Morphing and Shape Control using Unsymmetrical Composites

C. R. Bowen,[1,*] R. Butler,[1] R. Jervis,[1] H. A. Kim[1] and A. I. T. Salo[2]

[1]*Department of Mechanical Engineering, University of Bath*
Bath, BA2 7AY, UK

[2]*Sport and Exercise Science, School for Health, University of Bath*
Bath, BA2 7AY, UK

ABSTRACT: Unsymmetrical carbon fiber/epoxy composites with bonded piezoelectric actuators are investigated as a means to shape or morph, the composite structures. Both a cantilever and unsupported laminate structure are examined along with their response to applied strains (from piezoelectric actuators) and applied mechanical load; with particular emphasis on the characterization of shape/deflection, the influence of externally applied mechanical loads and methods of reversing or promoting snap-through of these materials from one stable state to another. A variety of shape change/actuation modes for such structures have been identified namely, (i) reversible actuation by maintaining a constant stable state using piezoelectric actuation, (ii) an increased degree of shape change by irreversible snap-through using piezoelectric actuation and (iii) reversible snap-through using combined piezoelectric actuation and an externally applied load.

Key Words: morphing, piezoelectric, composite, actuators.

INTRODUCTION

There is growing interest in structures that are able to change shape, or morph, to meet changing performance requirements. In the aerospace sector, for example, improved efficiency in aerodynamic control may be achieved by replacing traditional control surfaces such as ailerons by wings that can warp or have variable camber. Internal mechanisms and actuation strategies have been successfully applied to morph micro air vehicles, achieving high levels of manoeuvrability (Abdulrahim et al., 2004, 2005). In addition, such reconfigurations have been used to enhance helicopter rotor blade efficiency (Cesnik et al., 2004, Shin et al., 2005).

A variety of approaches have been investigated to achieve shape change in composite structures. These range from the use of compliant mechanisms (Lu and Kota, 2003; Ramrakhyani et al., 2005) to bistable concepts that exhibit some form of snap-through behavior from one stable state to another, occurring for example, within trusses (Seffen, 2004) or unsymmetric composite laminates (Schultz and Hyer, 2003, 2004). Methods that induce snap-through include the use of shape memory alloys (Hufenbach et al., 2002; Dano and Hyer, 2003), which can induce high strains (8%) at low frequency (Kudva, 2004) and piezoelectric materials that are able to generate high forces at high frequency, although the developed strains tend to be small (typically only 0.1–0.4%).

Since the maximum strain of the piezoelectric materials is small, the introduction of bending, buckling or bistability into a structure is often used as an amplification mechanism to generate useful deflections. Schultz and Hyer examined the deflection of a two-layer unsymmetrical cross ply $[0/90]_T$ laminate with a macro fiber piezoelectric composite bonded to its surface to achieve snap-through from one stable state to another. A potential advantage of this mechanism is that large changes in shape can be achieved, with limited power requirements, as continuous power is not needed (Schultz and Hyer, 2003, 2004). Although the piezoelectrics could be used to change the unsymmetrical composite from one state to another, it could not be used to reverse the snap-through. It was proposed that another actuator bonded to the reverse side of the laminate could be used to achieve this, but to date there has been no reported reverse snap-through using piezoelectric actuation.

While work to date has focused on the development of composite-piezoactuator models to predict the deformed shape, the aim of this article is to develop an

*Author to whom correspondence should be addressed.
E-mail: c.r.bowen@bath.ac.uk

1045-389X/07/01 0089–10 $10.00/0 DOI: 10.1177/1045389X07064459

experimentally focused study to explore the possible ways in which unsymmetrical composites and piezoelectric actuators can be used for shape change or morphing applications. A cantilever and an unsupported laminate are examined and their response to applied strains (from piezoelectric actuators) and applied mechanical loads; with particular emphasis on the characterization of shape change/deflection, the influence of mechanical loads and possible methods of reversing or promoting snap-through of these materials. This is of particular importance since it can serve to direct the approach that future modeling or applied research should explore to achieve or optimize large deflections or shape change in composite structures. The use of piezoelectric actuators to induce the shape change seems to be particularly attractive, especially when flexible and damage tolerant piezoelectric fiber-based actuators are now commercially available (Nelson, 2002) and single crystal-based piezoelectric materials and devices, which can exhibit relatively large piezoelectric strains (up to 1.5%), are being developed (Wilkie et al., 2004, Park and Kim, 2005).

At this point, it is of interest to understand the equilibrium states and shapes of an unsymmetrical composite and its possible response to a piezoelectric strain (ε_p). An unsymmetrical laminate, which has been cured at elevated temperature when held flat has three possible equilibrium states when cooled (Figure 1). For the relatively long edge lengths L_x and L_y considered in this study, the saddle shape is unstable (Hufenbach et al., 2002) and the laminate can have either of the two cylindrical states. If a piezoelectric patch is bonded to the surface of the laminate and a voltage V is applied to produce piezoelectric strain ε_p then actuation from one cylindrical state to the other may occur. It is seen that the laminate snaps-through from Cylinder I to Cylinder II by following the path **AB**. Alternatively, snap-through from Cylinder II to Cylinder I follows the path **CD** because of the instability of the saddle shape. Ideally, morphing of the laminate is achieved by reversible snap-through from each of these stable states.

EXPERIMENTAL SETUP

This section discusses, (i) the manufacture of the unsymmetrical composite cantilever and unsupported laminate, (ii) the piezoelectric actuators, and (iii) the bonding of the piezoelectric actuators to the composites.

Composite Manufacture

Unsymmetrical composites were manufactured for this work to operate as a simple cantilever and as an unsupported laminate. The cantilever was a four ply $[0/0/90/90]_T$ carbon fiber/epoxy composite measuring $300 \times 60 \times 0.52$ mm. The unsupported laminate was a $[0/90]_T$ carbon fiber/epoxy composite measuring $150 \times 150 \times 0.32$ mm, similar to that examined by

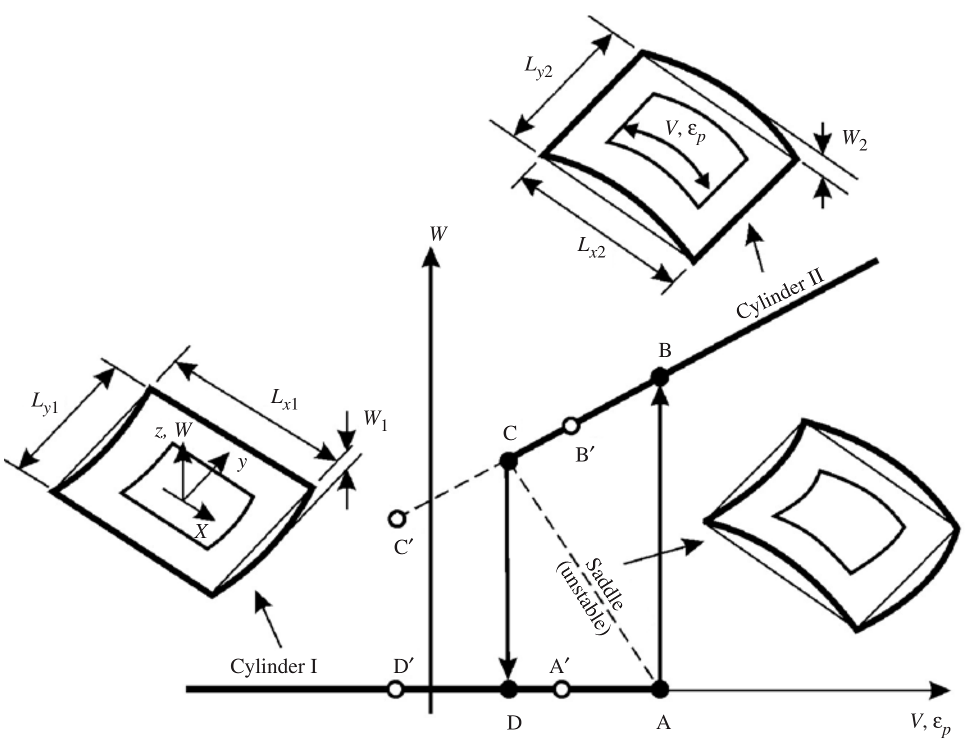

*Figure 1. Bistable member showing equilibrium states, and central displacement w against piezoelectric strain ε_p or applied voltage V. Note that application of a tip load to the cantilever effectively shifts points **ABCD** to **A′B′C′D′**.*

Schultz and Hyer (2004). The composite lay-up procedure was a standard method for the manufacturing of carbon laminates using carbon fiber prepreg sheet (HTA (12k) 913). The samples were laid up on a nonstick pad to ensure that the composite would not bond to the lay-up surface during the cure cycle. Once the layers had been placed a thermocouple was inserted into the prepreg plies to monitor the laminate temperature during curing. A release film was then placed over the sample and a breather layer was laid to assist in forming the vacuum during curing. The laminate was run through a standard cure cycle to a maximum cure temperature of 125°C and a pressure of 85 psi. Figures 2 and 3 show images of both the cantilever and unsupported laminate respectively, showing the curvature of the composites as a result of the unsymmetrical lay-up and the differential thermal strains induced into the composites during the cure cycle. Both the cantilever and the unsupported laminate were observed to have two stable states, which are referred to as 'State I' and 'State II' for the remainder of this article and are indicated in Figures 2 and 3. Note that both State I cases consist entirely of the Cylinder I of Figure 1. State II of the unsupported laminate is entirely Cylinder II whereas State II for the cantilever has a part of Cylinder II and part of Cylinder I.

Actuator Materials

The piezoelectric fiber actuators used were macro fiber composites (MFCs) from Smart Material Corp., USA, which consist of aligned piezoelectric fibers with an interdigitated electrode to direct the applied electric field along the fiber length. For the unsupported laminate a large (M-8557-P1) patch was used (110 × 75 mm) with an active area of 85 × 57 mm and an electrode spacing of 0.5 mm. The material used for the MFC was a Navy Type II. The maximum operating voltage was 1500 V with a maximum reported free strain of 0.1–0.135% at 1500 V (Smart Material Corp, 2005). For the cantilever structure a smaller (M-2814-P1) patch was used (37 × 17 mm) with an active area of 28 × 14 mm. The piezoelectric material, maximum operating voltage, and maximum strain were identical to the larger patch. Since the purpose of the piezoelectric is to induce a transition from State I to State II (and possibly vice versa), it is of interest to compare the maximum piezoelectric strain (ε_p) with the thermal strains (ε_t) of the composite during curing since ε_t is ultimately responsible for the curvatures observed in Figures 2 and 3. The thermal expansion coefficient (α) of the carbon fiber/epoxy is ~0 in the fiber direction and $\sim 30 \times 10^{-6}$°C^{-1} in the transverse direction (Potter and Weaver, 2004). Since the cure temperature used was 125°C the thermal strain in the fiber direction ($\alpha\Delta T$) was ~0.3%, greater than the piezoelectric free strains, but of the same order. The material properties of the carbon fiber prepreg and the piezoelectric MFCs are given in Table 1.

Actuator Attachment

A two-part araldite epoxy was used to bond the MFC actuators to the cantilever and unsupported laminate and Figures 2 and 3 show the location of the actuators for both the composites. The surfaces of the actuator and carbon fiber composite were cleaned and the surface of the composite was roughened to provide better mechanical adhesion. A small quantity of the adhesive was applied to the actuator and was evenly spread on its surface to form a film as thin as possible to ensure good strain transfer between the actuator

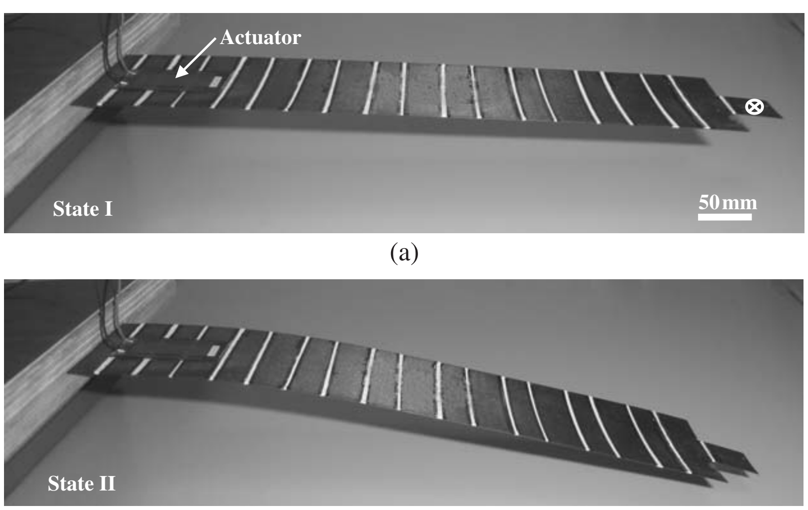

Figure 2. Cantilever structure, indicating location of piezoelectric actuator and stable states: (a) State I and (b) State II. No voltage was applied to the actuator in these images. The ⊗ indicates the location where the end load was applied (using a 2.8 g mass).

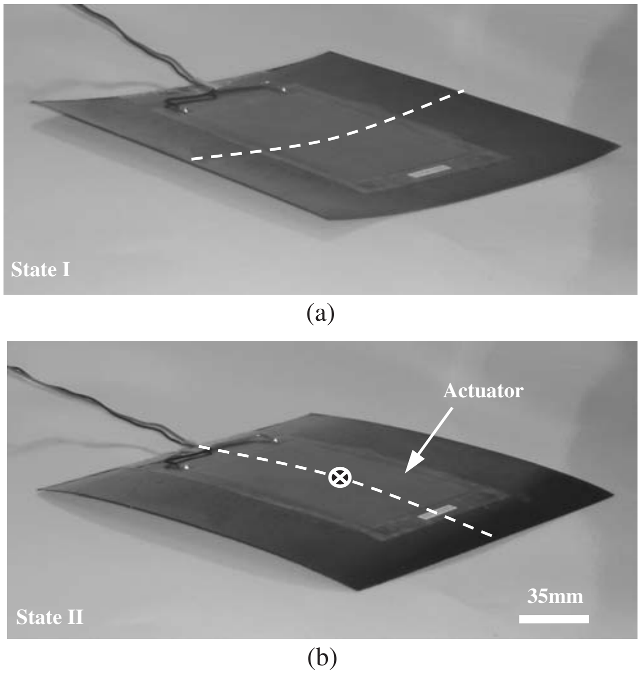

Figure 3. Unsupported laminate showing piezoelectric actuator and stable states (I and II): (a) State I and (b) State II. The dotted line indicates the region where two-dimensional profiles were measured using a non-contact laser profilometer. No voltage was applied to the actuator in these images. The ⊗ symbol indicates the location where the mechanical load was applied (using 0.5 N weights).

Table 1. Material properties of composite and MFC (from Smart Material Corp., 2005).

	HTA (12k) 913	Piezoelectric MFCs
E_{11} (GPa)	135	30.3
E_{22} (GPa)	18.5	15.9
G_{12} (GPa)	5.98	5.51
ν_{12}	0.29	0.31
Free strain per volt (10^{-6}/V) (low field-high field)	–	0.75–0.90
% strain at 1500 V	–	0.11–0.135

and composite. Once attached to the composite, the actuator and composite were placed beneath a weight to keep the composite and actuator flat and in good contact for 24 h while the epoxy was cured. Due to the applied load during bonding, the actuator was bonded to both the cantilever and laminate while held flat, with the direction of the main actuator strain (and its piezoelectric fibers) aligned along the axis of curvature. The actuator–composite lay-up is therefore $[0_{MFC}/0/0/90/90]_T$ and $[0_{MFC}/0/90]_T$ for the cantilever and unsupported laminate respectively. Significant changes in the curvature of the unsupported laminate of Figure 3 were observed after bonding on the actuator, therefore its overall shape was characterized 'before' and 'after' the application of the actuator. The addition of the smaller patch to the cantilever did not significantly change its curvature, although in order for the $300 \times 60 \times 0.52$ mm composite to be used as a cantilever and achieve the two stable states, four 20×20 mm corners on the composite were removed. After removal of the corners the composite was able to maintain the State I and State II in Figure 2. Potter and Weaver demonstrated that the removal of material from unsymmetrical composites can alter the stable states.

Displacement Measurement/Shape Change Characterization

For the unsupported laminate structure, deflections and overall shape change as a function of applied voltage were measured using a Proscan 2000 noncontact profilometer. The Proscan sensor uses a laser-based triangulation sensor to measure height (resolution 1 μm), which is coupled with a precision *x–y* table (resolution 1 μm) to scan the surface of interest. The laminate was attached to the movable table, which enabled the laminate height (*w*, Figure 1) to be measured while scanning in the *x–y* direction in increments of 10 μm. Two-dimensional profile scans of the laminate were taken at applied voltages of 0, 300, 600, 900, 1200, and 1500 V and Figure 3 shows the location where the two-dimensional scans were taken. In order to examine the deflection of the laminate under combined electrical and mechanical loading, 0.5 N (51 g) weights (up to a maximum of 4 N) were placed at the center of the structure and the experiment was repeated.

The bending deflections of the cantilever were too large ($\gg$10 mm) to be measured by the noncontact laser profilometer, therefore a motion analysis technique was used to examine the cantilever profile. A digital video camera recorder (Sony DCR-TRV 900E, Sony Corporation, Japan) operating at 50 fields/s was setup at 4.80 m from the cantilever with the lens axis perpendicular to the plane in which the bending occurred. A rectangular calibration object of 297×210 mm for scaling purposes was videotaped within the above plane before commencement of the actual experimental work. The camera view was restricted just outside the calibration object. After electrical potentials of 0, 300, 600, 900, 1200, and 1500 V were applied to the actuator, the cantilever was videotaped in each condition. Selected video clips at each voltage were subsequently transferred to a computer. The edge of the bent cantilever, and the four corners of the calibration object, were manually digitized on Peak Motus (Peak Performance, Colorado, USA); achieved by using a mouse to select 36 points at the edge of the cantilever in a random fashion. Despite careful setup, a slight roll (0.47°) of the camera was noticed during digitizing and this was corrected by rotating the coordinate system accordingly within Peak Motus software. The digitized area consisted of 1440×1152 pixels, resulting in an effective resolution of digitization of ~0.2 mm in both horizontal and vertical directions. After the scaling and reconstruction, the raw coordinates of 36 points were exported to the Excel software. After testing the best-fit, a fifth polynomial trend line was applied to the raw coordinates in order to recreate the profile of the cantilever in each condition.

The maximum voltage of 1500 V was insufficient to cause snap-through of the cantilever from State I to State II. However, it was found that a combination of voltage and an additional end weight was sufficient to achieve the snap-through. The experiment was therefore repeated with a small weight (2.8 g) attached to the end of the cantilever.

EXPERIMENTAL RESULTS

Change in Laminate Shape due to Actuator Attachment

In order to examine the effect of actuator attachment on the stable states and curvature of the two composite laminates, the overall shapes of the stable states were characterized 'before' and 'after' actuator attachment. The cantilever was not significantly influenced by the actuator attachment, but substantial changes were noted for the unsupported laminate. Table 2 shows a variety of unsupported laminate dimensions 'before' and 'after' actuator attachment, where the L_{x1}, L_{y1}, w_1, L_{x2}, L_{y2}, and w_2 dimensions are indicated in Figure 1.

In State I the dimension w_1 had reduced from 14 to 5 mm after bonding of the actuator and in State II the w_2 dimension had reduced from 20 to 6 mm. The decrease in w_1 and w_2 is a direct result of attaching the actuator to the composite when laid flat, unlike Schultz and Hyer (2004). If, after bonding the actuator, the laminate is placed in State II (as in Figure 3(b)), the piezoelectric actuator is likely to be in tension and restricts the State II curvature of the laminate, thus reducing w_2. If the piezoactuator then elongates in response to an applied voltage it would be expected that the curvature of the laminate and w_2 would increase (to a maximum of 20 mm, as in the initial 'before' state).

The influence of applied electric potential and combined electrical and mechanical loading on both the cantilever and unsupported laminate is now discussed.

Cantilever Shape Change

Figure 4(a) shows the shape of the cantilever at the various applied voltages, with the cantilever initially in State I at 0 V. Due to self-weight of the cantilever, an initial tip deflection of 26 mm is observed prior to the application of voltage. The application of the voltage results in a change in the cantilever profile with tip deflections in excess of 15 mm; where deflection is defined as the tip position at voltage V relative to its original position at 0 V. In this case, the maximum applied voltage of 1500 V could not induce a transition from State I to State II. However, maintaining the cantilever in State I enabled the deflections to be completely reversible, so that the cantilever returned to its original condition on removal of the applied voltage. One method of promoting a transition from State I to State II was to apply an additional load to the cantilever. Figure 4(b) shows data of the same cantilever with an additional mass (2.8 g) attached to its end, which, without piezoelectric actuation, was not sufficient to cause a transition from State I to State II. The influence of the end mass is to effectively shift points **ABCD** of Figure 1 to points **A′B′C′D′**. Hence state changes occur at lower values of piezoelectric strain and applied voltage. In this case a transition from State I to State II could be achieved at an applied voltage of 930 V, resulting in larger deflections and change in overall profile (Figure 4(b)). The change is profile is, however, irreversible since the cantilever remained in State II on removal of the voltage. Although not measured here, the tip deflection is expected to reduce by more than 15 mm on removal of voltage, since the stiffness of State II is less than that of State I.

Figure 5 shows the tip deflection as a function of voltage for the cantilever with and without an end load. The use of additional end loading resulted in a much larger change in cantilever profile and tip deflection (in excess of 50 mm). This indicates that a negative voltage would be required to produce snap-through from State II to State I, e.g., path **C′D′** in Figure 1; although in practice the application of a large negative voltage is avoided to prevent domain switching in the piezoelectric material. From examination of Figures 4 and 5, it can be seen that the deflections of the unloaded cantilever are not linear with voltage. This may initially be a result of the large tip displacements, but could also indicate rounding-off of the snap-through path **DAB** in Figure 1 due to the proximity of the clamped boundary, coupled with the fact that the piezoelectric patch covers only about 30% of the width of the cantilever. It is also worth pointing out that

Table 2. Dimensional changes 'before' and 'after' actuator attachment. The dimensions are defined in Figure 1.

Dimension (mm)	State I 'before'	State II 'before'	State I 'after'	State II 'after'
L_{x1}	151(±1)	–	151(±1)	–
L_{y1}	148(±1)	–	150(±1)	–
w_1	14(±1)	–	5(±1)	–
L_{x2}	–	145(±1)	–	149(±1)
L_{y2}	–	151(±1)	–	151(±1)
w_2	–	20(±1)	–	6(±1)

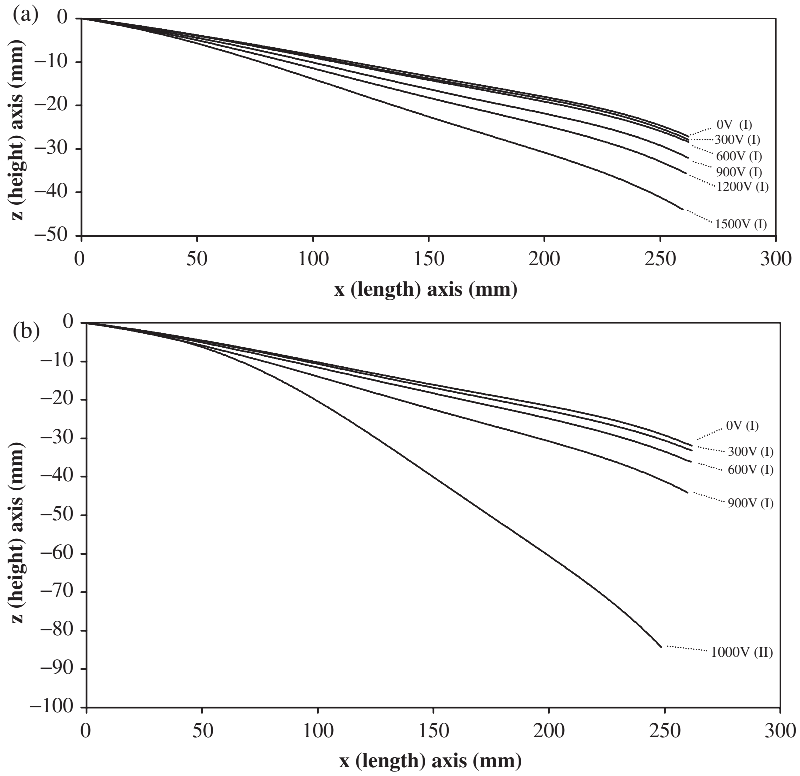

Figure 4. (a) Shape profile of cantilever at the applied voltages without an end load. The I or II in parenthesis indicates the equilibrium state of the cantilever. In this case the cantilever remains in State I and the deflections were reversible and (b) shape profile of cantilever at the applied voltages, with an additional end load of 2.8 g. The I or II in parenthesis indicates the equilibrium state of the cantilever. In this case the cantilever moved to State II at a voltage in excess of 900 V.

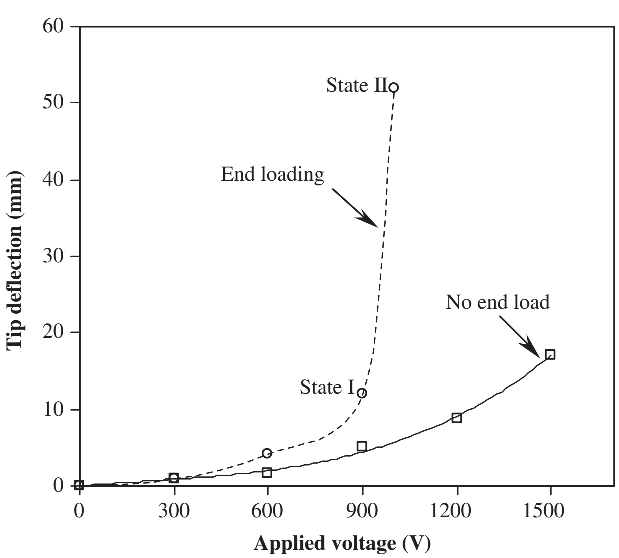

Figure 5. Cantilever tip deflection versus voltage with and without end loading. End loading results in transition from State I to State II at 930 V. Lines between data points are for guidance only. Changes in profiles are reversible with no end loading and irreversible with end loading.

state-change from one cylindrical shape to the other has only occurred over approximately 100 mm of the left-hand portion of the cantilever, (Figure 4(b)). The use of a second patch in the right-hand portion of the cantilever could produce a change of state in this region, resulting in a large increase in total displacement and the possibility of four stable states (Figure 6). The figure also illustrates use of a linear actuator, applying end shortening α and axial force P as an alternative (or complementary) control mechanism.

Unsupported Laminate Shape Change

Figure 7 shows the shape of the unsupported laminate under a range of applied voltages (0, 300, 600, 900, 1200, and 1500 V). Before initially applying a voltage to the piezoelectric actuator the laminate could be placed in either State I or State II, whose shape profiles are indicated as '0 V (State I)' and '0 V (State II)' in Figure 7 respectively.

When the laminate was initially placed in '0 V (State I)', it could snap-through from State I into State II at a relatively low voltage of 100–150 V. As the applied voltage was increased to 1500 V the curvature of the laminate in State II increased, as can be seen in Figure 7. On removal of the voltage the curvature of the laminate subsequently reduced but the structure remained in State II and therefore returned to the '0 V (State II)' position. Although the change in shape and displacement was relatively large (center deflections of up to 15 mm), the change was irreversible. Reversible actuation could be achieved by repeating the experiment, but with the laminate initially in '0 V (State II)'. As the voltage was increased, the curvature of the laminate increased in an identical fashion to the previous experiment, but the laminate returned to its original position on removal of the voltage. Although maintaining the laminate in State II, with no snap-through, reduced the degree of shape change there was still an appreciable reversible deflection (up to 8 mm at its center).

To date there has been limited evidence of achieving reversible snap-through using piezoelectric actuation. A method of achieving this was to combine the piezoelectric actuation with an externally applied mechanical load. Figure 8 shows the laminate with a 100 g mass located at its center, which is sufficient to ensure that the laminate snaps from State II to State I when no voltage is applied to the actuator (Figure 8(a)). As the applied voltage was increased (in this case 600 V) the piezoelectric actuation was sufficient to snap the laminate from State I to State II, as shown in Figure 8(b). On removal of the voltage the 100 g mass ensured that the laminate returned to State I, so that fully reversible snap-through and actuation could be achieved.

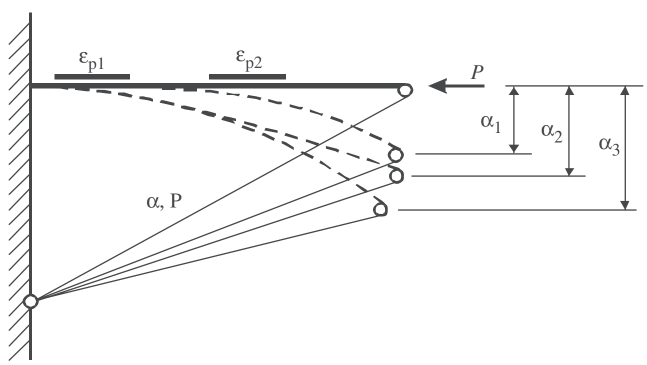

Figure 6. *Shape control of bistable cantilever showing one undeflected and three deflected positions. End shortening is introduced via the inclined member, while the two piezo-electric devices ε_{p1} and ε_{p2} either separately or together give a total of four stable equilibrium states.*

The degree of shape change, total deflection, and the voltage necessary to achieve snap-through are likely to be highly dependent on the amount of applied mechanical load. Therefore, experiments were undertaken for a range of mass loads (51, 102, 153, 204, 255, 306, and 408 g). Figure 9 shows deflection of the center of the laminate as the applied voltage is initially increased from 0 to 1500 V in 100 V increments ('up' cycle) and subsequently decreased to 0 V in 100 V steps ('down' cycle). Again, the deflection is defined as the central position of the laminate at voltage V relative to its initial position at 0 V. The arrows in Figure 9 indicate the 'up' and 'down' cycles for the mass loads which were studied.

When a 51 g (0.5 N) mass is used, snap-through from State I to State II is achieved at 200 V resulting in a relatively large increase in deflection between 100 and 200 V (Figure 9). As the voltage is increased to 1500 V, there is a more gradual, almost linear, increase in deflection as the curvature of the laminate increases. During the 'down' cycle, where the voltage decreases from 1500 V to 0 V, there is a gradual decrease in deflection. In this case, unlike the cantilever where the tip load promoted lower snap-through voltage, the effect of the mass is to increase snap-through voltage and to alter the stiffness of each state. A degree of hysteresis is observable since the deflections are higher for the 'down' cycle, compared to the 'up' cycle, possibly due to creep of the piezoelectric (Fett and Thun, 1998, Jung et al., 2001). There may also be additional frictional effects between the edges of the laminate (which are neither

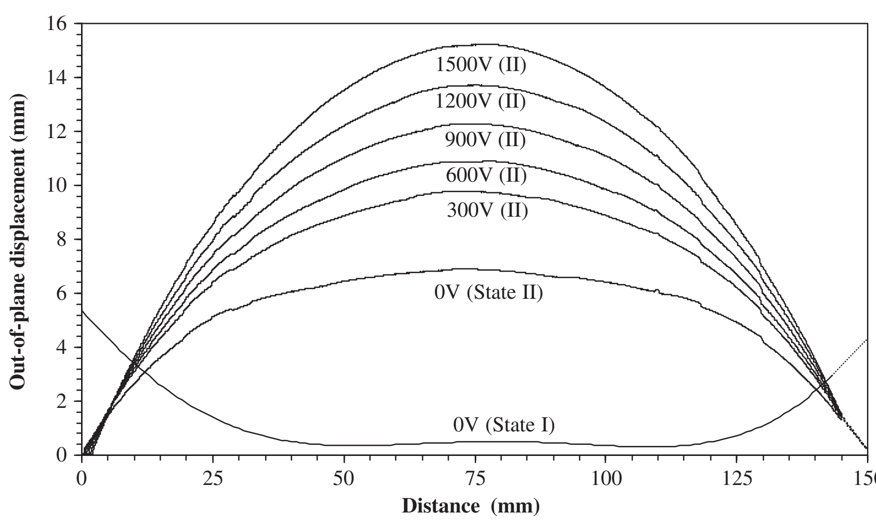

Figure 7. *Two-dimensional profiles of unsupported laminate at a range of applied voltages. Actuation between States I and II were not reversible without additional loading to the structure. Figure 3 shows the location of the two-dimensional profiles.*

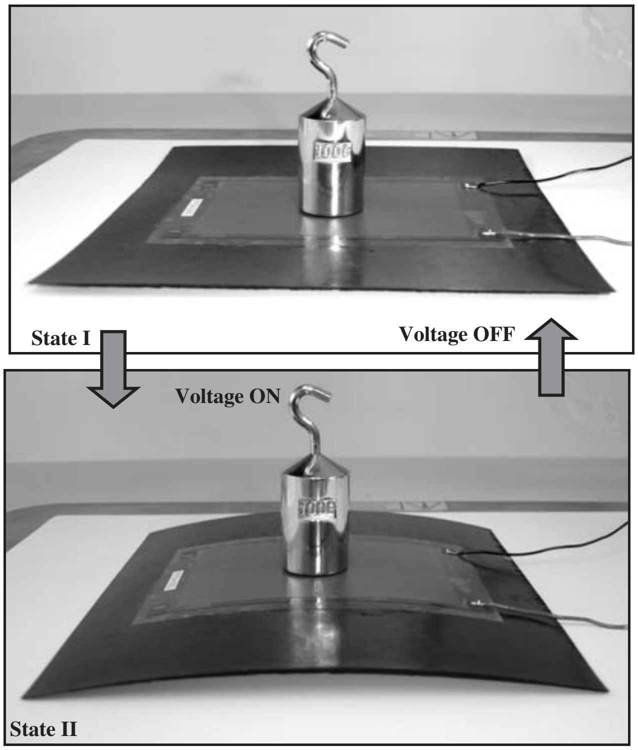

Figure 8. Demonstration of reversible transitions from States I and II using additional loading (in this case a 100 g mass). For 100 g, approximately 600 V produced a transition from I→II.

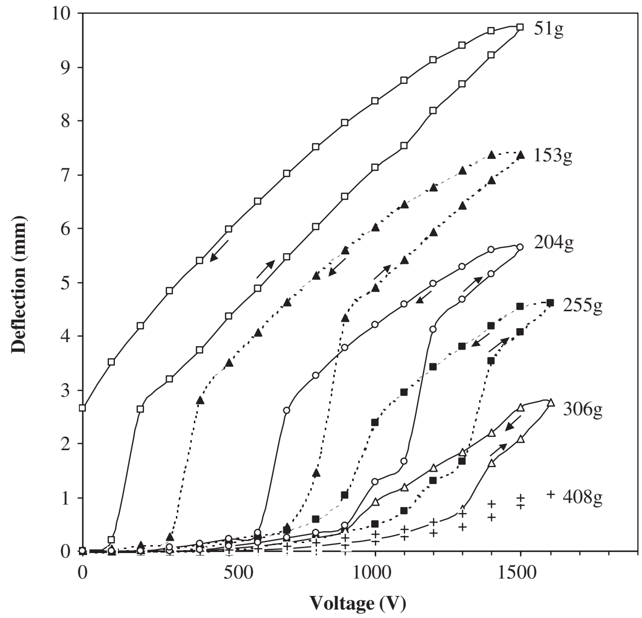

Figure 9. Voltage deflection curves of the unsupported laminate for a range of applied loads (50–400 g). Large step changes in deflection are a result of a transition from I→II or II→I. Lines between data points are for guidance only. Data for 102 g has not been shown for clarity.

straight nor perfectly parallel) and the flat surface on which it is lying on. Such an effect could prevent the relation for the 'up' cycle from coinciding with the relation for the 'down' cycle.

Since the mass of 51 g is insufficient to cause snap-through from State II to State I the deflection remains high on complete removal of the voltage, as observed for the unloaded laminate of Figure 7. While reversible snap-through was therefore not achievable for a 51 g load, Figure 9 shows that for masses greater than 100 g the laminate always returns to State I when the voltage is gradually reduced from 1500 V, enabling reversible snap-through and shape change. Figure 10 summarizes some of the data in Figure 9, including the voltages at which State I→II snap-through occurs during the 'up' cycle and State II→I snap-through occurs during the 'down' cycle (Figure 10(a)). As the magnitude of the mass is increased the voltage to achieve snap-through during the 'up' (I→II) and 'down' (II→I) cycles increases (Figures 9 and 10(a)). Figure 10(a) also shows that higher voltages are necessary to achieve a snap-through on the 'up' cycle, compared to the 'down' cycle. This can be explained by reference to the different paths **DAB** and **BCD** taken for, respectively, increasing and decreasing voltage in Figure 1. For the highest mass (408 g) no clear transition from State I to II was observed (Figure 9), but the loads used for the laminate were far greater than those that could be supported by the cantilever structure (2.8 g). Figure 10(b) is the maximum deflection (shown in Figure 9) as a function of applied mass and demonstrates that the total deflection decreases with increasing mass, as would be expected.

CONCLUSIONS

The use of piezoelectric actuators attached to unsymmetrical composites has been investigated to explore the possible ways in which unsymmetrical composite and piezoelectric actuators could be used for shape change or morphing applications. A cantilever and unsupported laminate has been fabricated and their response to applied strains (from piezoelectric actuators) and externally applied mechanical loads has been examined, with emphasis on characterizing the strain/deflection, shape profile, load carrying ability, and possible methods of reversing or promoting snap-through of these materials.

For the unsymmetrical cantilever examined, relatively large deflections and changes in profile could be achieved and two possible methods of utilizing such structures were explored. Reversible actuation could be achieved by maintaining the structure in State I, with tip deflections of up to 17 mm. A transition from State I to State II could be achieved with the application of piezoelectric actuation and an additional small end mass. Such a mode of operation resulted in maximum tip deflection in excess of 50 mm, but the deflection was not reversible for the range of applied voltages considered. However, the large tip

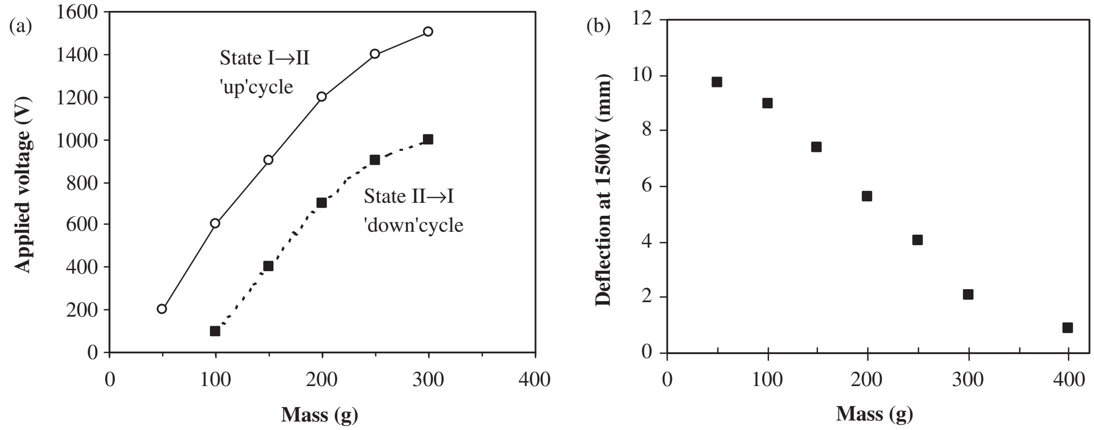

Figure 10. *(a) Voltages for State I→II and State II→I transitions during the 'up' and 'down' cycles and (b) deflections at 1500 V for the mass loadings examined. Lines between data points are for guidance only.*

deflection and profile change of the cantilever demonstrates large potential for application in morphing structures and further capability could be achieved through the use of additional piezoelectric patches at other lengthwise locations.

For the unsupported laminate structure three modes of operations were identified. For an unloaded laminate, reversible actuation could be achieved by starting with the structure in State II at 0 V. The application of the voltage increased the curvature of the laminate, which remained in State II for all applied voltages. Reversible deflections of up to 8 mm, without snap-through, were achieved. More significant changes in shape and larger deflections of up to 15 mm could be achieved by placing the structure in State I at 0 V, which transformed to State II at 100–150 V, followed by an increase in curvature with the voltage increase to 1500 V. As observed by Schultz and Hyer (2004), on removal of the voltage the structure remained in State II, so that the shape change was irreversible. A combination of piezoelectric actuation and an externally applied load was used to achieve reversible snap-through, although appreciable hysteresis was observed. For mass loads of 102–306 g fully reversible snap-through could be achieved. As the mass load increased, the voltage to induce snap-through increased and the total deflection decreased. While the cantilever structure offered large deflections and change in shape of profile, the unsupported laminate offered a much higher load capability.

The research demonstrates that when using unsymmetrical composites and piezoelectric actuators for shape change applications a variety of modes of operation are possible. Appreciable reversible deflections and shape change can be achieved by simply maintaining the unsymmetrical composite structures in a single stable configuration. Larger deflections and more significant shape changes can be achieved by inducing snap-though from one state to another using piezoelectric actuation, but it is possible that the resulting deflections are irreversible. To achieve reversible snap-through in the experiments conducted here it has been demonstrated that combined piezoelectric and mechanical loading offers a practical solution to the control and morphing of unsymmetrical composite structures. Ultimately, modeling of such structures for morphing applications requires the knowledge of their behavior under combined electrical and mechanical loading; along with the knowledge of the piezoelectric material, the unsymmetric composite, and the interface between the two materials. Such models need to capture nonlinear behavior at both material and structural levels.

REFERENCES

Abdulrahim, M., Garcia, H. and Lind, R. 2004. "Flight Testing a Micro Air Vehicle using Morphing for Aeroservoelastic Control," In: *45th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, USA, AIAA Paper 2004-1674.

Abdulrahim, M., Garcia, H. and Lind, R. 2005. "Flight Characteristics of Shaping the Membrane Wing of a Micro Air Vehicle," *Journal of Aircraft*, 42(1):131–137.

Cesnik, C.E.S., Mok, J., Parikh, A.S. and Shin, S. 2004. "Optimization Design Framework for Integrally Twisted Helicopter Blades," In: *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, USA, AIAA Paper 2004-1761.

Dano, M.L. and Hyer, M.W. 2003. "SMA Induced Snap-through of Unsymmetric Fiber-reinforced Composite Laminates," *International Journal of Solids and Structures*, 40(22):5949–5972.

Fett, T. and Thun, G. 1998. "Determination of Room-temperature Tensile Creep of PZT," *Journal of Materials Science Letters*, 17(22):1929–1931.

Hufenbach, W., Gude, W. and Kroll, L. 2002. "Design of Multistable Composites for Application in Adaptive Structures," *Composites Science and Technology*, 62(16):2201–2207.

Jung, H., Shim, J.Y. and Gweon, D. 2001. "Tracking Control of Piezoelectric Actuators," *Nanotechnology*, 12(1):14–20.

Kudva, J.N. 2004. "Overview of the DARPA Smart Wing Project," *Journal of Intelligent Material Systems and Structures*, 15(4):261–267.

Lu, K.J. and Kota, S. 2003. "Design of Compliant Mechanisms for Morphing Structural Shapes," *Journal of Intelligent Material Systems and Structures*, 14(6):379–391.

Nelson, L.J. 2002. "Smart Piezoelectric Fibre Composites," *Materials Science and Technology*, 18(11):1245–1256.

Park, J.S. and Kim, J.H. 2005. "Analytical Development of Macro Fiber Composite Active Twist Rotor," *Smart Materials and Structures*, 14(4):745–753.

Potter, K.D. and Weaver, P.M. 2004. "A Concept for the Generation of Out-of-plane Distortion from Tailored FRP Laminates," *Composites Part A – Applied Science and Manufacturing*, 35(12):1353–1361.

Ramrakhyani, D.S., Lesieutre, G.A., Frecker, M. and Bharti, S. 2005. "Aircraft Structural Morphing using Tendon Actuated Compliant Cellular Trusses," *Journal of Aircraft*, 42(6):1615–1621.

Schultz, M.R. and Hyer, M.W. 2003. "Snap-through of Unsymmetric Cross-ply Laminates using Piezoceramic Actuators," *Journal of Intelligent Material Systems and Structures*, 14(12):795–814.

Schultz, M.R. and Hyer, M.W. 2004. "A Morphing Concept based on Unsymmetric Composite Laminates and Piezoelectric MFC Actuators," In: *45th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, USA, AIAA Paper 2004-1806.

Seffen, K.A. 2004. "Bi-stable Concepts for Reconfigurable Structures," In: *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, USA, AIAA Paper 2004-1526.

Shin, S., Cesnik, C.E.S. and Hall, S.R. 2005. "Closed-loop Control Test of the NASA/Army/MIT Active Twist Rotor for Vibration Reduction," *Journal of the American Helicopter Society*, 50(2):178–194.

Smart Materials Corporation, 2005, http://www.smart-material.com/ (accessed 10/2005).

Wilkie, W.K., Inman, D.J., Lloyd, J.M. and High, J.W. 2004. "Anisotropic Piezocomposite Actuator Incorporating Machined PMN-PT Single Crystal Fibres," In: *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Palm Springs, California, USA, AIAA Paper 2004-1889.