# DESIGN OF COMPOSITE CONTROL SURFACES FOR TAILORED DEFORMATION USING FLUID STRUCTURE INTERACTIONS

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## ABSTRACT

In order to take full advantage of the lightweight characteristics of composite materials, design often needs to sacrifice stiffness and exploit the more favourable strength. However, this approach leads to structures that deform significantly under load. This paper outlines a numerical methodology which demonstrates control of the inherent flexible characteristics of composite structures to achieve a desired deformation response. An examination of the sensitivity of the structural response was conducted by asymmetrically varying the ply angles in a number of composite layers within the model. The results indicate that the layers in the skin have a large influence on the development of bend-twist coupling in the control surface. The research culminates in an examination of composite architecture options which result in specific levels of bend and induced twist deformation. This approach clearly shows that one can control the coupled deformation response and that this may have beneficial performance implications.

## 1. INTRODUCTION

High-performance sailing is an ideal field for the use of lightweight materials. Inshore and offshore sailing performance has increased rapidly in the last 30 years thanks primarily to the use of exotic materials in hull construction and sails. Round the world yachts, such as those in the Volvo Ocean Race and inshore yachts such as the AC72s used in the 34$^{th}$ America's Cup, are manufactured in carbon fibre reinforced polymer (CFRP). The advantageous specific strength and stiffness can dramatically reduce the weight of the hull.

Sailing boats have the ability to make forward progress towards the wind. This is achieved by careful balance of the aero- and hydro-dynamic forces generated by the sails and the underwater foils, respectively. The objective of the underwater foils is to act like a wing, generating a lift to counter act the aerodynamic side force. Common design philosophy is that one characterises the performance of the boat based on a known shape of the foil with the assumption that the shape of the foil does not change. In reality, no material is rigid and therefore deformation under load will occur.

In order to take full advantage of the lightweight characteristics of composite materials, design often needs to sacrifice stiffness and exploit the more favourable strength. However, this approach leads to structures that deform significantly under load. The philosophy taken in the current research is to embrace the knowledge that the structure will deform. But can the design of the composite architecture be exploited such that the resultant deformation can have a positive impact on performance?

Numerical models and simulations form an important part of the design of high-performance sailing yachts. For the application of a sailing yacht or a sailing foil in water, there are two aspects of the numerical simulation, fluids and structures. Banks et al. [1] investigated a curved sailing foil both experimentally and numerically. In particular, the numerical studies involved Computational Fluid Dynamics. However, the structural response to the fluid loading was not directly considered. Fully coupled Fluid Structure Interactions (FSI) simulations provide a pressure force created by the fluid loading and the deformation of the structure due to the pressure forces. This process happens iteratively as structural deformation and pressure are passed between the structural and fluid models with time.

The aim of the current research is to explore a single iteration of a fluid structure model of a sailing foil and to investigate the influence of changing the composite architecture of the foil, on the deformation. The model will introduce asymmetry in the composite architecture which results in a coupled response, i.e. bend-twist coupling [2].

## 2. FINITE ELEMENT MODEL DEVELOPMENT

A generalised composite marine control surface is used in the current research to provide a semi-realistic structure from which to understand response to fluid loading. The external geometry of the foil is a NACA 0018 section with a chord of 0.3m and span of 1.3m. As a first step in the analysis the foil is assumed to have no internal structure. The wall thickness of the foil is assumed to be 2.81mm comprising of ten layers of 0.281mm thick plies of high strength unidirectional carbon fibre with properties as specified in Table 1. The material assumed is based on SE84LV epoxy resin with T700 UD HS carbon fibre from Gurit. The base laminate architecture for the skin was [0, 90, 0, 45, -45]s for both sides of the foil. This provides a symmetrical laminate and therefore no bend-twist coupling provided that the load is applied through the shear centre of the geometry. The geometry was modelled in ANSYS and discretised using SOLID186 elements, which allow for layered materials. The boundary conditions were to fully constrain all degrees of freedom at one end of the foil. In order to prevent local deformation of the foil due to load application an additional boundary condition is added to maintain the cross-sectional shape at the free end of the foil.

**Table 1 CFRP material properties**

| Property | Value |
|---|---|
| Fibre weight | 300 g/m$^2$ |
| Cured ply thickness | 0.281 mm |
| $E_X$ | 129.2 GPa |
| $E_Y$ | 8.76 GPa |
| $E_z$ | 8.76 GPa |
| $\nu_{XY}$ | 0.335 |
| $\nu_{YZ}$ | 0.0172 |
| $\nu_{XZ}$ | 0.0172 |
| $G_{XY}$ | 5.76 GPa |
| $G_{YZ}$ | 5.76 GPa |
| $G_{XZ}$ | 5.76 GPa |

A local coordinate system is established for each element in the model such that the unidirectional properties of the CFRP were correctly applied. Figure 2 shows the cross-section of the foil with the normal axis of the elemental coordinate system visible. The mesh density used was assessed by applying a simple point load to the model with all the layers of the composite orientated to both 0° and 90°. This allowed for comparison with the analytical solutions for cantilever beams. A nominal point load of 200N was applied to the foil at 25% of the chord from the leading edge. This results in a small amount of positive twist as the shear centre of the foil was subsequently found to be at 27.8% of the chord.

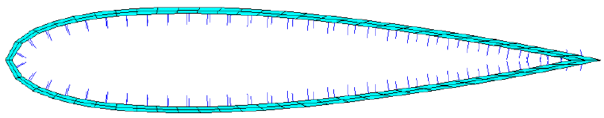

Figure 2 Correct element orientations as shown by the coordinate system normal.

### 2.1 SENSITIVITY OF MODEL TO PLY ORIENTATION

This model was used for a systematic sensitivity analysis to changes in the orientation of individual layers in the skin of the foil. The results provided are the bend and induced twist of the foil. Figure 3 shows the convention used for defining bend and twist. The displacement of the leading edge (LE) and trailing edge (TE) were used in conjunction with the known chord length and trigonometry to determine twist. Foil deflection was defined as the average of leading and trailing edge displacement.

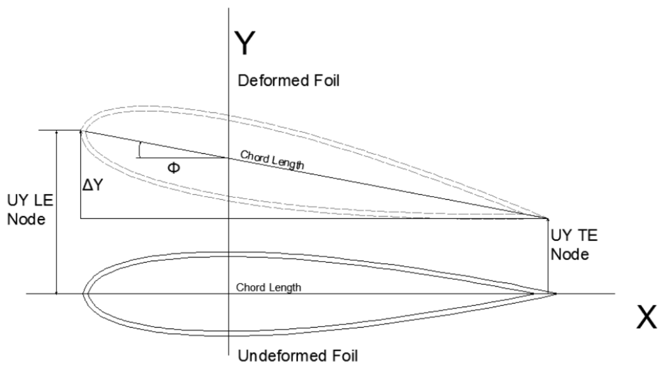


Figure 3 Convention for bend and twist used in the current paper

Figure 4 shows the concept of sweeping the outermost ply from 0° to 90°. Figure 5 shows the results of the outer ply sweep. Note the positive twist at the 0° ply angle is due to the load not being applied at the shear centre. The outer ply has greatest influence on the twist of the foil at a ply angle of approximately 30°. Similar trends are seen in the analyses of sweeping other layers in the thickness. The outer ply results are presented here as their influence is greatest due to the increased distance from the neutral axis of the foil. Figures 5 and 6 demonstrate this by comparing the deflection and twist values obtained from sweeping the outer ply (ply 1) and the 3rd ply from the surface (ply3).

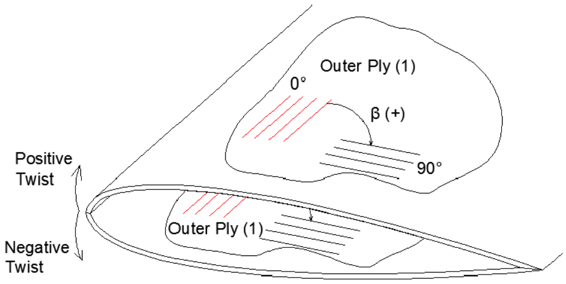


Figure 4 Sweeping of outer ply orientation from 0° to 90°

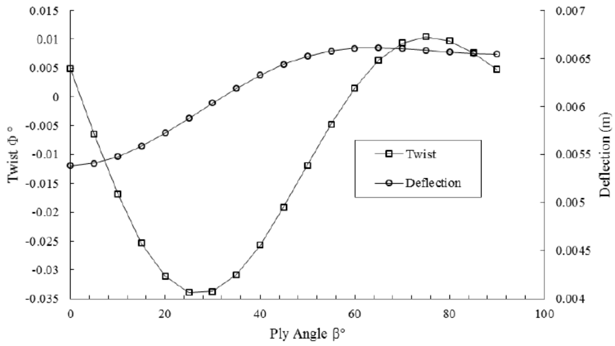


Figure 4 Change in twist and deflection with changing outer ply orientation

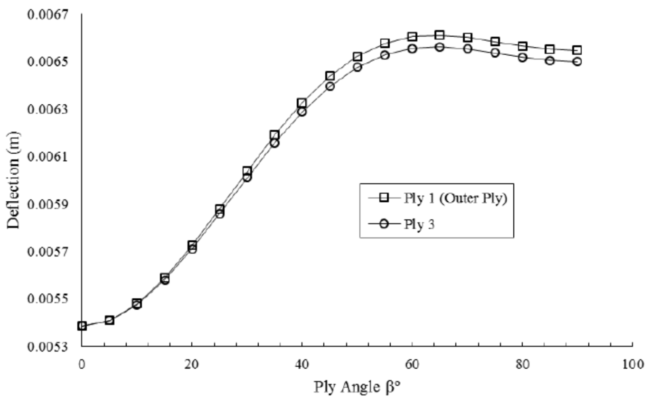


Figure 5 Comparison of deflection response when sweeping the outer (ply 1) versus the 3rd ply (ply 3)

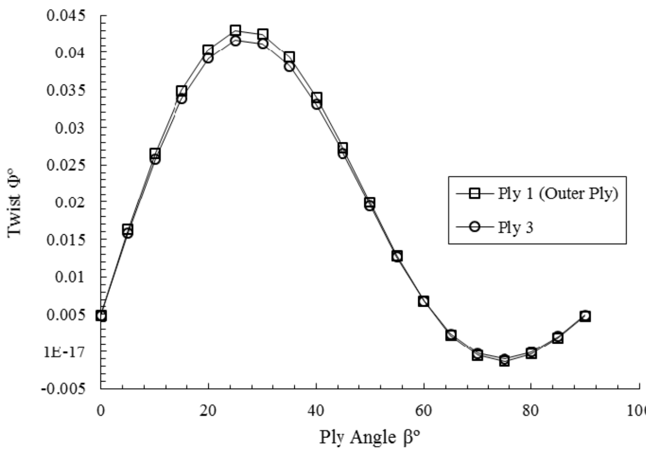


Figure 6 Comparison of twist response when sweeping the outer (ply 1) versus the 3rd ply (ply 3)

## 2.2 INTRODUCTION OF INTERNAL STRUCTURE

The model developed for the initial sensitivity of the structure to asymmetric laminate architecture clearly demonstrated the bend-twist coupling phenomena. However, the structure was relatively simple. It is known that there are central strength spars running down the length of sailing foils. These were introduced to evaluate what influence these would have on the bend-twist response. The structure contains two primary components; a CFRP central spar, constructed from two C-section profiles and a CFRP skin (Figure 7). This structure is analogous to a foil in a sailing yacht, but could be applicable to any structure subject to hydrodynamic or aerodynamic loading, e.g. turbine blade.

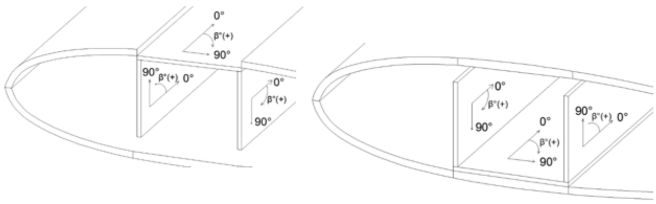

Figure 7 Configuration of the internal structure and associated ply direction convention

Figure 8 and 9 prolvide the results of the response of the foil with and without the internal structure for deflection and twist, respectively. It is clear in Figure 8 that the stiffness of the foil with the internal structure is dramatically increased across all outer skin ply angles. This is expected as there is an increase in the moment of inertia of the foil. In the twist response, it was shown (Figure 4) that the region for greatest influence is between 20° and 40° outer play angle. This is where the largest difference occurs when introducing the internal structure (Figure 9). This is due to the increased torsional stiffness attributed to the box beam internal structure.

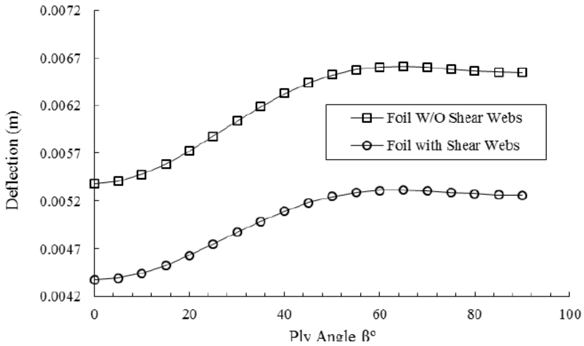


Figure 8 Comparison of deflection response of foil with and without internal structure with changing outer skin play angle

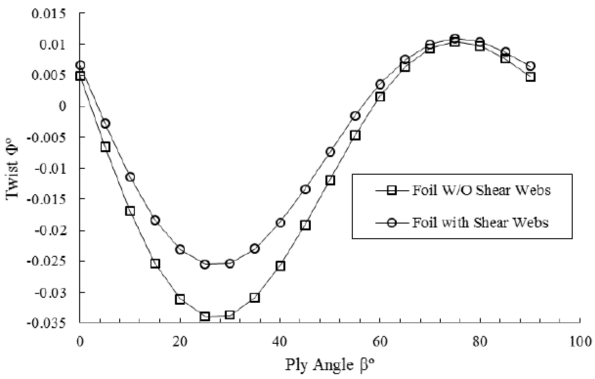


Figure 9 Comparison of twist response of foil with and without internal structure with changing outer skin play angle

An assessment was made to compare the influence of varying the ply angles in the internal structure against the skin laminate on the deflection and twist response of the sturcture. As can be seen in Figures 10 and 11 the magnitude of deflection and twist is greater when the ply orientation in the skin is changed. This is an expected result as the skins are further from the neutral axis. The results presented thus far give confidence that the model is behaving as expected.

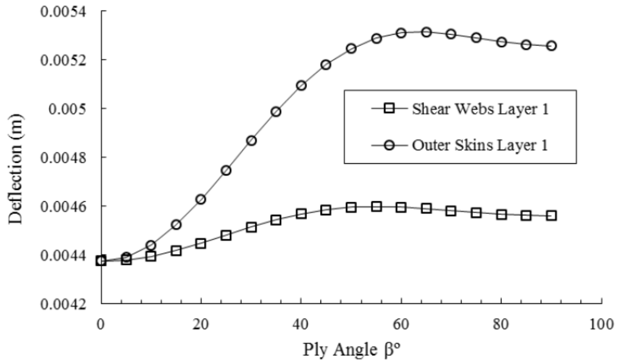


Figure 10 Comparison of deflection response when changing the outer ply of the skin versus the outer ply of the internal structure

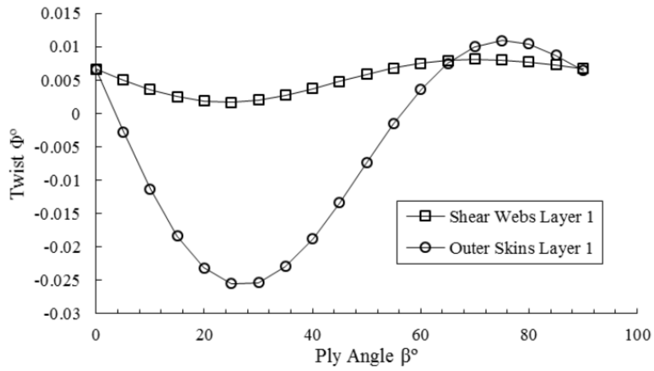


Figure 11 Comparison of twist response when changing the outer ply of the skin versus the outer ply of the internal structure

The sensitivity study presented in this section has shown the trends of response of the finite element model to a single point load. This has provided a level of confidence in the model to correctly predict the response of the structure. As the aim for this model is to use it as a design tool for a passivly adaptive structure a realistic load scenario must be applied. This will be obtained from a CFD analysis of the foil.

## 3. APPLICATION OF A REALISTIC PRESSURE FIELD

In order to ensure that the geometry developed in the finite element model was the same as that which produces the pressure field, the finite element geometry was exported as an STL file.

The CFD was conducted in OpenFOAM an open source Reynolds Averaged Naiver Stokes (RANS) solver. The STL file is used as the input geometry to the OpenFOAM meshing utility snappyHexMesh. Additional inputs to the CFD were the angle of attack of the foil, the velocity of the fluid and its density and viscosity. The CFD methodology was based on previous work[1] for a sailing foil.

The output from the CFD analysis is a four column matrix of x, y, z location and associated pressure for each CFD element. A MATLAB routine is used to interpolate this pressure cloud to provide a grid of pressures. The table of pressures is dimensioned and read by ANSYS before applying it to the surface of the foil. Figure 12 shows a 2D slice through the foil, this was conducted to assess, qualitatively, whether the mapping of the pressures had been conducted correctly.

The result from the application of the CFD loading to the base symmetrical laminate gave a tip deflection of 25.9mm and a small twist angle that increased the angle of attack. This is expected as qualitatively the centre of pressure is forward of the shear centre of the foil.

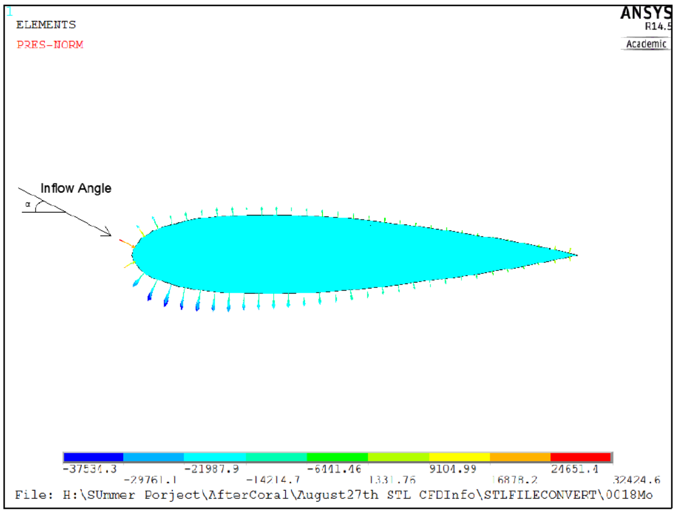

Figure 12 2D slice through foil showing applied pressure distribution obtained from CFD

## 4. DESIGN OF A FOIL FOR SPECIFIC RESPONSE

One of the key aspects of the current research is not to just determine what the response of the 'as designed' foil would be to a fluid loading, but to define the desired response and determine the required composite architecture.

As a case study the first aim was to alter the composite architecture of the beam to achieve a zero twist angle with a minimum change in deflection. The design curves from the sensitivity study (sections 2.1 and 2.2) of which only a few are presented here, used to determine which layers will be modified to achieve the goal. It was decided to only change the ply angles in the skin due to the magnitude of the response achieved compared to the internal structure.

Based on an analysis of the influence of each layer in the skin the 2nd layer from the surface was chosen. This was a 90° ply in the base laminate architecture. The design curve suggests that changing this ply angle to between -40° and -60° should result in a zero foil twist angle. The angle that closest met the goals of zero twist and minimum change in deflection was -48° which results in a change in deflection of less than 1%.

Using the complete set of design curves, a number of potential solutions to meet the design goals were found. By changing the outer ply from 0° to 5° gave a 0.5% change in deflection. Additionally, changing the outer layer by 3° and the 3rd layer by 2° gave a deflection of less than 0.3%. From a manufacturing perspective the latter two solutions, although better in their result, provide significant challenges in manufacturing tolerance. However, this result clearly demonstrates the ability to design the architecture to achieve a specific response. One key area of further work is to implement a more efficient search algorithm approach to finding the best solution which incorporates a qualitative assessment of manufacturability.

## 5. FLUID STRUCTURE INTERACTIONS

Section 4 demonstrated that given response criteria for the foil, a composite architecture can be found to meet those criteria. However, the solution is more complex that this static case. By designing the composite architecture to embrace deformation the hydrodynamic loading induced on the foil will be dependent on the geometry, which in turn changes with load. Therefore a Fluid Structure Interactions (FSI) simulation is required.

The implementation of the FSI in this research is referred to as 'loosely coupled'. The Finite Element Analysis (FEA) and the Computational Fluid Dynamics (CFD) are conducted independently of each other. Pressure data from the CFD is transferred to the FEA model via the previously described mapping technique (Section 3). The deformed geometry from the FEA is manually updated in the CFD. The transfer of information between the FEA and CFD and vice versa is conducted iteratively.

A single case study is presented here, an FSI loading of the zero-twist case from section 4. In the zero twist case the 2$^{nd}$ layer from the surface was rotated to -48°. The deformed shape after the first iteration is identical to that presented in section 4. The deformed geometry is then passed back to the CFD. As the first deformation shape had a zero twist, the angle of attack remained constant, but the geometry had deformed with a tip deflection of 20.7mm.

As the angle of attack of the clamped end of the foil has not changed for the second iteration, the only influence on the pressure loading is the change in bend and twist deflection. This alters the pressure distribution along the length of the chord and results in a twist change caused by the relationship between the centre of pressure and the shear centre of the foil. The angle of attack is actually reduced at the tip resulting in a force that reduces the tip deflection by 6mm, or nearly 30%. This clearly indicates that there is a fluid structure interaction occurring and that the design cannot be based on a single iteration of the FSI model.

## 6. CONCLUSIONS

A geometrically realistic test foil was designed and modelled in ANSYS to provide structural deformations under load. The model was developed successively to increase the complexity of the structure. A sensitivity analysis was conducted to understand the influence of the composite architecture on the response of the foil to load. A methodology of imparting a CFD load to the structure was developed and the passing of pressure and geometry information was established to allow for a FSI investigation. It was shown that the composite architecture can be designed to achieve a static case response but also highlighted that the FSI response needs to be evaluated as the pressure changes with deformation.

Clearly there is scope for further work in strengthening the coupling between the structural and fluids model and the use of search algorithms to improve the efficiency of finding the desired composite architecture which provides the required deformed response.

## ACKNOWLEDGEMENTS

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