

The application of thermally induced multistable composites to morphing aircraft structures

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ABSTRACT

One approach to morphing aircraft is to use bistable or multistable structures that have two or more stable equilibrium configurations to define a discrete set of shapes for the morphing structure. Moving between these stable states may be achieved using an actuation system or by aerodynamic loads. This paper considers three concepts for morphing aircraft based on multistable structures, namely a variable sweep wing, bistable blended winglets and a variable camber trailing edge. The philosophy behind these concepts is outlined, and simulated and experimental results are given.

Keywords: Morphing, Bistable structure, Variable sweep wing, Winglet

1. INTRODUCTION

The always present need for better aircraft performance is increasingly prompting designers towards the realization of “morphing” or “shape-adaptable” structural systems. Such systems should simultaneously fulfil the contradictory requirements of flexibility and stiffness allowing the aircraft to adapt themselves to achieve multi-objective missions. One primary advantage of such a platform would be the increased cost effectiveness of aircraft through eliminating the need for multiple, expensive, mission specific aircraft. However, from current trends in this research area, it is clearly evident that the practical realisation of a morphing structure is a particularly demanding goal with substantial effort still required.

It is indeed possible to create morphing structures just by deforming the main structural components; however such a “brute-force” approach requires significant energy to overcome the stiffness of the material. The weight penalty introduced with this approach can be counter-productive. An alternative solution consists of adding aerodynamic devices that help the structure to extract the force required for the actuation from the aerodynamic field¹. With this approach the scale of deformation achieved is usually very small and no significant variation in the flight envelope can be achieved. In fact, significant aerodynamic performance gains are achievable only through large overall changes in the aircraft geometry via wing sweep, area and/or span. At present, in both of these categories, such medium to large scale changes are obtained with complex and sophisticated mechanical devices significantly increasing installation and maintenance costs, as well as the structural weight of the airframe.

This paper presents a study on alternative structural configurations aimed at realising large changes in the geometry of the aircraft without making use of rigid bodies discretely hinged to the main airframe. The first concept is for the realisation of a variable sweep wing whereas the second and the third aim at changing the profile of the airfoil along the chord and along the span of the wing. Diaconu et al.² investigated different concepts to introduce multistable structures into aircraft systems. Mattioni et al.³ simulated bistable structures using finite element analysis. Anisotropic composites have also been used to tailor the structural properties for rotorcraft blades⁴ and morphing wings⁵.

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2. VARIABLE SWEEP WING

A wing with a variable sweep angle offers several benefits from the aerodynamic point of view such as the delay in the increased drag at Mach numbers close to unity and buffet onset⁶. From the structural point of view, there is the advantage that by changing the sweep angle structural loads are redistributed along the span reducing the bending moment requirements at the root sections. Variable sweep wings also pose significant disadvantages. The most accepted and widespread design for a variable sweep angle consists of a rigid wing that rotates around a pivot: this constrains all of the aerodynamic loads to act through the pivot producing a massive concentration of stresses. As a result, the large metal pivot needed to move the wings is complicated to build and install. This more often increases maintenance requirements and decreases fuel performance. An aircraft capable of moving its wing forward for fuel-efficient flight could never be as efficient as an airplane equipped with a straight wing. The same is true for aircraft with swept-back wings; they would always be more efficient than aircraft with swing-wings. It is clear that several improvements are needed to reduce these disadvantages.

The concept for a variable sweep wing structure proposed in this paper consists of two spars with an interconnected truss-rib structure⁷. The geometry of the preliminary design in the straight and swept-back configuration is shown in Fig. 1.

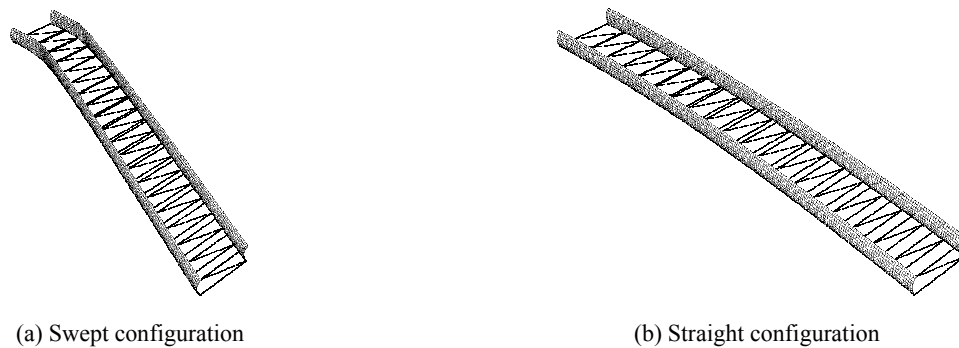


Fig. 1. Wingbox structure for the variable sweep wing

The main feature of the wing is represented by the spars. The curved cross-section provides two advantageous properties to the wing, namely the stiffness to resist bending moment and a hinge-like behaviour to the spar. The latter property is explained if we take a long rectangular shell and apply bending moments at its ends. Fig. 2 shows the resulting moment-displacement diagram.

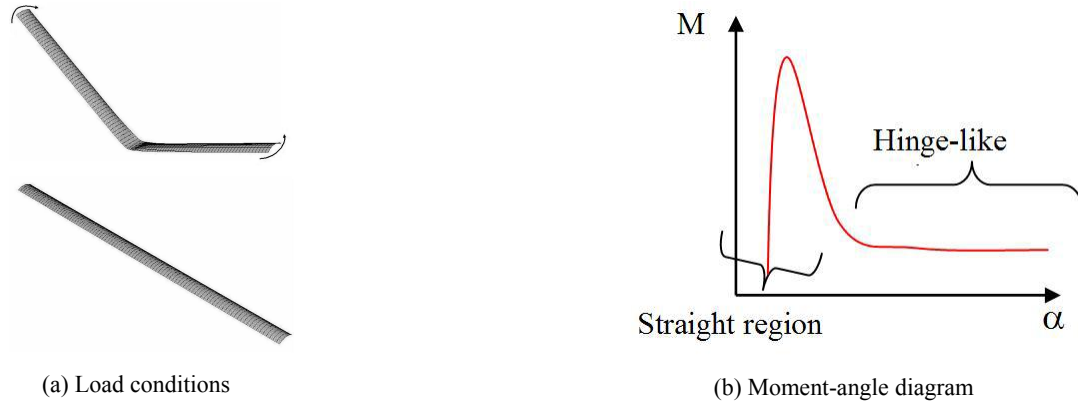


Fig. 2. Shell behaviour of the spars

At first, the shell exhibits an elastic deformation. Then, once a critical load is reached, it behaves like an elastic hinge, where for an increase of the rotation angle a constant force is required. If the load is removed, the shell returns to its original straight configuration. The magnitude of the load to induce the bifurcation in the structure and the radius r of the folded region, depends mainly on the material properties and the transverse curvature of the shell⁸, as shown by Eqs. (1) and (2)

$$r = \sqrt{\frac{D_{11}^*}{D_{22}^*}} R \quad (1)$$

$$M_y = \frac{D_{22}}{R} \quad (2)$$

where D_{ii}^* are the components of the reduced flexural matrix of the laminate, R and r are the undeformed transverse curvature and the deformed longitudinal curvature of the shell respectively. In Eq. (2), D_{22} is a component of the flexural matrix and M_y is the moment that has to be applied to a flat plate to produce the curvature $k_y = \frac{1}{R}$. The

particular choice of the truss-ribs is due to the kinematics of the structure, where the ribs must not constrain the spars during the sweeping. This translation occurs when the wing is swept-back; the height of the spar changes and the spar cross-section becomes flat, as shown in Fig. 3, therefore this degree of freedom is essential for the snap-through of the spars. The wing skin could present problems during the transition between the two configurations, as the wing plan-form changes from rectangular to rhomboidal requiring a consistent shear deformation of the wing skin. At present no definitive design for the skin has been investigated, however the latest studies on elastic skins suggest that a reinforced silicone based skin may be a suitable candidate. Such a skin would only carry membrane loads and therefore bending and torsion loads on the structure must be carried by the spars.

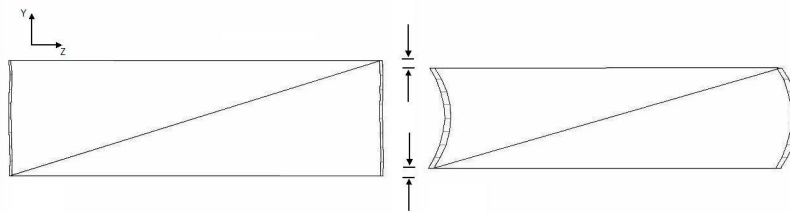


Fig. 3. Cross-section deformation

The advantage of the proposed spar design is that if the forward speed of the aircraft is below a given value, then the equivalent moment produced by the drag force will not be enough to snap the spars, resulting in the wing behaving like a conventional straight wing without any locking requirement. Once the speed is increased, and the drag force overcomes the critical moment to snap the spars, the wing will sweep back. The configuration thus achieved will result from the equilibrium between the internal elastic reactions and the drag force and the sweep angle will dynamically adapt to the variations of the flight speed. In principle it is possible to achieve both positive and negative sweep angle (i.e. forward swept wing for increased manoeuvrability).

To diminish the potential weight penalties and overcome the fatigue issues that might arise from this design, the spars are built with carbon-epoxy laminate. It must be pointed out that the choice of the matrix of the composite material is quite important, however a detailed study on an optimised matrix is beyond the scope of this study and here only epoxy based composites will be considered.

In order to understand which parameters are most important for the proposed application, a number of different stacking sequences, aspect ratios and curvature radii for the shell structures were tested numerically. Several simulations of the snap-through of the spar were performed and it emerged that the main parameter of interest for the sweep application is the curvature radius of the shell. This radius determines the bending performance as well as the critical load to be applied to activate the sweep mechanism. An initial curvature radius of 53.5 mm for the spar was chosen. Symmetric and unsymmetric laminates were considered, and the design that performed best is shown in Fig. 4.

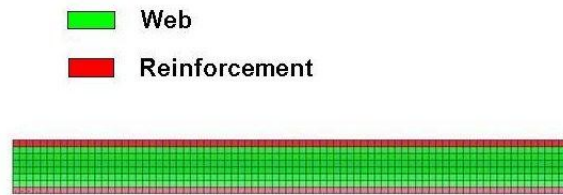


Fig. 4. Structural areas for the optimum spar

The green area (the web) consists of an unsymmetric laminate $[0^\circ/90^\circ]_T$ while the red area (the spar-caps) has an additional reinforcement of five unidirectional tapes at 0° and 5 mm wide. The unsymmetric laminate increases the depth of the shell during the cool-down process resulting in a reduction of the curvature radius from 53.5 mm to 28.5 mm. This increased the load required to induce bifurcation of the spars quite considerably. Furthermore, the residual stress field introduced with the unsymmetric laminate increases the elastic energy stored in the structure. This energy is then released during the snap-through, helping during the transition between the straight and the swept configuration.

All of the FE analyses were carried out using *ABAQUS*[®]. To model the spar structure S4R shell elements were used, while for the truss-rib structure T3D2 rod elements were chosen. The ribs were modelled as free to rotate while their displacements were constrained to follow the spars through multi-point constraints (MPC).

To simulate the cool-down process a non-linear static analysis was performed, while for the snap-through process, a stabilized Newton-Raphson scheme was used. The *STABILIZE* option introduces a volume proportional damping to the model in order to control the local instabilities that may affect the convergence of the solution. The damping coefficient is calculated on the basis of the model's response by assuming that the dissipated energy is a fraction of the strain energy.

To ensure accuracy the energy fraction was set equal to 5×10^{-11} , representing the lowest value where convergence is still achieved. During the bifurcation analysis, boundary and loading conditions are of paramount importance. In this analysis several options have been tested and the combination that performed best constrained all of the nodes at the tip section to rotate about the *y*-axis and translate along the *x*-axis, while for the nodes on the root section only the translation along the *z*-axis was allowed.

To induce the buckling of the wing-box two concentrated forces parallel to the z-axis were applied at two nodes on the root section. Loads and boundary conditions are shown in Fig. 5.

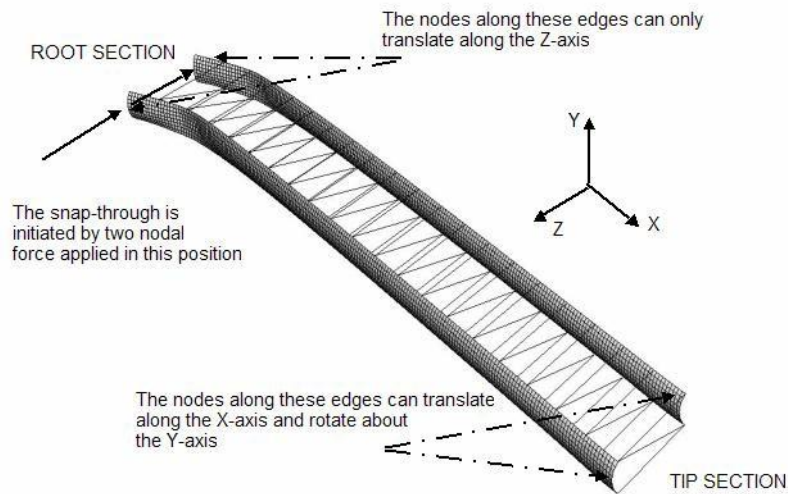
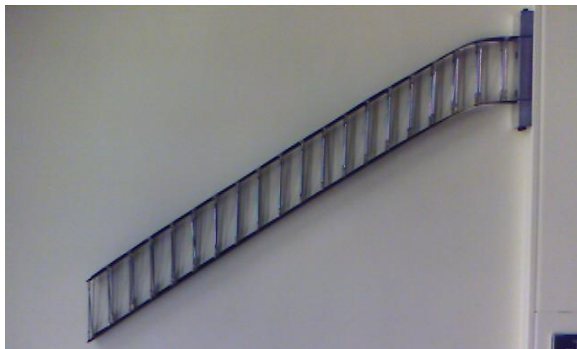
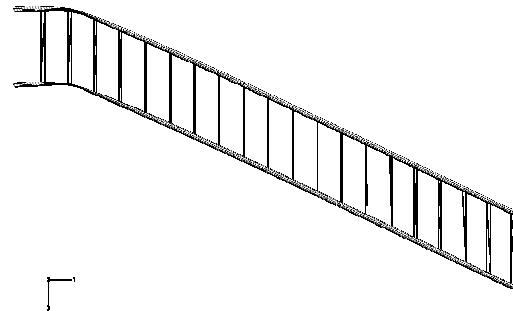


Fig. 5. Boundary condition for the numerical simulation

A preliminary wing-box structure, identical to the one described above, was manufactured and tested. The spar was manufactured using unidirectional carbon fibre / epoxy pre-preg cured on an aluminium tool with a curvature radius of 53.5 mm and a length of 1000 mm. The truss-ribs were built using 2 mm threaded steel rod with plastic ball-cup joints as hinges. The spar successfully snapped from the straight to the swept back configuration under its own weight plus an additional load of 5 N at 220 mm from the root section. The swept configuration and the position where the snap occurred matched the one computed with the FEA, as shown by comparing Figs. 6 and 7.



(a) Experimental model

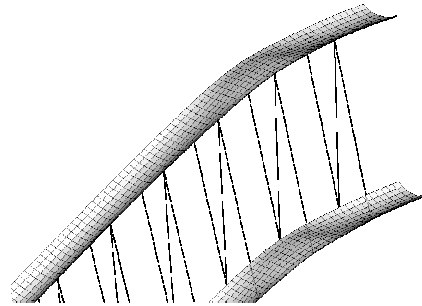


(b) Numerical Model

Fig. 6. Validation of the analysis: configuration



(a) Experimental model



(b) Numerical model

Fig. 7. Validation: detail of the hinge area

The experimental model was also tested statically to investigate the maximum load that the structure could withstand and also to analyse the critical failure modes when the limit load is reached. The wing-box was clamped to a rigid support and loaded. The force was applied at a distance approximately equal to 0.4 of the total length to simulate the resultant of an elliptical lift distribution. The first buckling instabilities were encountered with a load magnitude of 70.3 N. Considering that the spars have a maximum thickness of 0.625 mm, the load achieved is considered satisfactory. Moreover the collapse of the structure depends greatly on the effectiveness of the joints in the truss-rib structure and these tended to fail when subjected to a tension load. Thus the load bearing capability of the proposed spars is acceptable and a considerable increase in the maximum load could be achieved by re-engineering the rib joints.

3. BISTABLE BLENDED WINGLET

Bistable structures are obtained by introducing a residual stress field into the structure through pre-stress or thermal stresses. In this paper only thermally induced bistable composites are considered, and these structures may be obtained using unsymmetric laminates made of orthotropic material. Because of the difference in the coefficients of thermal expansion parallel to and transverse to the fibre direction, during the cool-down step of the manufacturing process a residual stress field is locked into the laminate and the unsymmetric stacking sequence produces moments that result in out-of-plane displacements. The main characteristic of unsymmetric laminates is that the internal stresses have more than one position of equilibrium making them bistable or multistable. This creates structures that can be at the same time flexible and stiff and opens up the possibility of combining several bistable components to obtain structures with multiple configurations.

The second application considered realises a high-lift device that can also be used during the cruise part of the flight envelope⁹. The idea is to mount a bistable panel, appropriately tailored (the stacking sequence and planform are shown Fig. 8), onto the tip of a traditional wing. When the panel is in its 'flat' configuration, the wing span is extended thus increasing the lift, while when the panel is in the deployed configuration it acts as a blended winglet optimising the aerodynamic performance for cruise flight. Fig. 9 shows the two configurations that the winglet possesses. The extended configuration has a chord-wise curvature that helps to generate lift (i.e. during take off). When the winglet is deployed the cross section is almost flat and the curvature due to the residual stresses allows the composite plate to behave as a blended winglet. The orientation of the laminate increases the wash-out (i.e. a reduction of the local angle of attack) towards the tip, a feature useful to delay flow separation at the wing-tip⁶. Fig. 10 highlights the effect of rotating the laminate axis and shows how the local angle of attack (i.e. wing sweep) may be reduced quite considerably towards the winglet tip. This will also increase the velocity at which the winglet will snap into the deployed configuration. To validate the concept a carbon fibre winglet has been manufactured and mounted on the tip of a rigid wing. The assembly has been tested in the wind tunnel at different angles of attack and air-speeds and for each configuration the aerodynamic loads and the velocity when the panel snaps have been measured. Table 1 shows the snap-velocity for different angles of attack.

After the winglet snaps all of the aerodynamic forces (lift, drag and pitching moment) reduced, confirming the possibility to use such a device to increase the lift in certain flight conditions such as take-off and landing. An actuation system¹⁰ to

allow the winglet to go back to the extended configuration is under investigation. This could eventually be used to optimise the wing shape during flight operations.

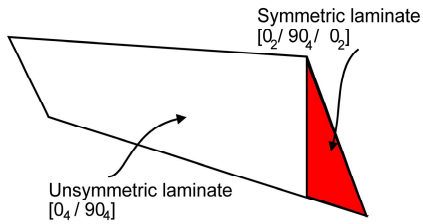


Fig. 8. Stacking sequence for the bistable winglet

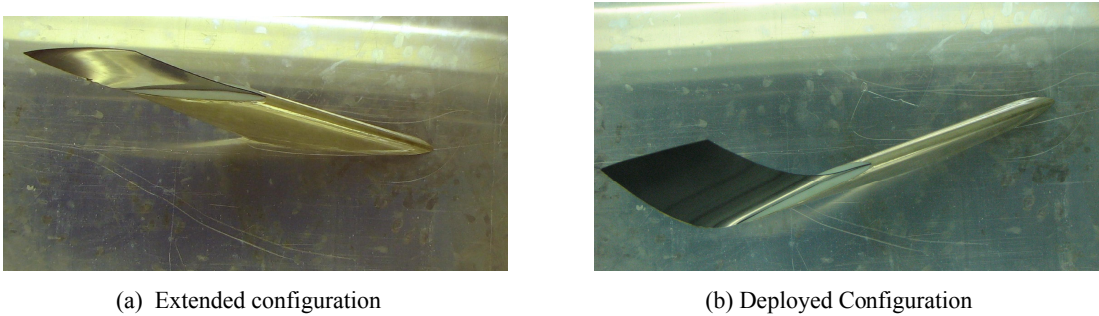


Fig. 9. The bistable winglet

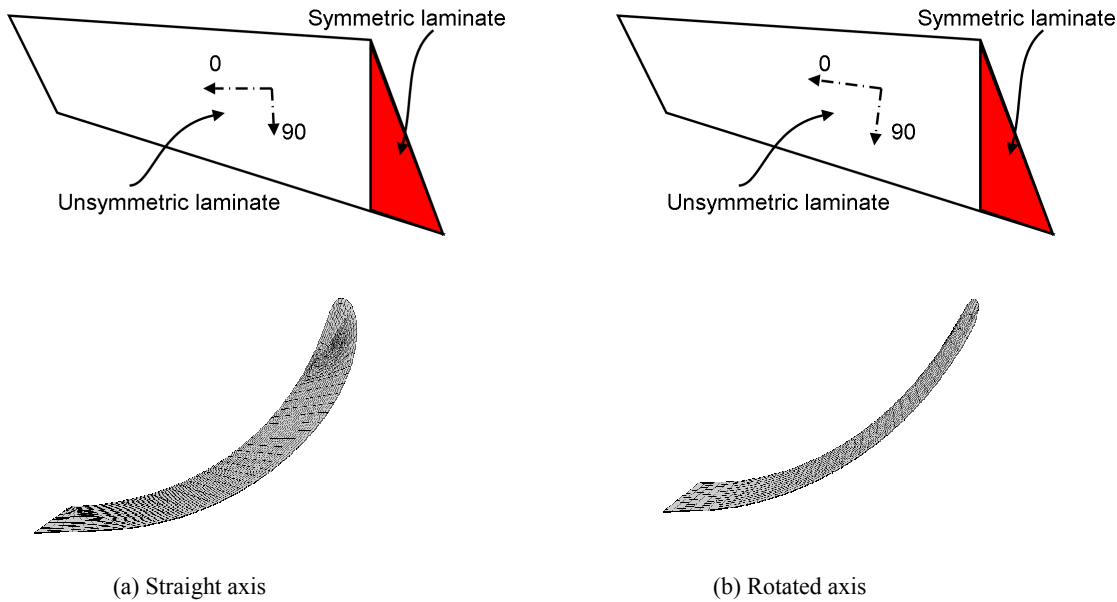


Fig. 10. The effect of laminate axis rotation for the bistable winglet

Table 1. The air velocity for the snap for the bistable winglet for various angles of attack

Angle of attack [°]	Airspeed at snap [m/s]
0	21.5
2.5	19
12.5	15.5

4. VARIABLE CAMBER TRAILING EDGE

This application concept is to realise a trailing-edge mounted device to change the camber of an airfoil by morphing its geometry⁹. The bistability of unsymmetric patches of composite material is used to drive the shape change. Fig. 11 shows the geometry and the stacking sequence areas for the device: the dark areas have an unsymmetric stacking sequence while the light areas are symmetric. It is important to note that the laminate is continuous from the upper skin to the lower skin when going around the trailing edge. Fig. 12 shows two of the achievable shape configurations. Two more configurations are obtainable (shown in Fig. 13) but for aerodynamic applications only the first two shapes are of interest.

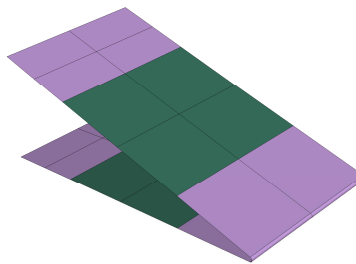


Fig. 11. Symmetric and unsymmetric stacking regions

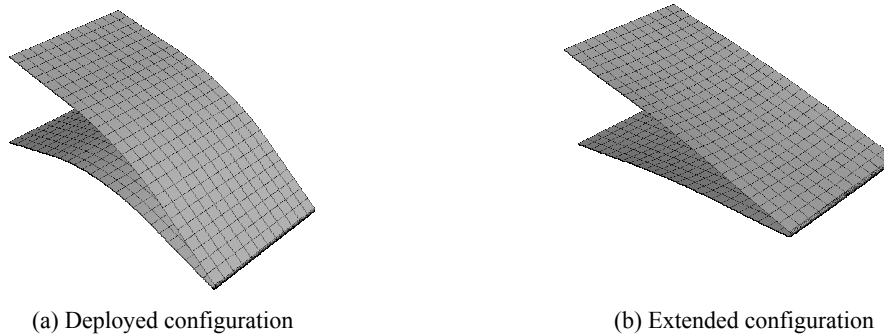
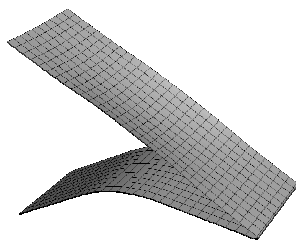


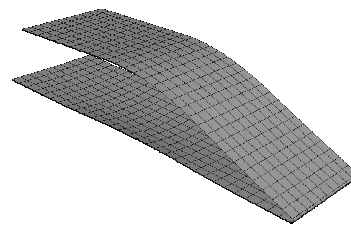
Fig. 12. Useful configurations for the variable camber trailing edge

A carbon fibre specimen has been built using an aluminium tool for the lay-up. Fig. 14 shows the two main configurations. The displacements measured on the test structure show a good agreement with those computed using FE analysis: the experimental model achieves an angular deflection of 21° while the numerical estimate is 20°. During actuation, the upper skin is fully clamped and two forces simulate the actuation load by pushing the left edge of the lower skin while the displacement is measured at the trailing edge, as shown in Fig. 15. During the actuation, the upper skin

bifurcates first with a load of approximately 20 N, and the lower skin follows when the magnitude of the load reaches 30 N. Once the structure is in either configuration and the edges are fixed in translation, the structure has considerable stiffness. When the left edges (see Fig. 15) are constrained, the trailing edge device becomes a triangular structure even when it is in the deployed configuration. Furthermore the continuity of the fibres around the trailing edge ensure that the stresses can be transmitted from the lower skin to the upper skin. A test rig to measure the maximum load the structure can withstand is under construction. Fig. 16 shows the simulation of the transition between the deployed and extended configurations (arrow pointing upward) and back (arrow pointing downward). As expected the behaviour is highly non-linear and furthermore the force required to extend the trailing edge (~ 30 N) is approximately a three times that required for the deployment (~ 10 N). This force is a measure of the load bearing capability in the two configurations and highlights the beneficial effect of having the higher stiffness in the deployed configuration. In this case the airfoil will have an increased camber and will therefore generate higher aerodynamic forces and hence higher structural loads.



(a) Alternative configuration 1



(b) Alternative configuration 2

Fig. 13. Other configurations for the variable camber trailing edge



(a) Deployed configuration



(b) Extended configuration

Fig. 14 Experimental model of the variable camber trailing edge

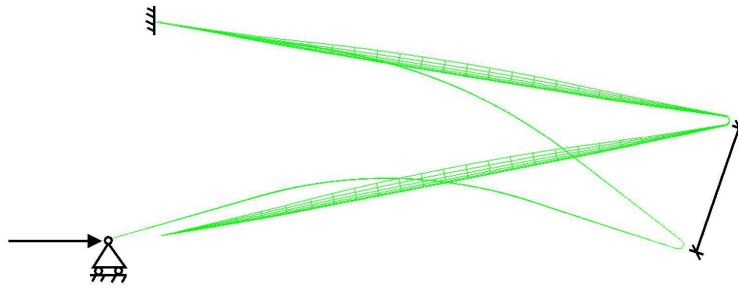


Fig. 15. Tip deflection and boundary conditions for the variable camber trailing edge

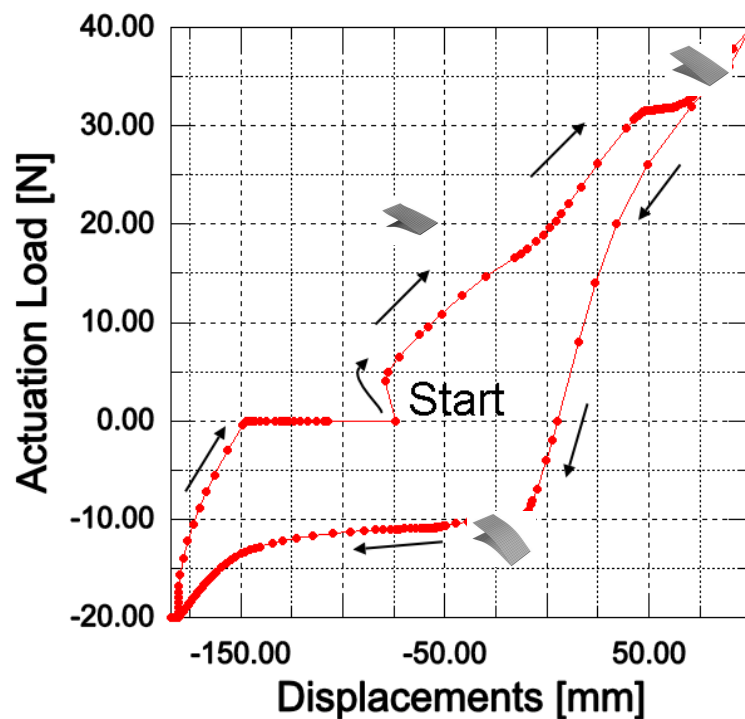


Fig. 16. Force displacement diagram for the variable camber trailing edge

5. CONCLUDING REMARKS

This paper presents three possible applications of bistable plate structures for the aeronautical engineering sector. The first was a novel swing-wing mechanism where the residual stresses were applied to modify the structural properties of the components of the wing structure. The variable sweep wing consists of a two spar shell-type structure with interconnected truss-ribs. The properties of this structure were investigated through finite element analysis and an experimental model was built to investigate the structural and kinematic behaviour of the real wingbox. The experimental model successfully achieved both backward and forward sweep angles. The structure was then tested with a static load to understand the failure modes when the critical load was reached. The second application was a bistable panel used as a blended winglet. In its extended configuration the panel is used as a high-lift device that snaps into a blended winglet at a given speed. After the transition into the winglet mode, a reduction in all components of the

aerodynamic force was measured during wind-tunnel tests, confirming the validity of the concept. This type of device successfully demonstrates that the energy from the aerodynamic flow is able to achieve shape adaptability. The third application was a trailing-edge device to vary the camber of an airfoil by morphing its shape. The approach was to embed unsymmetric patches of composite material in the upper and lower skin of the trailing-edge, resulting in four equilibrium configurations.

This paper has showed some of the possibilities in the use of thermally induced bistable composites to obtain morphing capabilities. The introduction of one bistable patch gives the structure two equilibrium configurations and it is (in principle) possible to obtain 2^N configurations by using N bistable components. However this may lead to unpredictable interactions between each stable state, and therefore care must be exercised when considering multistable structures.

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