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Bi-stable composites with piezoelectric actuators for shape change

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Abstract. Unsymmetrical carbon fibre/epoxy composites with bonded piezoelectric fibre actuators were investigated as a means to shape change, or morph, composite structures. A carbon fibre cantilever was examined along with its response to applied strains (from piezoelectric actuators), with emphasis on the characterisation of shape/deflection and the reproducibility of the shape/deflection of the structure.

Introduction

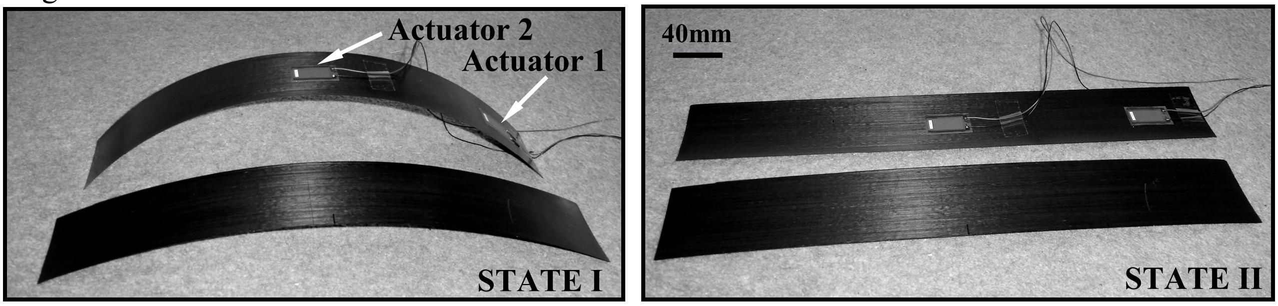
There is considerable interest in structures that are able to change shape, or morph, to meet changing performance requirements [1]; for example to achieve high levels of manoeuvrability in micro air vehicles [2] or to enhance helicopter rotor blade efficiency [3]. A variety of mechanisms have been investigated to achieve shapes change in structures. These range from the use of compliant mechanisms [4] to bi-stable concepts that exhibit snap-through behaviour from one stable state to another, occurring for example, within trusses [5] or un-symmetric composite laminates [6,7]. Materials used to induce snap-through include shape memory alloys [8,9], which can induce high strains (8%) at low frequency [10] 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%. However, the use of piezoelectric single crystals can produce up to 1% [11].

Due to the low maximum strain of piezoelectric materials, the introduction of bending, buckling or bi-stability into a structure is often used as an amplification mechanism to generate useful deflections. Shultz and Hyer [5,6] examined an unsymmetrical cross ply $[0/90]_T$ laminate with a macro fibre 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. The aim of this paper is to demonstrate the reproducibility of the response of a cantilever structure manufactured from an un-symmetric composite with bonded piezoelectric actuators to induce snap-through.

Experimental

Un-symmetric carbon fibre composites were manufactured using Hexcel M21/T800 carbon fibre epoxy pre-pregs. Two composites were manufactured; a ‘thin’ 2-ply sample with a [0,90] lay-up and a ‘thick’ 4-ply sample with a [0,0,90,90] lay-up. After laying-up the composite pre-pregs and curing at 180ºC at 100psi the samples were cut to 70mm x 425mm dimension. The thickness of the ‘thin’ and ‘thick’ composites was 0.45mm and 0.95mm respectively. Fig.1 shows both composites and their two stable states, designated as ‘State I’ and ‘State II’ which result from high temperature curing of their un-symmetric lay-up. Due to the lower stiffness and greater curvature of the thin composite, 28mm x 14mm piezoelectric macro-fibre composite (MFC) actuators from Smart Materials Corp., USA (Actuator no. M2814 d33) were bonded to the composite whilst in State II. Two actuators were used in an attempt to actuate them independently and provide a range of possible shapes, although only data from applying electric potentials to Actuator 1 is presented here. Fig. 1a identifies the location of the actuators.

Two separate analysing sessions were conducted using motion analysis techniques. The first was to analyse the shape of the composites, before attaching the actuators, and to repeat the snap-through to assess the reproducibility of the stable states/shapes. A digital video camera recorder (Sony DCR-TRV 900E, Sony Corporation, Japan) operating at 50 fields per second was set up above the composites which were bent into State I and placed on their side to minimise distortion due to self weight.



(a) (b)

Figure 1. Images of composites and their states. (a) State I and (b) State II. The actuators were attached to the thinner composite.

The camera lens was at the height of 2.70 m from the floor, and a plumb line was used to align the lens axis perpendicularly down and pointing to the middle of the analysing area. The plane, where the closest edge of the composite to the camera would be located, was calibrated with a rectangular calibration object of 349 mm x 262 mm for scaling purposes. Both thick and thin composites were bent into State I and the shape/profile was videotaped. The composites were straightened into State II and then bent again into State I, by hand, between the six individual recordings. The video clips were subsequently transferred to a computer. The edge of the bent composite, and the four corners of the calibration object, were manually digitised on Peak Motus® (Peak Performance, Colorado, USA); achieved by using a mouse to select 33 points at the edge of the composite. Firstly, the origin and the end of the composites were digitised, after which the further 31 points were selected in the approximate middle of the existing two points. This provided an approximately equal distribution of the points throughout the whole length of the composite. The digitised area consisted of 1440 x 1152 pixels, resulting in an effective resolution of digitisation of 300μm in both horizontal and vertical directions. After the scaling and reconstruction, the raw co-ordinates of 33 points were exported to Excel® software.

The second analysis was used to assess the shape change of the thin composite under piezoelectric actuation. For this experiment, electrical potentials were applied to Actuator 1 while the composite was held between two steel plates in a cantilever configuration, as shown in Fig. 2. In this case the video camera lens was located horizontally 2.70 m away from the cantilever. Again, the lens axis was perpendicular to the plane where the cantilever was located. This plane was calibrated at the same fashion as above.

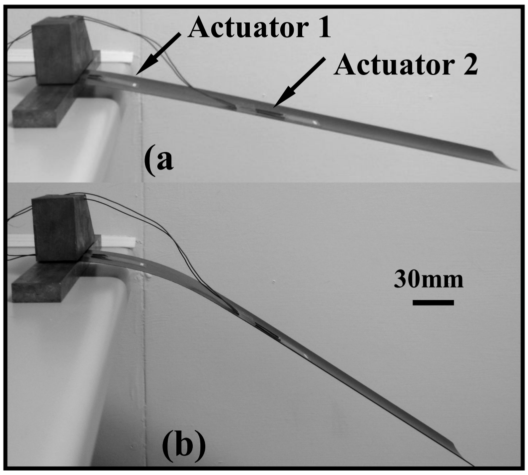


Figure 2 Thin composite used as a cantilever with stable states labelled (a) and (b). No electric potential was applied in these images.

The overall camera view had to be enlarged slightly due to expected larger change of the shape of the cantilever. Consequently, the effective resolution of digitisation changed to 400μm. When comparing the positional accuracy of a static point between each test (the clamped end point of the cantilever) the standard deviation was 227μm. To test the repeatability of the profile and deformation under piezoelectric actuation, four rounds of testing were undertaken with electrical potentials applied to the actuator in 100V increments until snap-through from the state in Fig. 2a to Fig. 2b occurred. There was no change is clamping conditions between each test. The videoclips were again transferred to a computer and the edge of the cantilever was digitised with 33 points, with further analyses handled in exactly same manner as above.

Results and discussion

Fig. 3 shows the measured shape profile of both the 'thick' and 'thin' composite in State I, with no actuators attached to either composite. The figure includes data from six individual measurements where the composites have been have been bent from State II to State I between each data set. Both composites produce reproducible shapes, observable from the low scatter of the measurements (198 data points in total for each composite) and a larger curvature is observed for the thin composite.

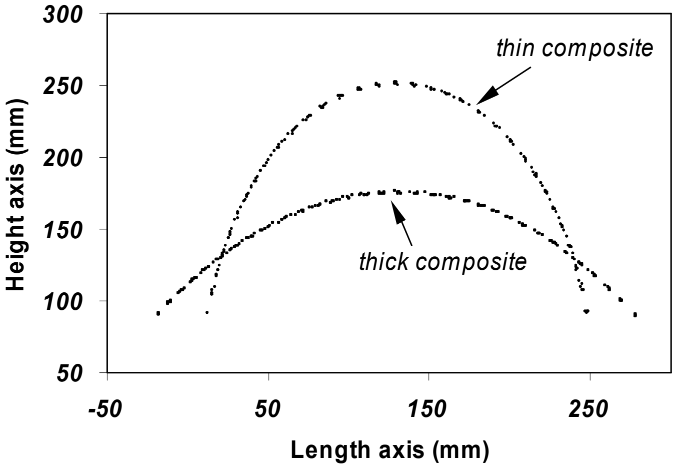


Figure 3. Composite profile in State I (no actuators attached). Data from 6 repeat profiles after moving from State II→I.

Fig. 4a shows the measured shape profile as a function of applied electric potential applied to Actuator 1 in Fig. 2 during the first test (Round 1). In the 0-400V range there is a gradual change in the profile which remains in the stable state shown in Fig. 2a, with snap-through to the state in Fig. 2b occurring at 500V, leading to a large but irreversible shape change. Fig. 4b shows the tip deflection in the height axis as a function of voltage, where a zero tip deflection in the figure corresponds to the position of the cantilever end point during the first test (Round 1) at 0Volts. For Round 1 the deflection is almost linear and reversible, until snap-through occurs at 500V.

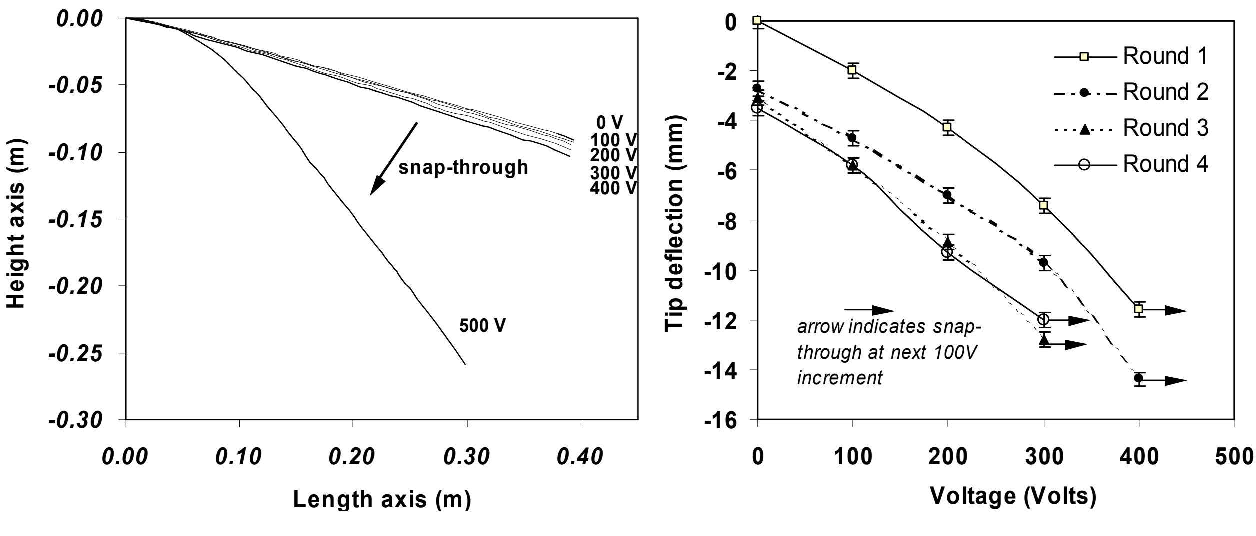


Figure 4. (a) shape profile for Round 1 at voltages 0 to 500V, (b) tip deflection versus applied voltage for four separate Rounds, showing variability in deflection and onset of snap-through.

When repeating the testing a similar gradient of the tip deflection-voltage response before snap-through was observed (see Fig.4b) with a mean gradient of 0.030mm/V and a standard deviation of 0.002mm/V. This is in contrast to the piezoelectric actuator displacement which is ~1200 times smaller at ~25nm/V (free displacement). Although the gradient in Fig. 4b is similar, the initial position of the cantilever tip at 0V moves to a lower height between each test. In addition, in the first two rounds the potentials of 0, 100, 200, 300 and 400 V applied to Actuator 1 kept the cantilever in the shape in Fig. 2a, and the potential of 500 V caused snap-through of the cantilever from to that in Fig. 2b. In the latter two rounds, the potential of 400 V caused snap-through of the cantilever. These changes in response could be due to non-linearity and hysteresis in the piezoelectric actuator or due to a change in the clamping conditions of the cantilever, although examination of the position of the clamping point revealed no significant movement between each test (less than the video resolution).

Conclusions

Unsymmetrical carbon fibre/epoxy composites with bonded piezoelectric actuators have been investigated as a means to shape change, or morph, composite structures. A carbon fibre cantilever was examined along with their response to applied strains (from piezoelectric actuators); with emphasis on the characterisation of shape/deflection and the reproducibility of the shape/deflection of the structure. The shapes formed by the unsymmetrical composites are reproducible and large changes in shape and deflections can be obtained by the use of piezoelectric actuators. Reversible shape changes in a single state are significantly less than irreversible changes that involve snap-through from one state to the other. Although the stables shapes are reproducible, changes to the clamping boundary conditions or the hysteretic nature of the actuator can lead to variability in the shape and deflections observed. Future research is to investigate multiple actuators along the length of the structure to introduce additional shape/profile change.

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