Morphing Wingtip Devices Based on Multistable Composites

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ABSTRACT
Application of multistable composites to adaptive aircraft structures has been limited, not only because of the very recent development of these materials but also because the simplest plate geometries and layer stacking sequences originate plates whose stable shapes are of little interest to morphing aircraft components. This paper focuses on the development of alternative configurations yielding plates whose deflection meets the typical requirements of morphing surfaces (such as pure bending about one axis or combined bending and twisting). These alternative configurations consist of different plate geometries, stacking sequences and plate constraints and an evaluation of the feasibility of the proposed solution and its contribution to the aircraft performance is investigated.

1.0 INTRODUCTION

Although the potential benefits of wingtip devices have been known since the early 20th century, it wasn't until recently that designs whose benefit (in terms of induced drag reduction) offset the penalties (extra cost and weight).

Furthermore, these devices are static and as such their configuration is the result of a compromise between the different (and sometimes conflicting) requirements of the various flight stages/missions. Moreover, the winglet designs must comply with geometric constraints imposed by airport terminals and maintenance facilities. Morphing devices can overcome these limitations by permitting winglets to adopt the optimum configuration for each scenario. Multistable composites are ideal candidates for this function since they are able to change shape without the need for permanent actuation (energy is only spent when changing from one shape to another; maintaining either shape requires no energy) and can withstand significant loads. One limitation of multistable composites is the fact that the number of stable shapes is limited - most multistable composites can only switch between 2 different shapes. If several multistable composites are combined, the total number of shapes is dictated by the combinations of shapes of individual composites. This increases the complexity (particularly in terms of the design of the actuation system to change from one shape to another) but makes for a significantly more powerful system. The number of shapes is, however, still finite which makes systems based on multistable composites more suitable for components where different discrete configurations are needed than to systems where a smooth, continuous movement is required (as in control surfaces).

Theoretical approaches to the design of components based on multistable composites are hampered by their non-linear behaviour (both during the manufacture of the composite and during the change from one stable shape to another - the "snap-through"). Furthermore, if this model is multidisciplinary (i.e. it combines thermal, structural and aerodynamic effects), an accurate analysis of the component's in-situ behaviour can be carried out and multidisciplinary design optimisation (MDO) can be carried out to obtain a component that best satisfies the design goals.

Wings generate lift by changing the airflow so that the air pressure beneath the wing is higher than the air pressure above the wing. This pressure differential causes the air in the high pressure region (beneath the wing) to flow to the low pressure region (above the wing) whenever it can, as is the case at the wingtip. This vortex of air flowing from beneath the wing to above it diminishes the wing's efficiency and poses a hazard to other aircraft in the vicinity. An approach to mitigate this problem consists in introducing a physical barrier to the flow of air from beneath the wing to above it. Many designs of such barriers have been presented and are collectively known as wingtip devices. All these designs come at a cost, both in terms of price and weight (which consequently entails an efficiency penalty) and it wasn't until recently

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that progress in terms of materials and structural engineering mitigated this penalty to the point where the benefits of winglets outweigh their disadvantages. Büscher et al [1] have shown that the penalty associated with the extra weight (caused by both the wingtip device itself and the stronger structure necessitated by the increase in wing root bending moment) must be taken into account when designing wingtip devices, since a wingtip device designed from a purely aerodynamic approach (e.g. so as to obtain the greatest reduction in induced drag) may not be the optimum design if the increase in drag due to the higher weight is taken into account.

Different flight conditions have different (and often conflicting) aerodynamic and structural requirements. A fixed design has static characteristics (shape; wetted area; location) that result in a sub-optimal solution for flight conditions in which a different trade-off between the increase in profile drag and the reduction in induced drag would be desired or when different centre of gravity and moment of inertia would be key to manoeuvrability. Hence, the potential benefits of winglets are never fully realised by a fixed design. Morphing winglets can overcome this problem by adapting to each flight condition's requirements and hence improve the aircraft's performance (speed; manoeuvrability; runway requirements; climb performance; range; endurance; fuel consumption) and/or extend its flight envelope. In the future, it may be possible to design morphing winglets for specific tasks, such as mitigating an aircraft's wake turbulence (which would allow closer spacing of aircraft during landing and take-off, thus improving runway's throughput), improving the wing's dynamic characteristics (flutter behaviour) or even controlling shock wave formation and/or propagation. Furthermore, morphing winglets change the wing's aerodynamic forces and moments as well as its centre of gravity. This can be used to augment or altogether replace traditional control surfaces [2].

2.0 MULTISTABLE COMPOSITES

Multistable structures are those than can have different shapes and which will retain either shape until they are forced to change (typically by applying an external load), i.e., energy is only required to change the structure from one shape to another but not to keep the newly acquired shape. Even though other solutions have been proposed (Kebadze et al [3] describe a multistable plate made up of several half-circular strips of beryllium-copper), multistable composites are the subject of great interest due to a combination of properties (most importantly very good strength to weight ratio) that make composites in general an ideal material for aerospace applications.

Orthotropic composites (such as carbonfibre+epoxy or glassfibre+epoxy) have different coefficients of thermal expansion α along different directions. Hence, when such a material is subjected to a temperature difference, it will experience different strains ε_i along each direction i:

$$\varepsilon_i = \alpha_i \times \Delta T \quad (1)$$

If several layers of such a material are stacked with different fibre orientations and cured together, once they are cooled down to room temperature the various layers will tend to have different strains. Since the various layers are bonded and cannot freely stretch relative to each other, the plate will develop a curvature that best accommodates the conflicting individual strains and that minimises the residual stresses associated with the inability of each layer to freely stretch by the amount given by eq. (1). This curvature (forming a saddle shape) is illustrated in figure 1.

As the cooling process progresses and the temperature change (relative to the curing temperature) increases, the magnitude of the plate's curvature also increases. If the temperature change exceeds a certain threshold (which depends on the plate's shape, dimensions, material and layer stacking sequence), there is no curvature of the plate that can accommodate the conflicting thermal strains of the various layers. When this happens, the influence of one of these conflicting thermal strains prevails (which one will prevail is determined by manufacturing and/or environmental constraints) and the plate acquires a curvature dominated by the thermal strains of one of the layers (figure 2a). However, significant residual stresses will be present (associated with the thermal strains of the other layer(s)) and if an appropriate load (generally referred to as the snap-through force) is applied to the plate, it will acquire a curvature dominated by the thermal strains of those other layers (figure 2b).

The key feature of multistable composites lays in the fact that this curvature will remain even after the load is removed. Either curvature is therefore stable and the plate's shape can be switched back and forth between both curvatures as many times as desired by applying an appropriate load. Suitable actuators include shape-memory alloys (SMA) [4] and macro fibre composite (MFC) piezoelectric actuators [5].

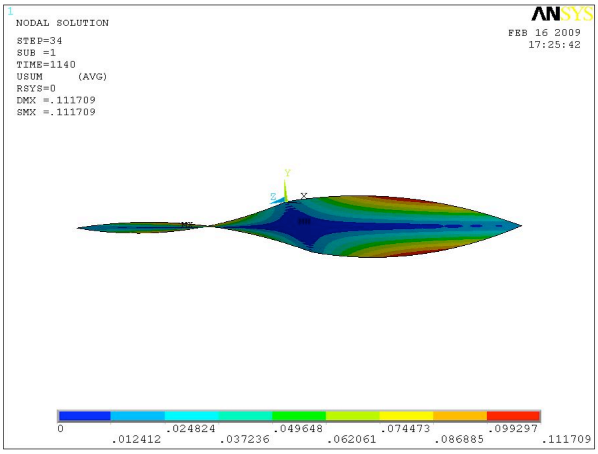

Figure 1: Saddle shape of a multistable composite combining two conflicting curvatures

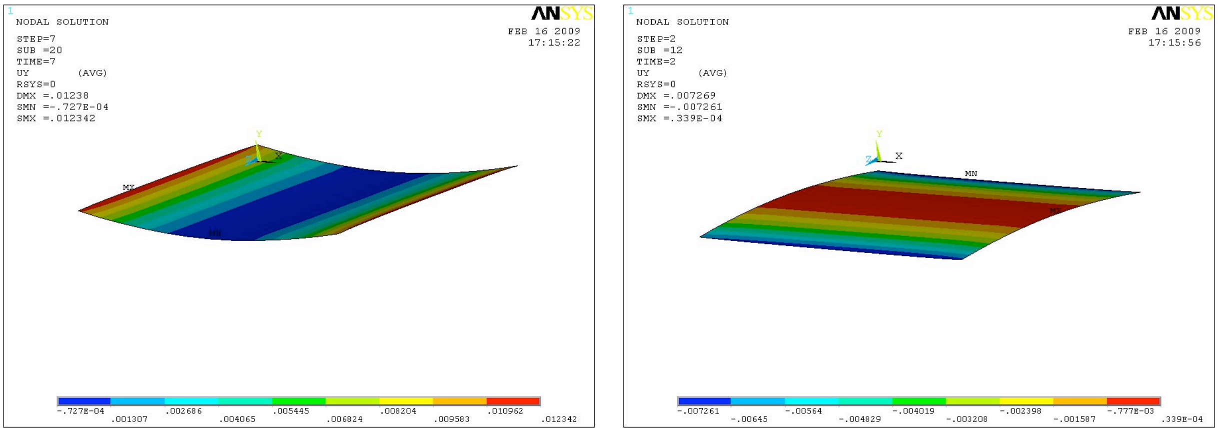

Figure 2: Stable shapes of a square multistable composite plate fixed at its centre

Multistable composites have significant advantages:

- Low weight
- Actuation is only required for the snap-through, i.e., only during the shape change. No energy is required to maintain either shape
- Being made of materials with very good stiffness and strength, multistable composites do not need a separate structure and can combine structure and morphing mechanism in a single component
- Furthermore, since composites (both multistable and conventional) can be made to virtually any shape, they may be used as monocoque components: combining structure and skin in the same component

However they also have important drawbacks:

- Even though the term "multistable composites" is generally used, most are actually "bistable composites", i.e., they can only switch between two different shapes. This reduces their adaptability and, in particular, seriously limits their use as control surface replacements or augmentation devices

- Size: composite plates (even when built as described above) only exhibit multistable behaviour if the ratio of the in-plane dimensions to the thickness exceeds a certain critical threshold (dependant on the material, geometry and curing temperature). Since the thickness cannot be reduced beyond a certain point (dictated by the thickness of each composite layer and the number of layers), this forces the in-plane dimensions to be above values of the order of 5cm for a typical plate
- Possibility of uncommanded snap-through: if the plate is subjected to a load greater than its snap-through force, it can change shape undesirably with potentially adverse consequences
- High cost
- Slow construction

Various concepts are analysed to explore the multistable composites' advantages while minimising the effects of their disadvantages. The major drawback is the limitation of each plate to only 2 different shapes. This can however be circumvented by combining various plates, as discussed in greater detail in the following chapter.

The simplest multistable composite plates are square plates made up of two layers of a composite material of resin and unidirectional fibres, with one layer's fibres perpendicular to the other layer's fibres (e.g. a [0,90] stacking sequence), fixed in the centre, and these have been object of study for some time (e.g. [6],[7]). However the shapes obtained with such plates (shown in figure 2 - two curvatures about different axes) are of little interest for application to wingtips. This prompts the need to devise different multistable composite plate designs (different geometry, stacking sequence and/or constraint).

Rectangular plates comprising two regions (one with a symmetric composite stacking sequence and another with an unsymmetric stacking sequence) have been proposed [8] to allow shapes of greater practical interest. Although the multistable behaviour is only associated with unsymmetric stacking sequences, the presence of a region with symmetric stacking constrains the plate and influences the overall stable shapes. Such plates will essentially bend along a single direction when snapped-through from a stable shape to another. The geometry of one such plate is shown in figure 3, along with the stacking sequence of both regions. An alternative approach is to use a square plate fixed along one of its edges (rather than at the centre). The shapes of one such plate are shown in fig. 4.

3.0 FINITE ELEMENT ANALYSIS

Multistable composites have an inherently non-linear behaviour. Furthermore, the geometries of interest from an engineering standpoint need not be regular shapes. These factors make it impossible to obtain general closed-form solutions for the behaviour of multistable composites. Numerical methods can however be used to study this behaviour. Finite element modelling (FEM) is an ubiquitous, well-tested tool for the analysis of mechanical components and can easily be integrated in a design optimisation procedure. Composite material models and elements with non-linear formulation are required for the analysis of multistable composites. Furthermore, if a finite element program with computational fluid dynamic (CFD) capabilities is used, a multidisciplinary analysis of the multistable composite plate can be carried out, combining aerodynamic and structural effects. The ANSYS finite element suite meets all these requirements and is used for the present analysis.

ANSYS includes two elements for the analysis of layered shells: SHELL91 and SHELL99[3]. The latter has a smaller element formulation time for elements with three or more layers but lacks some non-linear capabilities of the SHELL91 [9]. For this reason, SHELL91 was chosen to model the multistable plate.

[3] Newer versions of ANSYS have two additional elements: SHELL181 and SHELL281. Over the long term, these will replace SHELL91 and SHELL99 and the present project is currently being migrated to SHELL281.

SHELL91 is an 8-node shell element with six degrees of freedom at each node: translations in the nodal x,y and z directions and rotations about the nodal x,y and z-axes.

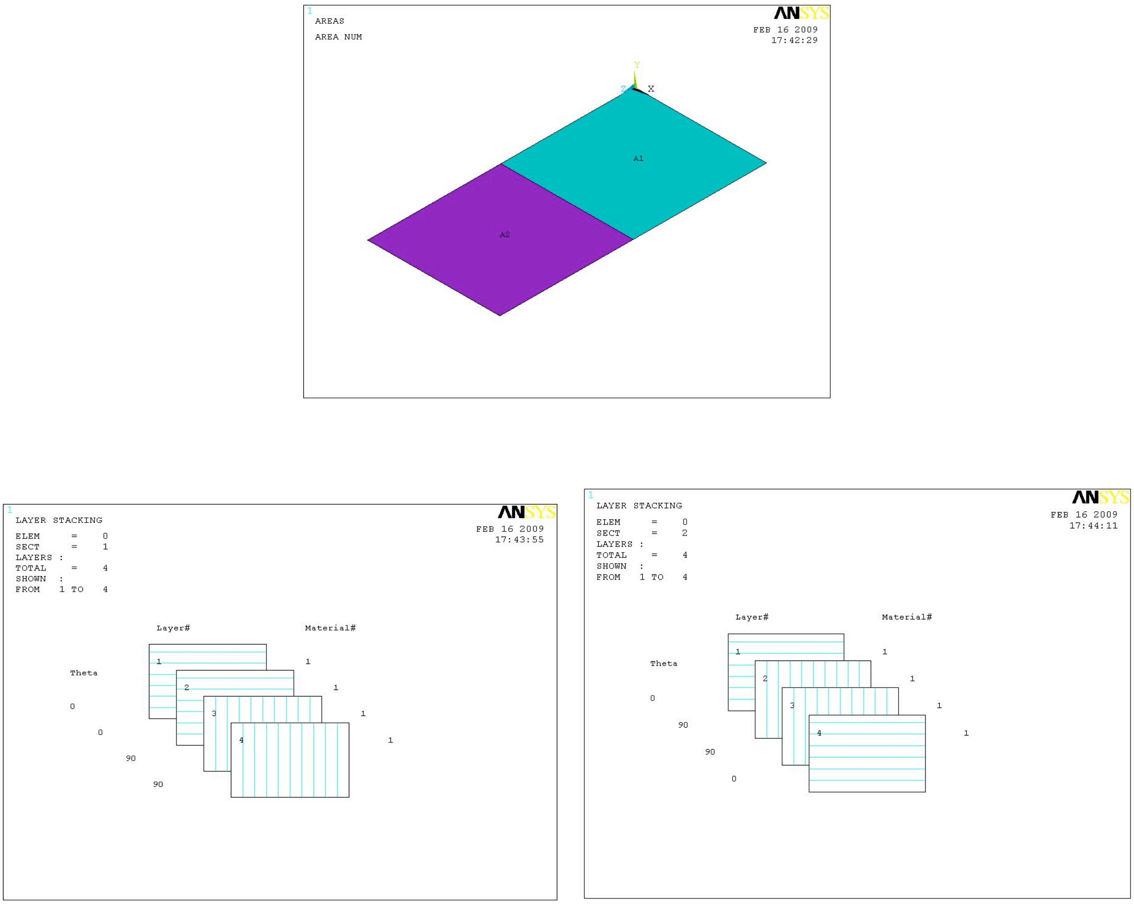

Figure 3: Geometry of a rectangular multistable plate (above) comprising one region (A2) with symmetric stacking (below, left) and one region (A1) with unsymmetric stacking (below, right)

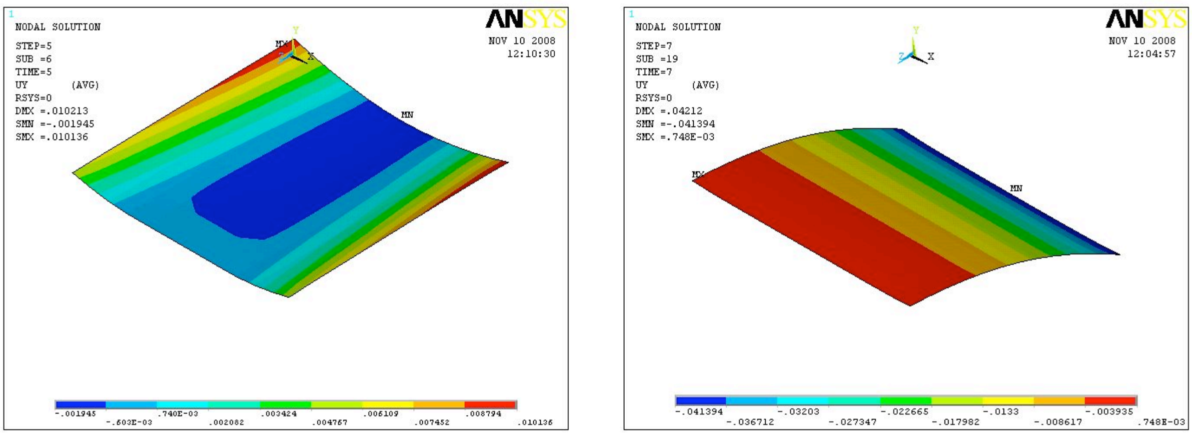

Figure 4: Stable shapes of a square multistable composite plate fixed along one edge

It is important to note that in a square plate the unstable saddle shape shown in figure 1 (combining the conflicting curvatures imposed by the various layers), although not found in the physical world for values of ΔT (temperature change relative to the curing temperature) above the threshold described in the previous chapter, is a mathematical solution to the problem. When analysing an ideal square plate (with equal length along both directions) and without any asymmetries, the finite element analysis converges to the saddle shape. To take into account the asymmetries that inevitably exist in actual plates (be it in the geometry or the material, which unlike in numerical analysis, can never be perfectly homogeneous in reality) and lead to the bistable shapes, some sort of imperfection must be introduced in the numerical model. This can be accomplished by simulating the square plate with a rectangular plate with nearly equal sides [10] .

The cool-down process is simulated by setting the initial plate temperature to the composite's curing temperature and then placing the plate at a lower temperature (equal to its normal operating temperature). To facilitate convergence, the plate can be cooled down in small increments at a time.

The snap-through is modelled by applying a load and determining the plate's shape under the effect of that load. It is then fundamental to remove the load and determine the plate's shape under no load. If it retains the new shape imposed by the applied load, there is multistable behaviour.

The simplest snap-through force is a vertical (through the plate's thickness) load at the corners with a direction contrary to the corners' deflection. However, this out-of-plane force is hard to apply in an actual wing. Another possibility is to apply a bending torque at the corners (in a direction contrary to the plate's curvature). This can be accomplished by having linear actuators (such as shape-memory wires) at both faces (top and bottom) of the multistable composite plate. If one of the wires stretches and the other shrinks, this originates a bending moment. This moment can be applied to the finite element model and its effect analysed.

The finite element model was validated by application to benchmark cases from the literature ([6],[10],[11]) showing good agreement with the published results.

Figure 5 shows the change of the plate shape as it is cooled and undergoes a change from a stable shape to another (snap-through).

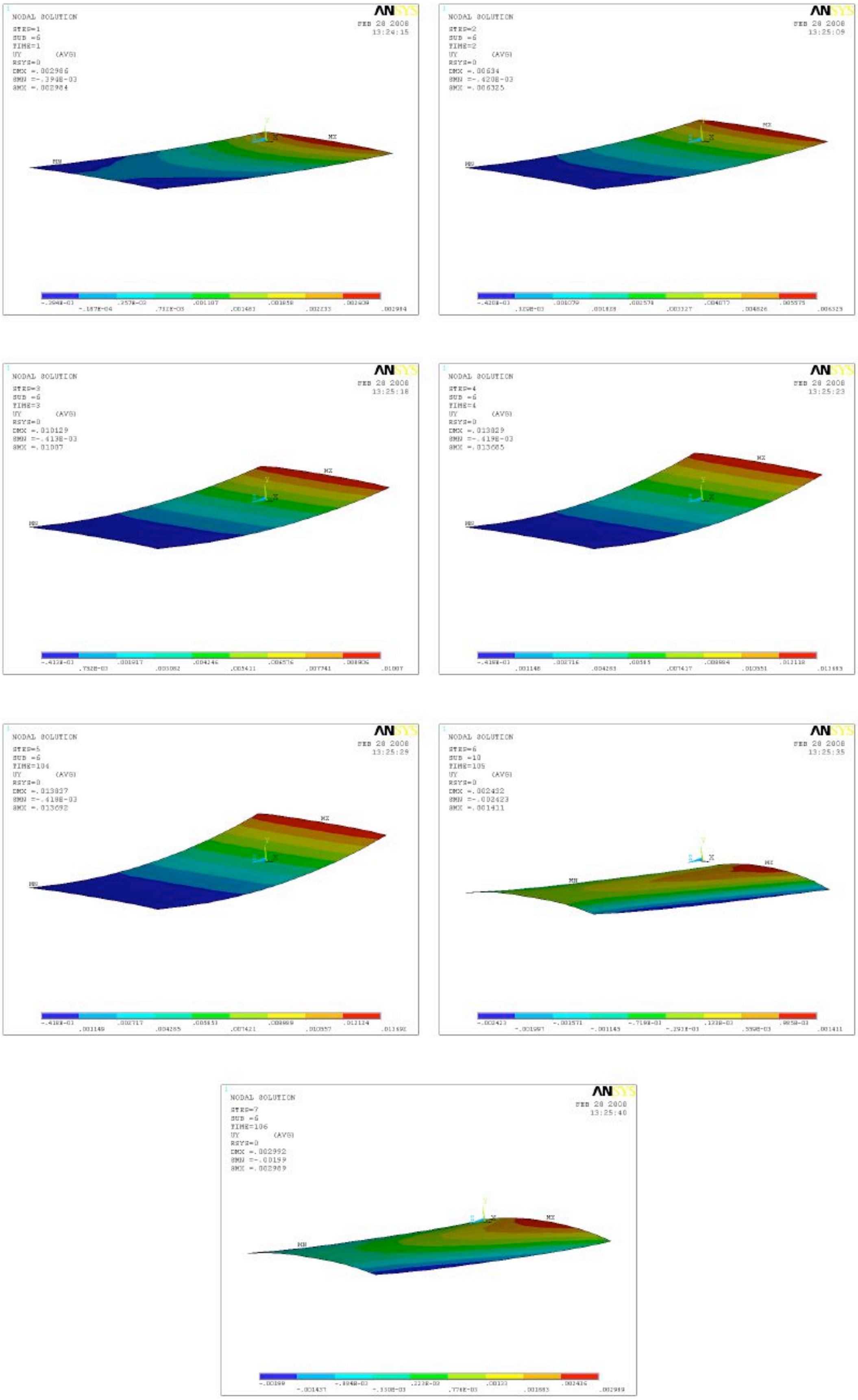

Figure 5: Cooling and snap-through of a multistable plate – steps 1 to 5 show the development of curvature as the plate cools from curing to room temperature; step 6 shows the plate's deflection when the snap-through force is applied; step 7 shows the plate shape after the snap-through force is removed.

The behaviour of plates made up of carbonfibre-reinforced epoxy and fibreglass-reinforced epoxy was compared and was seen to be similar. This is because the difference between the thermal expansion coefficient along the fibre direction and the thermal expansion coefficient perpendicular to the fibre direction is comparable for both materials.

When introducing multistable composites' advantages and drawbacks, it was seen that a major handicap was the limitation of each component to two different shapes. This can be circumvented by designing a mechanism made up of several multistable composite plates. If each plate can be actuated independently, the total number of shapes will be 2^n, where n is the number of plates. Figure 6 shows one such system with different actuation combinations. It is important to note that if the various plates are bonded along an entire edge, they become interdependent and no longer behave as individual plates would. Although the stable shapes of each plate remain very close to the stable shapes that an isolated plate with the same configuration would have, actuation of individual plates in a component made of various bonded plates is harder to achieve than in isolated plates (since the plate-to-plate connection interferes with the plate's shapes and since the load cannot be restricted to a single plate but instead is applied on a larger-scale component).

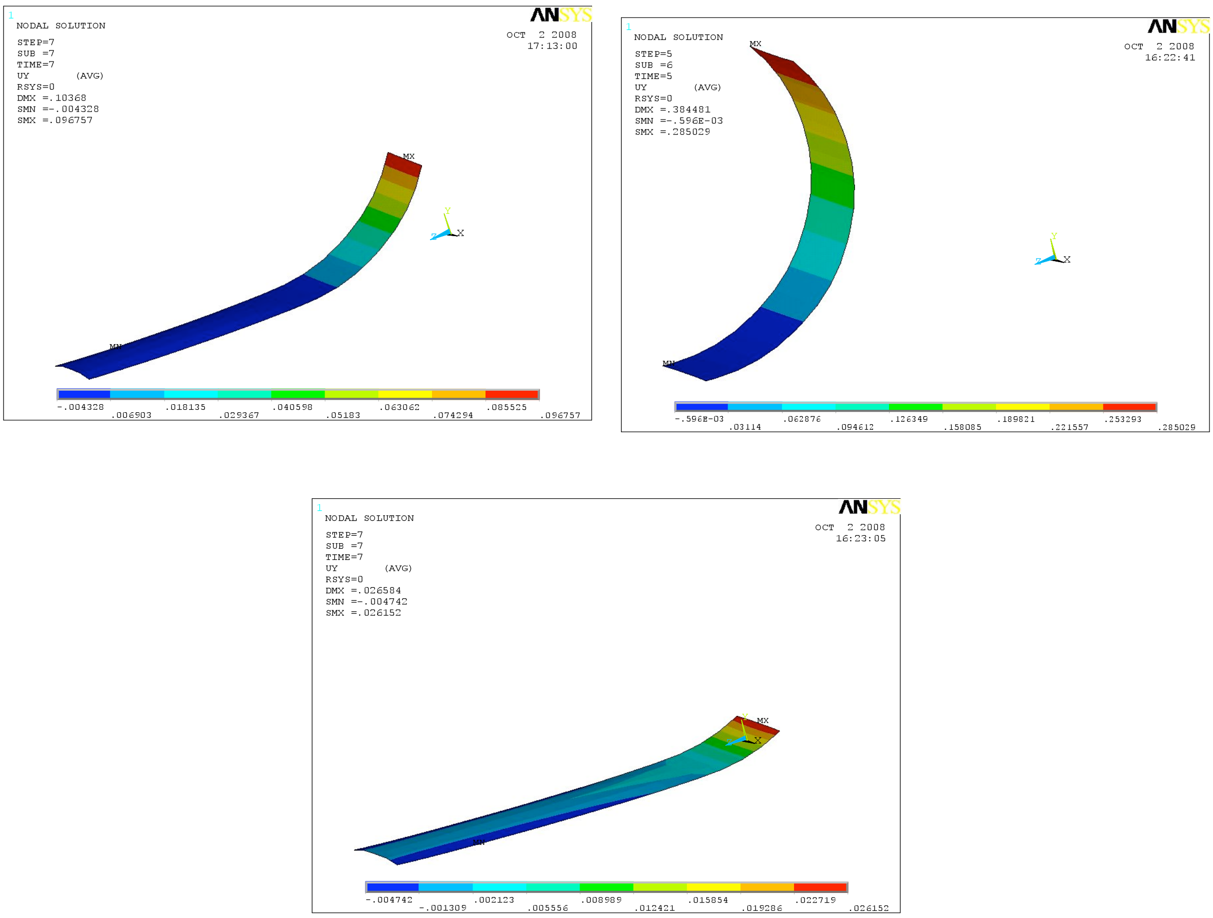

Figure 6: Different actuation combinations of a mechanism made up of several multistable composite plates

If the various plates are connected by hinges (e.g. servo-actuators) rather than just bonded together, the mechanism can change position in a continuous manner rather than being limited to a discrete set of configurations (as long as the controllable hinges have continuous motion as is the case with most servo-actuators). Such a system can combine the advantages of both concepts (multistable composites and conventional actuators):

- The multistable composites can change between radically different configurations (e.g. those required for the different flight conditions: taxi; take-off; climb; cruise; descent; landing). These are large-scale changes (suitable for the large geometry change of multistable composites) that happen at large intervals (thus taking advantage of the multistable composites' ability to retain a different shape with no energy consumption)

- The servo-actuator hinges can fine-tune the wingtip's configuration for each moment, taking advantage of the very high actuation precision of servo-actuators.

In addition, if the union of the plates to the hinges is properly located (on the same locations as the isolated plates were constrained), the plates are nearly independent and the behaviour of each individual plate is nearly identical to that of isolated plates. In particular, the individual actuation of each plate is much more straightforward than in components where the various plates are rigidly joined at their edges, as was the case for the previous design.

The servo-actuator must be rigid enough to resist the aerodynamic and structural loads to which the wing is subjected as well as the snap-through loads applied to the multistable composite plates. It can therefore be modelled in ANSYS through constraint equations (CE command) and/or node coupling (CP command). Either command replaces the servo-actuator geometry with a simple mathematical relation between nodes at the two plates connected by the servo-actuator. Figure 7 demonstrates this concept.

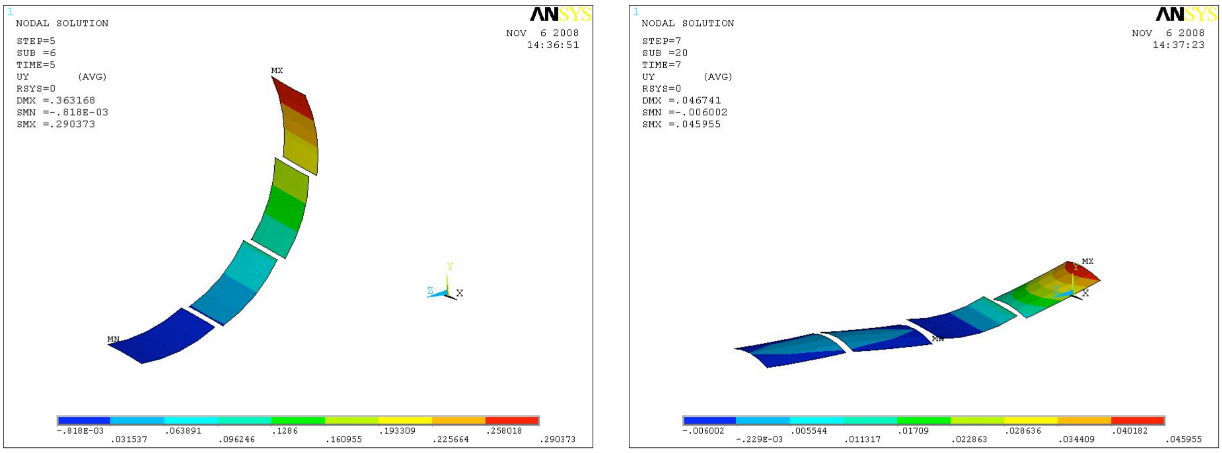

Figure 7: Hinged multistable composite plates before and after snap-through

The viability of mechanisms made up of a large number of multistable composite plates is however limited by the minimum size of each plate (below which it will not exhibit multistable behaviour).

4.0 OPTIMISATION

Morphing aircraft require components capable of significant displacements while keeping the volume and weight to a minimum (even more so in the case of small unmanned vehicles, currently undergoing significant interest and development). We therefore aim to maximise the ratio between the plate deflection and its in-plane dimension (length).

An optimisation procedure was applied to a rectangular plate with the same configuration proposed by Mattioni et al [8] and described above, but with the unsymmetrically stacked region occupying 90% of the plate's length (since is is this region that contributes to the multistable behaviour). The objective function is the ratio between the displacement of the plate's free edge from one stable shape to the other and the plate's length.

The design variables are:

- Plate thickness, with a minimum value of 0.72 mm (0.18 mm per layer as used in previous studies, e.g. [10]) and a maximum value of 4 mm (1 mm per layer, as multistable behaviour only exists for large enough values of planar dimensions in relation to the thickness)

- Plate width (equal to 90% of the plate's length, i.e. the unsymmetrically stacked region is square) with a minimum value of 4 cm (as multistable behaviour only exists for large enough values of planar dimensions in relation to the thickness) and a maximum value of 9 cm (determined by the viability of application of this component to a small unmanned aerial vehicle).

The optimisation method is ANSYS' First Order method. As the name implies, this is a gradient based method that determines the search direction based on steepest descent or conjugate direction approach, followed by a line search procedure. This is the most accurate of ANSYS' optimisation methods, having the disadvantage of being the most computationally intense as well as more prone to being trapped in local minima. These characteristics make it unsuitable for problems with very long analysis time or defined by highly irregular functions (i.e., the objective function's dependency on the design variables cannot be adequately captured by low order polynomials). Since neither of these conditions are present in the current problem, the First Order method is a suitable choice.

Table 1 – Multistable composite optimisation results

	Initial design	Optimum design
Plate thickness [mm]	0.72	0.72
Plate width [cm]	6	7.1459
Displacement/Length	0.132	0.189

The design obtained with this optimisation procedure allowed a 43% improvement in the objective function (displacement/length), thereby significantly increasing the viability of application of multistable composite plates to morphing structures of small unmanned aerial vehicles.

5.0 DISCUSSION

Morphing winglets based on a single multistable plate cannot be used for control surface replacement or augmentation due to the inherent limitation to two different shapes. Use of such a configuration (single multistable plate) for adaptability of the wing to the different flight conditions is possible but of reduced interest (once again due to the availability of only two different shapes). Mechanisms composed of several multistable plates are more suited for morphing winglets but are also of greater complexity and significantly larger. The optimisation procedure allowed a major increase in the ratio between the multistable plate's displacement and its size (thereby increasing the shape changing capabilities) but at the cost of further increasing the size. The displacement obtained with this optimised design is approximately 1.5 cm, enabling promising shape changes, particularly if several plates are combined. Adaptive winglets made up of as little as two multistable composite plates hinged by a controllable servo-actuator, requiring a total length in the order of 20 cm per wing are viable for small to medium sized unmanned aerial vehicles but not for smaller UAVs.

The finite element models allowed the analysis of many different configurations. Although multistable plates with displacement close to pure bending were the main focus, other concepts were studied. Plates exhibiting a combination of bending and twisting can be obtained by having the fibres oriented obliquely relative to the plate's length and width. Fixing the plate's corner (as opposed to its centre or along one edge) produces similar results.

5.1 Future Work

The structural finite element model will be included in a multidisciplinary analysis using ANSYS (for the structural analysis) and CFX (for the aerodynamical analysis), with the following goals:

- Better understanding of the behaviour of the multistable composite wingtip device in flight
- Investigation of whether uncommanded snap-through may occur
- Study of the interaction of the adaptive wingtip with the flow (e.g. aerodynamic behaviour and vortex

generation)

Most importantly, this integrated aero-structural model can form the core of a multidisciplinary optimisation (MDO) procedure of the morphing winglet. Also, it will be fundamental to conduct a dynamic analysis of the snap-through process (i.e. determining the wingtip's behaviour during the multistable plate's shape change) before the designed mechanism can be built and tested (in wind tunnel and/or in flight).

6.0 CONCLUSIONS

Adaptive winglets have the potential to significantly improve aircraft performance as well as its flight envelope. Multistable composites are a candidate technology for the development of morphing winglets. A finite element model of multistable composite plates was created in order to analyse the effects of cool-down and snap-through and determine the shapes associated with each plate's characteristics. This finite element model allowed the study of a very large variety of configurations (comprising different geometries, constraint locations, materials, fibre orientations and stacking sequences), of which the most suitable for application to morphing winglets are described in this presentation. An optimisation procedure was carried out resulting in a design with a significant improvement in the ratio between output (displacement) and size. The configuration obtained is suitable for application in small to medium unmanned aerial vehicles. Components made up of several multistable composite plates were also presented and analysed and, in the case of servo-actuated hinged multistable plates, were seen to show great potential for application to morphing winglets.

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