Morphing of ‘flying’ shapes for autonomous underwater and aerial vehicles

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ABSTRACT

Autonomous vehicles are energy poor and should be designed to minimise the power required to propel them throughout their mission. The University of Southampton’s School of Engineering Sciences is actively involved in the development of improved designs for aerial and maritime autonomous vehicles. The ability to adapt or ‘morph’ their shape in-flight offers an opportunity to extend mission range/duration and improve agility. The practical implementation of such systems at small scale requires detailed consideration of the number, mass and power requirements of the individual actuation elements. Three approaches for minimising actuation requirements are considered. The first uses a combination of push-pull actuators coupled with a snap-through composite lay-up to achieve alterations in shape. It is proposed that such a system could be applied to the trailing edge of an autonomous underwater glider wing instead of the more usual servo operated trailing edge flap. The anisotropy achieved through use of different composite ply orientations and stacking can also be used to generate bend-twist coupling such that fluid dynamic loads induce ‘passive’ shape adaptation. The third approach uses a detailed understanding of the structural response of buckled elements to applied control moments to deform a complete wing. At this stage of the research no definitive conclusions have been drawn other than that all three approaches show sufficient promise and can now be applied to one of the autonomous vehicles.

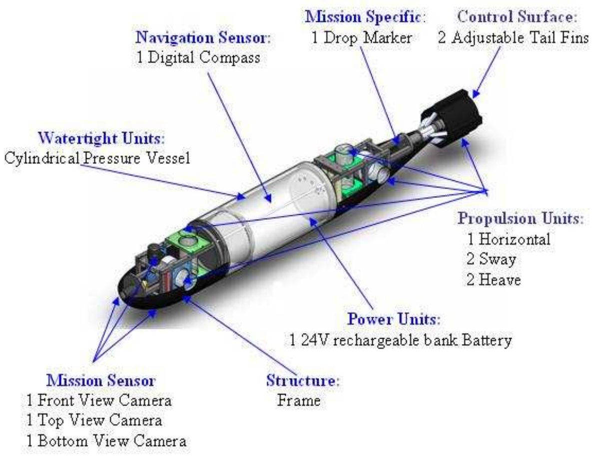
1.0 INTRODUCTION

A common requirement for autonomous vehicles is the need to minimise energy usage for a given payload mass and associated volume. The ability to adjust or ‘morph’ the vehicle wetted shape allows optimal propulsion efficiency to be achieved at multiple operation speeds and vehicle attitudes. On-going work at the University of Southampton into future generation autonomous vehicles has identified a number of alternative strategies for achieving such shape control systems.

The aim of the work presented is to review the links between actuator systems and adaptive or ‘smart’ structural elements suitable for use in autonomous ‘flying’ vehicles. The eventual goal is a methodology identifying the trade-off between the number of actuators and size of the set of achievable shapes on possible performance enhancement. The selection of the set of actuators has implications for the applied control strategy and the sensor requirements. To illustrate this methodology three alternative combinations of actuators and advanced structural elements are considered based on application of possible actuators to flexible composite hull/wing fairings and propulsor blades. Such actuation systems include linear actuators[1], inflation/deflation, shape memory alloys, and ‘intelligent plastics’[2].

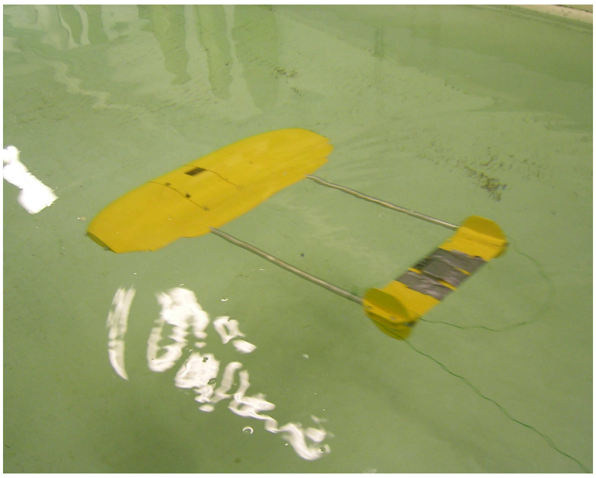
2.0 MORPHING POTENTIAL OF AUTONOMOUS VEHICLES

Figure 1 illustrates four of the autonomous vehicle fleet under development at the University of Southampton. A common feature to all of these is the need to achieve long duration missions with a high degree of agility, eg. carry out missions were the vehicle needs to be able to manoeuvre within a confine region in order to achieve some or all of its mission goals. Such requirements are well suited to the context of adaptable shapes.



(a) National Oceanography Centre, Southampton, Autosub Series

(b) Delphin –developed for SAUC-E Student AUV competition 2008



(c) SOTON-Glider – underwater AUV using net buoyancy for propulsion

(d) University of Southampton UAV in flight

Figure 1 Southampton's Autonomous vehicles

The Autosub series of vehicles, as illustrated in Fig 1(a), are designed for medium duration underwater missions (1-4 days), travel at ~1.6m/s and have recently operated at depths up to 6000m. Fig 1(b) shows the Delphin vehicle which is a prototype platform designed to investigate long-range concepts. Two design features are under consideration to extend mission length for a long-range concept. These are.

(1) The use of a bend-twist composite propeller blade that would allow the AUV to operate at a range of speeds at similar efficiencies. Typically, the hydrodynamic shape is optimised for a single service speed at

minimum power and so when required to run at slow speed there is a large drop in efficiency associated with the low Reynolds number operation of the fixed pitch propeller. Ideally, if the bend-twist can be tailored correctly the propeller rpm can be maintained and the propeller can operate at a much higher efficiency.

(2) A related problem is the change in flow over the nose and at the stern cone, again associated with a change in service speed. The ability to modify the nose curvature as it approaches the main cylindrical body could control laminar separation bubbles. Likewise deforming the tail cone approach to the propeller blade could help alter the wake fraction seen by the propeller.

Figure 1(c) shows a prototype advanced underwater glider concept. These machines use changes in net buoyancy to ‘glide’ up or down within the ocean. They are designed for long duration missions of the order of months and can traverse across a whole ocean. Their use of energy is therefore critical. A difficulty with the original gliders is their limited ability to manoeuvre. The ability to use small alterations (low energy actuators) at the tips of the lifting surfaces could significantly enhance their manoeuvring.

Figure 1(d) shows a prototype air vehicle for long range ocean survey work. For this case the intention is to warp the entire wing using internal structural elements held in a post buckled state. This returns to the original ideas of the Wright brothers but using carbon composite internal system in place of the external control wires of their bi-plane.

2.0 ACTUATORS

Through the combination of fibre-reinforced composites and actuators, it is possible to design structures that have the ability to change shape. Structures that can change shape are often termed morphing structures. In recent years the National Aeronautics and Space Administration (NASA) has shown significant interest in morphing structures; much of this interest has been directed towards morphing wings of future aircraft [3, 4, 5]. In addition, the Air Force [6] and the Defence Advanced Research Projects Agency (DARPA) [5] are conducting research to examine adaptive structures on aircraft. Mechanical actuation technologies vary widely in their intrinsic displacement, force, speed and efficiency, as exemplified by the range of active materials that have been developed to meet diverse needs. Many are currently used in applications ranging from ultrasonic motors to micropositioners, adaptive optics and medical stents. There exists an unmet need for materials that can enable generalised, large scale, structural actuation. Existing ferroic materials, such as piezoelectrics, electrostrictors and magnetostrictors, require high operating voltages or magnetic fields and often have more bandwidth than necessary, while generating low strain and force capability when compared to, for example, conventional hydraulics. Shape memory metals are amongst the highest energy density active materials and can deliver several percent strain with high actuation force, but, being dependent upon thermal phase transitions, are intrinsically slower and require temperature regulation for their operation.

Examples of ferroic based actuators include RAINBOW (Reduced And Internally Biased Oxide Wafer) actuators[7], SMA (Shape Memory Alloy) actuators[8], MFC (Macro Fiber Composite) actuators[9], and THUNDER (THin layer UNimorph ferroelectric Driver and sensor) actuators[10]. Such actuators are useful for the applications listed above, although they have very low strain and force capabilities, and also require a constant supply of electrical power for operation. As such they are not useful for the active adaptation under consideration here.

Quackenbush *et al*[11,12] described a ducted propeller with a deformable shroud that produces a steering force. The deformation was provided by electrically-actuated Shape Memory Alloy (SMA) cables. Potential advantages of this technology for naval applications were claimed, including enhanced low-speed manoeuvring for submarines; reduction or elimination of conventional steering surfaces; and elimination of hydraulic actuators in favour of all-electric components. Experiments in a water tunnel produced significant side force with relatively small change in the angle of duct trailing edge. The major issues with this concept for full scale applications are the difficulties associated with the mechanical complexity and the power required for SMA deflection. Braided pneumatic actuators[13] have higher strain and force capabilities and could therefore be useful in the field of adaptive structures, though are complex and costly and when attempting to optimise availability, reliability and maintainability, would probably not be suitable.

High strain, high force mechanical actuation technologies are desirable for numerous applications ranging from micro-electromechanical systems (MEMS) to large scale “smart structures” that are able to change shape to optimise performance. Koyama *et al* [14] considered simultaneous electrochemical expansion of the LiCoO2/Graphite cathode/anode couple for use in larger adaptive structures and claim that actuation under stresses of up to ~20MPa is achievable. Again however, such technology requires a continuous source of electricity. Actively adaptive devices often require a continuous supply of current in order for the morphing structure to stay deformed.

Thus it would be desirable to have some method of holding a shape change without having to apply a continuous current to a device. It is thought that composites that have two stable equilibrium shapes at operational temperature and can be “snapped” from one to the other by a temporary force or moment could be beneficial in the realm of shape changing blades. Structures in the post-buckled regime also exhibit large deformation control for small force variations and so can be used in systems where power is limited and continuous control surface variation is required.

3.0 SNAP-THROUGH COMPOSITES

Composites with an un-symmetric layup are generally characterised by warpage phenomena due to residual stresses caused in the manufacturing process or during operation conditions. For certain cases of un-symmetric fibre reinforced, and textile reinforced, composites more than one stable deformation state occurs due to the residual stresses caused by thermal effects, moisture absorption, and chemical shrinkage. In certain cases the thermally induced stresses which develop during processing can cause out-of-plane curvature as the laminate cools from the processing temperature to operational temperature. Depending on stacking sequence and geometry, these processing stresses may cause the laminate to have more than one stable configuration with out-of-plane curvature at operational temperature. In the case of the existence of two stable equilibrium states, a snap through from one stable deformation state to the second state is possible which can be initiated by forces and moments generated by adapted actuators. After snap through, the panel will remain in the new configuration until new forces are applied. The curvature of these multiple configurations can be significantly different, resulting in different structural forms, Figure 2.

An advantage of using this characteristic to develop morphing structures is the ability to have multiple shapes without continually supplying power; that is, power is required only to transform the structure from one shape to another and not to hold it in the transformed shape with continuous application of force.

The phenomenon of un-symmetric laminates having multiple stable configurations at room temperature was first considered in 1981 [15], previous to this it had been assumed that the cured shape of an un-symmetric laminate was that of a saddle, Figure 2(b). Consequently Hyer [16,17] successfully modelled the room-temperature shapes of un-symmetric cross ply graphite-epoxy laminates using the Rayleigh-Ritz technique and classical lamination theory (CLT) with the addition of nonlinear terms in the strain-displacement relations. It was found that, for certain geometric conditions, there were three room-temperature equilibrium shapes: an unstable saddle shape, Figure 2(b), which is predicted by geometrically linear CLT, and two stable cylindrical shapes, Figure 2(c) and Figure 2(d), which cannot be found without the geometrically non-linear terms. For other geometric conditions, there was only the saddle shape, which in these cases was stable.

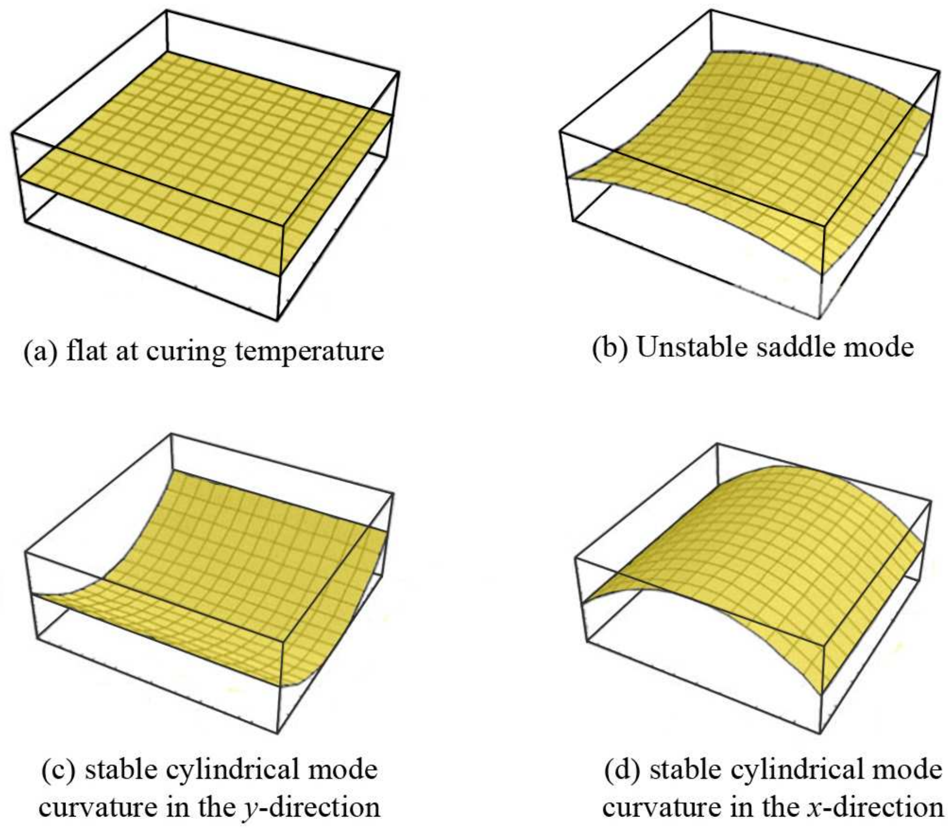


Figure 2 Four modes for snap-through composite panel (adapted from [19])

To this point, the laminates under consideration were all cross-ply laminates – i.e. those with layers at 0^o and 90^o only. Jun and Hong [18] began to expand the previous theory for un-symmetric laminates with arbitrary layup angles. Dano and Hyer [19,20], Ren *et al* [21], and Potter and Weaver [22] continued to explore the mechanics of un-symmetric laminates by expanding the Rayleigh-Ritz formulation to more general angle-ply laminates and comparing the predictions with physical experiments measuring the response of the laminates to simple applied forces. The correlation between predicted results, experimental measurements, and FEA was found to be quite good, in both terms of movement levels and in terms of strain response. A phenomenon, noticed by Potter *et al* [23], regarding the snap- through process of un-symmetric laminates was that it was observed to take place not as a single bifurcation but as two closely coupled bifurcations, as first one side snaps through and then the other.

Schlecht *et al* [24] developed simple active deformable composite structures based on un-symmetric laminates and incorporated shape memory alloy (SMA) wires. The theory was modified to incorporate those effects from the SMA wires, and compared to Finite Element Analysis (FEA) results with good agreement. Hufenbach *et al* [25] began to introduce a level of automation into the actuation method by integrating NiTi (smart alloy) wires in the composite layup. There was good correlation between experimental and predicted results. Schultz's [26] research combined several mathematical modelling techniques, albeit primarily the Raleigh-Ritz technique, elasticity-type solutions and the finite element method to predict shapes of un-symmetric laminates with piezoelectric layers attached. Experiments were used to confirm that the proposed models accurately predicted the response of un-symmetric laminates to the effects of activating the piezoelectric layers. The use of piezoelectric actuators was further examined by Bowen *et al* [27] for different combinations of piezoelectric actuators and externally applied load suggesting that a combination of the two offers a practical solution to the control and morphing of unsymmetrical composite structures. Hufenbach *et al* [28] extended the already comprehensive theory still further to predict the shapes of the laminates with integrated Macro Fibre.

3.1 Composite actuators.

While the possibility of using snap-through composites in morphing structures has essentially been the motivation for the majority of the previous work it is only recently that conceptual ideas have been proposed. Mattioni *et al* [29] investigated an alternative design for variable sweep wings. It consists of a two-spar carbon fibre reinforced wing, with truss like ribs. The spar uses snap-through composites to increase the moment of inertia to withstand bending stresses and, under certain loading conditions, to behave like an elastic hinge to allow the sweep angle of the wing to change. Schultz [30,31] has considered a system consisting of two curved shells that are joined at the longitudinal edges to form an airfoil-like structure with two stable configurations. These configurations were shown to have a difference in axial twist. Several composite and one steel model were considered as proof-of-concept designs, and FEA was used to study how changes in the geometric input values affect the shape and operational characteristics of the structures.

3.2 Numerical Example

As an example a four layer square plate with carbon/epoxy layers each 0.1222mm thick and side lengths of 0.25m is studied using modified CLT, based on samples described in [26]. The plate is flat at curing temperature and is cooled to room temperature. The material properties for the layers are given in Table 1. The composite laminates throughout this study consist of thin layers, or lamina, that are made of either glass or carbon fibres in several different matrix materials, and are manufactured on a flat aluminium plate. The possibility exists for an arbitrary number of layers may be stacked together with arbitrary ply orientation angles. In order to consolidate and cure these composite laminates, they are heated under pressure. In the case of symmetric laminates, a panel that is cured on a flat form tends to remain flat after cure and cooling to the operating temperature. A laminate is symmetric if the material, angle, and the thickness of the plies are the same above and below the mid-plane [32], as illustrated in Figure 3. The thermally induced stresses developed in un-symmetric laminates will cause curvature to develop as the panel cools. As already noted, the laminates of interest are thin un-symmetric laminates with more than one stable equilibrium state at room temperature.

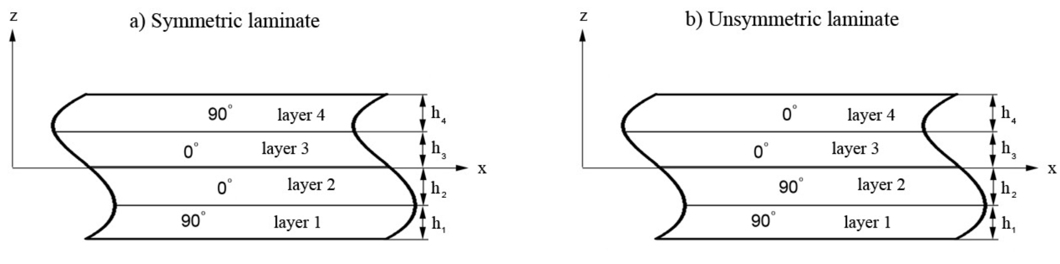


Figure 3 **Schematic of a) a symmetric laminate and b) an un-symmetric laminate**

Cross ply laminates, laminates with only 0^o and 90^o fibre orientations, are examined because they have the simplest laminate stiffness matrices, and modelling the behaviour of cross-ply laminates is more straightforward. Un-symmetric cross-ply laminates also have greater room temperature curvature, and lower bending stiffness, than other un-symmetric laminates. The increased curvature will make it more difficult for an actuator to snap the laminate; however, the lower bending stiffness of cross-ply laminates should mitigate this effect. Figure 3(b) is a schematic of a typical laminate construction under investigation.

Table 1 **Layer properties used in the initial model, [26].**

Property	Carbon/epoxy layers
E_1 (GPa)	171.0
E_2 (GPa)	8.76
G_{12} (GPa)	5.76
v_{12}	0.335
v_{21}	0.0172
α_1 (/°C)	0.5094×10^{-6}
α_2 (/°C)	27.6×10^{-6}

The panel shape can be represented by its curvature in the x (κ_x) and orthogonal in-plane direction y (κ_y). Figure 4 shows the effect of temperature reduction on curvature. At point A (cure temperature), both curvatures are zero since the laminate is flat. As the temperature reduces the curvature values are of equal magnitude but opposite sign. This corresponds to a shallow saddle shape, Figure 2(b). As the temperature decreases further, to point B, the temperature-curvature relationship bifurcates. With a further reduction in temperature this relationship follows either path BC, path BD or path BE. With path BC, the curvature in the x-direction increases, whilst curvature in the y-direction decreases. At room temperature the curvature in the y-direction virtually disappears and the laminate takes the form of Figure 2(c). With path BE the curvature in the y-direction increases whilst that in the x-direction decreases. At room temperature the curvature in the x-direction is negligible and the laminate takes the form of Figure 2(d). Lastly, with path BD the curvatures in both directions increase and stay relatively equal in magnitude but opposite in sign. This corresponds to the saddle shape, Figure 2(b). A stability analysis shows that paths BC and BE are stable, but path BD is not. At room temperature, application of force causes the laminate to snap through from the configuration represented by point C to that represented by point E.

3.3 Manufactured Specimens

Three different sets of $[0_2/90_2]$ snap-through panels have been manufactured; a glass fibre/epoxy panel, a carbon fibre/epoxy panel, and a glass fibre/polypropylene panel. In order to compare the effect of different fibre reinforcements and resin matrices on the curvature of the samples, measurements were taken from each sample of the chord length and the chord height of the specimen and the radius of curvature calculated as illustrated in Figure 5. Table 2 gives the two orthogonal curvatures and also typical coefficients of thermal expansion for each fibre type and matrix.

The specimens with glass fibre reinforcements had similar curvature at room temperature with the best performance from the glass fibre/epoxy laminate. This is at variance with previous work of carbon fibre/epoxy laminates which reported $12.8 m^{-1}$ (0.078m radius) [26] due to the large difference between the coefficient of thermal expansion (CTE) of carbon and that of epoxy. In this case it is thought that the smaller curvature of the carbon fibre/epoxy specimen was caused by a high fibre volume fraction thus resulting in too little resin for the difference in CTE to cause a large curvature.

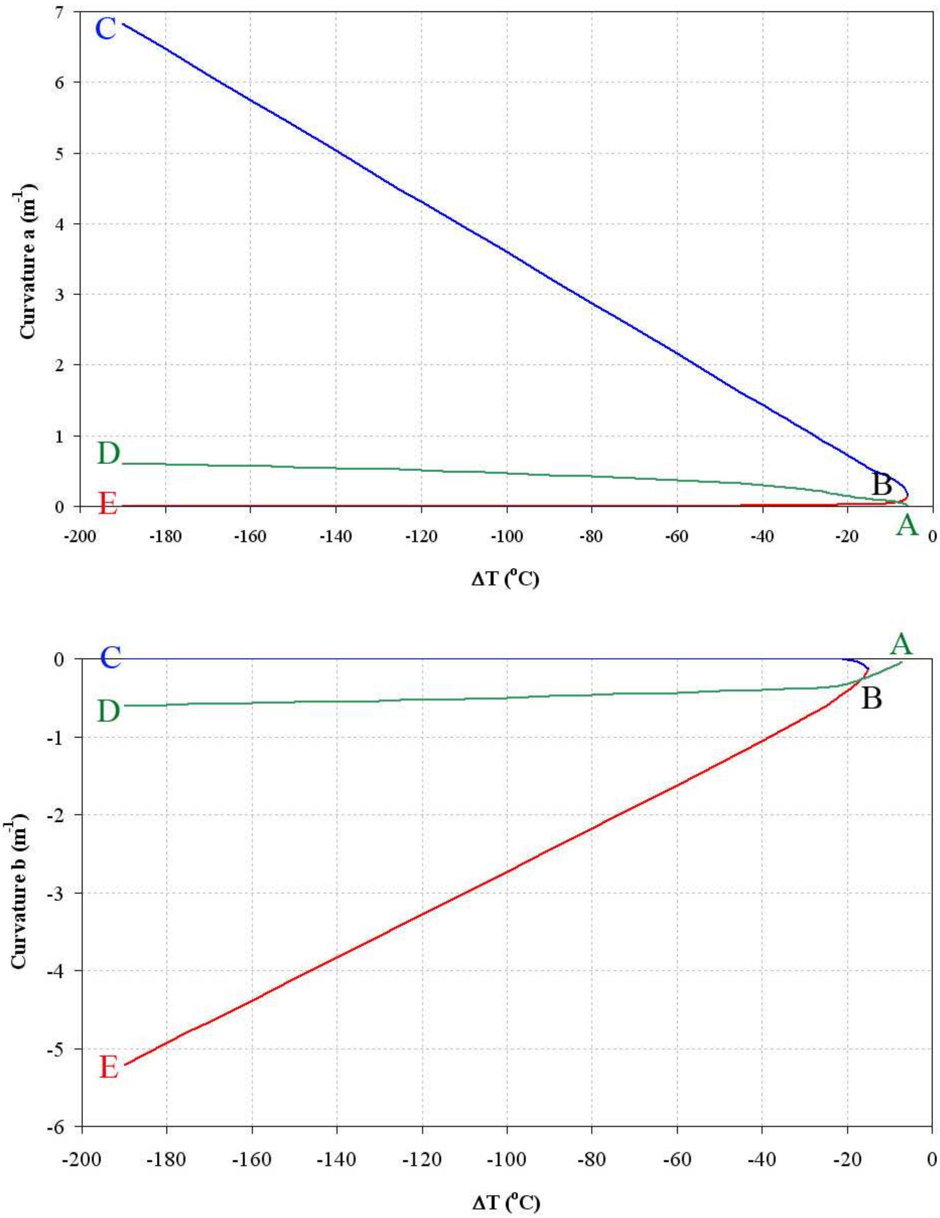


Figure 4 Temperature-curvature relationship of a square [02/902] carbon-epoxy laminate

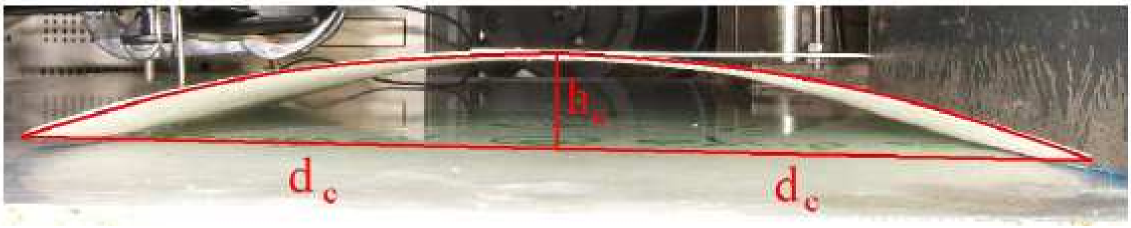


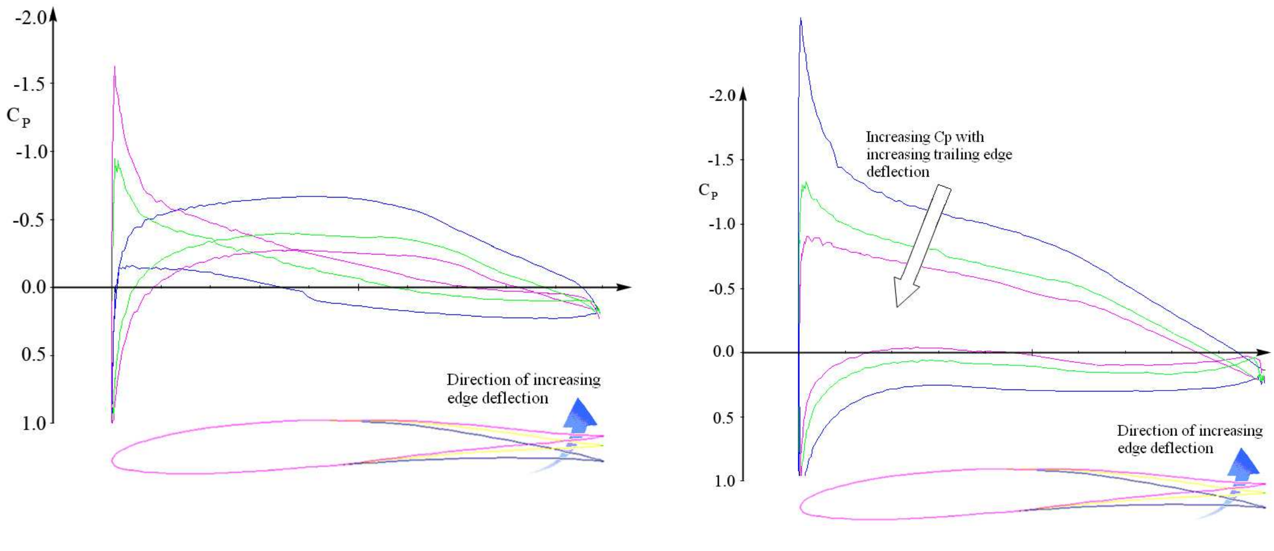
Figure 5 A test specimen in stable 'snapped' condition

Table 2 **Measured values of snapped-through curvature the samples**

Type of Laminate (CTE (x10^{-5}/°C))	*a* curvature (m^{-1})	*b* curvature (m^{-1})	Radius of curvature *a* (m)	Radius of curvature *b* (m)
Glass Fibre (2.2) /epoxy (5.4)	3.91	2.87	0.256	0.348
Carbon fibre (0.2) /epoxy (5.4)	2.02	1.69	0.495	0.592
Glass fibre (2.2) /Polypropylene (8.6)	3.53	2.17	0.283	0.460

3.4 APPLICATION TO AUTONOMOUS VEHICLES

The ability to use a solenoid type device to move between two stable states could be applied at the trailing edge for some or all of the span of an UAV wing, towards the wing tips of the span on gliding AUVs or on the nose/tail cone of conventional self propelled AUVs. As an example of the likely change in pressure distribution two cases were run using Xfoil [33] for an assumed distorted shape for last third of chord. A span-wise series of such panels could give a reasonable level of ability to 'tune' the local lift/drag characteristics of the wing or if applied to a propeller blade the sectional performance for a given wake. Figure 7 illustrates a potential design methodology applicable to a propeller blade.



(a) Cambered foil at 0^{o} incidence (b) Cambered foil at 6^{o} incidence

Figure 6 Pressure distributions on foil using snap-through panels for last third of chord.

4.0 ADAPTIVE SKELETAL STRUCTURES

An alternative approach to modifying the external shape of a wing directly is to use a central spine to withstand the load and to surround it with a structure that follows deformation of that central spine. We consider two different strategies to achieve this.

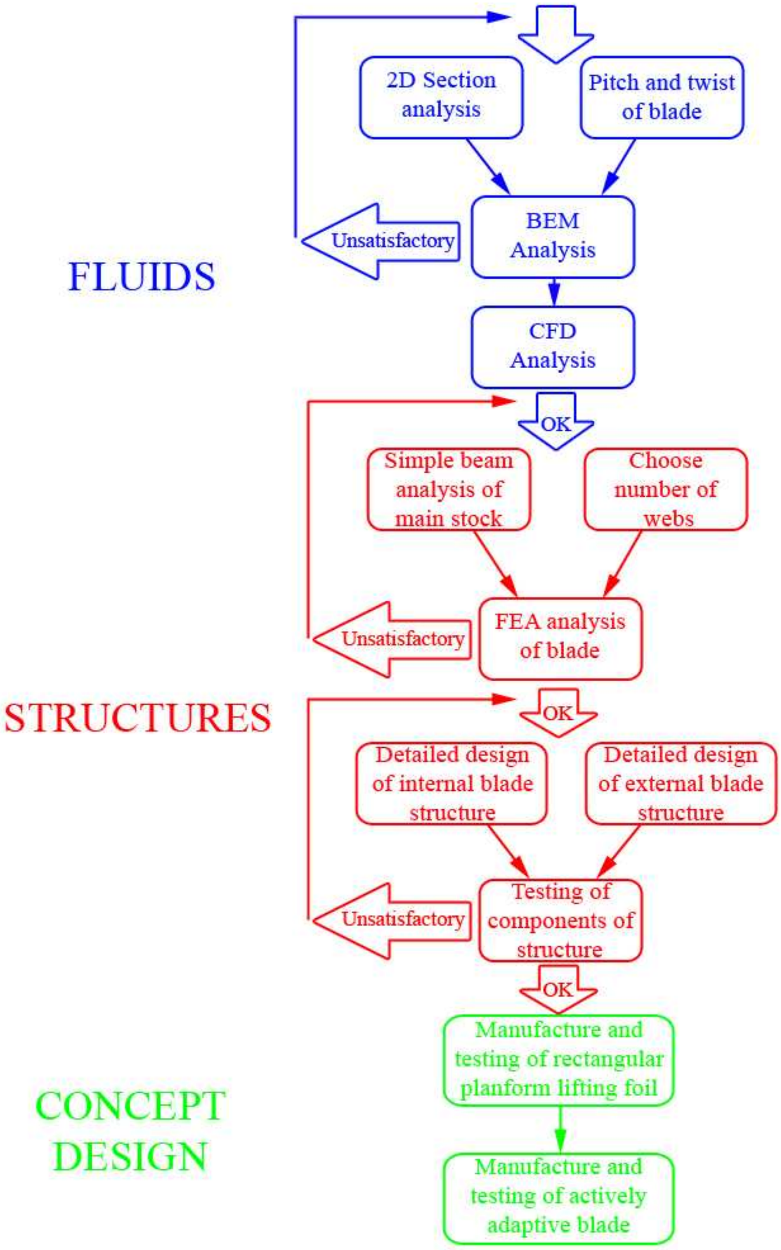


Figure 7 proposed fluid-structure design methodology for a propeller blade with active adaptation

4.1 Bend twist coupled beams

An adaptive textile composite, sometimes referred to as a smart material or intelligent material, is a structure tailored to exhibit desirable elastic deformation behaviour not necessarily proportional to the imposed load. An example of such a structure would be a box beam so tailored that an imposed cantilever load results in twisting as well as bending, although no torsional load was imposed. Reversible behaviour would be exhibited if, in addition, an imposed torsional loads results in bending as well as twisting, although no cantilever load was imposed. Such a structure is said to exhibit bend-twist coupling. The elastic coupling can be varied over the span by appropriate selection of ply angles, thicknesses and spanwise layup. The resulting anisotropy provides direct bending-axial torsion elastic coupling not possible with metallic blades. There are added benefits of a large reduction in manufacturing costs when compared to steel. A 60-70% reduction in production costs was seen in the marine propeller industry upon embarkation of research into coupled composite propeller blades, along with smoother power take up, reduced blade vibration, reduced noise, and better fatigue performance [34].

For conventional laminated composites constructed of orthotropic layers, the level of anisotropy is determined by the fibre orientation with respect to the primary loading direction. Fibres orientated at an angle, θ, can be used to produce either bend-twist coupling or extension-twist coupling. Kooijman [35] found that the mirror layup, Figure 8(a), is required for bend-twist coupling, and the helical layup, Figure 8(b), is required for extension-twist coupling to be exhibited. In the case of coupled spars, it is considered beneficial to use braided planforms rather than a more conventional lamination method. A key advantage in using braided planforms is the relative ease of manufacturing compared to conventional laminated composites. Moreover, the structural box is continuous, and fatigue/damage tolerance performance is better than conventional laminated composites [36].

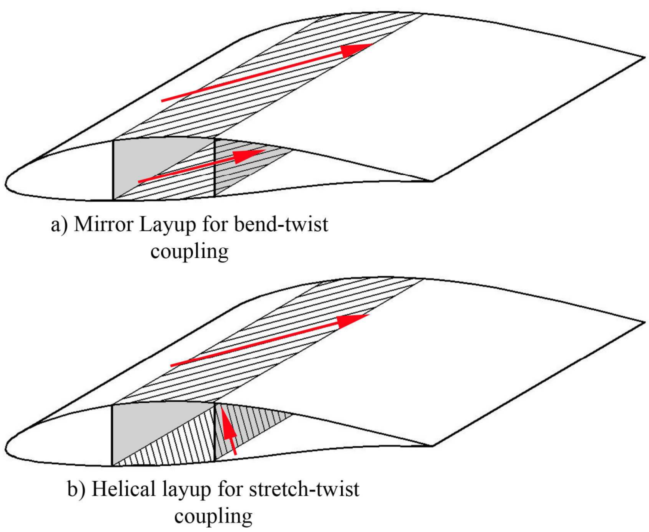


Figure 8 **a) Layup for bend-twist coupling and b) layup for stretch-twist coupling**

The use of a single braided pre-form would produce the helical layup, Figure 9(a). If, however, a single pre-form is cut and used in two halves to create a double box beam, the mirror layup can be achieved , Figure 9(b). This is thought to be significantly more robust than the patch layup technique for creating bend-twist coupling, which has joint strain incompatibilities and is prone to de-lamination when exposed to cyclic loads, Figure 9(c) [36]. A series of beams are currently under construction to demonstrate the capabilities of bend-twist coupling. There are two modes of operation with such a structure forming the spine of a lifting surface. This could be either as a passive system that simply responds to the loads applied and could effectively through its twist behave like a controllable pitch propeller and maintain a higher efficiency or a moment actuator could be applied at the root to induce a twist which the combination of fluid loading and internal stresses develops a more appropriate shape.

4.1 Pre-loaded internal spine system

It is also possible that a deformable internal spinal structure could produce shape control with a limited number of low-power actuators. This is achieved by adopting a preloaded internal spinal system that moves through the desired shape changes under the control of a very limited number of actuators (in an UAV just one each for the two tip cambers, one for each wing twist and one for the common root camber). In effect control system complexity is traded for passive structural sophistication. This provides a low-power, light weight means of aerofoil shape control with independent control of camber and twist[37].

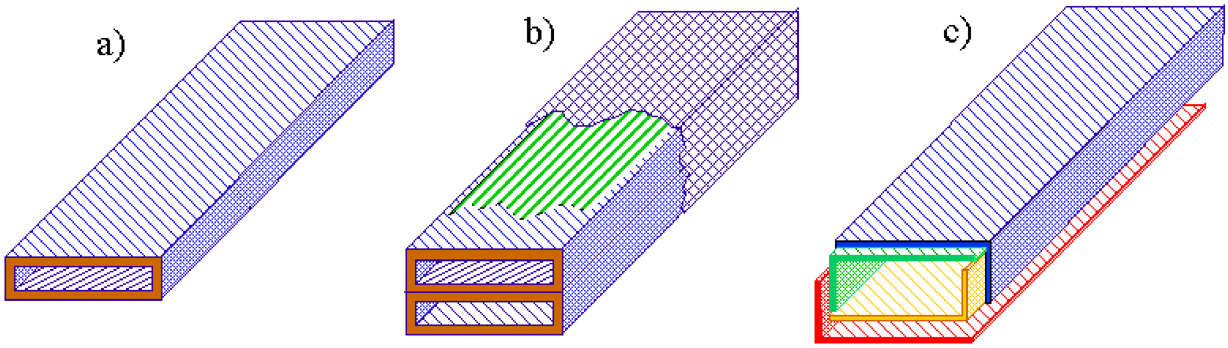


Figure 9 a) Single box layup, b) double box layup and c) patch layup

The simplest way to envisage the spinal structural approach proposed is to consider a partially buckled simply supported Euler strut subject to an eccentric end load, as depicted in Figure 10. Such a strut takes up a half sine wave shape whose amplitude is controlled by the end loading. Moreover, this amplitude is linked to the end-loading in a highly non-linear way, so that modest increases in load result in significant changes in shape (see Figure 11). Next let the properties of the strut vary along its length. In such cases the shape adopted ceases to be a pure sine wave and becomes dependent on the way the strut properties vary. With an appropriate choice of properties the buckled shape can be made to conform to the camber line of an airfoil. Now as the end load is varied we have a means of varying the camber line. If the strut is then connected to a semi rigid pre-tensioned elastic skin via a flexible foam core this affords a means of aerofoil section shape control. The selection of properties is here accomplished via an inverse design procedure[1] whereby an optimizer is used to control the structural properties and end loads and a commercial FEA code (Abaqus) is used to asses the deformed shape. The objective function used is the sum of the square of the differences between the desired and actual deformed shapes.

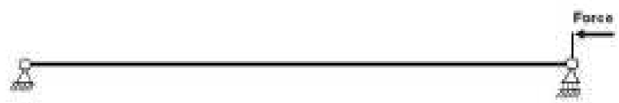


Figure 10 Example of a beam-column with eccentric load.

The curves in figure 11 show the non-linear behaviour of the beam-column, as a fraction of the Euler critical load. The greater the eccentricity is, the greater the concentrated moment at the end of beam-column. Consequently, the buckling behaviour is not as dramatic as for a classical column. Moreover, increasing the load after the critical state is reached causes the lateral deflection to continue to increase as the load rises, but the stiffness remains positive ($P/P_{cr} \geq 1$), which indicates the beam-column has a post-critical reserve strength. The aim here for the spinal structure is to gain control of large displacements using small force variations. The more the eccentricity is increased the greater the slope of the force displacement curves [38,39]. Therefore, a small eccentric loading gives us the desired effect. Given all these data, we choose to analyze beams with 0.3% eccentricity as this assures robust solution convergence in Abaqus, while still giving significant deflections for small force changes. We have found that with only 0.1% eccentricity numerical instabilities can occur during optimization.

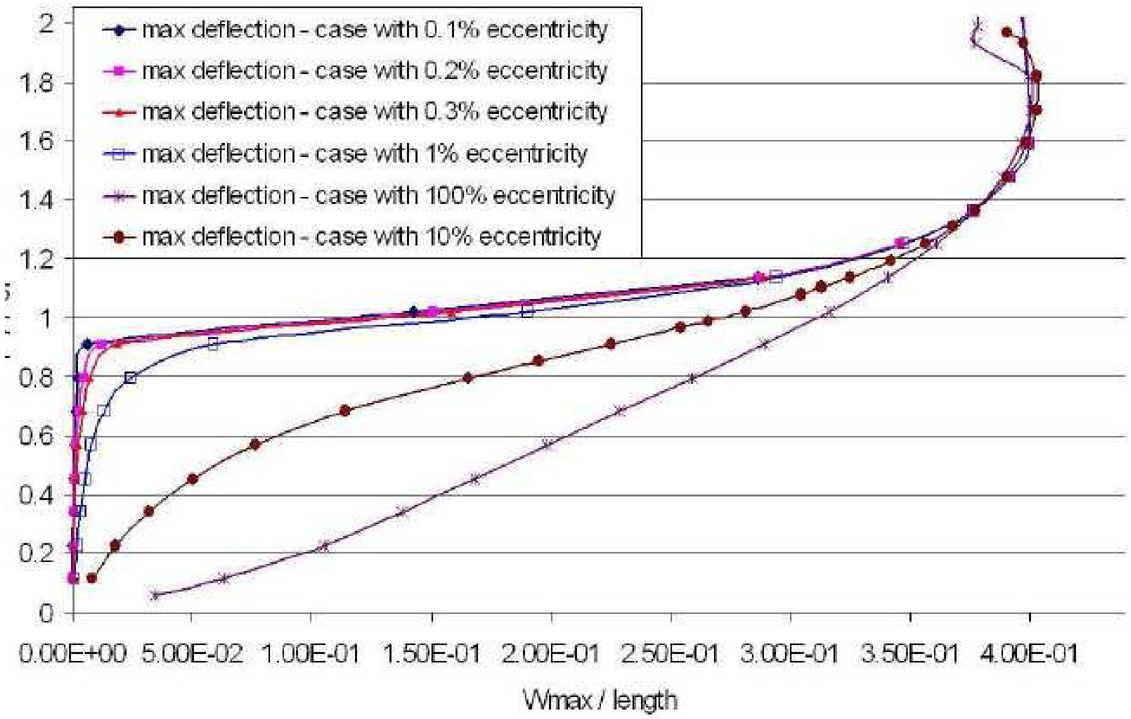
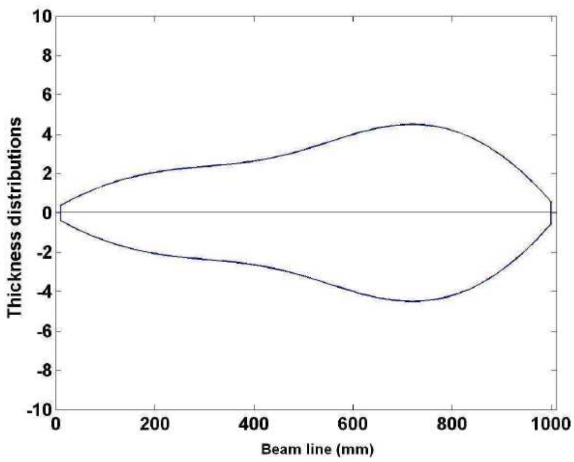


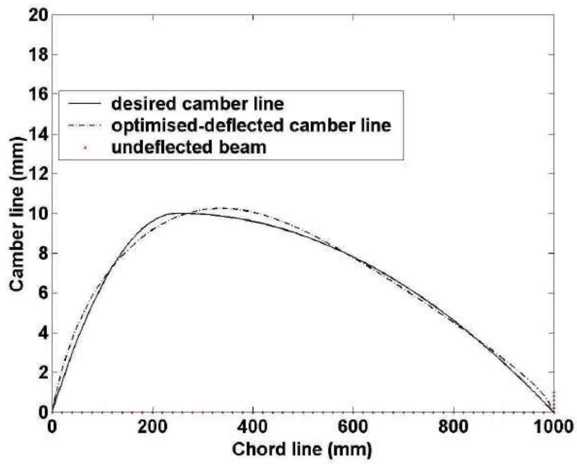
Figure 11 Behaviour of beam-columns in non-linear regime, with different eccentricities

4.2.1 Camber/plate thickness optimization

Figure 12 shows the result of an optimisation process to determine the required thickness of a spinal element for a cambered two-dimensional section such that an eccentric would allow the section to achieve a desired camber. In this case the section was represented using a NURBS curve. In reality it is the whole plan form of a wing that requires control. If we take the geometry of figure 12 to create a wing plate that is 1600mm wide and 1000mm deep and then load it eccentrically and non-uniformly along its edge we gain control of the whole wing, see figure 13(a). To begin we will consider two cases: one with only two point loads, one at each corner and one with a linearly varying load. The point loads model would, of course, be easier to control in terms of using actuators to achieve the required shapes. In both cases the loading is defined by the value at the two extreme edges and so it is possible to produce contour maps of deflection as these two quantities change. These are plotted in figures 13(b-d). In both cases some of the calculations become unstable and so the plots show regions where there is a lack of continuity as the forces alter. Nonetheless the overall trends can clearly be seen. These show that a range of camber variations can be achieved with these simple forcing arrangements, although rather higher forces are needed if simple point loads are used. The resulting deflected shapes for several particular loading cases are plotted in Figures 14 and compared to equivalent NACA shapes. While the basic trends desired are apparent these are, however, not so accurate in terms of the NACA four digit family as the 2D strut model. To improve on the agreement with the desired NACA shapes would require further optimization effort, but now using plate analyses and also varying the plate properties both along the camber-line and across the span.

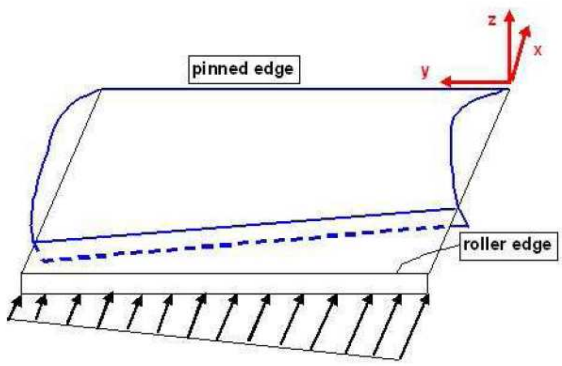


(a) Optimal thickness distribution with NURBS approach.

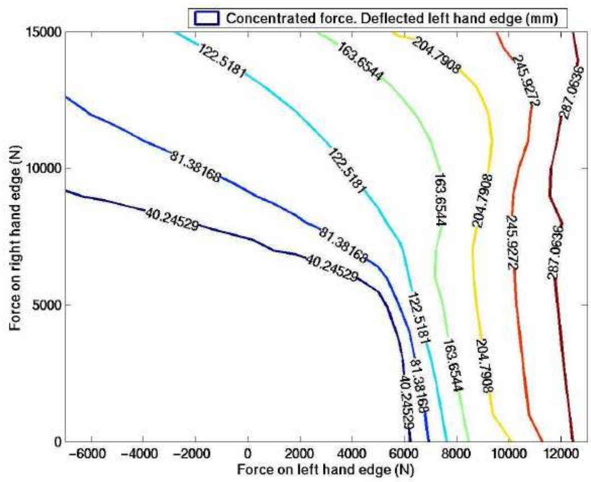


(b) Optimized camber line obtained with the NURBS parameterization using GA (min error=9.10 mm^2).

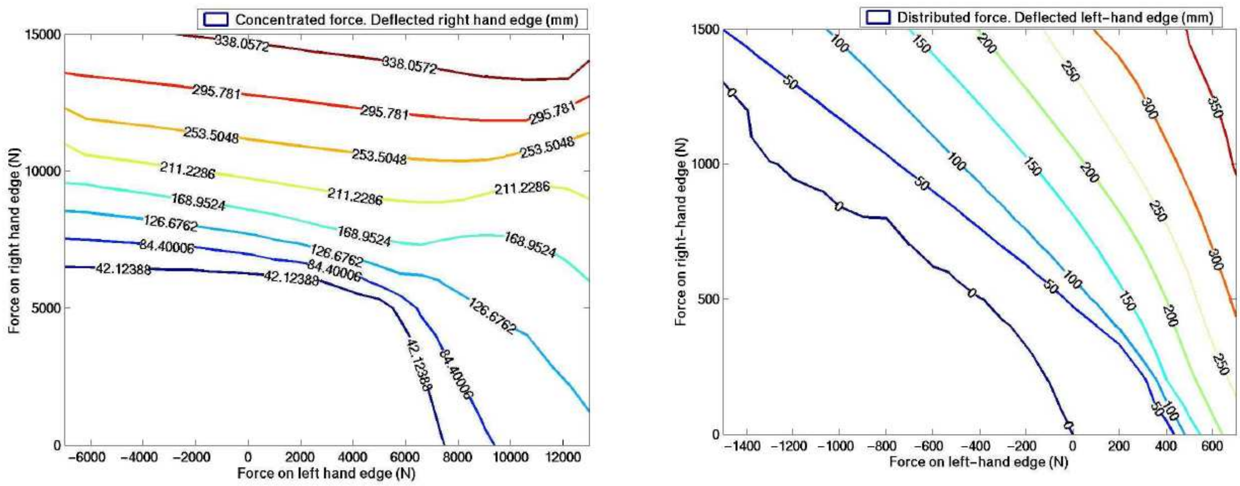
Figure 12 optimisation of spinal element line along camber line for a NACA 4 series foil section



(a) The lateral deflected shape of a plate, under a compressive non-uniform distributed load



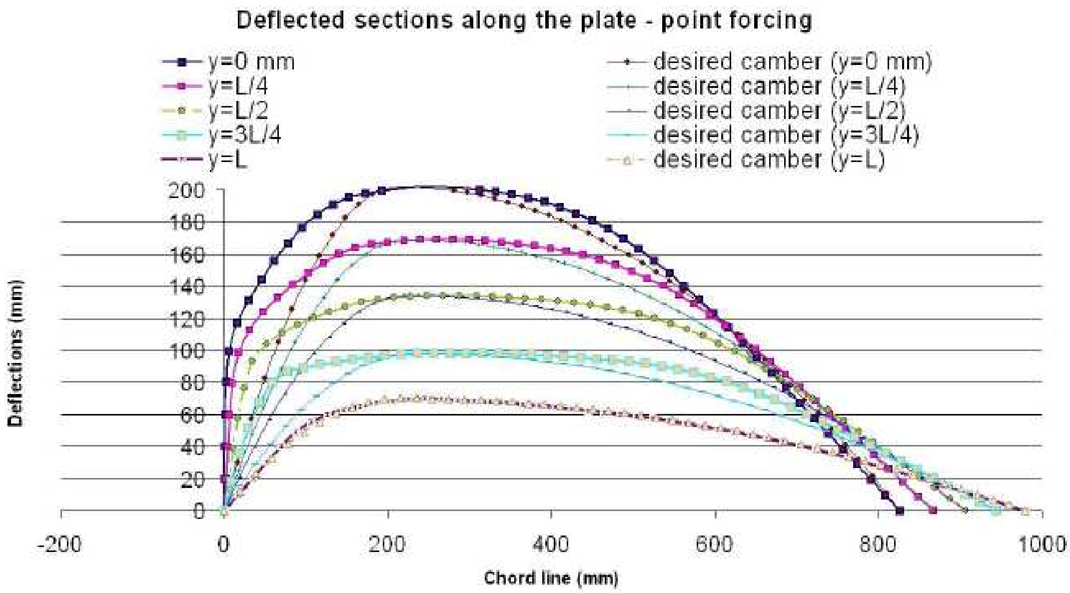
(b) Contour plot of the plate response on its left-hand edge – point forcing



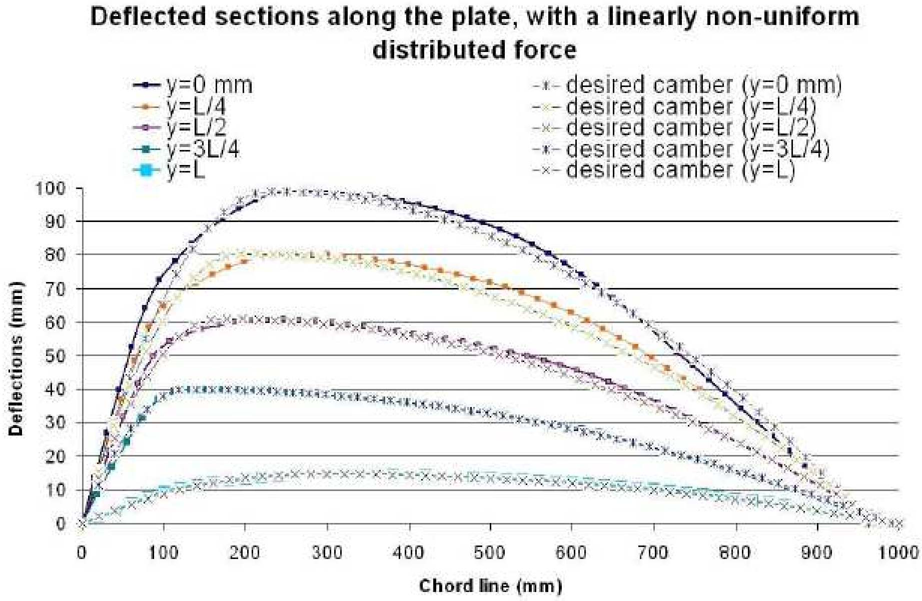
(c)Contour plot of the plate response on its right-hand edge – point forcing

(d) Contour plot of the plate response on its left-hand edge – linearly varying load

Figure 13 Deflection response of a plate to concentrated and distributed loads



(a) Point forcing



(b) Linearly varying load

Figure 14 Deflected shapes of four equally spaced sections along the plate

5.0 CONCLUSIONS

The on-going research programme in autonomous 'flying' vehicles at the University of Southampton is exploring the possibilities of adaptive, 'morphing', structures. The review of three possible techniques (push-pull actuated snap-through composites, bend-twist coupled composite beams, and post-buckled deformable struts/plates) has shown that all three show considerable promise but that there is still a considerable bridge between laboratory based operation and associated theoretical analysis of such structural elements and achieving robust and reliable systems applied on actual vehicles. Our eventual objective is to minimise the number, mass and power requirements of the necessary actuation systems to achieve active control. It is intended that all three of these approaches will be applied to some of the University of Southampton prototype platforms (maritime or aeronautic) in the near future.

It is likely that the first system using 'snap-through' composite structural elements will be applied to the trailing edge of submerged control surfaces to remove the necessity for a trailing edge flap or rotary mechanism. These elements allow low energy transition from one shape to another. A suitable combination or array of such elements could allow multiple shapes to be achieved.

The use of bend-twist coupling can be either used as a passive method of controlling for example propeller blade pitch distribution or combined with an actuator to actively deform an outer wind or control surface shape.

The third approach would use the bend-twist properties to passively adapt shape based on the selection of composite plys and lay-up. The final approach uses pre-loaded spinal structures to morph a whole wing using 2 or 3 actuators that generate a non-linear response. The design of the optimised spinal elements is tuned to achieve a continuous range of desired shapes. The uses of advanced optimisation based design search algorithms will allow detailed understanding of the fluid dynamic performance of the wing of a UAV with the control system.

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