TIME AND TEMPERATURE DEPENDENCE ON THE SNAP-THROUGH BEHAVIOUR OF ADAPTIVE BISTABLE COMPOSITES

M. Gude, W. Hufenbach, C. Kirvel*
Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology (ILK), Holbeinstraße 3, 01307 Dresden, Germany
* Corresponding author (christian.kirvel@tu-dresden.de)

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1 Introduction

Bistable fibre-reinforced polymer laminates constitute an interesting approach for adaptive structures and gained some attention in the recent decades. The characteristics of bistable laminates are two opposing distorted, almost cylindrical shapes that can be converted into each other by bending moments. The distortion of laminates is usually a result of residual stresses that come with an unsymmetric architecture of fibre-reinforcement. As several studies [1,2,5] focussed on, the simplest bistable laminate is a two-layered cross-ply laminate where the curvature emerge vertically to the fibre direction on either side of the laminate. Since the structure stays steadily in one of the two curvature shapes, energy is only necessary for the switching between both shapes. Therefore only a short impulse is necessary to initiate that snap-through. Such an impulse can be induced by flat actuators like shape memory alloy (SMA) wires or piezoceramic actuators – like commercially available products such as Macro-fibre composites (MFC) – that can be attached to the surface of the laminate or embedded into it. The feasibility of such hybrid structures has been proven by several researchers, e.g. [3,4,6]. Single actuation with only one flat actuator on one side of a cross-ply laminate (see Fig. 1) have been studied as well as complete actuation cycles with a second actuator on the backside for reversing the bistable structure (2-way-effect).

This study addresses active bistable laminates with 2-way-effect and the influence of temperature and continuous switching operation for a longer duration on the performance of that laminate type in different experimental setups.

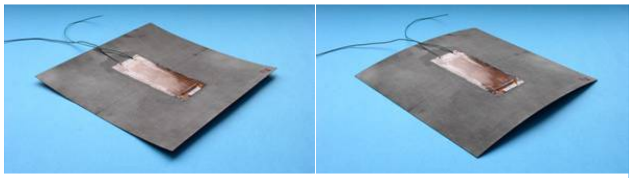

Fig. 1 Bistable unsymmetric cross-ply laminate with one attached MFC in its two stable equilibrium states

2 Preliminary work

Semi-analytical models using energy principles have proven to be an efficient instrument for conceptual design and parametric studies [1-4,6]. Those models have been subject of former studies of the authors and used for pre-dimensioning feasible experimental specimens, therefore shall be described briefly.

Displacements of the laminate are approximated by so called Rayleigh-Ritz functions satisfying the essential boundary condition of the mechanical system. Quadratic functions have shown to be convenient for describing the expected cylindrical bending of unsymmetric laminates with sufficient accuracy and fulfilling the boundary conditions. For considering rather large laminate deflections, extended strain-displacement-relations are necessary leading to a system of nonlinear equations. Solving that system of equations leads to the coefficients of the approximating displacement functions. Those functions describe the deformation of the bistable laminates due thermally induced residual stresses and the influence of actuators. Fig. 2 shows exemplary the two equilibrium states of a bistable unsymmetric laminate with an MFC attached to the upper surface in displacement plots achieved by the aforementioned mathematical method. Furthermore, that method allows predicting the actuator induced snap-through of a bistable unsymmetric laminate.

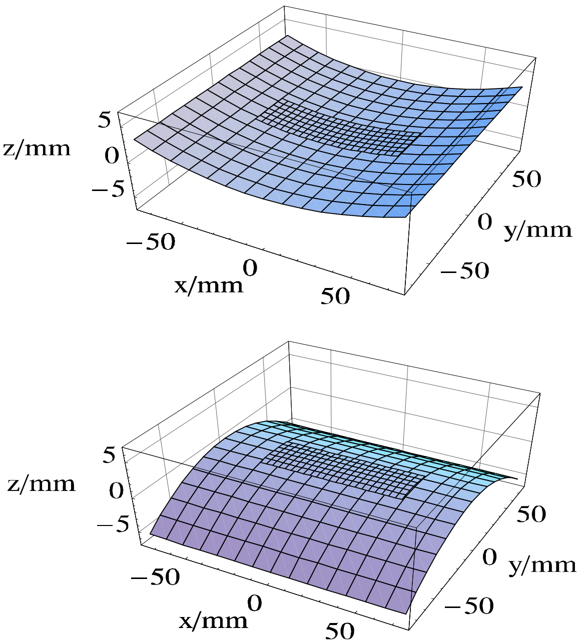

Fig. 2 The two stable equilibrium shapes of a cross-ply laminate with one attached MFC (semi-analytical model)

Another procedure for preliminary design of active bistable laminates is using the Finite Element Analysis (FEA). Although FEA is more time consuming, it enables approaches for solving intricate problems like nonlinear material behaviour or a more realistic mapping of the bonding process. The FE program ANSYS offers two strategies simulating the MFC induced snap-through behaviour of bistable laminates. The program provides special coupled-field brick elements enabling electro-mechanical analyses, simulating explicitly the material behaviour of piezoelectric materials when charged with an electric field. Due to reasons of compatibility and convergence, the whole laminate should be modelled using brick elements, leading to a considerably elevated numerical and therefore time consuming effort. Another approach is using shell elements and a thermal analogy to the behaviour of piezoelectric materials. Shell elements offer a more efficient method modelling thin laminates, as a significant lower number of elements is required and therefore a faster solving process possible. The missing piezoelectric properties will be compensated by appropriate defined thermal expansion behaviour of the active layer. The differing layup over the laminate area has to be considered when meshing the hybrid laminate with layered shell elements. Generally, the large deflections of the unsymmetric laminate require a nonlinear structural analysis and a stepwise application of loads. Furthermore, simulating the cooling down process of the laminate leads to bifurcation, that makes it necessary forcing the structure into one of the two possible stable equilibrium shapes by applying small geometric imperfection or small forces.

For the design of feasible laminate/actuator configurations a parametric FE model using volume elements has been examined. A series of five deformation plots in Fig. 4 shows the simulations results of a complete 2-way snap-through cycle of an exemplary laminate/actuator configuration. The sequence starts at the top with the first equilibrium shape (a), both MFCs being inactive. Charging the upper MFC, the other one staying passive, the laminate flattens to a critical shape (b) and snaps into the second equilibrium shape (c). As the upper MFC gets inactive the lower one is getting charged, reducing the curvature of the second cylindrical shape from beneath until it reaches stage (d) and the laminate turns back into the first equilibrium shape (e).

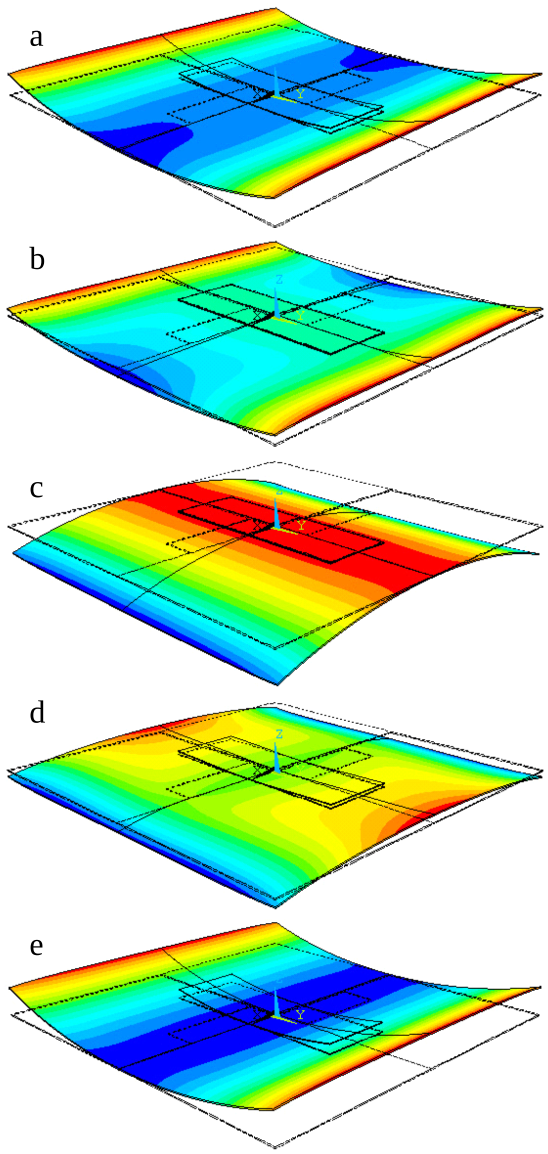

Fig. 4 Sequence of a simulated 2-way snap-through of an active bistable laminate with FEA

3 Experiments

The experimental studies are based on the configuration of a rectangular [0°/90°] carbon fibre-reinforced epoxy polymer laminate (200 × 180 × 0.6 mm³) with a balanced layup and two MFC actuators of the type M8557P1. The MFC patches are bonded by 2-component epoxy resin crosswise to either side of the laminate. Each actuator has been bonded separately with the aid of a vacuum bag, holding the whole assembly flat against a planar base.

In order for using a photogrammetric measuring system (PONTOS), tracking three dimensionally the displacement of the specimen, its surface needs to be prepared. Markers have been added in a regular pattern on one side of the test specimen (see Fig. 3). For reasons of simplicity and keeping the influence of required measuring aids at a minimum, just a quarter of the laminate surface has been applied with markers. Furthermore, it is assumed deformations of the laminate occur symmetrically around the middle of the laminate. Accordingly, the whole structure has been clamped vertically at its centre, allowing every movement around the centre and eliminating biased influence of gravity. The motion analysis software of the PONTOS system provides with stereo image based evaluation techniques 3D coordinates of the measuring points. Those coordinates are used calculating the curvatures along the axes which the markers are attached on.

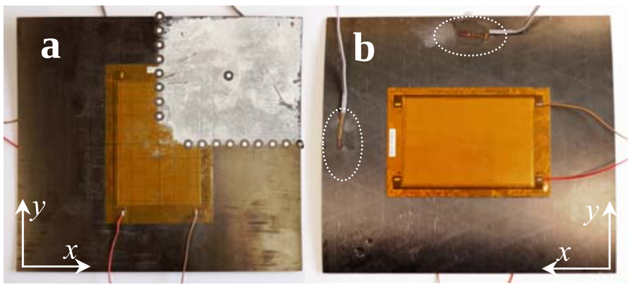

Fig. 3 Test specimen in front view (a) and back view with applied strain gauges (b)

A voltage amplifier provides both MFC with a high voltage (up to 1500V) over different channels so each actuator can be addressed and driven separately. Accordingly, a special LabVIEW program has been written controlling the voltage supply of each actuator and defining certain voltage slopes. As described later a counter for actuation cycles has been implemented as well as criteria for stopping long term test series.

The diagram in Fig. 5 shows exemplary a full cycle of a 2-way actuation where the hybrid laminate is snapped forth and back. Here, the course of the two curvatures (blue and red dots) of the laminate along the coordinate axes, which coincide with the symmetry lines, is outlined over time. The time dependent progresses of the voltages which drive the two MFCs attached on fore- and backside are overlaid with dashed lines. The actuation cycle starts with the hybrid laminate staying in the "blue" – according the drafts in the diagram – stable cylindrical equilibrium shape and activating the MFC on the concave (upper) side with a steadily increasing voltage. The MFC on the lower side remains inactive. As the upper actuator expands, the laminate flattens, being perceptible by the decreasing curvature κ_x. Meanwhile, the other curvature κ_y (red dots) rises slightly. The sudden jump, or drop respectively, of the curvatures after about 3 seconds (gray vertical line) indicates the snap-through, when the bistable laminate turns from the "blue" stable shape into the "red" one. At this time the actuator voltage reached a value of 435 V – the first snap voltage. The control program of the voltage amplifier keeps the voltage in the upper MFC rising until it reaches 1000 V and reducing it steadily with the same rate to zero. The laminate remains in the "red" equilibrium shape although its curvatures alter, κ_y slightly and κ_x significantly, reaching their extreme values when both actuators are without voltage at about 12 seconds, marking the end of the first half of one cycle. The second half starts when the lower MFC is getting activated and expands with increasing voltage (red dashed line), whereas the upper MFC stays passive. The curved laminate is flattening again until the second snap-through occurs, flipping it back to the first (blue) equilibrium shape at about 17 seconds. The value of the second snap voltage is 845 V. After reaching 1000 V the voltage in the lower MFC is decreasing to zero and fading out the actuators influence on the cylindrical shape of the laminate. Therefore, curvatures return to their original values.

Both snap voltages differ significantly (second being almost twice as high as the first) – as the curvatures in both unaffected equilibrium shapes also do – what are significant signs of the imbalance of the two equilibrium states due to imperfections of the bistable structure, but shall not be of further interest. To overcome those imperfections and focus on full actuation cycles in further studies, a minimal voltage for both MFCs was determined that guarantees a 2-way-effect.

Further studies are based on the main features of the described full actuation cycle, whereas repeated switching cycles for long term actuation studies have to be carried out with a far higher frequency.

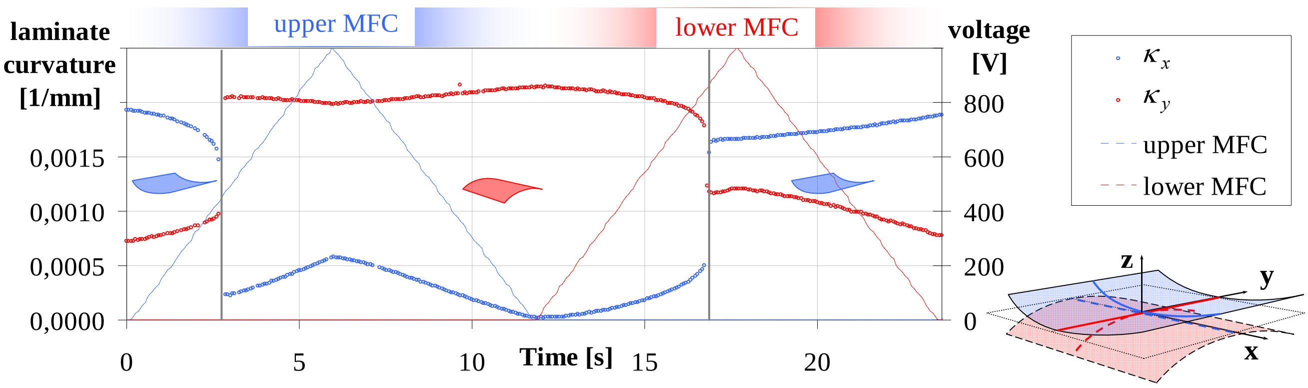

Fig. 5 Curvature-voltage-curve within a complete actuation cycle of a piecoelectrically driven bistable laminate (200 × 180 mm²)

4 Results

One main aspect of the research is the influence of the ambient temperature on the switch behaviour of the active bistable structure, especially how it will affect the snap voltage. Since the residual stress related distortion of a fibre-reinforced laminate is highly dependent on the difference of the cure temperature and the operating temperature. A climatic chamber was used to change the temperature of the test specimen over a range of -40 to 35 °C (see Fig. 6).

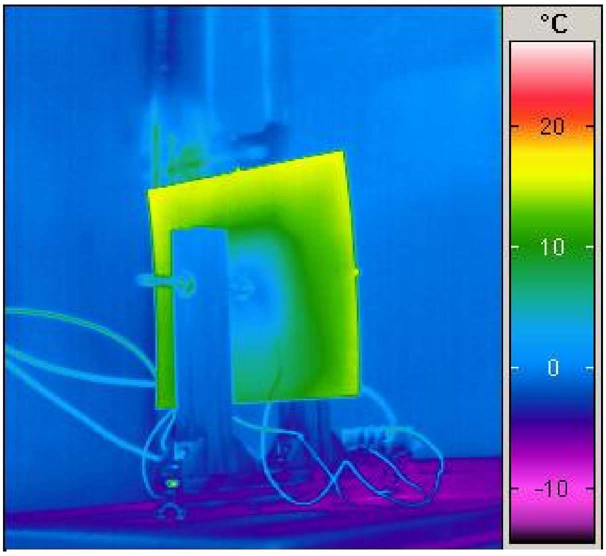

Fig. 6 Thermography picture of the climatized specimen in the test rig

Beneath a temperature of -10 °C, the laminate distortion is too large for initiating a snap-through by the MFCs. Above a temperature of 27 °C, bistability of the investigated structure vanishes. As depicted in Fig. 7, the lower the temperature the higher is the snap voltage, dropping almost linearly with increasing temperature. As expected, there is a high correlation between curvature and snap voltage. Furthermore, it is relevant whether increasing the MFC voltage to reach a minimal value (upper limit) for complete snap-through cycles or decrease the voltage against a lower limit where snap-through stops.

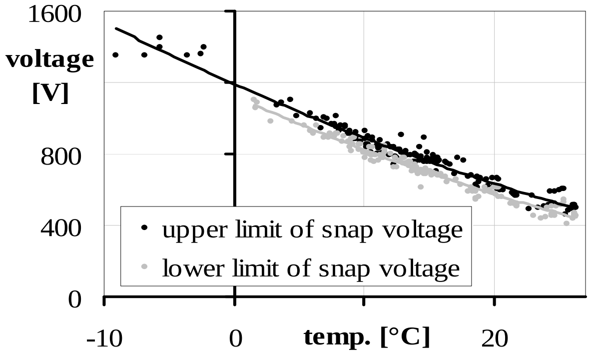

Fig. 7. Temperature dependence of the snap voltage of an active bistable laminate

The difference amounts to about 50 to 75 Volts here. Another important issue especially for practical applications addresses the impact of continuous operation. Especially long term studies with their high number of full actuation cycles demand an automated method of detecting full cycles with complete forth and back snap-through. For this purpose two strain gauges have been attached on the edge regions of the laminate (highlighted areas in Fig. 3b and points in the sketch of Fig. 8) detecting maximal and minimal strains, respectively, in x- and y-direction.

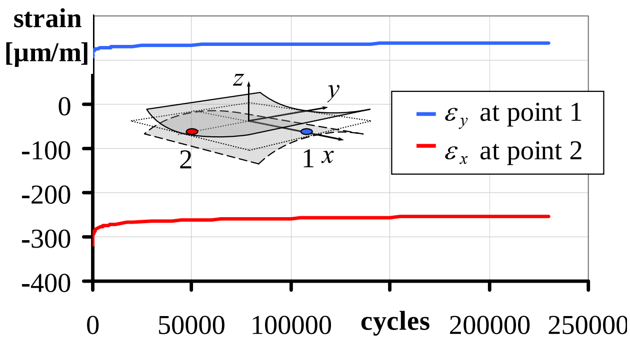

Fig. 8. Long-term deformation behaviour of active bistable laminates due to continuous cyclic actuation

The signals of the strain gauges are interpreted by the LabVIEW program. When the measured strains exceed successively two predefined thresholds a full cycle is counted. Otherwise, when thresholds are not exceeded multiple consecutive times the test series is aborted, usually to be traced back to a loss of bistability. Fig. 8 shows the results of a test series achieved by a switch frequency of 2 Hz. Within the first 30,000 cycles, a settling range can be observed where the strains converge to a value that stays almost constant for the rest of the switch cycles. At the end of the test series, reverse actuations infrequently fail. These dropouts are accumulating until finally the reverse effect of the specimen is totally lost most likely due to moisture absorption – leading to curvature decrease – and creep processes, typical for omnipresent operating conditions. Despite the large number of switching procedures delamination between MFC and the carrying laminate could not have been detected.

5 Conclusions

Results of studies which focus on the influence of temperature and high cycle 2-way actuation for piezoelectrically driven bistable cross-ply laminates have been presented.

The high temperature dependency of the residual stresses in bistable laminates restricts deeply the temperature range within the application field. An approximately linear relation between temperature and snap voltages, which trigger the snap through between the two equilibrium shapes, could be detected. Whereas, the snap voltages decrease with rising temperature. At a lower temperature limit the MFC reaches its capacity – failing to initiate snap-through – and at the higher temperature limit bistability of the laminate vanishes. Those issues might be faced by choosing a thermally more stable matrix material.

A limiting factor of long term operation is curvature retardation – or loss of bistability in the worst case – most likely due to moisture absorption, as bistability can be regained partially by drying the laminate. Stiffness degradation due to fibre or matrix damage can mostly be ruled out. Hygroscopic behaviour is mostly matrix related. Sealing the surface being waterproof or using a hydrophobic matrix system could help to overcome moisture related retardation.

The presented studies have been limited to epoxy based composites and the application of MFC as active elements due to their simple processability and availability. Using other composite materials and actuator components opens up a huge variety of active bistable systems that can enhance the requirement profile immensely.

6 Acknowledgement

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