

MRS Singapore - ICMAT Symposia Proceedings

Symposium W

Active composites based on bistable laminates

C.R.Bowen^{a*}, H.A.Kim^a, A.I.T. Salo^b,^a Faculty of Engineering and Design, University of Bath, Bath, BA2 7AY, UK^b Sport and Exercise Science, University of Bath, Bath, BA2 7AY, UK

Abstract

This paper describes the manufacture, characterisation and actuation of functional composites using asymmetric bistable composites. Such laminate structures are finding interest in applications such shape changing applications, energy harvesting and de-icing. In this paper results are presented for bistable structures that are actuated by a variety of mechanisms to induce ‘snap-through’ between states or a change of shape in a single state. This use of piezoelectric ceramic based actuators (Macro Fibre Composites), shape memory alloys and thermal actuation are examined. The actuators characteristics of each system, such as bandwidth, power and energy requirements, are described and compared.

© 2013 The Authors. Published by Elsevier Ltd.

Selection and/or peer-review under responsibility of the scientific committee of Symposium [Advanced Structural and Functional Materials for Protection] – ICMAT.

Keywords: piezoelectric; composite; bistable; actuation; smart

1. Introduction

Asymmetric bistable laminates have been considered for a number of potential applications ranging from shape change [1] to energy harvesting [2] and de-icing [3]. Bistable composites are asymmetric laminates, can maintain two different shapes and are often coupled to some form of actuation, either to induce a transition between each stable state (‘snap-through’) or to provide a change of shape within a single state. Figure 1 shows the two stable states, ‘State-I’ and ‘State-II’, of a bistable carbon fibre reinforced plastic (CFRP) of dimensions 150mmx150mm; in this case the laminate has been combined with a piezoelectric macro fibre composite (MFC) which is the actuator component. The CFRP is an asymmetric [0/90]_T laminate where an anisotropy of the coefficient of thermal expansion between the individual plies leads to a residual stress on cooling from the high cure temperature (~180°C) and produces laminate curvature.

Under particular conditions (e.g. a sufficiently length/thickness ratio) the thermal stress produces two stable equilibrium states. For shape changing applications such structures are of interest since a large structural deformation can be achieved by actuating the laminate between its two stable configurations; although there are concerns regarding their low stiffness [4]. Actuation of a bistable skin could also be of interest for de-icing system where a change in shape debonds an ice layer on the laminate surface [3]. The cured shape and snap-through behaviour of bistable laminates has been investigated [5] and actuation of these laminates using piezoelectrics [6], shape memory alloys [1,7] and thermal patches [8] examined. The aim of this paper is to provide examples of actuation of these structures with a description and comparison of the actuation characteristics of each approach to aid in actuation selection.

* Corresponding author. Tel.: +44 1225 383660.

E-mail address: c.r.bowen@bath.ac.uk

2. Actuation of bistable laminates

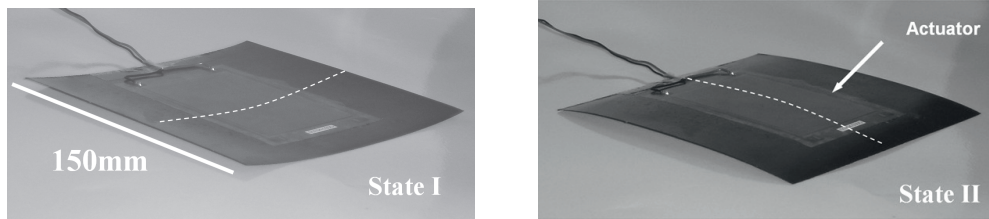


Fig. 1. Example of unsymmetric bistable laminate $([0/90]_T)$ with piezoelectric actuator in (a) State I and (b) State II.

2.1. Piezoelectric actuation

Piezoelectric actuator materials include ceramics, such as lead zirconate titanate (PZT), and polymers, such as polyvinylidene difluoride (PVDF). Both materials are capable of high frequency actuation and rapid response since the ferroelectric dipoles react quickly to an applied electric field. PVDF type actuators have not been used to induce snap-through of bistable laminate since their low stiffness ($\sim 8\text{GPa}$) compared to the host structure, such as CFRP ($\sim 200\text{GPa}$). The higher stiffness of PZT type materials ($\sim 30\text{--}50\text{GPa}$) makes them more appropriate but they require high electric fields ($\sim 2\text{kV/mm}$) to achieve the maximum deflection. This can often lead to high drive voltages, especially if the electrode separation is of the order and 1mm , as is the case of MFC devices [9]. In addition the maximum strain is relatively low ($\sim 0.1\text{--}0.2\%$) and since the purpose of the piezoelectric is to induce a transition from each stable state, it is of interest to compare the maximum piezoelectric strain with the thermal strains (ϵ_t) of the bistable laminate during curing since ϵ_t is ultimately responsible for the curvatures in Figure 1. The thermal expansion coefficient (α) of the carbon fibre/epoxy is ~ 0 in the fibre direction and $\sim 30 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ in the transverse direction [10]. Since the cure temperature used was 180°C the thermal strain in the fibre direction ($\alpha\Delta T$) is $\sim 0.45\%$, greater than the piezoelectric free strains, but of the same order. The use of piezoelectric ceramics to induce the shape change therefore seems attractive, especially when flexible and damage tolerant piezoelectric fibre based actuators (e.g. MFCs) are now commercially available in sizes of $\sim 100 \times 100\text{mm}$ or smaller. High strain piezoelectric single crystals are also available with strains of up to 1.5% ; although they are costly, low stiffness and available in limited shapes.

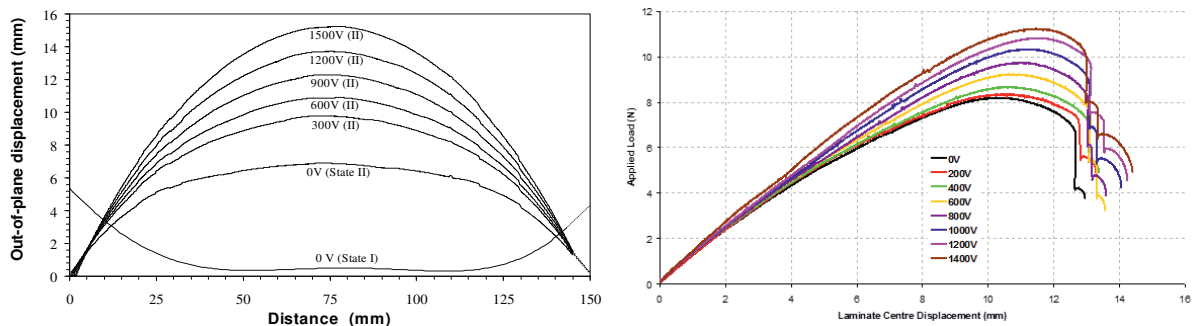


Fig. 2. (a) actuation of bistable laminate using piezoelectric actuation [6]. Note high voltages associated with need for high electric fields and electrode separation of approximately 1mm . (b) load-deflection characteristic of laminate in a single state with applied voltage

Figure 2a shows the shape of the laminate in Figure 1 under a range of applied voltages. Before applying a voltage the laminate can be in State I or State II, whose shape profiles are indicated as '0V (State I)' and '0V (State II)' in Figure 2a respectively. When the laminate is initially in '0V (State I)' it exhibits snap-through from State I into State II at a voltage of $100\text{--}150\text{V}$. As the applied voltage is increased to 1500V the curvature of the laminate in State II increases and on removal of the voltage the curvature of the laminate subsequently reduces but the structure remains in State II. Although the change in shape and displacement is relatively large (centre deflections of up to 15mm), the change is irreversible. Due to the small piezoelectric strains reversible actuation can only be achieved by maintaining the laminate in '0V (State II)', with no snap-through, which reduces the shape change (up to 8mm at its centre). Figure 2b shows that control of the snap-through load of the laminate can be tailored by the applied voltage; this is achieved as a result of an increase in curvature with voltage since the stiffness of the laminate remains unchanged with voltage (see early force-displacement data in Fig 2b). Figure 3 shows the displacement of the laminate with voltage and time in a single state and highlights the instantaneous response of the piezoelectric with applied voltage. It is of interest to note that after an initial displacement at each voltage, due to the rapid

response of electrical dipoles, there is a gradual ‘creep’ of the laminate (see inset of Figure 3). This creep is a result of slower domain motion within the ferroelectric ceramic and can lead to an increase in displacement of the order of a 1-2% of the total displacement per time decade. Domain motion can also lead to a hysteretic response of the piezoelectric, necessitating closed-loop control if precise control over laminate position/displacement is required.

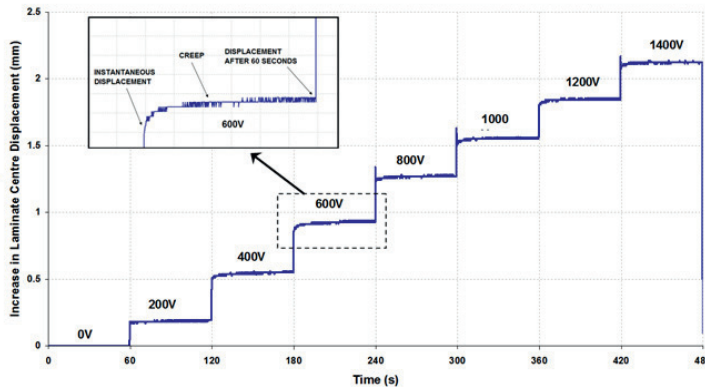


Fig. 3. (a) displacement of laminate with voltage in a specific state, note rapid response and subsequent creep behavior.

2.2. Shape memory alloy (SMA) actuation

An alternative actuation mechanism is SMA which can provide a high force and high strain (~8%). SMA actuation has received less interest for bistable structures than piezoelectric actuation due to its slow response time and low bandwidth; e.g. typical frequency of $<10^2$ Hz compared to greater than 10^4 Hz for a piezoelectric ceramic. We have combined the advantages of the piezoelectric and SMA materials to achieve self-resetting bistable composites [7]. The approach uses piezoelectric actuation to provide a rapid snap-through of a bistable cantilever (State I→II) with a fine degree of control and a relatively slow but high strain SMA actuation to reverse the state change (State II→I). The bistable cantilever beam structure with piezoelectric patch (MFC) and SMA wire actuators is shown in Figure 4a. Starting from its raised state (State I) the cantilever profile with 0 to 1200V applied to the piezoelectric is shown in Figure 4(b). Applying voltages between 0 and 1200V increases the deflection but the cantilever remains in State I. At 1300V there was a large deflection and snap-through from State I to II, but the cantilever cannot be returned to State I using the MFC patch alone due to its low strain capability. After snap-through from State I to State II, the voltage applied to the SMA wire was increased from 0V to 11 V at 1V interval and cantilever beam profiles are shown in Figure 4(c). In this case the applied voltage provides Joule (resistive) heating to achieve a martensite to austenite phase change in the SMA and induce a shape memory effect. Small deflection changes are seen between 0 and 5V as the temperature in the SMA wire had not reached the transition temperature. There was a more marked change between 5V and 8V although the cantilever beam remained in State II. This non-linear strain behavior is in contrast to piezoelectric actuation, indicating that while SMA actuation may be appropriate to induce snap-through between states it is less able to actuate and control shape within a single stable state. Snap-through from State II to I was observed at 9V. On removal of the voltage to the SMA, the cantilever beam returned to its original (0V) State I profile and this reversible actuation was repeatable indicating that the piezoelectric snap-through from State I to State II was sufficient to deform (twin) the SMA wire and enable fully reversible snap-through. It is of interest to compare the power and energy requirements for actuation methods. A comparison of Figs. 4(b) and (c) reveal the different power requirements of the two actuator materials. The piezoelectric requires a high voltage (>1000 V) and electric field (~1-2kV/mm) with low current (since the piezoelectric is a dielectric) while the SMA requires a lower voltage (<15 V) with high current (up to 1A). The piezoelectric is primarily a reactive (capacitive) load while the SMA is a resistive load. Based on the MFC (25x14mm) capacitance (C) of 0.61nF and a maximum current of 50mA (for the power supply), the time (t) to attain a voltage (V) of 1300V is $CV/I_{\max}$, i.e. 15 μ s. This equates to a peak power ($0.5CV^2/t$) of 32J/s for piezoelectric actuation and a total energy of 1mJ ($0.5CV^2$). For the larger 85mm x 57mm MFC actuator in Fig. 1 its higher capacitance (9.3nF) leads to a higher power for 1300V on 0.015J; the actuator capacitance scales with its area. A voltage (V) of 15V and current (I) of 1A for the SMA equates to a lower power (VI) of 15J/s, which is applied for longer periods (3s) to achieve sufficient Joule heating, which a larger total energy (power x time) of 45J.

2.3. Thermal actuation

Since the laminate curvature originates from thermal strains as a result of cooling from an elevated cure temperature, the laminate would flatten as heated. Here we employ aligned-carbon nanotube (A-CNT) heaters on the laminate since their low weight, flexibility and efficiency could make an ideal combination for this application [3]. The nanocomposite layer consists of an aerospace grade surfacing film and electrically-conductive aligned carbon nanotubes (A-CNTs) ~10 nm in diameter and more than 100 μm long formed by chemical vapour deposition process [11]. This fibrous shape allows them to make reliable electrical contacts with each other even though they have less than 5 vol% loading in the resistive heater. An image of the bistable CNT-composite laminate in two stable states is shown in Figure 5, with the CNT nanocomposite patch and copper contacts visible on the top surface. The profile shape of the laminate center at each input voltage is shown in Figure 6a. When the laminate is heated by the A-CNT the height of the laminate curve reduces and the laminate flattens and eventually undergoes snap-through from State I to State II at 5V with a current of 0.6A, equating to a power (VI) of 3J/s which is lower than the piezoelectric and SMA. Figure 6b shows the response of the mean laminate temperature to a constant input voltage of 5V from ambient temperature to snap-through. For the first 2.5s the temperature of the laminate remains close to ambient, this time is required for the CNT patch to begin to heat up. Once heat transfer to the laminate begins its mean temperature increases to 33.8°C at which it exhibits ‘snaps through’, after 28s. While the power is lower than the SMA and piezoelectric is must be applied for longer, leading to a higher energy requirement (84J) that both the SMA and piezoelectric.

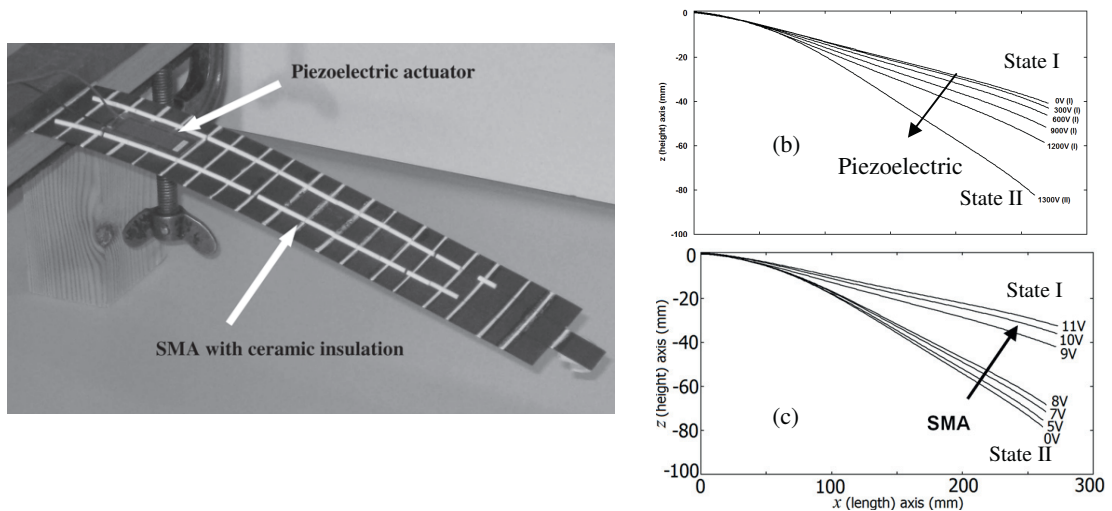


Fig. 4. (a) actuation of bistable laminate using both piezoelectric and shape memory actuation. After (a) initial snap-through by piezoelectric (25mmx14mm), (b) high strain of shape memory enables ‘resetting’ of laminate. Note differences in voltage for piezoelectric and shape memory [7].

3. Conclusions

This paper provides a comparison of the actuation mechanism for bistable laminates. Piezoelectric actuation offers high frequency and rapid response time and an approximately linear relationship between strain and voltage providing control of shape within a specific state, although there are issues such as creep and hysteresis due to domain motion. The electrical load is capacitive in nature, compared to the resistive load of SMA and thermal heaters, and while the peak power levels can be high (32J/s) it does not need to be applied for long periods so that total energy is low (0.015J for a 85x57mm MFC, equating to $3\mu\text{J}/\text{mm}^2$). Their relatively low strain levels (0.1%) are lower than the thermal strain (0.45%) which makes reversible snap-through difficult and the high electric fields can require high drive voltages (up to 1500V for 1mm electrode spacing). MFC patches are commercially available in specific dimensions which make scaling more complex for larger structures. SMAs provide high actuation strains (8%) which exceed the thermal strains, providing a route for reversible snap-through between state states. Since the actuation is dependent on a phase change within the material due to resistive heating (Joule heating) there is less control over the displacement within stable state. Joule heating is typically low voltage and high current, with intermediate power levels (15J/s) for periods of seconds and total energy was 45J for the device here. The need for thermal cycling of the SMA wire limits to shape change to low frequency or slow response times (several seconds). Since the material is in the form of wires integration with the host structure can be more complex. Thermal actuation using CNT heaters enables control by reducing the thermal strains to provide control over shape and provide snap-

through. The peak power levels (3J/s) are low compared to piezoelectric and SMA materials but the response is the slowest (28s) since whole structure must be heated in addition to the heater itself. For thermal heating of the device considered here snap-through required 85J for a 30x40mm heating, equating to 70mJ/mm². CNT may be of particular interest where heating and shape change are desirable, e.g. thermal actuation of a bistable laminate could be used for a highly efficient combined thermo-mechanical de-icing system; using heat to both melt the base of the ice formation, weakening its bond to skin, and deform the skin to apply shear to debond the ice-skin interface simultaneously. In addition the vapour deposition route means that larger areas could be more readily produced compared to piezoceramic patch actuators.

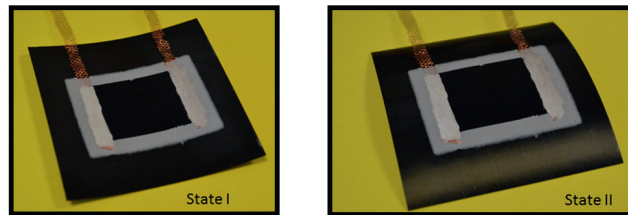


Fig. 5. Unsymmetric bistable laminate $[(0/90)_T]$ with carbon nanotube heaters in (a) State I and (b) State I. Laminate is 80x80mm. CNT is 30x40mm.

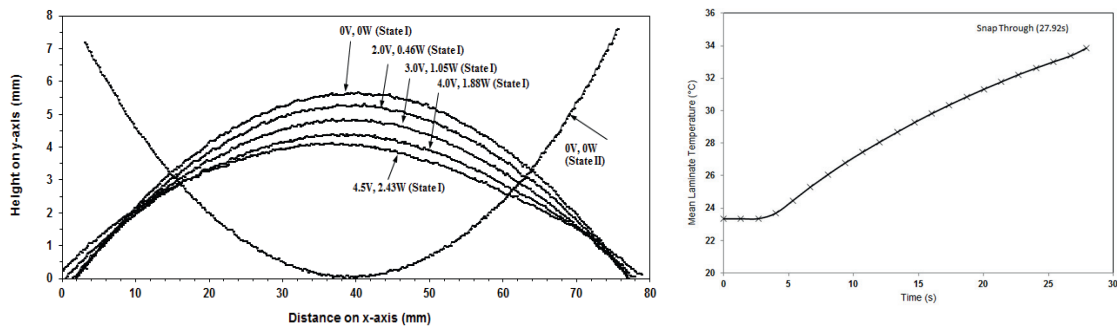


Fig. 6. (a) Actuation of bistable laminate using thermal actuation [3]. Note low voltages. (b) Displacement of laminate with voltage in a specific state, note slow response of displacement [3].

Acknowledgements

Bowen acknowledges funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement no. 320963 on Novel Energy Materials, Engineering Science and Integrated Systems (NEMESIS).

References

- [1] Dano, M. L., Hyer, M. W., 2003. SMA-induced snap-through of unsymmetric fiber-reinforced composite laminates, *International Journal of Solids and Structures* 40, p.5949.
- [2] Arrieta, A.F., Hagedorn, P., Erturk, A., Inman, D.J., 2010. A piezoelectric bistable plate for nonlinear broadband energy harvesting, *Applied Physics Letters* 97, 104102.
- [3] Brampton, C.J., Kim, H.A., Buschhorn, S.T., Lee, J., Pickering, S.G., Wardle, B.L., Bowen, C.R., Actuation of bistable laminates by conductive polymer nanocomposites for use in thermal-mechanical aerosurface de-icing systems, submitted to Sci Tech conference 2013.
- [4] Daynes, S., Weaver, P.M., 2013. Stiffness tailoring using prestress in adaptive composite structures, *Composite Structures* 106, p.282.
- [5] Hyer, M. W., 1981. Some observations on the cured shape of thin unsymmetric laminates, *Journal of Composite Materials* 15, p. 175.
- [6] Bowen, C.R., Butler, R., Jervis, R., Kim, H.A., Salo, A.I.T., 2007. Morphing and shape control using unsymmetrical composites, *Journal of Intelligent Material Systems and Structures* 18, p.89.
- [7] Kim, H. A., Betts, D. N., Salo, A. I. T., Bowen, C. R., 2010. Shape memory alloy – piezoelectric active structures for reversible actuation of bistable composites, *AIAA Journal* 48, p. 1265.
- [8] Li, H., Dai, F., 2012. Numerical and experimental study on morphing bi-stable composite laminates actuated by a heating method, *Composites Science and Technology* 72, p.1767.
- [9] Bowen, C.R., Nelson, L.J., Stevens, R., Cain, M.G., Stewart, M., 2006. Optimisation of interdigitated electrodes for piezoelectric actuators and active fibre composites, *Journal of Electroceramics* 16, p.263.
- [10] Potter, K.D., 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, p.1353.
- [11] Wardle B.L., Saito D.S., Garcia E.J., Hart A.J., de Villoria, G.R., Verploegen E.A., 2008. Fabrication and characterization of ultrahigh-volume fraction aligned carbon nanotube-polymer composites, *Advanced Materials* 20, p. 2707.