AIAA JOURNAL
Vol. 48, No. 6, June 2010

Technical Notes

Shape Memory Alloy–Piezoelectric Active Structures for Reversible Actuation of Bistable Composites

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DOI: 10.2514/1.J050100

I. Introduction

As COMPOSITE and smart-material technology reaches a level of maturity, there are increasing opportunities for innovative integrated structures with multifunctionality and adaptability. One such enabling technology attracting interest is that of asymmetric composite laminates, which exhibit bistability and are able to *snap through* from one stable state to another. This property offers a unique advantage in terms of shape control with minimum power requirements for aerospace applications since a continuous energy supply is not necessary to maintain deflection.

Asymmetric laminates such as a $[0/90]_T$ laminate have an anisotropic thermal response to the elevated temperatures experienced during manufacture. For laminates with a high edge-to-thickness ratio, this leads to the development of two stable cylindrical states at room temperature [1]. Snap-through between the two cylindrical states is achieved by application of an in-plane strain, applied via an external force or actuation. These characteristics are of particular interest in applications requiring large deflections with relatively small power requirements.

Two smart actuation mechanisms have been considered to induce an in-plane strain, namely a piezoelectric material and a shape memory alloy (SMA). An advantage of the piezoelectric strain, often applied using a fiber-based patch, is its high bandwidth, which allows a rapid state change. In addition, since piezoelectric strain is almost proportional to applied electric field (and voltage), a higher degree of deflection control is possible compared with SMA [2].

A major limitation of piezoelectric materials is that they are capable of only a relatively low strain ($\sim$0.1%). Figure 1 depicts a typical hysteretic response of an asymmetric composite to an applied in-plane strain. The laminate will snap through from cylindrical State I to II following the path **AB**. However, the state change from State II to I follows path **CD** due to the unstable equilibrium of the saddle shape. Previous research has found that piezoelectric actuation is able to induce a one-way state change (e.g., **AB**) but is usually insufficient to reverse the state change (e.g., **CD**). Bowen et al. [3] was only able to achieve a reversible state change by applying an additional compressive mechanical load. Schultz et al. [4] achieved a reversible state change by attaching two piezoelectric patches on each side of a laminate; however, it was necessary to apply a voltage above the recommended working range of the piezoelectric actuator.

An alternative actuation mechanism is SMA, which is able to induce high force and high strain ($\sim$8%). However, SMA actuation has received less interest due to its slow response time and low bandwidth [5]; maximum operating frequencies are lower than 10 Hz for SMA, compared with over 10 kHz for piezoelectric ceramics [6]. Dano and Hyer [7] demonstrated the feasibility of the SMA actuation on bistable structures by attaching SMA wires on bridge-like supports above the laminates.

This technical note introduces an actuation mechanism, termed shape memory alloy–piezoelectric active structures (SMAPAS), that combines the advantages of the piezoelectric and SMA materials to achieve self-resetting bistable composites. The approach uses piezoelectric actuation to provide a rapid snap-through (State I $\rightarrow$ II) with a fine degree of control and a relatively slow but high-strain SMA actuation to reverse the state change (State II $\rightarrow$ I). For fully reversible actuation (I $\leftrightarrow$ II) the snap-through deflection using the piezoelectric actuation must be sufficiently high to deform (twin) the SMA material, thus enabling the shape memory effect to be used.

II. Experimental Investigation

A. Manufacturing of SMAPAS Demonstrator

A thin cantilever beam of $[0/0/90/90]_T$ carbon-fiber/epoxy material was used to demonstrate the two-way actuation. This was the same structural configuration used in a previous study that showed that two-way actuation was not achievable using a piezoelectric actuation only [3]. The dimension of the cantilever beam was $300 \times 60 \times 0.52$ mm manufactured using HTA (12k) 913 prepreg sheet. The composite lay-up procedure was a standard method for the manufacturing of carbon laminates through a standard cure cycle to a maximum cure temperature of 125°C and a pressure of 85 psi (586 kPa).

The piezoelectric actuator used was a macrofiber composite (MFC) from Smart Material Corp., USA, which consists of aligned piezoelectric fibers with an interdigitated electrode to direct the applied electric field along the fiber length. The MFC patch (M-2814-P1) has an operating range -500 (contraction) to 1500 V (extension). The dimensions were 37×17 mm with an active area of 28×14 mm and a thickness of 0.3 mm. A two-part araldite epoxy was used to bond the MFC actuator where the direction of the main actuator strain (and its piezoelectric fibers) was aligned along the axis of curvature (Fig. 2). The surface of the carbon-fiber composite was roughened to provide a better adhesion surface. After applying a thin

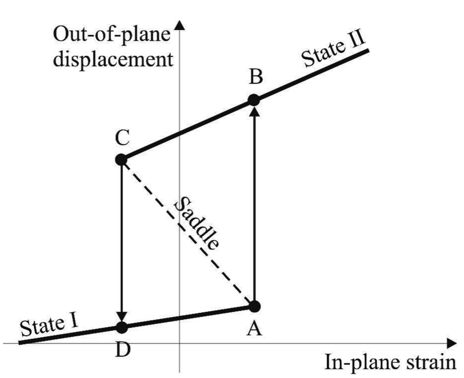

Fig. 1 Multi-equilibria of an asymmetric composite and its response to in-plane strain.

Received 27 July 2009; revision received 21 Oct. 2009; accepted for publication 29 Oct. 2009.

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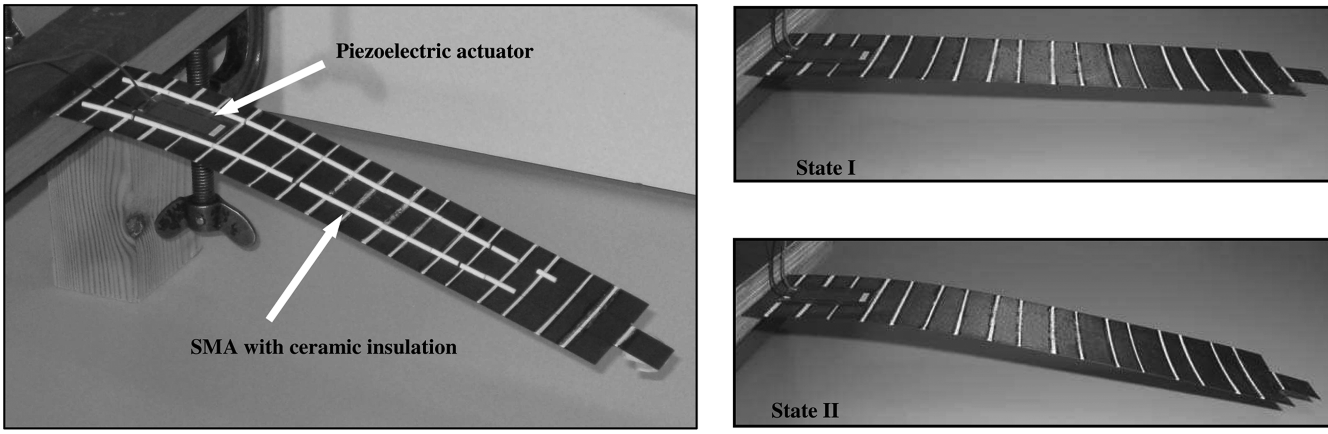
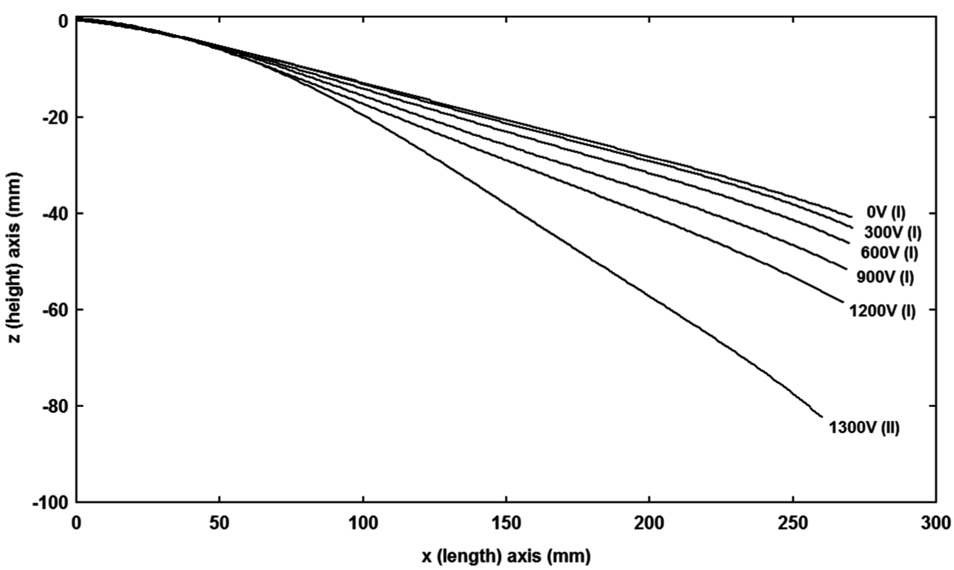
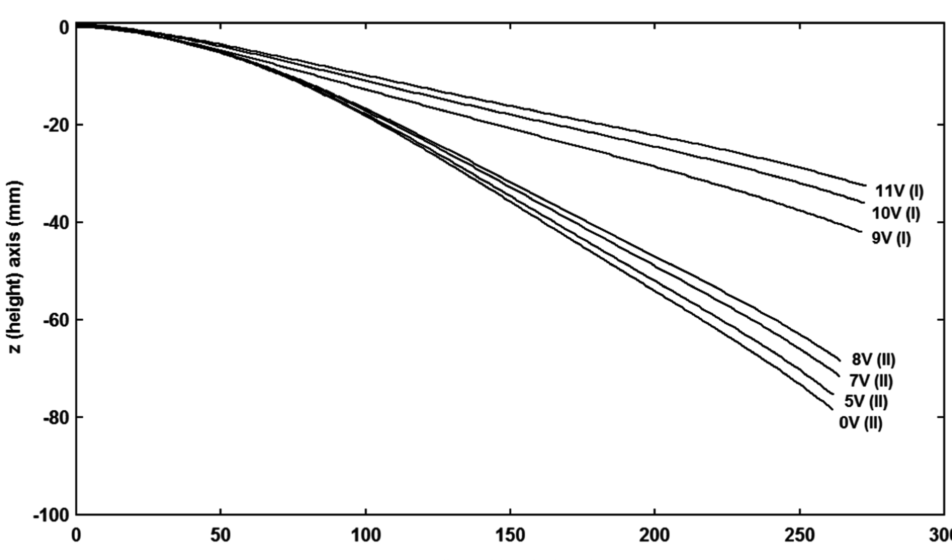


a) b)

Fig. 2 Cantilever beam: a) test rig for reversible actuation and b) two stable states.



a)



b)

Fig. 3 Shape profile of the cantilever beam: a) varying applied MFC voltages and b) varying applied SMA voltages. The I and II in parentheses indicate the equilibrium states.

film of adhesive to the actuator to attach to the composite laminate, they were held flat under a weight to provide a good contact while the epoxy was allowed to cure for 24 h. The amplifier used to apply an electric potential for piezoelectric actuation was a TREK PZD700 with a maximum unipolar voltage (V) of 1.4 kV, maximum current (I_{max}) of ± 50 mA, and slew rate of $100\ V/\mu s$.

SMA actuation was achieved by application of a voltage to heat a NiTi SMA wire (0.175 mm diameter) [8]. The four 20×20 mm corners removed from the composite allowed the SMA to be clamped to the cantilever beam. The SMA wire was electrically and thermally insulated by a series of ceramic thermocouple tubes, and the wire was wrapped around the end tab of the cantilever beam and clamped at the opposite end. The two ends of the SMA wire were then fixed behind the clamping point to tighten and remove any slack. Figure 2a shows the cantilever beam setup, showing the rectangular cantilever and the location of both the MFC patch and SMA wire. A small end mass was added to the cantilever to ensure sufficient deformation of the SMA on snap-through from State I to II. Figure 2b shows the two stable states of the bistable cantilever structure (SMA not shown).

B. Characterization of Actuation

Deflections and shape as a function of actuation were characterized using a motion analysis technique as in Bowen et al. [3]. A digital video camera recorder (Sony DCR-TRV 900E, Sony Corp., Japan) was set up 4.80 m from the cantilever with the lens axis perpendicular to the side plane of the sample. A rectangular calibration object of 346×262 mm for scaling purposes was videotaped before commencement of the actual experimental work. The cantilever beam was videotaped at each actuation voltage, and the video clips were transferred to a computer. Voltage steps of 100 V for MFC actuation and 1 V for SMA actuation were applied with a time step of approximately two minutes between each measurement. The cantilever beam profile was manually digitized on Peak Motus® (v8.5,Vicon, USA) by using a mouse to select 34 points approximately uniformly at the edge of the cantilever beam. The four corners of the calibration object were also manually digitized. The digitized area consisted of 1440×1152 pixels; hence, an effective resolution of digitization was ~ 0.3 mm in both horizontal and vertical directions. Following the scaling and reconstruction, these 34 discrete coordinates were then exported to Excel software and a fifth-order polynomial least-squares fit was used to recreate the profile of the cantilever in each condition.

III. Results and Discussion

The first part of the experiment was to examine the cantilever deflection due to piezoelectric actuation while no voltage was applied to the SMA. The cantilever beam was initially in its raised state (State I) at 0 V and the shape of the cantilever beam profile was recorded for the positive voltage range of the MFC piezoelectric actuator (maximum of 1500 V). The results at 0, 300, 600, 900, 1200, and 1300 V are presented in Fig. 3a. It was observed that applying voltages between 0 and 1200 V increased the deflection of the cantilever beam but the structure remained in State I. At 1300 V there was a significant change in the deflection as a result of snap-through from State I to II. On removal of the applied voltage a small reduction in the deflection was observed but the structure remained in State II. The cantilever could not be returned to State I using the MFC patch alone, consistent with the previous findings [3]. Comparing this result with that presented by Bowen et al. [3] the snap-through voltage requirement of 1300 V in this work was 300 V higher due to the increased stiffness caused by the addition of the SMA wires to the upper surface of the cantilever beam.

The second part of the experiment examined the cantilever beam deflection in response to SMA actuation. After snap-through from State I to II using the piezoelectric and removing the piezoelectric voltage, the input voltage to the SMA wire was increased from 0 to 11 V at 1 V intervals. The cantilever beam profiles at 0, 5, 6, 7, 8, 9, 10, and 11 V are shown in Fig. 3b. In this case the purpose of the applied voltage was to provide sufficient Joule (resistive) heating to achieve a martensite-to-austenite phase change in the SMA and induce a shape-memory effect. Small deflection changes were seen between 0 and 5 V as the temperature in the wire had not reached the transition temperature. There was a more marked change between 5 and 8 V although the cantilever beam remained in State II. Snap-through from State II to I was observed at 9 V. Upon removal of the voltage to the SMA, the cantilever beam returned to its original (0 V) State I profile as in Fig. 3a. This reversible actuation was completely repeatable, indicating that the piezoelectric snap-through from State I to II was sufficient to deform (twin) the SMA wire and enable fully reversible snap-through using the SMA–piezoelectric combination. A comparison of Figs. 3a and 3b reveals the different power requirements of the two actuator materials. The piezoelectric requires a high voltage (>1000 V) with low current, since the piezoelectric is a dielectric. The SMA requires a much lower voltage (<15 V) with high current (up to 1 A), which corresponds to a power of 15 W. The piezoelectric is primarily a reactive (capacitive) load, while the SMA is a resistive load, necessitating different levels of rectification and power. Since piezoelectric strain is proportional to electric field, the voltage requirement of the piezoelectric actuator could be lowered by reducing the interdigitated electrode spacing of the MFC.

IV. Conclusion

This study demonstrated that reversible state changes are achievable in a bistable cantilever beam of $[0/0/90/90]_T$ by combining materials to form a SMAPAS. It has been established that an asymmetric composite exhibits two stable cylindrical states and the state change can be induced by in-plane strain. Previous studies have shown that the snap-through from State I to II can be actuated by a piezoelectric; however, it is not possible to induce a reversible state change within a recommended operating range of the piezoelectric patch. This study used piezoelectric actuation to induce a rapid change from State I to II, which also deformed an attached SMA wire. Since deformed SMA materials induce a high force and high strain with low bandwidth on Joule heating, a change from State II to I was possible to *reset* the bistable cantilever beam. In addition, a degree of controllability within each state was demonstrated for the piezoelectric, and to a lesser extent for the SMA material. In this paper we have considered primarily the static response of the SMAPAS mechanism as a proof of concept. Following on from this feasibility study, research continues to understand the dynamic response, develop numerical models for design and optimization of SMAPAS systems, and develop manufacturing methods for embedding the actuator materials within the structural composite, with particular emphasis on the influence of SMA heating on the structural integrity of the composite laminates.

Acknowledgement

The authors gratefully acknowledge the support provided by the U.K. Ministry of Defense. This work was carried out as part of the Materials and Structures Technology program consortium.

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Associate Editor