. The second transition stage occurs when  $w_{BC}$  switches sign, thereby resulting in the completion of snap-through. Potter et al.<sup>14</sup> observed a similar multi-stage snap-through response in thermally-cured FRP laminates.

The actuation energy ( $W_h$ ) of the composite is calculated as the product of the force measured by the load cell and the stroke required to flatten the composite. Figure 4 shows actuation energy plotted as a function of  $w$ . The energy profile has two peaks, indicating two stages in snap-through. The results are compared with simulations based on an analytical laminated-plate model in which the stable shapes are calculated as a function of actuation force using strain energy minimization. High-order displacement polynomials are used to model the snap-through load. The model is described in detail by Chillara and Dapino.<sup>12</sup> The simulated energy profile is obtained as a function of a monotonically increasing axial force (force-controlled). Therefore, there is sharp drop in  $w$  but not  $W_h$ . The simulations compare well with experimental data. The simulated snap-through energy is higher than the measured value (higher peak) by 7.7%, 12.1%, and 6.7% in samples with prestrains of 0.4, 0.6, and 0.8, respectively. The corresponding error in the simulated  $w$  at snap-through relative to the measured displacement is 6.2%, 2.43%, and -8.8%.

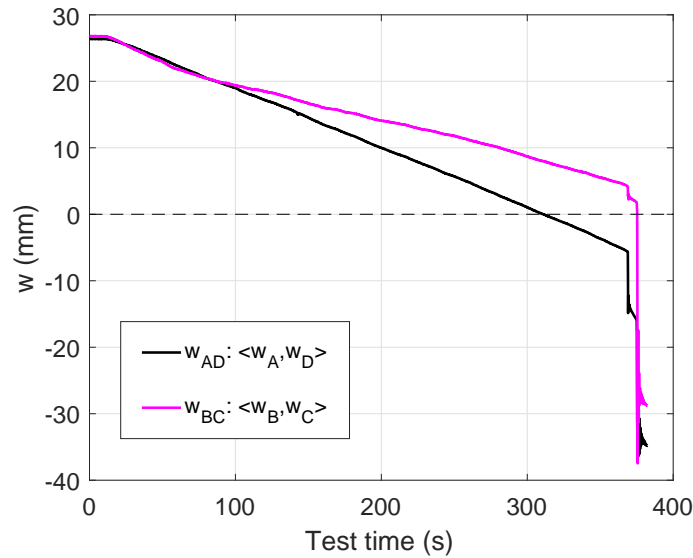


Figure 3: Measured out-of-plane displacement of edges  $\overline{AD}$  and  $\overline{BC}$  in the composite.

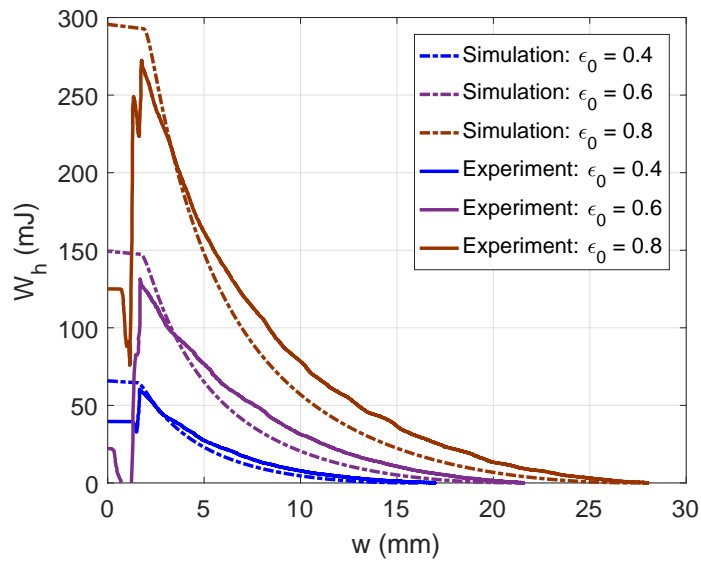
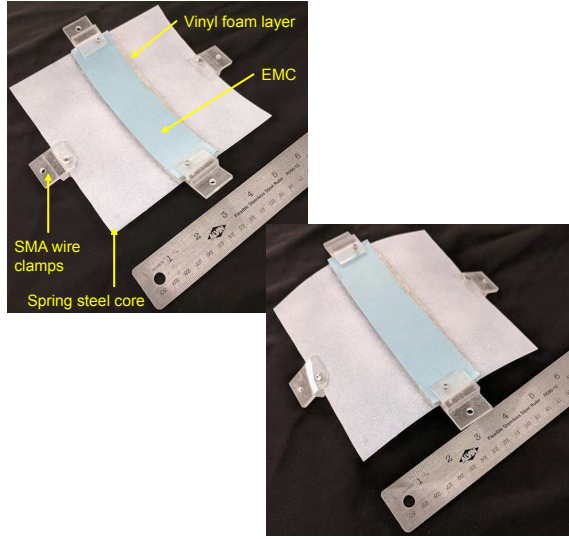


Figure 4: Work done on the composite by an axial force as a function of EMC prestrain  $\epsilon_0$  for  $\epsilon_{90} = \epsilon_0$ .

#### 4. DEMONSTRATION OF AN SMA-ACTUATED BISTABLE COMPOSITE

In-plane actuation has been shown to be relatively energy efficient when the actuator is mounted on the convex face.<sup>12</sup> This mode of actuation is made practically viable by smart materials. In this section, in-plane actuation is demonstrated using shape memory alloy wires in the configuration shown in Figure 1(a).

A square composite sample is fabricated with dimensions as shown in Table 1. A 3.2 mm thick vinyl foam layer is added between the EMC and the spring steel core. The foam layer is brittle and its modulus is measured to be 25 MPa. However, when bonded to the steel core, it is flexible and serves to reduce the interlaminar shear between the EMC and the core. Figure 5(a) shows the stable shapes of the composite. The value of prestrain applied to both EMCs is 0.35. The maximum out-of-plane displacement, when the composite is curved about the  $X$  and  $Y$  axes, is measured to be 15 mm and 14 mm respectively; assuming constant curvature,



(a)

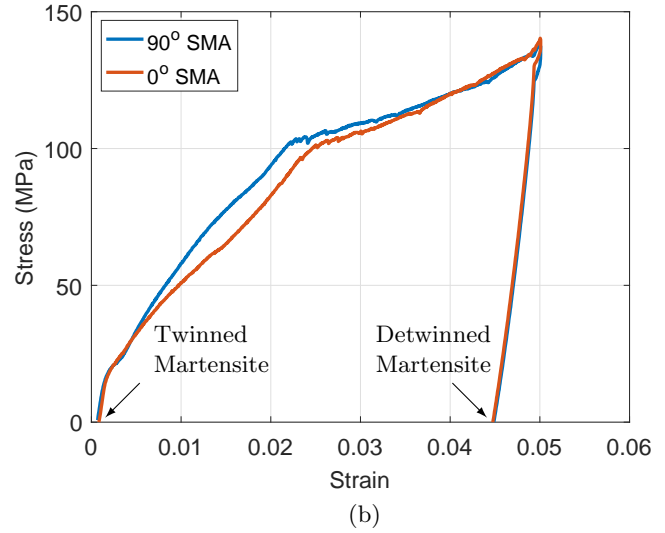


Figure 5: (a) Stable shapes of a passive bistable composite sample and (b) room temperature (25°C) response of the 90° and 0° SMA wire actuators.

Table 2: Measured material properties of a NiTi-6 shape memory alloy wire.

$E_M$ (GPa)	$E_A$ (GPa)	$C_M$ (MPa/° C)	$C_A$ (MPa/° C)	
20	40	6.3	7.5	
$A_s$ (° C)	$A_f$ (° C)	$M_s$ (° C)	$M_f$ (° C)	$\epsilon_L$
48	62	23	7	0.045

the corresponding curvatures are  $0.0051 \text{ mm}^{-1}$  and  $0.0048 \text{ mm}^{-1}$  respectively. NiTi-6 SMA wires of 0.58 mm diameter (Fort Wayne Metals Inc.), with measured material properties as listed in Table 2, are installed on the composite at a distance of 5.3 mm from the geometric mid-plane. The stress-strain response of the trained SMA wires at room temperature is shown in Figure 5(b). Each SMA wire is held at its ends using polycarbonate clamps and its in-plane motion is constrained using plastic bridges as shown in Figure 6. With the composite curved about the  $X$  axis, the 90° and 0° SMAs are installed in the detwinned Martensite and twinned Martensite phases respectively. Each wire is connected to a DC power supply rated at 10 A and 30 V.

The SMA wires are actuated by supplying a constant current. In the first step, only the 90° SMA is heated until the composite snaps from its curvature about  $X$  to curvature about  $Y$ . Composite shape is recorded at 100 frames per second using a motion capture system with reflective markers installed at points  $A, B, C$ , and  $D$  as shown in Figure 2. Out-of-plane displacement is reported as the average of  $w_A, w_B, w_C$ , and  $w_D$  relative to  $w_O$ . The influence of the 0° SMA on the post snap-through response of the composite is plotted in Figure 7. The dotted lines indicate the composite's response in the absence of the 0° SMA. It is observed that the time required for shape transition is higher in the presence of the 0° SMA. This SMA dampens the post snap-through vibrations to yield a second stable shape. Therefore, the demonstrated SMA actuators not only provide two-way actuation, but also enable an almost vibration-free shape transition. The resulting curvature is smaller in the presence of the 0° SMA since a fraction of the composite's strain energy is spent in detwining the SMA. The loss in curvature is minimal when the SMA is designed to undergo complete transformation from twinned to detwinned Martensite. Lastly, it is seen that shape transition occurs in two distinct stages. Such a response is expected because a non-uniform contraction of the 0° SMA, due to sliding friction in the bridges, can result in partial snap-through.

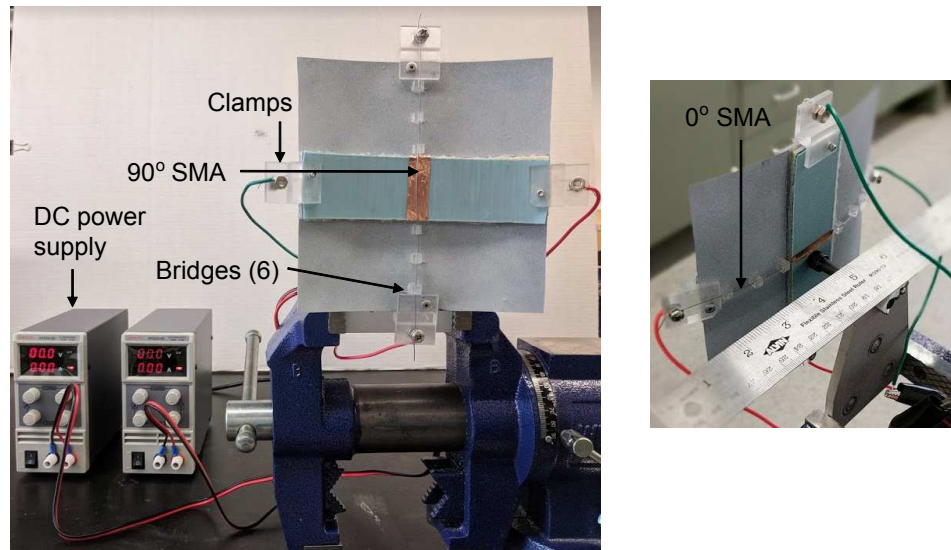


Figure 6: Setup for a shape memory alloy-actuated bistable composite.

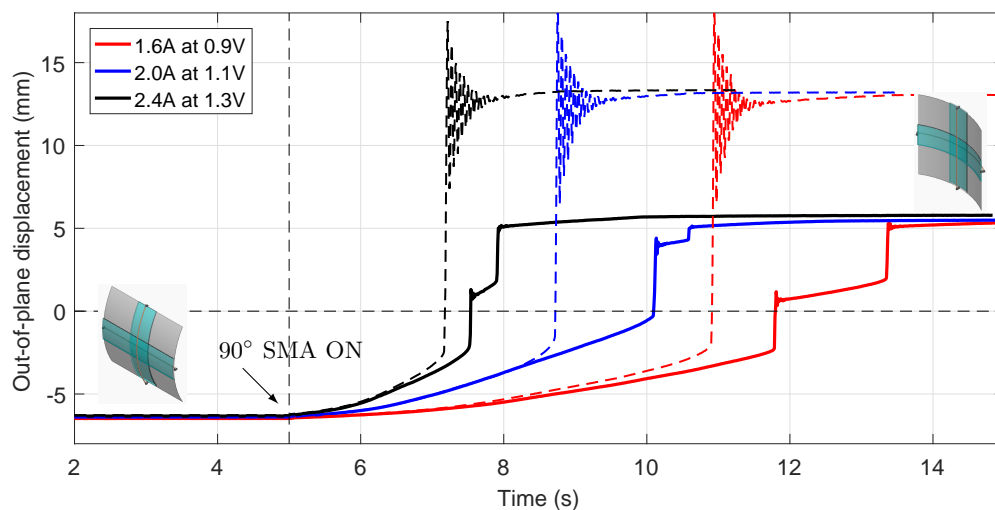


Figure 7: Snap-through transition in a shape memory alloy-actuated bistable composite. Dotted lines indicate the response in the absence of a  $0^\circ$  SMA.

Figure 8 shows snap-through and snap-back to demonstrate the complete operation of the composite. The response is plotted for three values of constant current. The time taken for complete snap-through is 8.4s, 5.5s, and 3s for an applied current (power) of 1.6 A (1.44 W), 2 A (2.2 W), and 2.4 A (3.12 W) respectively. The corresponding times for snap-back are measured to be 6.4s, 3.5s, and 2.5s respectively. Partial snap-through can be minimized or eliminated by maximizing the power applied to the SMA and by minimizing friction.

## 5. CONCLUDING REMARKS

A mechanically-prestressed laminated composite, in which bistability is achieved by applying prestress to select laminae, is presented as an alternative to thermally-cured FRP bistable laminates. In composites with a  $90^\circ$  EMC/core/ $0^\circ$  EMC configuration, the stable shapes are weakly coupled and can be tailored independently using



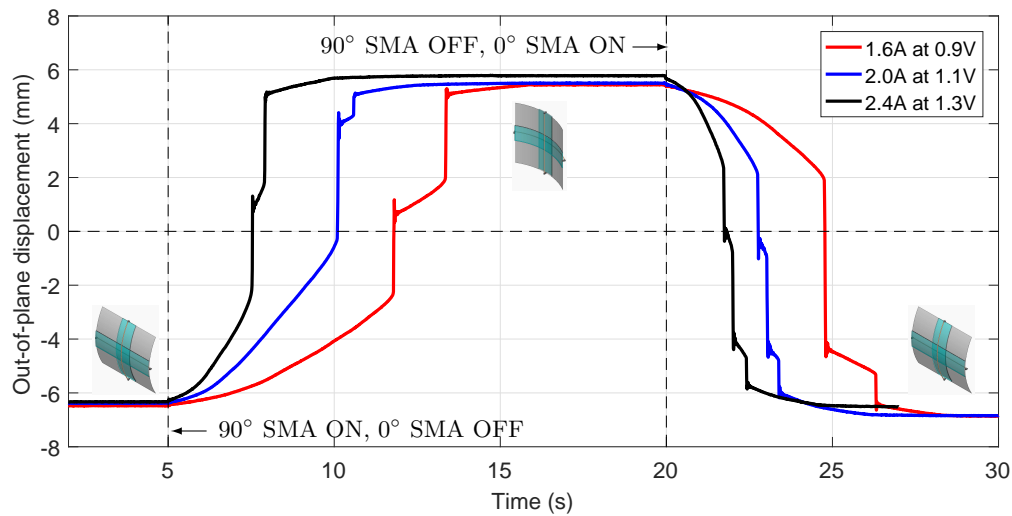


Figure 8: Complete shape transition profile for a shape memory alloy-actuated bistable composite.

EMC prestrain. This weak coupling enables one to design embedded actuators that can be sequentially activated to achieve shape adaptation. An approach for the actuation of bistable composites has been illustrated using shape memory alloys as an example. SMA actuators also serve as dampers to enable a vibration-free shape transition in bistable composites.

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