Development of a design tool for investigating lay-up schedule designs of a composite windsurfer fins

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Resumo

Este projeto consistiu no desenvolvimento de uma ferramenta para a investigar diferentes esquemas de laminação de uma quilha de windsurf. O projeto pode ser dividido em três partes importantes. A primeira consiste no desenvolvimento de uma ferramenta para transformar distribuições de pressões 2D obtidas através do estudo hidrodinâmico em distribuições 3D para posteriormente serem importadas no programa de estudo paramétrico da quilha. A segunda, e mais importante, consiste no desenvolvimento de uma outra ferramenta para efetuar o estudo paramétrico da quilha e a terceira consiste na aplicação e teste de ambas as ferramentas em simultâneo.

A ferramenta para o estudo paramétrico da quilha permite ao utilizador alterar as características do plano de laminação das quilhas e estudar o seu comportamento estrutural de uma forma simples e rápida. Para isto é necessário utilizar a primeira ferramenta que prepara o input hidrodinâmico para posteriormente ser importado nas simulações do programa de elementos finitos. No final do projeto uma série de simulações foram executadas e dois estudos paramétricos foram completados:

Um para entender a forma como as diferentes distribuições hidrodinâmicas afetam a deflexão máxima e o angulo de torção da quilha e outro para testar a ferramenta de modelagem paramétrica e analisar o efeito da variação da orientação das fibras e do material no comportamento estrutural da mesma.

Palavras Chave: Materiais compósitos, estudo paramétrico, hidrodinâmica, ANSYS, distribuição de pressões 2D/3D, deflexão e angulo de torção, orientação das fibras

Abstract

This work presents a design tool for investigating lay-up schedule designs of a composite slalom windsurfer fin. Three main developments were made throughout this project. The first consists in creating a tool to transform 2D pressure distributions obtained from the Computational Fluid Dynamics (CFD) study to import in a parametric design tool. The second, and most important, consists in the development of a parametric design tool and the third and last one consists in the application of the tools developed to a slalom windsurf fin. This tool allows the user to change the lay-up schedule of the fin and analyse its structural response quickly and simply. Throughout this project, a series of simulations were run, and two distinct parametric studies were conducted. One for understanding how the simplified hydrodynamic load would affect the maximum deflection and tip twisting angle and the other to test the parametric design tool and vary the fibre orientation and material types also to verify how those two variables would be affected with such input changes.

Keywords: Composite Material, Parametric study, Hydrodynamics, Finite element analysis, pressure distributions 2D/3D, deflection and torsion angle, fiber orientation.

Table of Contents

List of figures

List of Tables

Glossary

CFD – Computer Fluid Dynamics

FEA –Finite Element Analysis

FSI – Fluid-Structure Interaction

LSB – Laminar Separation Bubble

US – Upper Surface

LS – Lower Surface

AoA – Angle of attack

FRP – Fibre-reinforced Plastic

FEM – Finite element methods

UD – Unidirectional

CW – Carbon Woven

FVF – Fiber Volume Fraction

CAD – Computer Aided Design

ENTZ – America´s cup New Zealand Team

LASEF – Laboratory of Simulation in Energy and Fluids

IST- Instituto Superior Tecnico

List of Symbols

α - Angle of Attack [º]

θ – Fiber orientation angle [º]

C_l or C_L - Lift Coefficient

C_L – Coefficient of lift

C_d or C_D - Drag Coefficient

C_m or C_M - Moment Coefficient

L - Lift Force $[N]$

D- Drag Force $[N]$

M - Moment $[Nm]$

p - Pressure $[Pa]$

ρ - Specific Density $[\frac{kg}{m^3}]$

c - Chord [mm]

R_e - Reynold´s number

ε – Strain (proportional deformation) [mm]

σ- Stress $[Pa]$

A-Area $[m^2]$

$\#_m$- Force, strain and stress of matrix

$\#_f$- Force, strain and stress of the fiber material (reinforcement)

$\#_{cl}$ - Force, strain and stress of the composite material

1. Introduction

Windsurfing is a very young sport that emerged around the mid-20th century. The first milestone achieved on this sport was when S.Newman Darby invented the universal joint, which allowed the sail to be attached to the board for flexible movement[1]. During the past decades there have been highs and lows for the windsurf sport but from the beginning of the 21st century, windsurf has newfound a resurgence with the development of new equipment, wider boards, improved sails, new fins and other rigging equipment.

This project focus on the smallest but the essential piece of equipment that composes the windsurf rigging equipment - The fin. This project is the continuation of an ongoing investigation[2] started in 2016 in collaboration with a fin manufacturing company, F-Hot fins which were looking to develop a programme to perform structural analysis of their fibre reinforced plastic windsurf fins. The Finite element method (FEM) to analyse the ultimate strength of the fin and other structural parameters was previously developed[2]. For calibration and validation purposes, a single point load was used as the load acting on the fin in both the Finite Element Analysis (FEA) and the experimental tests. To improve this existing tool and to approximate the load to real hydrodynamic loads, the concentrated load was substituted by a hydrodynamic load, distributed over the entire surface of the fin. In addition to this, a new feature was created, which enables to change input variables such as the fibre orientations and fibre materials and analyse their impact on the structural integrity of the fin.

The thesis starts with a background review on the windsurf research papers that mainly focus on hydrodynamic investigations. Following this, a dedicated chapter covering the three research projects performed on the 37 RS windsurf slalom fin is presented. The first consists of the hydrodynamic study, which was then used for developing the program to transform the pressure distributions[3]. This tool, which is mentioned as MATAN tool throughout the project, consists of a MATLAB code that transforms 2D pressure distributions into 3D which are then imported into ANSYS. The second consists in the experimental study carried out at the Emmerson cavitation Tunnel which was used for comparison purposes with the FEA tool[4] and the third is the structural analysis which consists in the FEA model in which the parametric tool is based on[2].

The theoretical background covers the technical aspects of the hydrodynamics, windsurf mechanics and composite materials. With the information gathered in this chapter, it was possible to understand if the results of the design tool were inside a realistic range and also to understand what variables could be changed to achieve different fin deflections and tip twisting angles of the fin.

The results of the project can be divided into three parts. The first one consists in the presentation of the new developed parametric tool and its working principle and the generation of the MATAN program. The second consists in a parametric study performed to select a range of velocities and angle of attack (AoA) for further investigation using the parametric design tool and the third consists in the application of the parametric design tool to examine how the fibre orientation and material change would affect the structural behaviour of the fin (max. deflection and tip twisting angle).

The tools developed throughout this research project are easy to use and can be applied to different fin geometries by simply changing the 3D model and some additional parameters. The downside of the tools are the long running times and the difficulties with data transportation from one tool to another. These transformations may lead to incorrect results if not done correctly. For this reason, the last chapter suggests some future work that can be done in this field of study to simplify the overall process which consists in integrating the hydrodynamic and structural analyses into a single software using Fluid-Structure Interaction method (FSI) which allows for a better, faster and more accurate solution.

1.1. Problem Definition

F-Hot fins and other fins manufacturing companies use expensive composite materials and sophisticated manufacturing processes to manufacture their prototypes for testing and evaluating their durability and reliability. A wide range of fins with multiple flex options are manufactured every year for testing purposes to suit the conditions of all riders.

While FEA may never eliminate the need for real-world testing, advances in FEA and other types of simulations have dramatically reduced the number of physical prototypes required for product development resulting in lower costs and quicker solutions. The FE model developed before[2] is a good starting point for the structural analysis of the windsurf fin. The goal of that research was to develop calibrate and validate the fin FE model, and for that reason, the tests were performed with a single load point representing a concentrated load. Using this set-up, the FEA could be replicated in the physical, mechanical tests performed on a servo-hydraulic machine. This approximation which was necessary for the validation of the FE model may lead to very different results from reality as the flow on the vicinity of the fin presents a complex behaviour which can hardly be described by a single point load.

In parallel with this investigation, another study on the hydrodynamics of the fin was also being carried out[3]. One of the deliverables of this work was the 3D pressure distributions at different sea conditions, which could then be imported on the FE model for structural analysis[3]. Due to the lack of computer capabilities and time constraints, it was only possible to gather 2D pressure distributions, and for that reason, an intermediate program for extrapolation purposes also had to be developed.

This project consists of addressing the two problems identified before and in combining the structural analysis with the hydrodynamic loading into a single tool to investigate different lay-up schedules of the fin. Manufacturers may use this tool to investigate the effects of changing the lay-up schedules of their fins quickly and evaluate their structural behaviour.

1.2. Aim

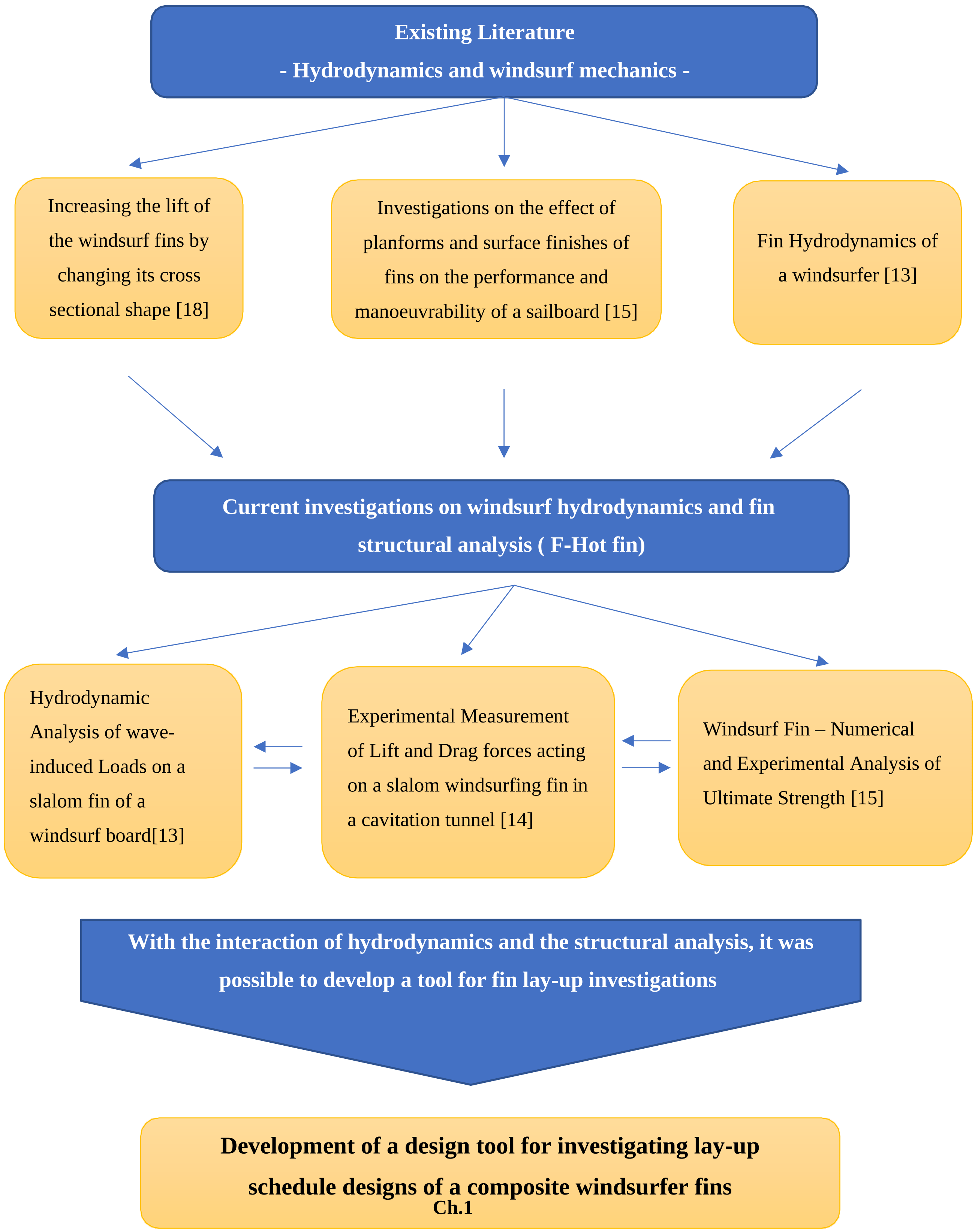
This research project aims to develop a design tool for investigating lay-up schedule designs of a composite slalom windsurfer fin and to propose a revised composite windsurfer fin design for future fabrication via a parametric study using structural FEA model and simplified hydrodynamic loading.

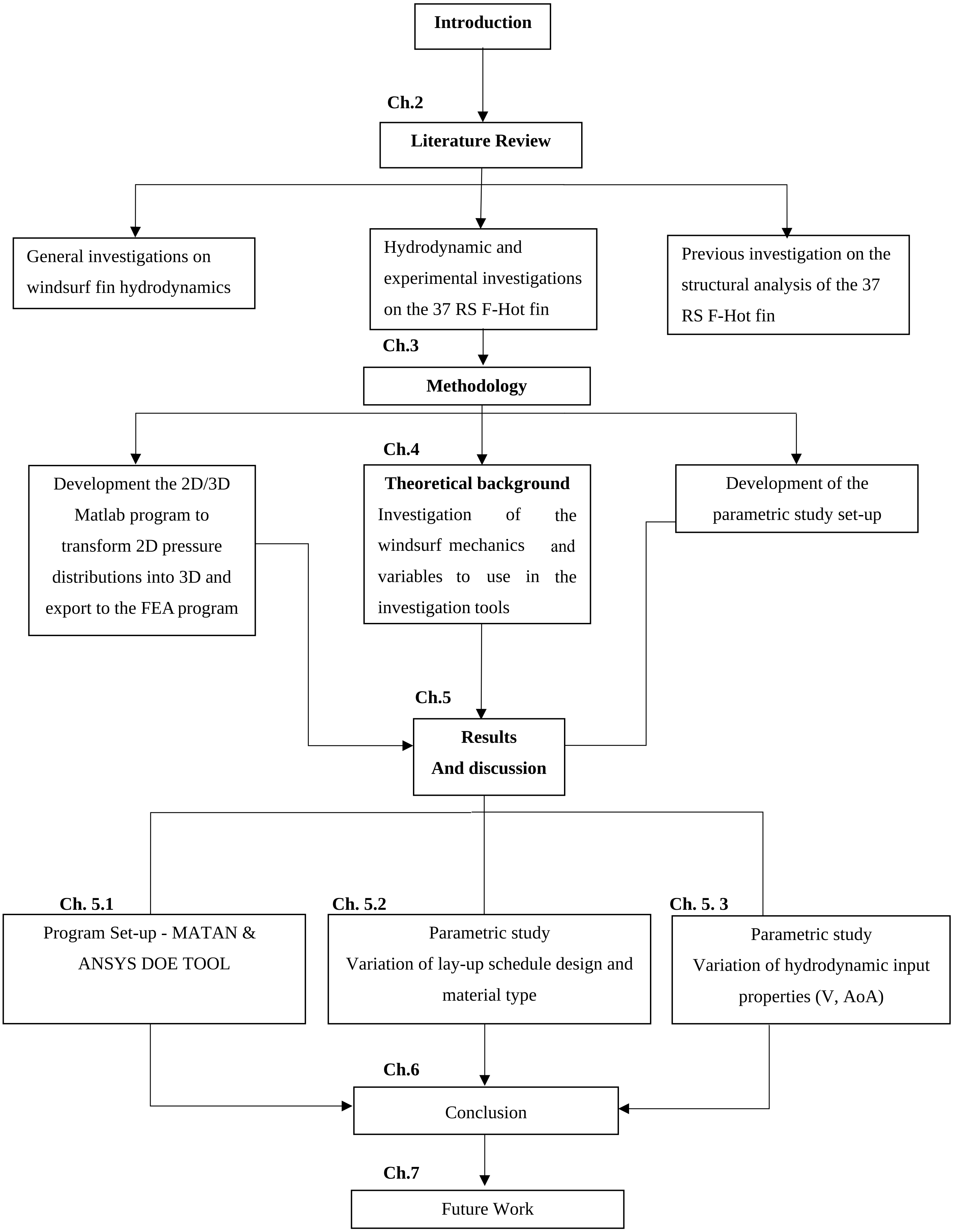
1.3. Objectives

- To develop a program to transform a 2D section cut CP distribution into approximated 3D pressure distributions over the entire Lower and Upper surface of the fin (LS and US).
- To link the pressure output of the Matlab program and the input of the ANSYS – Structural analysis software.
- To create a parametric design study to define the essential parameters for evaluation in order to define the range of the parameter and specify the constraints.
- To perform a parametric study and determine which of the many parameters have an impact on the performance measure(response) of interest.

1.4. Dissertation Structure

The following flowchart helps the reader to envisage the correlation between investigations.





Introduction
Ch.2
Literature Review
General investigations on windsurf fin hydrodynamics
Hydrodynamic and experimental investigations on the 37 RS F-Hot fin
Previous investigation on the structural analysis of the 37 RS F-Hot fin
Ch.3
Methodology
Development the 2D/3D Matlab program to transform 2D pressure distributions into 3D and export to the FEA program
Ch.4
Theoretical background
Investigation of the windsurf mechanics and variables to use in the investigation tools
Development of the parametric study set-up
Ch.5
Results
And discussion
Ch. 5.1
Program Set-up - MATAN & ANSYS DOE TOOL
Ch. 5.2
Parametric study
Variation of lay-up schedule design and material type
Ch. 5. 3
Parametric study
Variation of hydrodynamic input properties (V, AoA)
Ch.6
Conclusion
Ch.7
Future Work

2. Literature Review

This chapter starts by introducing some history of the windsurf sport and highlights the functions and influences of fins on the overall performance of windsurf boards. Windsurf fins are with no doubt the smaller pieces of equipment that compose a windsurf kit but are one of the most important ones as it wouldn´t be possible to counteractcounter act the side force generated by the sails nor give direction to the board without them.

The design tool to be developed in this project uses a simplified hydrodynamic load as input in the Design of experiment (DOE) programme. For a more in-depth understanding of the hydrodynamics on windsurfing fins, a series of previous investigations are presented. Although the majority of these investigations are not directly related to the tool that is being developed in this project, they present much information that will be used for comparison and validation purposes. These papers are fundamental for an initial understanding of the complex flow conditions experienced by a fin under a windsurf board and other important aspects that were considered during the development of the design tool.

The more recent investigations presented at the end of the chapter focus only on the 37 RS F-hot fin and were developed concurrently. For the development of this design tool, the initial FEA model adopted was taken from the Finite element analysis developed before [2] and the simplified hydrodynamic loading generator was based on previous CFD analysis[3]. This chapter includes all the investigations done so far in this field of study and sums up the different inputs used for the development of the design tool.

2.1. Composites in Maritime Industry

Fibre-reinforced polymer composites (FRP’S) have been successfully used in marine applications for several decades in areas such as sailboards, dinghies, super-yachts, workboats and leisure crafts. More recently, FRP’S have been used in less well-known applications such as bearings, propellers, commercial hatch covers and pipes [5].

The first marine application of FRP composite materials was in the construction of boats shortly after World War II (1947). Boat builders started using with FRP composites to replace old materials such as timber which was becoming increasingly scarce and expensive [6].

In parallel with the fast-growing use of FRP’S in the shipbuilding industry, significant advances have been made in the oil and gas industry in the last three decades in areas such as modules, protection, equipment and pressure vessels.

After the 1950s, surfboards also started to be manufactured using composite materials, mainly due to its lightweight, which was taking advantage of three principal materials; foam core, resin and fibreglass. Nowadays it is common to see sailing boats, surfboards and other nautical sports equipment embracing new composite technology and materials such as carbon fibre, carbon nanotube, epoxy mixtures and other composite materials.

Figure 1 – Left - Offshore platform oil pipes composite material, Right - Mega-Yacht made of fibreglass [7][8]

Figure 2 - Windsurf slalom fins made of carbon fibre [9]

Lightness, strength, durability, and ease of production make composite materials one of the most convenient choices in the maritime industry and especially in the production of windsurfing fins.

Since the beginning of the composite materials in the maritime industry that windsurf fins are made of FRP'S. Windsurfing is a quite relatively new sport, and only for a few years, the boards were made of wood[1]. Nowadays, windsurf boards, fins and the various rigging parts are under constant development since the sport is evolving at an impressive rate and new world records are being broken year by year. New boards are manufactured every year, and new fins and new rigging equipment must be developed accordingly to create better and lighter windsurf sets. The increase of performance which most of the times increases speed or manoeuvrability led windsurfing manufacturers to develop new forms of skegs and fins with different internal structures.

Although the fins are under the water and most of the times are not noticed, they are one of the essential parts of the windsurf set. Windsurf fins are crucial for resisting the side force generated by the wind and have an extremely importance on the windsurf board velocity, control and manoeuvrability. A 36 cm long fin just as the 37 RS f-Hot fin which is being investigated here must oppose the same lateral force produced by a 7 or 8 m sail. Different windsurf disciplines require different fin shapes which have different mechanical behaviours. These shapes are often long and narrow and require certain flexibility and stiffness for achieving better performance of the board. Nowadays, the modern planning board designs aim to reduce the wetted length to a minimum, thereby elevating the role of the fin in generating the required sideways force. The magnitude of the lifting force generated by the fin used on new planning hull windsurfer boards varies between 300 N and 600 [10]. The magnitudes of drag generated by the fin typically vary between 20 N and 50 N (the drag from the fin accounts for approximately one-sixth of the total drag, (with the drag due to windage and the drag of the hull accounting for the rest).

2.2. General researches on windsurf hydrodynamics

The nature of the flow around a windsurf fin is governed by the geometric shape, its orientation and speed in the flow, as well as other flow parameters such as depth of immersion, temperature, viscosity, density and localised pressure [11]. When the immersion is not maintained which often occurs often when sailing in rough waters, flow separation and spin out (severe loss of lift) due to ventilation will be experienced by the fin as air can pass into the low-pressure region of the fin thereby destroying the integrity of the fin. Other causes such as cavitation or loss of control due to the fin geometry not being suitable for the sea conditions make it extremely difficult to predict all the flow conditions that a fin is subjected to.

If a streamlined shape is considered, which is expected under normal sea conditions, the nature of the flow can be predicted through experimental techniques or reference to empirical data. The empirical data available comes mainly from the aeronautical industry since there has been an extensive investigation on the flow around a wing in the past decades [12]. Since the fin is effectively acting as a lifting surface, although positioned vertically and not horizontally, the classical lifting theory used to model the operation of an aircraft wing can be employed to investigate the fluid around the fin. Following recent advancements, a third approach that combines the pure experiment and the pure theory has been developed [13]. Computational Fluid dynamics complement the experimental and empirical approaches, but it will not soon replace either of these approaches. The future of fluid dynamics will rest upon a proper balance between experimental and empirical approaches while computational fluid dynamics will help to interpret and understand the results of the theory and experiment, and vice-versa [14].

Previous studies have almost exclusively focused on the analysis of the flow around the fins and, as far as we know, no previous research has conducted investigations on the design and performance of windsurfing fins under different environmental conditions.

Researchers from the University of Exeter and Southampton, UK [15] investigated the effect of platforms and surface finishes of fins on the performance and manoeuvrability of a sailboard using four different fins and three surface finishes. This work uncovers some of the fluid dynamics involved in the design of fins.

The same researchers together with a researcher from the Technical University of Eindhoven, Holland [16] investigated the effect of tip flexibility on the performance of a new windsurf fin which was at the time considered as one of the best fins ever designed, the so-called blade type fin. This fin was better than other fins, especially for high-speed windsurfing. Based on real-world tests, windsurfers suggested that a slight increase in tip flexibility results in higher performance than using rigid tips.

A more recent paper published in 2007 [17] presents an investigation concerned with modelling the movement of the windsurfer to determine over a finite number of sails of prescribed shape, the maximum velocity a windsurfer can reach. For this study, there were many variables such as wind speed, the weight of the surfer, the size and shape of the surfboard and the corresponding fin. Naturally, to reach maximum speed, the windsurf, the board must plan first, which in turn depends on the size of the board and its fin. It is evident that a bigger sail would turn into the higher velocities, but the windsurfer needs to be able to withstand the sail with his hands and bodyweight. In addition to this, the fin would also have to be able to withstand high hydrodynamic loadings, which turn to be the focus of this project.

Simon Pagg and Xavier Velay from the University of Bournemouth investigated a way of increasing the lift of the windsurf fins by changing its cross-sectional shape [18]. Since these lifting surface devices must operate on both tacks, a geometrically symmetrical cross-section is typically used which inhibits the maximum values of lift that could be generated if the fin was asymmetrical and with camber. An asymmetrical cross-section didn´t seem to be a big problem to unfold since they presented a relation between the camber ratio, the lifting coefficient and the angle of incidence. What they assumed is that, when the fin is under normal loading conditions the median line of the lifting section deviates from a straight line which makes an asymmetric fin and indicates that the lifting section is cambered. Together with that relation he also used the variation of lift with the angle of attack and camber to show that for a given range of angles of attack, a cambered lifting section would have a more significant coefficient of lift value than a comparable symmetrical section which would offer a solution to the design problem presented before. In addition to the increase of the coefficient of lift, a cambered lifting section decreases the drag coefficient, which is beneficial for the overall performance of the board. The drawbacks of lifting section devices and especially with windsurfing fins are that they are operated in very different environments and operate optimally at only one angle of attack. To overcome this, in aeronautics and sailing racing fields, engineers and researchers have implemented mechanically hinged leading and trailing edges. In the windsurf field, an American inventor came up with a design solution which consisted of a hinged deck mechanism on the board which would activate flaps on the fin creating the desired camber. This system required a specially designed board and has not been developed into a commercial product yet [10].

Although there are many studies in the field of the hydrodynamics of windsurfing fins, the research in structural analysis of the windsurf fin remains limited. The last research presented by Simon Pagg and Xavier Velay in terms of the methodology is quite similar to what is being researched in this project but considering different variables. The hydrodynamic study of this fin was performed in parallel with this project and consisted of extensive research on the hydrodynamics of this specific fin geometry and provided pressure distributions at different angles of attack and different velocities. With those pressure distributions, it was possible to develop in this project a simplified design tool to change the lay-up schedule and other material properties and analyse the fin response under different conditions.

2.3. Previous and Current Research on the 37 RS-3 F-Hot fin

The different papers that contributed to the investigation of the fluid flow around immersed lifting devices such as windsurf fins are presented before, but for this research project, a new approach had to be introduced. This project started simultaneously with two other projects; One which consists in the hydrodynamic analysis of wave-induced loads on a slalom fin of a windsurf board [3] and the other that investigated the hydrodynamics of the same slalom windsurf fin with more emphasis on experimental measurements of the deflection of the fin, analysis of the flow around the fin and assessment of the cavitation and spin out situations[4].

Both investigations are significant for the development of this structural analysis investigation tool. Before these investigations, an FEA model of the fin was developed and validated experimentally. The previous research on structural analysis of the fin can only be considered as the first step towards a more profound understanding of the fin structural behaviour because the hydrodynamic study was not conducted at the time, and the hydrodynamic study was approximated only with a point loading setup to replicate the mechanical structural testing was used – the hydrodynamic pressure was not used. Since chaotic changes in pressures and velocities characterise the conditions surrounding a fin especially under competitive environments due to sudden changes in direction, a new approach to approximate the pressures of this environment had to be introduced.

The development of the hydrodynamic models to predict the pressure distribution around the fin are extremely important for this project first because the pressure distributions obtained during those investigations will be used as input loads of the FEA model and second because it will approximate the structural behaviour of the fin under its real operating conditions.

2.3.1. CFD analysis of the 37 RS-3 F-Hot fins [3]

The investigation of the wave-induced loads on the windsurf fin was initially done in 2D as a starting point.

For this investigation, the authors used XFOIL, which is an interactive program used for the design and analysis of subsonic isolated aerofoils to predict the pressure distribution over the fin 2D cross section. This program allows the user to choose a NACA aerofoil shape, which has the most desired characteristics based upon the real shape of the lifting device being investigated [19]. The fin presents a symmetric shape with no camber and a relatively low thickness to chord ratio. Among the various symmetric NACA aerofoil shapes, the NACA0012 seemed to have the most similar characteristics of the 2D cross-section of the fin. The selection parameters for determining the appropriate NACA aerofoil shape are explained in detail in the hydrodynamic investigation conducted at IST [3].

This investigation covers 5 case studies where the various hydrodynamic analysis was conducted. The first case study consisted ofin conducting a 2D analysis of different NACA profiles and compare with the windsurf fin profile. The 3D geometry of the windsurf fin was section cut the in three regions to select the closest NACA foil based on the thickness to chord ratio. Both computations were run at Re 0.46 x10^6 and AoA of 0°. This initial case study showed that there was an increase in pressure just after the leading edge, which was not expected. This was caused by a concavity, present in the upper surface of the fin which was inducing a contrary pressure gradient.

To determine the cause and eliminate such pressure gradient adversity, the coordinates of the fin profile were manually adjusted, and more coordinates were added to aim for a smoother transition between the XFOIL panels. This case study allowed to understand the ranges of lift and pressure coefficients for these 2D aerofoil shapes and become familiar with XFOIL software and its limitations, such as the convergence issues [3].

The second case study was conducted to validate the XFOIL results obtained before. To perform such an experiment, a 2D profile of a wing, which was already tested in a wind tunnel, was analysed using XFOIL. The results comparing the drag and lift coefficients were satisfactory as both tests have shown to behave similarly up to AoA of 10 degrees. After 10 degrees of AoA, boundary layer separation occurs, and the XFOIL results start diverging from the experimental ones. The results obtained before for the 2D profile of the windsurf fin were also validated with this case study which allowed the CP distributions to be transformed into 3D pressure distributions using the MATAN program explained in page nº18. The analysis of the recirculation phenomena which cannot be adequately explored using XFOIL was done in another case study.

The third case study consists of the CFD analysis of the slalom windsurf fin. For this type of analysis, there are a series of software's available. To perform Fluid-Structure Interaction (FSI), it would have been important to use the same software for the CFD and FEA. However, it was not the case, and some difficulties were encountered along the way to combine both investigations. ANSYS and STARCCM+ are two multidisciplinary platforms for simulation and design of products. The different selection was mainly based on the software's availability at the different departments where the investigations were taking place. At one of the University departments, where the CFD investigation was taking place, STARCCM+ is the most used software, and there are many experts in this area which could provide support whereas, at the other institution, the platform used for the FE analysis is ANSYS. Despite the impossibility of importing the pressure distributions from the STARCCM+ CFD simulations to ANSYS structural analysis, it was possible to find a way of reshaping the problem and manage to approximate a 3D pressure distribution using the output of STARCCM+

In this case study, different aerodynamic models and mesh characteristics were tested to approximate the CFD simulation results of the E387 profile to the real ones obtained with experimental testing. After several iterations, the mesh characteristics and hydrodynamic models that better approximated the CFD results to the real results were selected and were applied in the following case study, which consisted of investigating the windsurf fin hydrodynamics.

In case study four, a Mesh convergence test for the windsurf fin section was performed. The number of cells was decreased until a satisfactory result was obtained inside the minimum error margin of 5%. The lower number of cells was chosen to shorten the computation time and increase the analysis range.

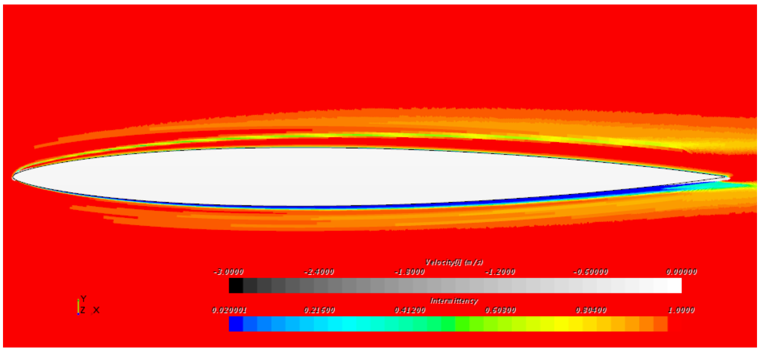


Figure 3 - Pressure distribution of the P113 airfoil - an approximation of the fin geometry at AoA 4°, γ – Reθ [3]

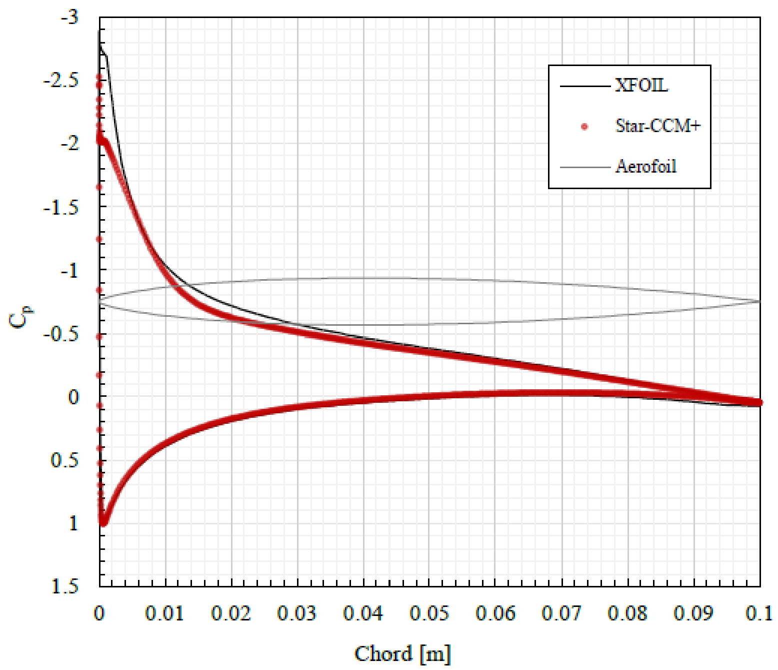


Figure 4 - Pressure Coefficient for the aerofoil P113, AoA 4°, γ – Reθ [3]

The previous case studies were fundamental to validate the results of the 2D windsurf fin section, but no natural features developed by the aerofoil geometry were shown yet. The fifth case study allowed to visualise and understand how the flow around the foil behaves and in addition to that, it was also used to export the 2D pressure distributions at three different velocities and various angles of attack (AoA) for the FE analysis.

The simulations were conducted for three different velocities, but only the case for Re 5 x10^5 is mentioned in their paper[3]. The remaining simulations and respective results were generated only to be used as input for the structural analysis. The following figures show that there are regions of laminar bubble separation, which governs the flow around the fin and the hydrodynamic coefficients. The flow separation increases as the angle of attack are raised until a point where the flow entirely separates from the suction side, creating a recirculation bubble covering the lower pressure surface.

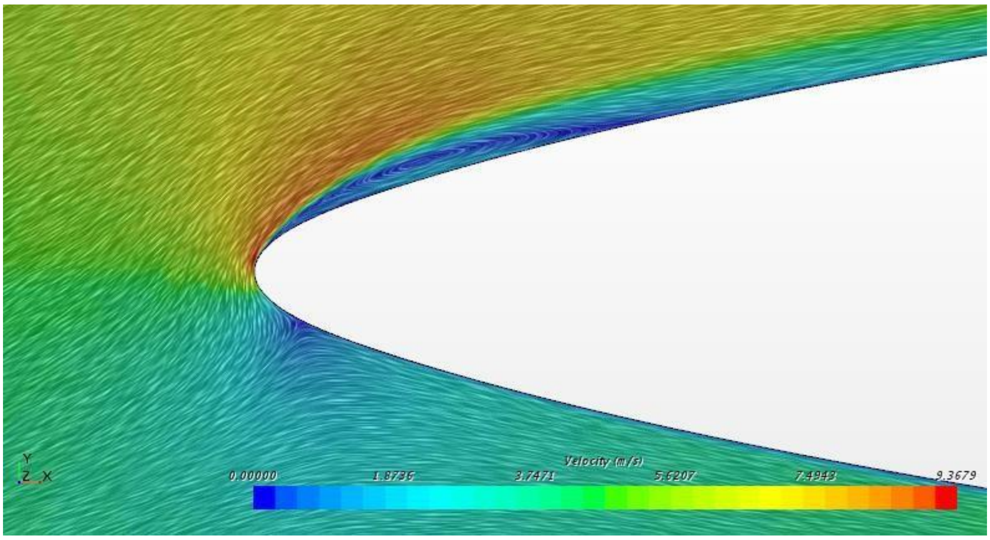


Figure 5 - Recirculation bubble at the leading edge plus stagnation point [3]

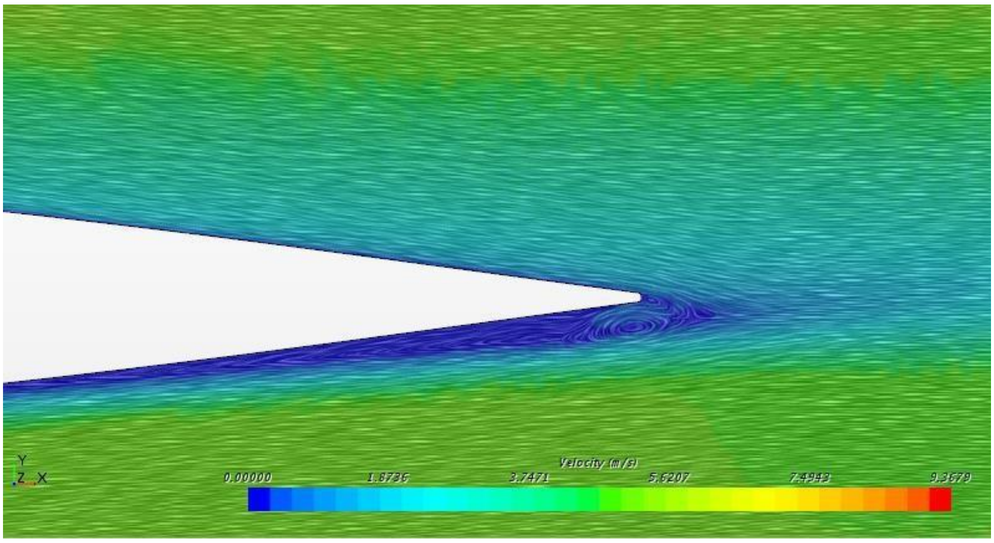


Figure 6 - Trailing edge recirculation bubble [3]

The MATAN program mentioned in the following subchapter was initially created to read the output from XFOIL (which consisted of a simple C_p distribution) and transform it into a 3D pressure distribution. The drawback of this initial approximation is that the 3D effects were not accountable and the transformations from C_p to pressure values was not very accurate. To overcome this problem and improve the quality of the pressure distributions, the 3D fin geometry was section cut in 36 equally spaced sections and different pressure distributions along the entire span of the fin were obtained. These distributions for different velocities and different AoA were imported into the program to be interpolated over the full surface of the 3D fin and then imported into ANSYS for the FEA study.

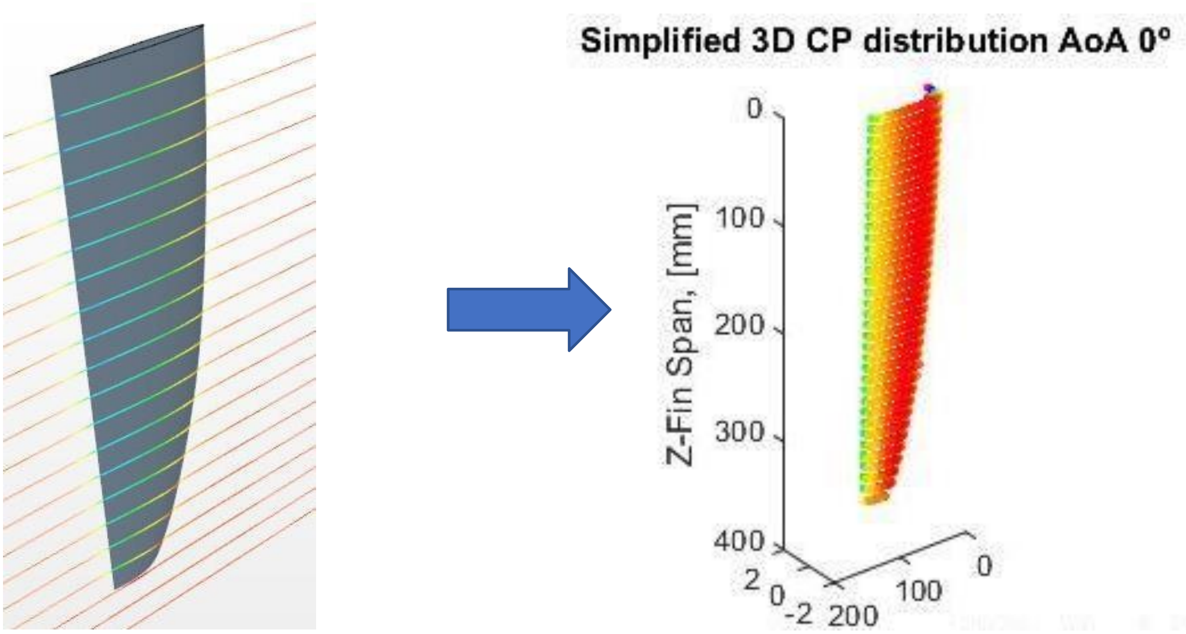


Figure 7 – Right - StarCCM,, Left - Matlab

2.3.2. Experimental analysis of the 37 RS-3 F-Hot fin

In collaboration with the current series of the project on the 37 RS F-Hot fin, an investigation on the measurements of lift and drag forces acting on the fin was conducted in the Emerson Cavitation Tunnel[4]. They used some of the design tool outputs to compare their results, but the dissimilarities in setup and measurement between the FEA and their experimental work did not allow for a valid comparison. Nevertheless, it is an interesting work which is fundamental for further validation of the design tool. It will be required to work on the setup and make sure the velocity ranges and environments are equal to allow for comparison and then proceed with the validation of the lay-up schedule design tool.

The initial attempt of their investigation consisted of generating a method which would evaluate the risk of snapping the fin. To do so, they used the maximum reaction force of 1000N obtained from the previous structural analysis of the fin. This preliminary force calculations allowed them to estimate an initial range of values of the lift and drag forces at different velocities and angles of attack. Following this and before initiating the experimental tests, they also used XFOIL together with XLFR5 program to generate lift and drag plots for a NACA aerofoil shape just as it was done in the hydrodynamic investigation explained before. The XLFR5 results showed a sudden increase in drag at an angle of attack of 8º, which results on the fin loss of lift, also called stall or spin-out. Although there are some differences in the NACA aerofoil shapes used in this project and the other presented before, both agree with the stall angle of 8º.

The experimental work conducted in Emerson Cavitation Tunnel consisted of evaluating the lift and drag forces of the fin provided by the F-hot company at different angles of attack and velocities. This experiment consisted of making a structure that was holding the fin at different positions inside the cavitation tunnel. This structure was connected to a load cell with three different sensitive load sensors which would transmit the forces and moments via coupling rods. The results of force obtained from the experiment were 75% lower than the results obtained from the simulations, which may be explained by a series of reasons. The main reason is that the 3D effects are not replicated exactly in the XLFR5 and the other reason may be due to the difference between the NACA aerofoil shape and the real fin 2D cross-sectional shape. The maximum lift force encountered was approximately 216 N, which is significantly lower than the results obtained using CFD. This maximum lift force occurred at an AoA of 8º followed by an increase of drag force. After an AoA of 15 degrees, wake separation takes place, and the analysis becomes very complex mainly due to convergence problems. The higher drag values occurred at higher velocities and higher angles of attack, but the contribution of drag to the total force was almost negligible.

Apart from this divergent result, there are also some limitations associated with the cavitation tunnel. The first limitation is that the flow velocity can only go up until 5 m/s which is equivalent to ~10 Knots and the second reason is that the width of the cavitation tunnel prevents the fin from being freely rotated due to small clearance to the tunnel side walls. The rotation is not so important since windsurf fins operate at small AoA, but the operational speed of a windsurfer is rarely lower than 10 knots.

These velocity and space limitations don´t allow to experimentally investigate the fin hydrodynamics and structure behaviour of the fin neither under normal operating condition nor under more competitive conditions such as the ones found in competitive environments. It would be particularly important to conduct such experiments to validate the FEA model.

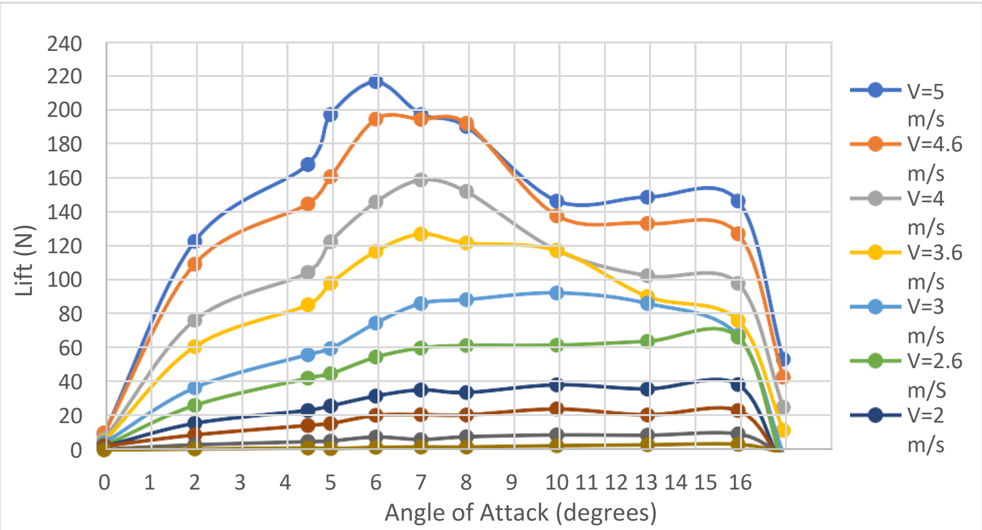


Figure 8 – Experimental data from the Emerson Cavitation Tunnel – Lift vs AoA [4]

In addition to the lift force analysis, this research also included an attempt to track the fin tip position with speed increase using photogrammetry. To conduct such an experiment, a camera was placed beneath the foil testing section to take pictures of the fin while it was deflected and twisted with the increase of flow velocity or increase of angle of attack. Unfortunately, it was not possible to capture all the images needed to recreate 3D deflected models of the fin using the power of photogrammetry, and for that reason, some adjustments were made just to give a rough estimation of the deflection. This experiment would have been of great interest since the hydrodynamic efficiency and control changes as the aerofoil deflects and twists. The results show that deflection increases with speed and angle of attack even after the stalling angle. This was not expected since the lift forces are much higher than the drag forces so it would be interesting to do an in-depth investigation using photogrammetry and the cavitation tunnel for better understanding the behaviour of the fin underwater especially to use for comparison purposes with the FEA model.

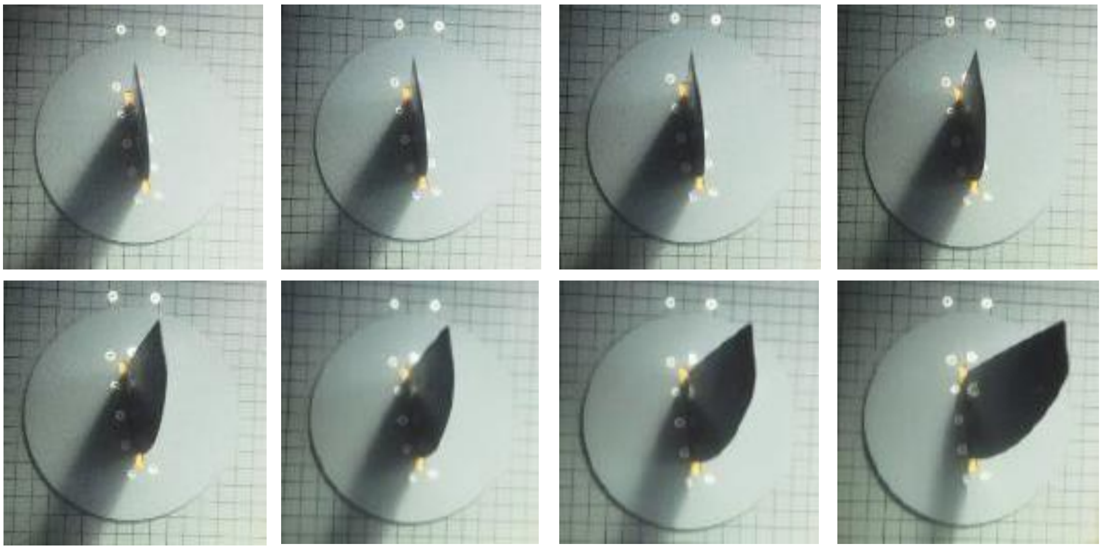


Figure 9 - Fin in cavitation tunnel at 15 degrees from 0-5m/s [4]

In general terms, both papers are great contributors to the overall investigation of the hydrodynamics of slalom windsurf fins. We are leaving in an era where science and technology are transforming sports and athletes at a rapid rate. Every year there are new sails, new windsurf disciplines and new records that athletes and companies try to break. For keeping up with the innovation of windsurfing equipment such as sails, boards and rigging equipment it is necessary to be able to re-create those experimental tests performed at the cavitation tunnel and the Mechanical tests performed at IST in a quicker and coupled way which is, in fact, the goal of this project.

2.4. Structural analysis of the 37 RS-3 F-Hot fins and FEA model

The development of this design tool is continuous work started in 2017. The initial investigation consisted of the experimental and numerical structural analysis of the windsurf fin [2].

That investigation aimed to develop an FE model employing commercial software ANSYS and analyse the structural response of the fin using linear and non-linear analysis. The hydrodynamic analysis was not available at the time, so a simple point loading was used to allow verification of the FEA model with practically achievable mechanical tests on an actual fin. The final part of the investigation consisted of the calibration and validation of the developed numerical model using experimental methods. The experimental tests were conducted using a mechanical servo-hydraulic test machine and a real scale fin provided by the F-Hot fin manufacturer. It is important to highlight that the FE model used in the present design tool was taken from this work and adapted to allow for importing the hydrodynamic loading from the CFD study and to allow lay-up schedule design changes.

Software's available for composite structural analysis has been in the market and the Universities for few years, and there is an opportunity now to use these software's and analyse the structural responses of complex geometries such as windsurf fins with complex internal structural arrangements in a much faster and quicker way. The motivation of the previous project was the interest of F-Hot fins manufacturer in obtaining a structural model to allow faster and easier analysis of the foil sections, planforms and lay-ups of these fins.

The FE investigation started by gathering the different fibre and resin mechanical properties and calculating their thicknesses. In addition to that, the fin manufacturer also provided a lay-up schedule of the fin describing the fabrics to be applied and their respective locations. The FE model was developed in ANSYS workbench using the add on module ANSYS Composites PrepPost (ACP) [20] which is dedicated to the modelling of layered composites structures. The FE model characteristics are mentioned in Chapter 4.6.1.

The Mechanical test was prepared simultaneously with the simulation tests, and the objective was to perform the same test experimentally to validate and calibrate the numerical model. The mechanical tests consisted of applying a point load at a quarter chord, which is the centre of pressure of the hydrodynamic loading. The loading was applied under displacement control at a speed rate of 0.1 mm/s up to approximately 40% of the estimated failure load as the fin would be used for other hydrodynamic analysis at a cavitation tunnel. The tests were performed at 40% and 80% of the fin span, which is where the centre of pressure of a semi-elliptic loading is [2].

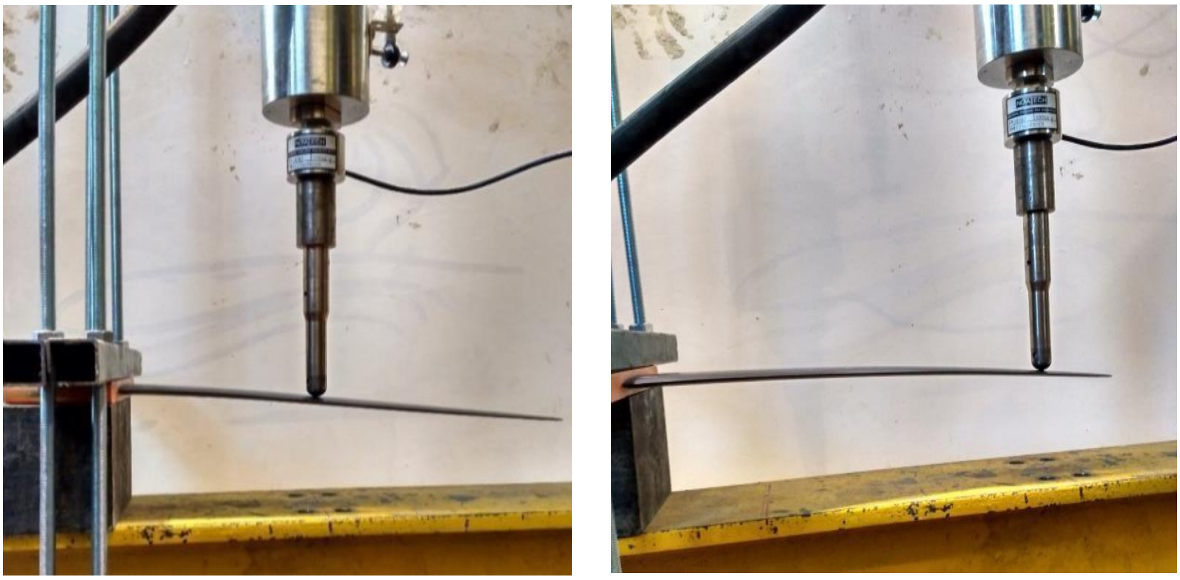


Figure 10 –Left - Mechanical Test at 40% and Right - Span length; Right - Mechanical Test at 80% Span length [21]

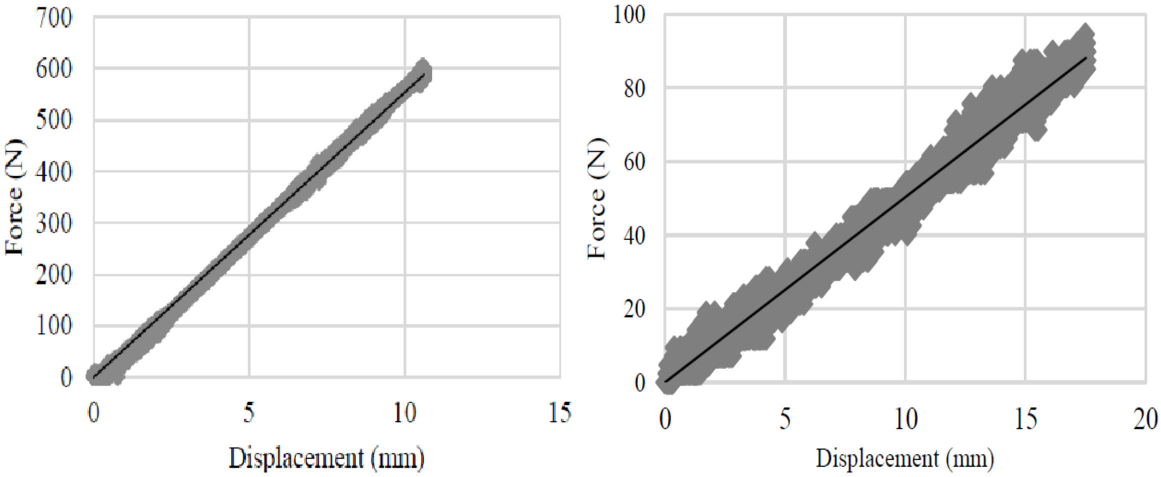


Figure 11 – Left - Force Displacement Plot at 40% Span length; Right - Force Displacement Plot at 80% Span length[21]

A similar experiment was performed in ANSYS, but with the application of a concentrated point load of 1000 N. The results are shown in Figure 12 – Left indicates an overestimation of the strength of the fin.

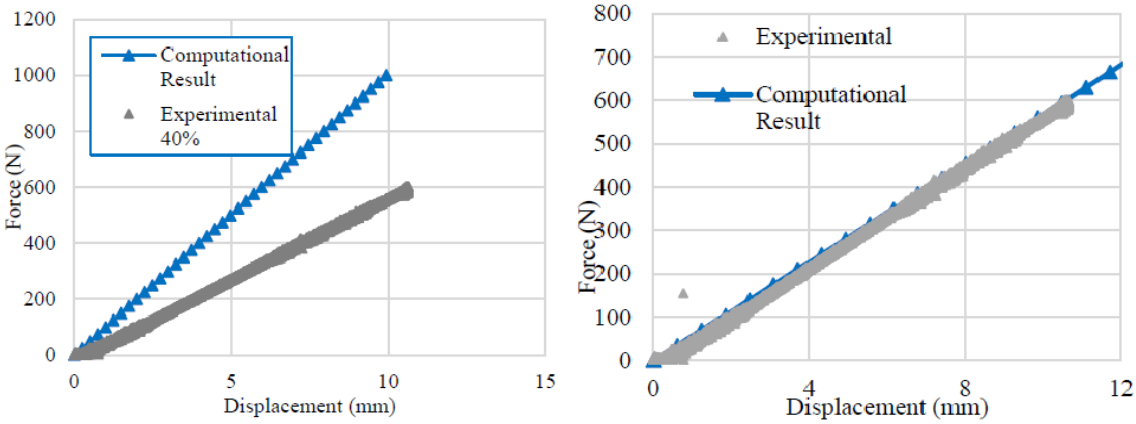


Figure 12 – Left- Computational vs experimental, Right - Force-Displacement plot (40% span)[21]

The calibration consisted of adjusting the young moduli of the fibers to approximate the numerical results to the experimental ones. The resulting force-displacement plot obtained is, as shown in Figure 12 - Right.

The numerical results obtained in ANSYS workbench facilitate the visualization of the structural behavior and the characteristics of the fin geometry.

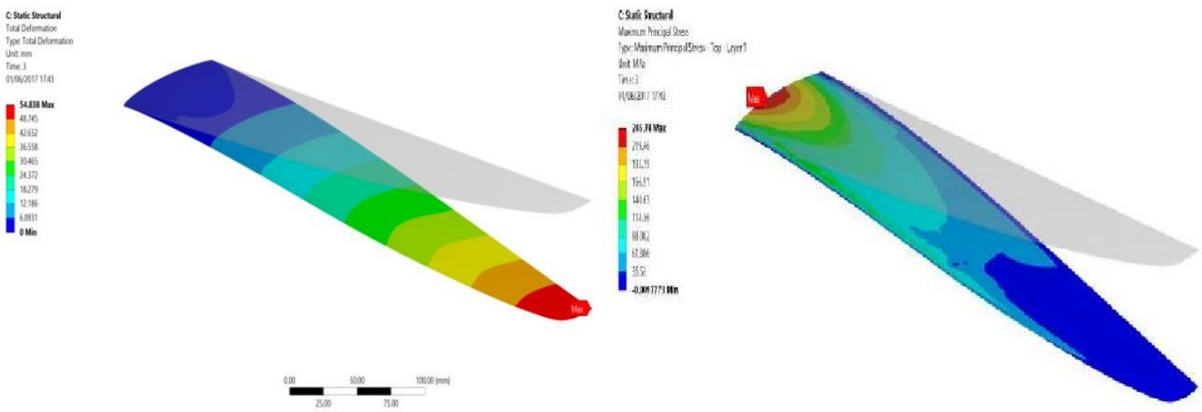


Figure 13 – Left - Displacement plot ; Right - Principal stresses plot [21]

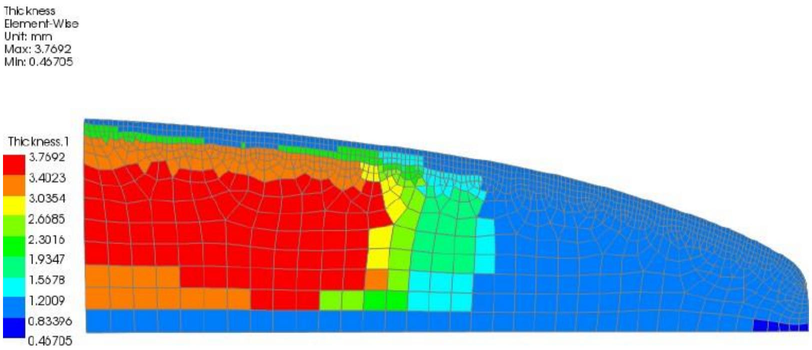


Figure 14 – ACP Model Thickness distribution [21]

The fin displacement when its subjected to a point load at a quarter chord and 40% of the span length is shown in Figure 13 – Left. The maximum deformation occurs at the tip of the fin as it's the furthest point from the fixed end, also called the root of the fin. The red area indicating higher values of stresses at the root of the fin is also expected as this is the area with a higher thickness, which results in a higher concentration of stresses.

The last part of that investigation consisted of conducting a failure analysis of the fin using the FE model. The paper presents a variety of failure modes that can be applied to composite materials but only focuses on going into detail and explaining one mode, which is the Tsai and Wu failure Criterion [22]. The failure analysis of conventional isotropic materials such as steel is much simpler than the failure analysis of anisotropic materials such as composite materials. The strength of composites can be divided into micro or macro mechanics failure analysis being the micro level the analysis of the plie's strength, whereas the macro level analyses the strength of the whole composite structure. It is known from the composite structure's theory that the failure of the plies occurs sequentially as the applied load increases. In other words, some of the s stack up plies can fail first and weaken the adjacent plies which may fail too until the remaining plies fail, denoting the ultimate failure. This progressive failure, which occurs very often in composite materials, is very complex. The Tsai-Wu failure criterion is a material failure theory widely used for anisotropic composite materials which have different strengths in tension and compression [22]. A detailed explanation of this theory can be accessed at [21].

After generating a colour plot of the Tsai-Wu Criteria, it can be noted that the ply failure occurs at the 1st Ply, which is under compression, showing a Tsai Wu factor of 1.0307 that indicates failure.

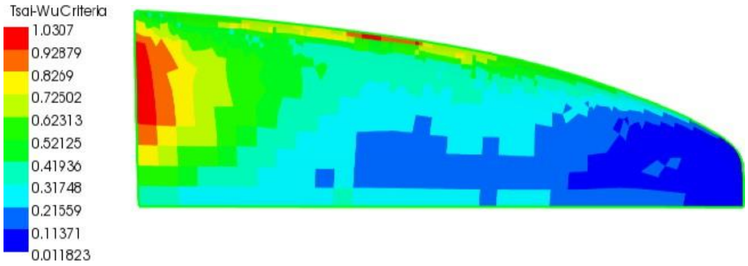


Figure 15 – Tsai Wu Failure Criterion [21]

Since this criterion does not indicate what kind of failure occurs, the maximum stress and maximum strain criterions were also implemented and analyzed. The first criterion states that the composite structure fails when the stress exceeds the allowable failure stress. This criterion does not consider interlaminar stresses. The results show that to occur failure, the maximum applied force must be higher than 2050N, where the failure factor is 1.018. As expected, the critical stress value is at the compressive part of the fin, near the fixed support. For the strain criterion, the maximum applied force is 825 N, which also occurs at the compressive side of the fin.

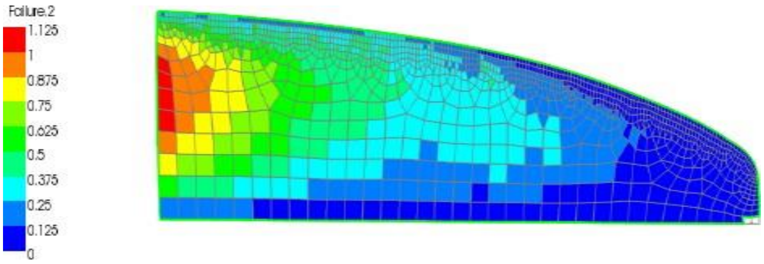


Figure 16 – Stress distribution over the fin surface[21]

2.5. 2D/3D MATAN program

The input of the FEA is the pressure distributions obtained from the CFD analysis. At the initial stage of this project, only the XFOIL results were available, which provided a unique insight into the behaviour of the NACA shape that had a very similar cross-sectional profile of the fin. Hence the results are those of an infinite wing which is defined as a single aerofoil.

For the FEA, it is required to input a 3D pressure distribution around the geometry of the fin. There are three main limitations with the CFD – XFOIL results; The first is that the input for the structural analysis software must be a surface pressure distribution represented as a table of loads (x, y,x,p) which can be imported and mapped into ANSYS WORKBENCH – Structural.

The second is that XFOIL generates a series of hydrodynamic results such as C_p, C_L distributions and other parameters only for a NACA aerofoil shape which means that the pressure values had to be scaled considering the real two-dimensional cross-section coordinates of the fin. The third is that, in two-dimensional analyses, the three-dimensional effects which influence lift and drag forces in finite wings such as the windsurf fin are not considered.

These problems arose because this is a multiphysics investigation which consists of the study of two interacting physical properties, the fin structure and the fluid flow around the fin. To avoid such problems, it is highly recommendable to use the same software package for the CFD analysis and the FEA. Since it was not possible to use the same package and perform coupled analysis of the fin, a MATLAB program was created to transform the 2D pressure distribution into a 3D simplified pressure distribution.

In general terms, the program imports the 2D pressure distributions at the non-dimensional x,z coordinates and the x,y,z coordinates of the real 3D geometry. The coordinates are then scaled, a mesh is created, and an interpolation based on the triangulation-based nearest neighbour method is computed. A diagram explaining the main steps of the program is mentioned below:

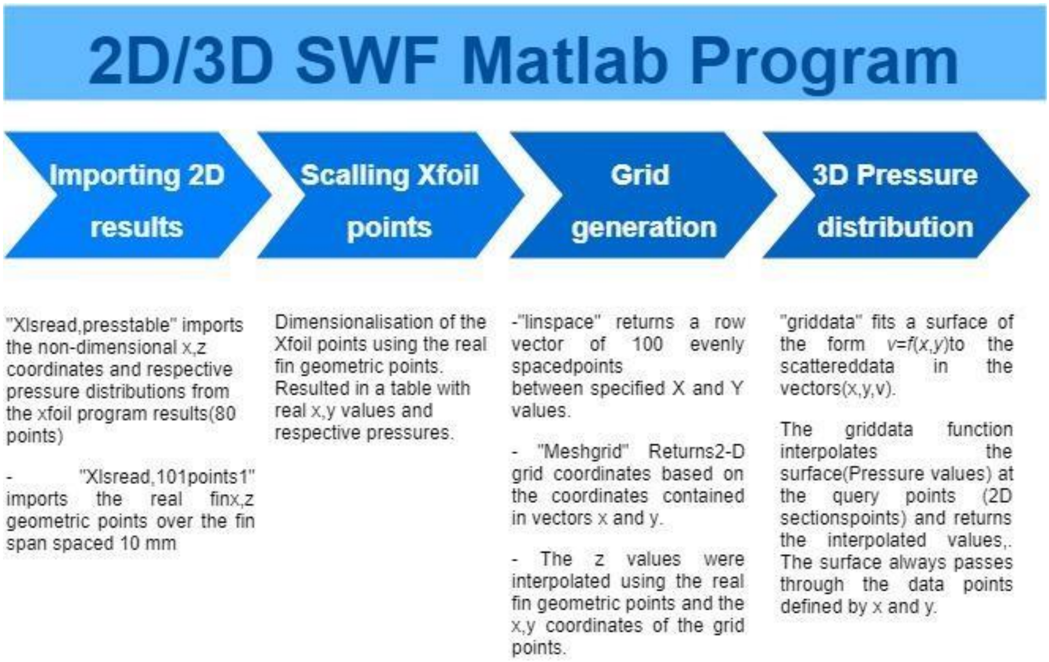


Figure 17 – 2D to 3D Pressure distribution diagram

This program can be adapted to different kind of inputs and different fin geometries. Although it's a simplified approximation, it can be used for many applications as an initial approximation of pressure distributions. Prof. José Manuel Pereira which is an expert in the aerodynamics field and computational fluid analysis and was also supervising the investigation of the wave-induced load of the fin confirmed the suitability of this program for an initial estimation of the pressure distribution. However, it was also suggested to use the same program and the same interpolation method to interpolate the pressures at non-dimensional x coordinates of a 2D cross-section of the NACA aerofoil shape that accounted for the 3 effects.

3. Methodology

To create a parametric design tool to improve the performance of existing fin designs more quickly and cheaply and to make new fin designs at a reduced cost, a series of questions had to be addressed. The first and probably most important to address was to investigate the research papers in this field and relate them this research. This is shown in chapter 2.2, and it can be concluded that, although there are very few similar investigations on windsurfing fins, they were fundamental for the initial steps of this project. The conditions of the flow around the fin and the pressure values, for example, were of great use to understand if the initial pressures distributions obtained from the CFD study were in an acceptable range. However, it can be noticed that the existent papers on this subject are more directed towards the hydrodynamics around the fin and not towards its structural behaviour.

The lack of information in this subject and the need to improve the initial study on the structural behaviour of the windsurf fin gave the motivation to define a clear path to accomplish the final goal of this project. Initially, it was thought that it would have been possible to obtain a surface pressure distribution from the CFD study, which was being conducted in parallel by another student, but the processing time only allowed them to export 2D pressure distributions. This setback emerged the need for developing the tool to transform the 2D pressure distribution into 3D, which was explained in detail in Chapter 2.5 and is mentioned throughout the project. Without this tool, it wouldn´t have been possible to import the pressure distributions on the FEA program and apply the desired simplified loading. With the development of this tool, the 2D C_P distribution exported from the CFD study was transformed into 3D pressure distributions, but there was no external data to use for comparison purposes and validation of results.

The second problem to address was that the velocity range of the CFD study was between 8-14 knots which is a small range considering that the velocities of the slalom windsurf fins are rarely lower than 20 knots and can go up to 40 Knots. For this reason, another study was performed to understand the effect of increasing the velocity on the pressure distributions.

The theoretical background allowed to find and calculate some unknown variables based on previous works and data gathered by experts in the windsurfing field. The twisting angle range, for example, was not known until this data was accessed and evaluated. In addition to this, the theoretical background also gave an insight into the different inputs of the 2D to 3D pressure distribution generator and the parametric design tool.

Following this, the FEA simulation program previously developed in another research [2] was modified and improved. The external table of the loads toolbox was added to the project schematic to allow the user to import pressure distributions, and the DOE tool, which allows the user to change the lay-up schedule settings quickly was also added. Most of the model, as well as the simulation settings, were kept original. Only minor changes on the fin layer thickness were performed to improve the accuracy of the model. Other geometry properties of the fin were adjusted, and an additional section rule was added to make sure the layers of the top side wouldn´t overlap the layer of the bottom side. This change can be observed in detail in sub-chapter 5.1.2.1.

After being familiar with the input variables and having a general idea on the output ranges, a simulation to replicate the experimental measurements conducted at the Emmerson cavitation channel was performed and the results compared with the FEA results.

Following this, a series of AoA and velocities were selected based on real-life data covered in the theoretical background – Chapter 4.2 and the deflection, maximum stress location and twisting angle were plotted against AoA and velocity to understand their relationship.

The final tasks consisted of varying materials and fibre orientations, understanding the trends between them and select a fin design for future fabrication. During these experiments, it was noted that the fins were twisting to the opposite side as it was supposed from some literature papers. This occurrence gave the motivation to model a simple composite plate with a fibre orientation of 45º and understand the relation between fibre orientation and twisting direction, which was not clear from the literature review.

4. Theoretical Background

This chapter presents some of the background required for using the parametric design tool. The composite material part which describes the constituents of the fin, the fibre/resin types and their properties and the stacking up sequence. All the above characteristics and variables may be changed in the parametric design tool, but for this specific research, only some of them will be selected for further analysis. The second part is related to the windsurf mechanics. The variables that change the simplified hydrodynamic loading imported into the parametric design tool may be known before selecting the most appropriate windows of values and decrease the number of simulations. The flexing behaviours of this specific type of fin must also be known to further verify in the results if the fin is flexing in the expected direction and if the twisting angle is in a reasonably realistic range. Although this doesn´t validate the parametric design tool, it is a good indicator to verify if the program is correct.

The end of the chapter presents the FEA package used and introduces the DOE tool, which is responsible for changing the lay-up schedule for every simulation. A deeper explanation of this is in the methodology chapter.

4.1. Composite Materials

Windsurf fins are manufactured in composite materials, which are the combination of two materials with very different properties. With the appropriate combination of matrix and reinforcement material, new composite material can be made to exactly meet the requirements of a particular application. The initial primary concern when making a windsurf fin it’s his specific strength. Fins must be strong to withstand the hydrodynamic forces and light to make the overall windsurf set-up light, which results in increased performance. The second concern depends on the type of fin. There is a wide range of windsurfing fin types for the various disciplines, and there are also fins made for recreational sailing. The same fin geometry for a specific discipline must also be made of different sizes and with different stiffness variations. The advantages of composite materials in windsurf fin manufacturing is visible. They are strong, light, stiff and most important, they can be manufactured in different shapes easily. It is important to understand some basic composite material concepts before performing any parametric design optimisation.

A finished fibreglass product is made of two constituents: A Binder or matrix and a reinforcement. The first one is a liquid resin which hardness to a rigid but brittle solid and the second is the fibre reinforcement that is placed in the liquid before it hardens. This reinforcement cured resin its high strength.

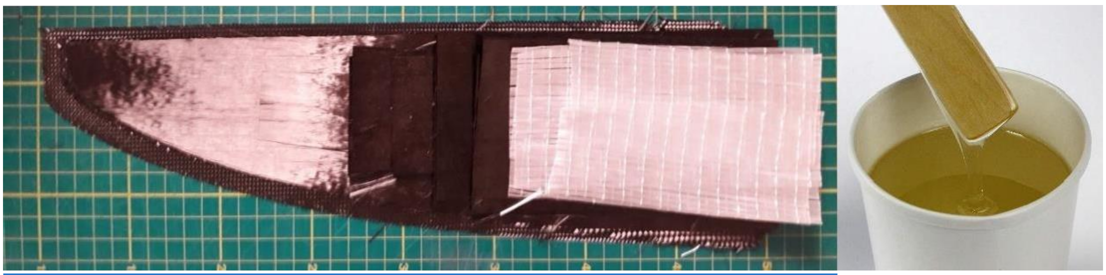


Figure 18 – Left - Reinforcement - Fibre Reinforced Plastics (FRP) and Right - Matrix – Epoxy (Liquid state) Epoxy Resin

Figure 19 - F-Hot Slalom Fin after curing process [9]

Although there are a wide variety of composite materials with different kinds of binders and reinforcements, the most often used in the marine sector are Fibre Reinforced Plastics (FRP´s). FRP is a composite that consists of high-performance fibres embedded in a polymer matrix just as shown in Figure 19 - Left.
The key design parameters to consider during the manufacturing of a fibreglass product are:

1) Fibre material/ Properties
2) Resin properties
3) Fibre orientation and stacking-up sequence
4) Fibre volume Ratio

4.1.1. Fibre materials and Properties

There are several fibre reinforcement materials characterised by very different properties. The fibres are often selected because of their mechanical properties. For example, in the fin manufacturing industry carbon fibre gives the best combination of strength and rigidity whereas E-glass, the most commonly used fibreglass type, is better suited for extreme flex patterns since it has a lower elastic modulus.

Figure 20 – Left - F-Hot Fiberglass/Carbon fibre Fin and Right - Fiberglass Fin [9]

Figure 20 - Left shows an example of a fin which is manufactured using the two types of reinforcements. This combination of reinforcements allows manufacturing fins with the desired flexing characteristics for a certain sailing set-up. Some fin manufacturing companies manufacture the same fin model with different flexing and

twisting patterns based on windsurfer weight, sail size, board type and other variables. Another decisive factor which has a significant impact on the carbon/glass fins over the G10 is the price. Carbon fibre offers great performance and lightweight benefits, but it is far more expensive than fibreglass or G10 (a high-pressure fibreglass laminate also used in the windsurf fin manufacturing).

4.1.2. Resin Properties

The matrix material binds the reinforcement, gives the composite component its shape and determines the quality of the surface[23]. Composite materials matrices can be divided into three main groups: Metal matrix composites(MMC), Ceramic matrix composites(CMC) and Polymer matrix composite(PMC). The first two types are typically used in high-temperature environments like engines and the third type, is the most commonly used matrix material in the marine industry. Thermosets is one type of PMC and, as the name implies, is a class of polymer-based resin that becomes irreversibly hardened by thermal and/or chemical (catalyst or promoter).

The most widely used thermoset in commercial,mass-production applications is the polyester resin. Unsaturated polyester resins(UPR) represent 75% of the total resins used in the composite industry[24]. This type of resin is particularly used in the marine industry. Polyester resin is by far the resin most commonly found in the fabrication of dinghies, yachts and workboats built in composites. Polyester is a versatile resin that can be modified during its application. The balance of mechanical, chemical and electrical properties make polyester resins a place in all segments of the composites industry.

The second most commonly used resin in the marine industry is an epoxy resin. Epoxy is used in the race boat industry, America´s Cup and the Volvo Ocean Race. Luxury sailing brands such as Wally and Baltic yachts use Epoxy in some of their boats. During the past 10 years, also a few production boatbuilders started using epoxy as their first resin selection. Hanse yacht e-line implemented epoxy resin in the production of three new yachts back in 2006. The use of epoxy resin resulted in a 10 to 12 – per cent weight reduction over traditional laminating techniques. The advantages of epoxy are the better adhesive properties (the ability to bond to the reinforcement or core), longer working time, better mechanical properties (particularly strength and stiffness) and reduced degradation to water ingress. Windsurf manufacturing industries such as F-Hot fins use epoxy resin to manufacture their windsurf fins. Although cost differential makes Epoxy more than twice as expensive, the cost of production is only 35% higher, and the advantages are far better than polyester - extra feel, longevity, performance, responsiveness. Another reason for the epoxy selection over polyester in the windsurfing industry is that each fin takes a relatively low quantity of resin which at the end doesn´t increase the price that much when compared to bigger constructions such as dinghies or sailing yachts.

The last and less known resin used in the marine industry is vinylester resin. Vinylester resin is stronger than polyester and cheaper than epoxy resin. This resin is a mid-way resin between polyester and epoxy in both quality and costs. Vinylester resin offers better resistance to moisture absorption but usually needs to be thinned out using liquid styrene, which makes the air hardly respirable and it's susceptible to atmospheric moisture and temperature. The major drawback is that vinylester bonds very well to fibreglass but offers a poor bond to Kevlar or carbon fibres.

4.1.3. Materials and Manufacturing

There are a variety of ways of manufacturing windsurf board fins depending on their material. One of the most common processes for fins made of fibre reinforced plastics is the Resin Transfer Moulding (RTM) process. The process used by F-hot fin industry is not exactly an RTM process because the resin is not injected into a mould but applied manually. The manufacturing process of the F-hot fins starts with the mould preparation and the application of a thin layer of gel coat to provide a good surface finish. Following this, they hand-lay up 19 layers of fabric on a female mould along with the resin which is previously mixed with other chemicals. The layers are then compacted against the mould to ensure air bubbles are removed and to impregnate all the layers. At a specific stage of the curing process, a small amount of epoxy-fibre cuttings paste is applied in both parts (top and bottom side of the fin) to fill any potential centre void and then they are bolted together to squeeze out any excess resin.

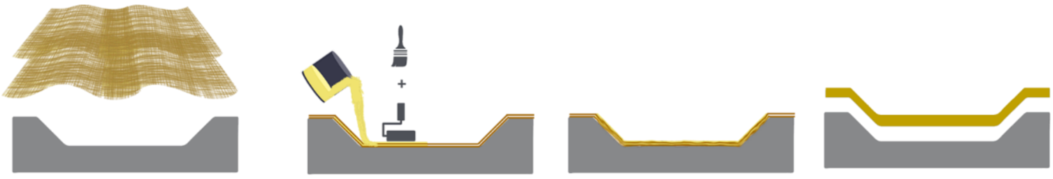


Figure 21 - Han lay-up of fabrics and resin [25]

This process is repeated for the other side of the fin, and then both faces are compressed together using tightened bolts through the flanges of both sides of the mould. Using heat, high pressure and a filler paste (of epoxy and cut fibres), the top and bottom moulds are pressed together, and the part is ejected as one single piece. The two sides of the fin are hence effectively cured as a single piece without any of the potential problems associated with bonding.

4.1.4. Fibre orientation and stacking up sequence

The third factor to take into consideration when selecting a reinforcement is the direction of the fibre strands. Fibre orientation is particularly important in the mechanical properties of composite materials. Fibres can be continuous or discontinuous depending on its application. Continuous fibres are normally aligned and have better overall composite properties than discontinuous fibres, which tend to be randomly or partially oriented.

Materials can be distinguished in two main classes when taking into consideration the dependence of the material on the mechanical properties. Metals and polymers are Isotropic materials, and if loaded along its 0º,45º or 90º direction, the modulus of elasticity is the same in each direction ($E_{0º} = E_{45º} = E_{90º}$). The same applies to other mechanical properties such as Poisson's ratio, ultimate strength and thermal expansion coefficient. Composite materials are anisotropic materials because their properties vary with the direction of the material (for example, fibre direction). For such cases, the moduli presented before for isotropic materials will be different in each direction ($E_{0º} \neq E_{45º} \neq E_{90º}$).

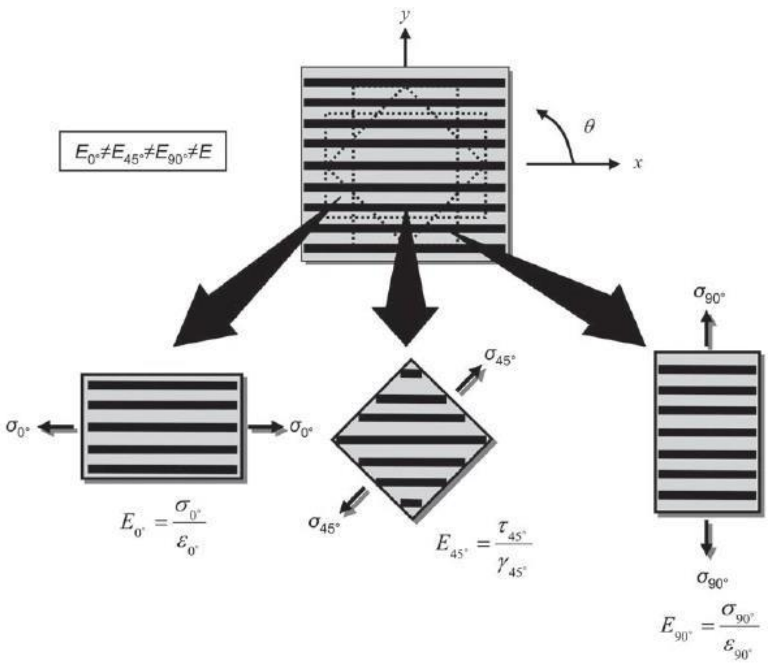


Figure 22 - Element of continuous fibreglass composite ply under stress [26]

In the anisotropic class of materials, there is a sub-class called orthotropic materials, which is the class that better characterises many laminated composites. Orthotropic materials have properties that differ in three mutually perpendicular directions. This dependence of the material orientation on the mechanical properties makes composite materials complex to analyse. However, this dependency may also be an advantage to achieve some properties that couldn´t be achieved with any other material – high material properties may be aligned with expected high loading conditions.

The coordinate system used to describe the fibre orientation in ANSYS is the principal material coordinate system, as shown below.

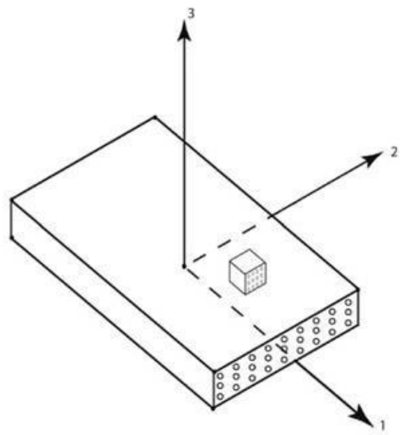


Figure 23 - Principal material coordinate system [21]

The 1-axis is parallel to the fibres (θ=0º).
The 2-axis is perpendicular to the fibres (θ=90º).
The 3-axis is defined to be normal.

The negative angles are counted counterclockwise between axis 1 and 2.

4.1.4.1. Bend-twist coupling

Bend-twist coupling is a property of some composite materials that when subjected to loading conditions that would normally result in pure bending, undergo both bending and twisting. This effect is already being used in wind turbine and tidal blades and is starting to be applied to foil structures[27].

In the slalom windsurf manufacturing industry the bend twist-coupling can be used to improve the performance of the slalom windsurf fin by tailoring the material properties of a laminate and generate the desired deformation response.

It was mentioned before that for every windsurf discipline, there is a specific fin type with a specific shape. Fins manufactured for wave riding must have very good flex properties to allow for good grip and looseness on the waves. To achieve such characteristics, they are manufactured with raked profiles which allow the tip to flex off when it's needed. On the other hand, slalom fins present a more straight, long and elliptical profile to achieve high velocities while maintaining the desired bearing. Controlling the bend-twist coupling effect of the fins could allow for manufacturing slalom fins with elliptical profile to bend more without changing its shape and could also allow decreasing the flex off properties of a raked wave fin, also maintaining its shape. This design tool that allows for performing quick changes on the lay-up schedule, which results in different bend-twist behavior of the fin for the same fin geometry may be very useful for creating new fin flexing patterns.

The bend-twist coupling occurs when the fibres at the opposite sides of the laminate shear centre are oriented in the same direction (just as the fin lay-up schedule). The twisting angle of a slalom windsurfs fin increases along its spanwise length, meaning that at the root there is a higher angle of incidence than at the tip. If a load is applied at the shear centre of the anisotropic plate at a certain distance from its centroid, the plate will not twist. This is because the elastic modulus is the same in all the directions, and the plate will bend. For generating twisting on such case, the load had to be applied off the shear centre or to a non-symmetric geometry.

A simplified case to understand this coupling effect is shown in Figure 24. The beam has its fibres oriented asymmetrically and has greater stiffness along the fibre direction than along the transverse direction. The top half of the beam, above the neutral axis, experiences tension coupled with shear to the left whereas the bottom part of the beam experiences compression coupled with shear to the right. When the beam is bending, it experiences those shear forces and rotates in the counterclockwise rotation.

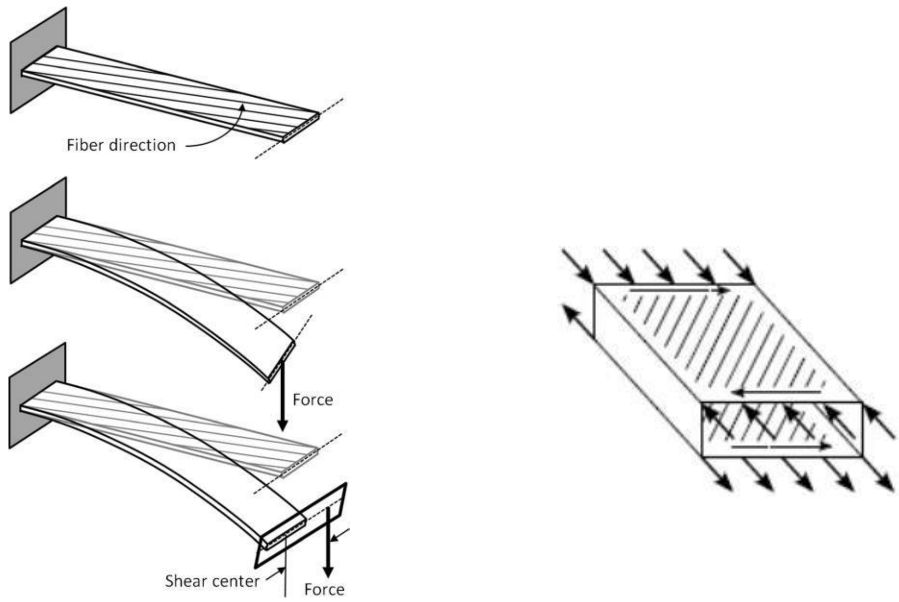


Figure 24 - Bend - Twist effect in composite beam with asymmetric fibre orientation [28]

The fin behaves just like a beam, and for that reason, it will bend and twist according to what is mentioned before. There are cutting-edge investigations on this effect on sailing foils where the fibre orientation of outer plies (usually the full ones) are oriented in different directions to improve the performance and structural integrity of the foil. In this research project, the focus is not only to verify if the fin is twisting and how the twisting varies with velocity and angle of attack but also to change the fibre orientation and understand how the twisting of the fin can be controlled. For instance, the same fin model may be manufactured in different ways for different sea conditions or different sailor's weight.

4.1.5. Fabric types

The selection of fibre strands orientation, which is based upon the desired mechanical properties/behaviour of the composite material often dictates the type of fabric. The most commonly used fabrics in the marine industry are as follows.

- Unidirectional (UD)
- Woven Fabrics (Cloth and Woven Roving WR)
- Chopped Strand Mat
- Multi-Axial Fabrics

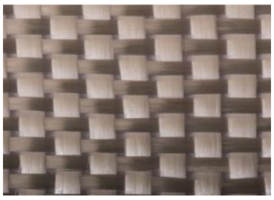
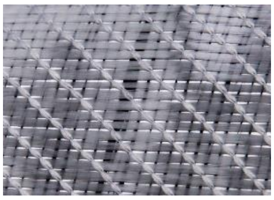
Fabric Type	Main Characteristics	Picture
Unidirectional Fabric (UD)	• Fibres run in one direction • Ability to place fibres exactly in-line with load paths • Straight and un-crimped fibres • No strength in the transverse direction	
Woven Fabrics	• Continuous fibres interlaced • Plain weave pattern • Most common reinforcement in the marine industry • Strength in longitudinal and transverse directions	
Chopped Strand Mat	• Randomly oriented Short glass fibre strands • Higher draping handling and wetting out characteristics • Equal properties in all the directions • Low in-plane mechanical properties • Heavy and inefficient laminate	
Multi-Axial Fabrics	• A cloth type fabric just like woven roving • Fibre lying flat versus the crimped WR • Greater strength and stiffness compared to WR • Higher glass to resin ratios compared to WR	

Table 1- Main characteristics of the fabrics used in the marine industry – Pictures retrieved from [29]

The following figure shows a stacking sequence, which is also named the lay-up schedule. The different laminas or plies are stacked in a particular way to provide the desired mechanical characteristics to the composite. The sign convention is important to further understand the effect of ply angle variation in the following chapters.

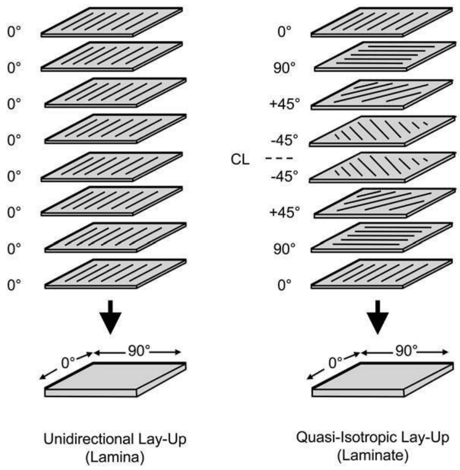


Figure 25 – Stacking of plies into a composite laminate with different angles of fibre orientation[30]

4.1.6. Fibre volume fraction – FVF

The fibre orientation and its concentration cannot be looked at separately as different fabrics will require more matrix content than others. According to A. M. Al-Mukhtar investigation [31], the strength and modulus of elasticity increase as the fibre volume fraction increases, as shown in Figure 25.

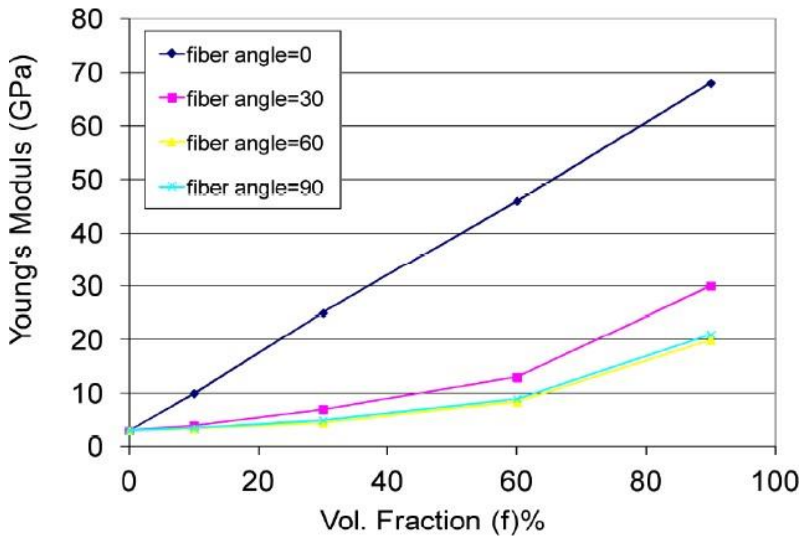


Figure 26 - The effect of fibre volume fraction and Angle on the strength of E-Glass composites [31]

reinforcement form	possible range of fibre volume fractions (%)	typical value for fibre volume fraction (%)
unidirectional	50 – 70	65
woven	35 – 55	45
random mat	10 – 30	20

Figure 27 - Typical fibre volume fractions [32]

The highest fibre to volume fraction is obtained with unidirectional reinforcement. When all the fibres have the same diameter, they can be arranged in a perfectly parallel sequence which results in the maximum fibre volume fraction, which is about 70%. After this, it becomes hard for the matrix to surround the fibres. Apart from the required FVF, it is important to have good bonding between the fibres and the matrix to ensure that the load is properly through the composite. Failure in doing so may enhance the fibres to separate from the matrix during loading.

FVF is not a design variable that goes into the design parameters of the program, but it affects the density and volume of the fin, which means it is important and must be carefully chosen. FVF can be important to lower the weight of a fin or to make it cheaper. Although it is not an independent variable, it can be changed for the optimisation of the fin more as well. The calculations of FVF for the 37 RS F-Hot fin were based on the technical specs of the fabrics and resins provided by F-Hot fins manufacturer.

4.2. Windsurfing Mechanics

The output of the CFD analysis comes as Cp distributions at different velocities and must be transformed into pressure distributions, which is how the parametric design tool reads the data. This sub-chapter focus particularly on presenting the basics of the aerofoil theory, which was used to perform this transformation of data. Since there were no papers evidencing maximum values of stresses and deflection of windsurfing fins under specific conditions, a windsurf company called Maui Ultra fins was contacted and made available a series of specific data gathered during a long period [33]. By manipulation of variables on the airfoil theory formulas, it was possible to relate the twisting angle with the velocity to achieve a possible range of twisting angles which was not known before. This information doesn´t validate the parametric design tool, but it helped to confirm that the results of the parametric design tool were in an acceptable range.

The final sub-chapter introduces the different fin types and their flexing behaviours. The advantage of applying a simplified hydrodynamic load over a point load is that the fin would be subjected to different forces which would make him bend and twist. The direction of bending and twisting are important as they give a first indication of the parametric design tool results, and for that reason, they must be known.

4.3. Aerofoil theory

From physics, it is known that the fin gives direction to the windsurf board, and it prevents the board to sail sideways. If the fin is cut halfway through its spanwise length and looked from the bottom, the outline shape of such geometry would look like an aerofoil shape. The same principle that explains how wings lift aeroplanes and ailerons push Formula 1 onto the track can be used to explain the side force generated by the fin that counters acts the sail force.

The fin is essentially a wing of an aeroplane that instead of creating lift in the upward direction creates it in the sideways direction. Figure 30, which represents the aero-hydrodynamic forces applied to the body (board, rig and sail) shows that the fin is slightly angled off to the flow. This angle is called side slip angle which is just as an angle of attack of a wing. The nose of the board rarely points at the course that the windsurfer is taking because there must be an angle of attack between the flow and the leading edge to generate lift and counteract the side force of the sail. The aerofoil theory is complicated but can be simplified to three conservation laws (mass, energy and momentum). When the flow approaches the upper surface of the leading edge of the aerofoil, the air is deflected downwards and is squeezed against the aerofoil continuing towards the trailing edge. As the velocity increases, the pressures decrease, which creates a pressure difference between the upper and the lower surface (mass and energy are conserved). Since the aerofoil is always at an angle of attack, it creates a downward momentum, which in turn pushes the aerofoil upwards.

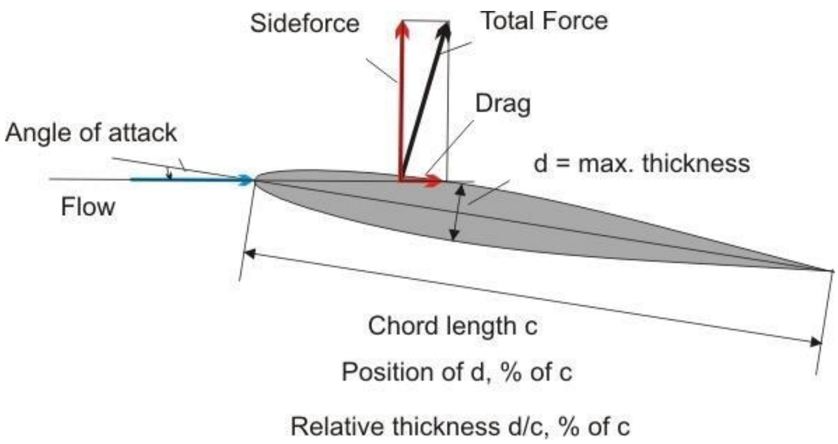


Figure 28 - Fin chord geometry [18]in characteristics [28]

$$T = Lsin(\alpha) - Dcos(\alpha) \quad (4.3.1)$$

$$N = Lcos(\alpha) - Dsin(\alpha) \quad (4.3.2)$$

The fin geometry is symmetric since it must generate lift in both tacks. The hydrodynamic analysis was performed on a section foil, just like in Figure 28 - Fin chord geometry [18]in characteristics [28]Figure 28 that matched with the fin section. The output from XFOIL gives C_P values at different percentages of the chord. This coefficient of pressure values was then transformed into pressure values and transformed into a 3D distribution.

The 2D Pressure distributions were gathered for velocities between 8 and 14 Kn and AoA from 2º to 16º. For higher velocities, the pressure distribution was extrapolated using a regression function. The velocities of interest are between 20 and 40 Kn, which are the velocities often achieved during slalom competitions, which represent the most realistic and extreme loading cases. The following equations were used to calculate the pressure from the coefficient of pressures exported from XFOIL and to understand the ranges of angles of attack that the fin is subjected to under different velocities.

$$C_P = \frac{P - P\infty}{\frac{1}{2}\rho V_\infty{}^2} \quad (4.3.4)$$

$$L_{FN} = q_H S_{FN} C_{LFN} \quad (4.3.5)$$

$$D_{FN} = q_H S_{FN} C_{DFN} \quad (4.3.6)$$

$$L_{FN} = F_K \quad (4.3.7)$$

$$F_K = q_H S_{FN} C_{L\beta}\beta \quad (4.3.8)$$

$$C_{DFN} = C_{DFN0} + \frac{C^2{}_{LFN}}{\pi Ae} \quad (4.3.9)$$

According to equation 4.3.4 and to the equilibrium conditions specified before it is possible to calculate the leeway angle.

For small angles $\cos\theta = 1$

$$\beta = \frac{F_K}{q_H S_{FN} C_{L\beta}} \quad (4.3.10)$$

The coefficient of the lift was not known, but for having an initial guess of the range of angles, some examples retrieved from the windsurf literature review were used. At 20 Knots and a maximum sail force of 500 N, the sideslip angle would be approximately 3 degrees whereas at 45 Knots for the same maximum sail force but with a smaller sail and fin the angle would be only 0.6º. These low theoretical values of angle of attack are expected, but higher values will be used in the simulations for simulating the worst-case scenario.

4.4. Windsurf experimental aero-and hydrodynamic forces

This chapter is dedicated to present some of the mathematical foundations of the mechanics, aerodynamics and hydrodynamics of windsurfing. It is important to understand what are the physical influencing factors that affect sailing performance. The physical limits in terms of maximum speeds, course angle and wind angles must be known to validate the input pressures gathered from the CFD study. By specifying a constant sailing force all influencing variables depending on the wind speed, the course and the sailing speed, as an independent variable can be determined. Particular attention is given to understanding how the maximum sailing speed, course angle and the sideslip angle (angle of attack of the fin) are related.

The main forces acting on a windsurf system can be grouped as following [13][33]:

1) The aerodynamic wind force acting on the sail at its centre of pressure
2) The gravitational sailors' weight acting downwards through its centre of gravity
3) The hydrodynamic force acting upward on the bottom of the board
4) The sideways hydrodynamic force acting on the fin
5) The thrust force created by the sail pressure difference
6) The hydrodynamic drag force created opposed to the forward component of the resultant force acting on the sail

The aerodynamic sail force acting on the sail causes a heeling moment which is balanced by the sailors' weight. To simplify the problem, the equilibrium principle can be applied to the body (a combination of board, rig and sailor). The sum of the moments acting on that body in two perpendicular planes is equal to zero; therefore in mathematical terms this can be expressed as:

$$\Sigma M = 0$$

$$Fa = G\ b$$

$$F = G\ \frac{b}{a}$$

$$F = 0.4\ G$$

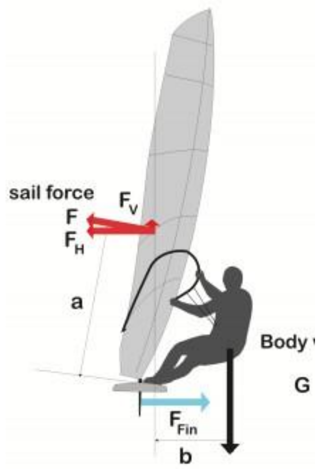


Figure 29 - Steady state condition windsurf system [33]

According to Rick Hanke from Maui Ultra Fins [33], the average sailors' distance from the board (b) is approximately 0.96 meters whereas the centre of pressure of the sail is in average about 2.4 meters. It is evident that these values vary according to the sailing area and shape and sailor physiognomy and skills.

This basic formula can be used for predicting the maximum forces that the fin must withstand in normal operating conditions. If a sailor plus rig weights 110 kg and its weight are leaning out 0.96 meters from the centre of the board, the moment created is approximately 1036 Nm. Considering that the sail is angled 15º from vertical to windward, the horizontal component of the heel becomes 417N. Because of the angled sailing angle caused by the sailor position, there is also a lift component created which corresponds to 111 N. Subtracting this lift force from the weight gives 321 N.

The lever arm between the centre of gravity and the centre of the board changes with the strength of the wind, sea conditions, the size of the sail and other factors but for an initial guess, those values can be considered.

The second equilibrium condition is that the thrust or also called drive force must be equal to the total drag force. When this happens, the body is said to be in a steady state, which means that it is sailing at a constant velocity. Figure 30 is a schematic with all the forces acting on the system. The lift and drag generation are explained in detail in the following chapters.

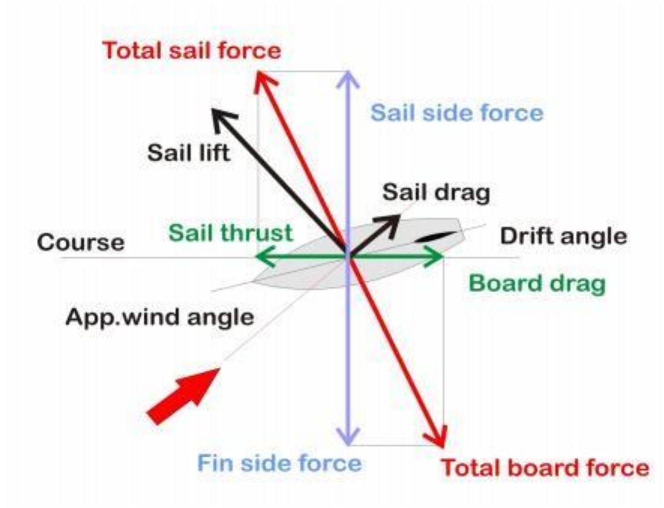


Figure 30 - Aero- and hydrodynamic forces and angle definitions on a windsurfing board, top view, all forces in the horizontal plane, all moments = 0 [25]

The other limitation apart from the weight is the apparent wind angle. Due to the low hydrodynamic drag generated by a windsurf board when it starts planning, sailors can reach very high speeds, sometimes higher than the wind speed. What happens in such situation is that, although they are sailing downwind at an exact wind angle of 130º or 140º the apparent wind is shifted to the nose of the board at an angle of 60º for example. The sail force component depends directly on the apparent wind angle. The thrust of the windsurfer increases with stronger winds and a larger apparent wind angle, but it decreases with sailing speed. The side force, which is the force acting upon the fin, increases up to the total force which must match with the sail force. Figure 31 illustrates the relation explained before.

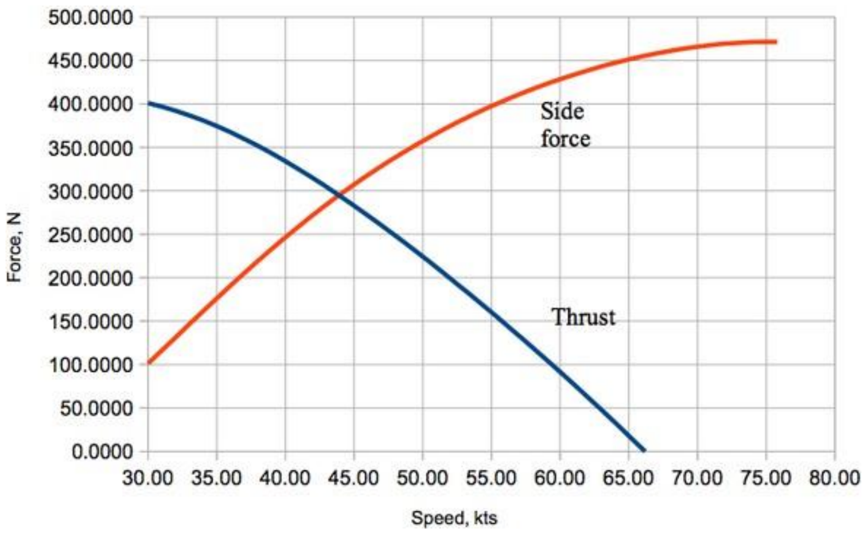


Figure 31 - Thrust and side force of windsurfer at given course with constant sail force [33]

Knowing that the sailors' weight limits the total sail force and the apparent wing angle which is a function of sailing speed, wind force and course the maximum speed an approximation to the ranges of speeds that may be achieved during a slalom windsurf race can be determined. These speeds are important as the worst-case scenarios in terms of sail force and will be used for the static structural analysis. The French windsurfer legend Antoine

Albeau broke his world speed record, achieving 53.27 knots while speed sailing in Luderitz, Namibia. This is a record, and the sailing conditions were created on purpose for this which doesn´t happen in a windsurf slalom race. According to the windsurf experts [33], the speed relative to the wind speed could be a factor of two at low speeds(less than 25 knots), but it is one at high speeds (about 50 kn) which means that in a normal slalom windsurf race, the speeds will be between the 25-40 Knots range approximately.

4.5. The windsurf Fin

There is a wide range of fins in the windsurf industry. For each discipline, there is one model which has a specific outline shape, and the same model is often manufactured for different sail sizes and sailors' weight. This project focuses on windsurf slalom fins which are similar to race model fins but slightly shorter, slimmer and stiffer. They can be tilted slightly backwards just like the F-hot fin RS-3 model shown in Figure 20- Left.

From the literature review on composite materials used in the marine industry, it was seen that there is an enormous range of variables that can be changed, which affect the strength and stiffness of the fin. The whole project is around this topic, which consists in creating a tool which correlates the changes in input variables with the output behaviour of the fin. Particular attention will be given to the influence of the fibre orientation on the bending-coupling effect of the fin. From the previous chapter, it is known that the maximum moment is 500 Nm at the box/root. If the F-hot RS -3 fins would be used in with the sail, rig and board set-up that generates that moment, the reaction force of fin at the root would be approximately 2800N.

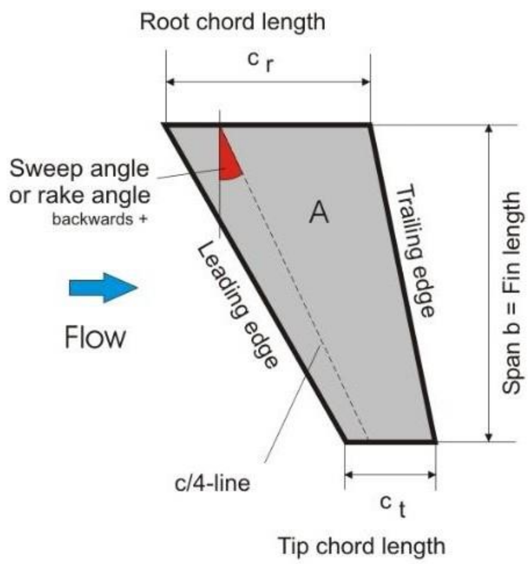


Figure 32 – Fin parameters [33]

The force concentration of the fin is at approximately a quarter chord and 40% of the fin length from the root. In the first research project on the windsurf fin, the FEA of the fin was conducted and accompanied by experimental validation. An initial force of 1000 N was applied to that location, and then for the failure analysis, it was increased 2.5 times. Although there was a difference between the FEA and the experimental results, they were satisfactory in terms of fin deflection, strength and stiffness. The location of the concentrated load changes with the shape and geometry of the fin, which means that it is not very accurate to assume that it will be at that specific location. In addition to this, when the fin is under hydrodynamic loads, it tends to bend (flex) and twist along its longitudinal axis.

With this initial experiment only, the deflection of the fin was visible, but the twisting which is also very important for sailing performance was left for further investigation since it couldn´t be generated with a single point load.

With the output from the hydrodynamic investigation of the fin [3] and the MATAN tool, created to generate the 3D pressure distributions over the fin surface, it became possible to approximate the hydrodynamic forces that act on the fin in real life with the hydrodynamic forces applied in the FEA model. By doing this, it was also possible to verify the twisting angles of the fin under different sailing speeds and angles of attack.

The fin flexing and twisting depend on the stiffness, which is determined by the elastic behaviour of the material. When a sailor starts sailing, the fin will counteract the force of the sail which causes the fin to flex. Bending results in loss of side force, which also results in loss of thrust/performance. Slalom fins are considerably long, which makes it difficult for fin manufacturers to decrease fin deflection keeping the optimum fin geometry from a hydrodynamic point of view. When the maximum sailing speed or performance is not the goal of the windsurfer, a more flexible fin would provide a smoother feeling of control. In terms of twisting the same applies. Slalom windsurf fins do not twist like freestyle or free ride fins because they have almost no rake. The trailing edge is almost perpendicular to the root chord.

Windsurf experts state that having no twist is better for upwind angles have the windsurfer can maintain better the angle of attack of the fin whereas having twist allows depowering the fin to some extent but makes the board less directional stable. At the end of the day, it depends on the application. In addition to these effects that directly affect sailing performance, twisting may also be used to momentarily avoid spin-out. When the fin twists, the tip of the fin is twisted into the flow, which reduces the angle of incidence from the root to the tip. Fin twisting reduces the fin tip vortices and therefore induced drag providing more control. This effect is also called wash-out in the aerodynamics field.

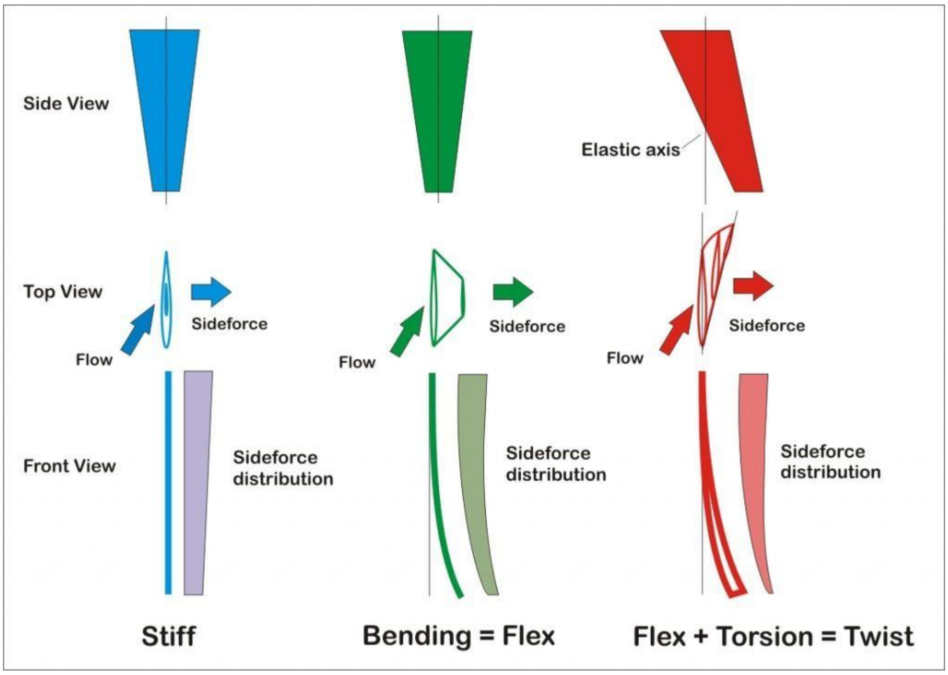


Figure 33 - Stiffness, Bending (Flex) and Torsion (Twist) [33]

4.6. The 37 RS-3 F-Hot windsurf Fin Model

The windsurf slalom fin investigated in this project is one of the various models of the Fin manufacturer F-Hot fins based in Southampton, Uk. The 3D model used for the FEA investigation was previously modelled for the numerical and experimental analysis of the windsurf fin [21]. This investigation is an ongoing investigation, and for that reason, the 3D and FEA model will solely be improved and adapted to apply the distributed load and to perform the parametric design study.

Figure 34 – Fin 37 RS 3 [21]

The fin is a slalom windsurf fin of the "standard" type which means it has a moderate stiffness. It has 370 mm of length and 110 mm at the root chord. The NACA profiles with the most similar profiles and thickness to chord ratio are the NACA0008 and NACA0012. All the required calculations were performed using ANSYS library and other external sources

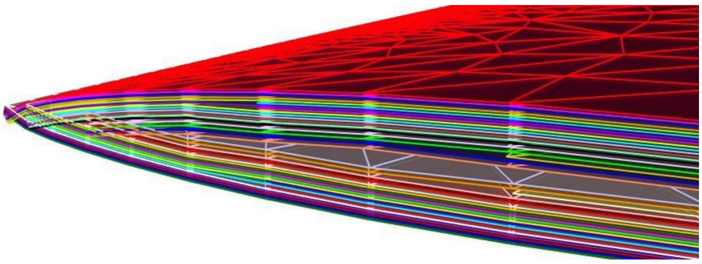


Figure 35 - Fin layers - 19 up and 19 down

4.6.1. Fin characteristics

The lay-up schedule, fibre materials and fibre orientation were given by the F-Hot company and input in the ACP module of ANSYS. The thickness of the cloths was calculated using the FVF equations, and the properties of the materials gathered from the ANSYS engineering data library and also external sources [2].

	Layer	Material	Observation
At Full size	1	100g Weave Carbon	45°x45°
	2 & 3	200g Weave Carbon	45°x45°
	4 & 5	100g Unidirectional Carbon	
	6	100g Unidirectional Carbon	50mm wide
	7 & 8	100g Unidirectional Carbon	70mm wide
	9 & 10	100g Unidirectional Carbon	70mm wide
	11 & 12	100g Unidirectional Carbon	70mm wide
	13 & 14	100g Unidirectional Carbon	70mm wide
	15,16,17,18 & 19	200g Unidirectional E-Glass	50mm wide

Table 2 - Original Lay-up schedule

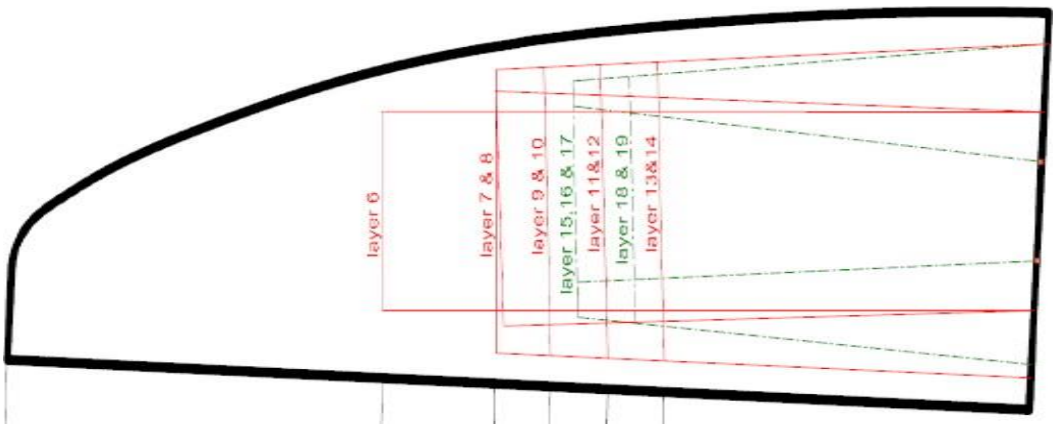


Figure 36 - Lay-up schedule of original 37 RS F-Hot fin

The numbering of layers increases from the outer layer to the inner layer. The first full layers are numbered 1-5. The other layers are cut according to the lay-up schedule of the manufacturer. The properties of the fabrics were gathered from the previous study on the fin [2] and are shown below.

Fabric \ Properties	Grammage [g/m2]	Density [g/cm^3]	FVF [%]	Fabric thick. [mm]
E-glass	200	2.580	27.570	0.281
Carbon (UD)	100	1.500	39.560	0.169
Carbon (WR)	100	1.470	40.040	0.170
Carbon (WR)	200	1.470	40.040	0.374

Table 3 - Properties of the Fabrics

The two sides of the fin are cured together as one piece, but there is the potential for a gap between the laminated FRP faces. At the root, this gap is approximately 4 mm, and it decreases gradually along the span of the fin. This small gap is filled with a glass reinforced epoxy paste applied at the same time as the hand lay-up of the fin main structural faces before they are brought together under pressure and then cured at elevated temperature.

4.7. FEA in Composites

FEA software's enable design engineers to perform various types of virtual experiments such as applying a load to a structure and see how it will respond. The benefits of FEA are that, once the model is created, it is much cheaper and faster than any physical testing. For complex projects, high processing power may be required.

Considering the fin of the windsurf board, it can be quickly understood why FEA is one of the bests solutions to perform structural analysis. First, the fin has relatively small dimensions which means it can have a very fine mesh and still not require very high computer capabilities and second, FEA software's such as ANSYS introduced an ACP module a couple of years ago which allows the user to specify the layer properties, stacking-up sequence and other properties which enable the user to create a virtual model with almost no differences from the real model.

The FEA model of the fin is described in detail in the initial investigation paper [2]. In the following chapter, the ACP module is introduced with emphasis on the two new features added to the investigation, which are the table of loads and the excel spreadsheet interaction of the ACP module.

4.7.1. ACP module and DOE

Composite materials refer to a material consisting of two or more constituents. The physical properties of each constituent create a final product with other specific properties. This scenario is difficult to predict in real life, and so it is even more difficult to virtual model it. ANSYS developed a friendly-user module of the WORKBENCH tool which allows the user to specify complex definitions that include numerous layers, materials, thicknesses and orientations. The engineering challenge is to predict how well the finished product will perform under real-world working conditions. There are not many books or internet resources to understand how composite materials are modelled in ACP, but for this project, the main source of information was gathered from ANSYS composite pre-post user guide [34].

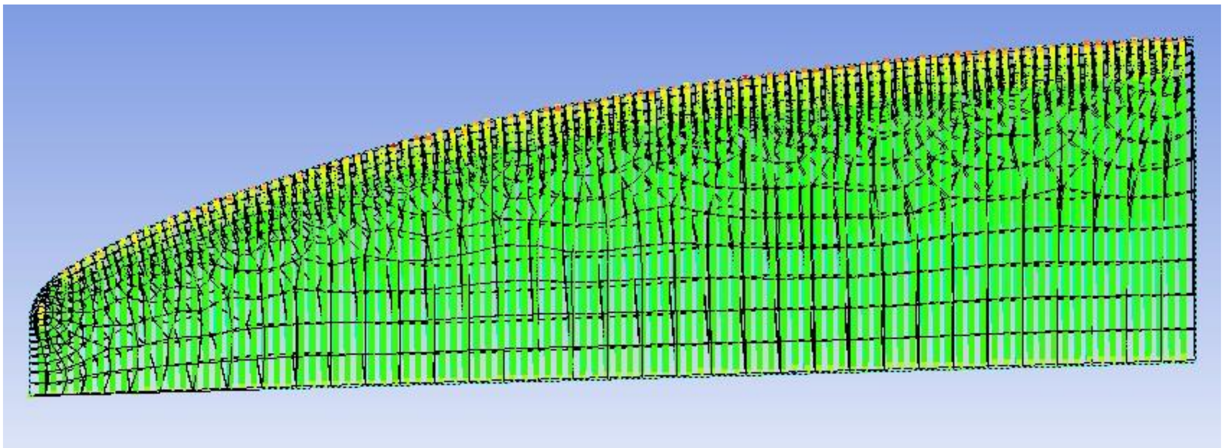


Figure 37 - Profile preserving field mapping

The table of the loads feature was fundamental for this project since it allowed to import the pressure distributions from MATLAB and map them accordingly to the nodes of the ANSYS model. ANSYS field mapping was set-up for making a "profile preserving" mapping which consists in taking the profile of the variable (in this case, pressure) on one mesh, and matches or maps it to the other mesh in the best way possible. Since the pressure distribution was mapped into more than 13000 nodes over the entire surface and the model mesh had approximately 2500 nodes, all the model nodes were mapped. The more source nodes, the more target nodes are mapped. 16 out of the 13838 nodes were not mapped because they were outside the model. This happens because there are small differences from the CAD geometry and the discretised model of ANSYS.

The other ACP feature which enabled to perform quick changes on the model lay-up schedule is the excel spreadsheet interaction. After manually setting-up the model which can take some time due to the many input parameters required and due to the many ANSYS windows that have to be open and saved simultaneously, an excel file containing all the most important physical model characteristics can be exported into the desktop. Figure 38 represents an example of the exported excel spreadsheet. For this case, each spreadsheet has two sheets. One for the TOP layers and one for the DOWN layers. For each side, there are 19 layers all numbered. For each layer, there are columns for all the characteristics such as Name, coordinate system, ply angle, ply material, ply number, a number of layers, draping and selection rule.

type	ModelingGroup						
id	layersdown						
name	layersdown						
END DEFINITION							
BEGIN DATA							
name	id	oriented_selection_set_1_id	ply_material	ply_angle	number_of_layers	active	global_ply_nr
1.DOWN	1.DOWN	OrientedSelectionSet.DOWN	fabrics/Cw 100g	45	1	VERDADEIRO	21
2.DOWN	2.DOWN	OrientedSelectionSet.DOWN	fabrics/Cw 200g	45	1	VERDADEIRO	22
3.DOWN	3.DOWN	OrientedSelectionSet.DOWN	fabrics/Cw 200g	45	1	VERDADEIRO	23
4.DOWN	4.DOWN	OrientedSelectionSet.DOWN	fabrics/Cud	-30	1	VERDADEIRO	24
5.DOWN	5.DOWN	OrientedSelectionSet.DOWN	fabrics/Cud	-30	1	VERDADEIRO	25
6.DOWN	6.DOWN	OrientedSelectionSet.DOWN	fabrics/Cud	0	1	VERDADEIRO	26

Figure 38 - Excel spreadsheet interaction for the first 6 layers DOWN

For example, the first layer at the downside is a 100 grams carbon woven fabric oriented 45 degrees. For the parametric study and optimisation, this tool allows the user to save much time since it is only required to set-up the model once and then change the cells in the excel spreadsheet and import it again. After doing that, the ACP module only needs to be updated, and the simulation may run again.

It is always important to visually double-check the model especially when varying the orientation of the fibres. Since there are two sides, one up and one down, the signs must be correctly assigned as positive or negative otherwise undesired results may be obtained. This module also allows the user to check the model graphically. For the fibre orientation, there is an option which allows seeing the reference direction, fibre direction and the reasonable directions of the various layers.

For improvement purposes, some minor geometry changes were applied to the model developed in the previous research project. Those changes and the new simulation times are explained in the following chapters.

5. Results and Discussion

This chapter presents the results obtained throughout the project. The first main results are the two tools developed: One is the MATAN tool mentioned before which is used for transforming the 2D C_p pressure into 3D pressure distributions and the other is the parametric design tool (FEA). Both tools are the pillars of this project as they are fundamental for performing any parametric study on the windsurf fin design.

For running the simulations, the user must be familiar with the MATAN tool as it is required to simulate every hydrodynamic change (see step-by-step instructions on page nº18). In other words, every time the velocity or Angle of attack is changed, a new pressure distribution must be generated and imported into the parametric design tool. The first two sub-chapters focus on explaining how these tools function together and what steps must be followed for every simulation.

Following this, the first simulation performed using the parametric design tool is presented. This simulation didn´t use the new advantages of the tool and consisted in simply applying a distributed load of 250 N throughout the fin at a quarter chord from the leading edge to compare the deflection results with the ones obtained in the Emmerson cavitation tunnel experiment.

Chapter 5.3 shows all the simulations run at different hydrodynamic conditions and their effect on the deflection and twisting angle of the fin. These results were performed based on the information gathered before in the literature review and the theoretical background. The velocity and AoA range are 8-40 Kn and 1 to 16 degrees, respectively. The initial action taken towards this situation consisted of eliminating the not realistic hydrodynamic occurrences based on the theoretical and experimental information gathered throughout the project. By doing this, the number of simulations decreased significantly, narrowing the window of different hydrodynamic conditions to simulate. For the remaining data, a series of simulations were run to understand the relationship between the input hydrodynamic variables, velocity and AoA and the output variables being investigated in this research, maximum deflection and tip twisting angle.

From these simulations, only the cases that approximated the most the hydrodynamic conditions experienced by a windsurf fin on a slalom environment were selected and taken over to the parametric design study. Low velocities and high AoA are not experienced by slalom windsurfers, and for that reason, there is no point for making a parametric study using these values.

The last part of this chapter consists of changing the fibre alignment and fibre material and evaluate how the fin maximum deflection and twisting angles are affected.

5.1. Preparations of the programmes (MATAN & PARAMETRIC DESIGN TOOL)

5.1.1. Generation of simplified hydrodynamic load

The MATLAB code used to generate the simplified hydrodynamic load was denominated as MATAN and it imports the XFOIL results from an (*.xlsx) file which are the pressures P at 80 2D x, y coordinates along the chord of the fin and maps it to x, y, z,P coordinates over the entire top and bottom surface. An excel file was created to transform the coefficient of pressure values into pressure values which contains the environmental variable characteristics such as the free stream velocity and AoA and the constants (eq. 4.3.4)

MATAN directly imports the values from this file, which means it must be set-up correctly.

<u>The steps below must be followed before running any simulation:</u>

1) Copy the coefficient of pressure values (C_p) and coordinates (x, y) from the file "Xfoil_Export.xlsx" to the "importcp1" file in the required columns. There is a sheet for each velocity (8-14 Kn) and, for each velocity there are a series of AoA (1º-16º).

2) Most of the parameters used in the equation 4.3.4 are fixed. Only the free stream velocity must be changed according to the simulation being conducted at the time.

3) Once this is done, MATAN file may be open and run.

MATAN working procedure is explained in Figure 17, chapter 2.5. The filers to be imported may be in the same folder as the MATLAB program. After performing the calculations, MATAN generates three plots for each side.

The first MATLAB figure is showing the scaling of the non-dimensional coordinates from XFOIl to the real fin chord dimensions and the respective 2D pressure distribution at a span location of 300 mm from the root.

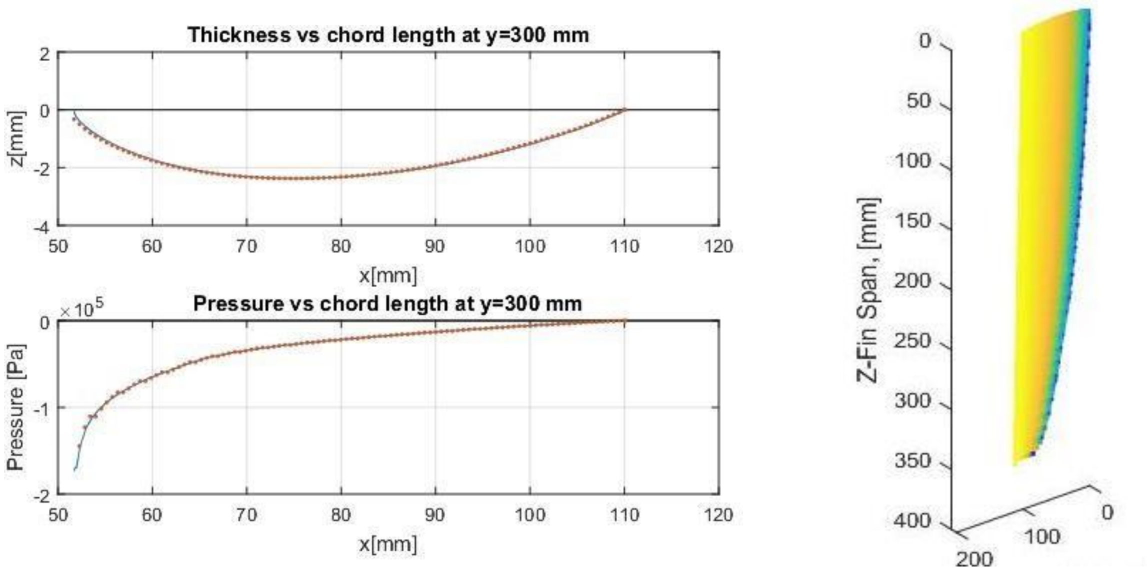


Figure 39 - MATAN - Scaling chord coordinates and attributing pressure values

5.1.2. FEA model

Although this model was extensively used in the previous investigation on the slalom windsurf fin [2], it was advised to check the set-up and especially the ACP module where all the composite properties and stacking up sequence were input. This model has 19 layers in each side and a series of rules that limit some of the layers. For example, the first five outer layers are full, which means they are laid over the entire surface of the fin. The remaining layers are smaller than those and are placed more towards the root where the maximum stress point is supposed to be located and also where the thickness of the fin is larger.

5.1.2.1. FEA improvements to the previous model

The first correction of the model consisted of creating a spanwise section cut at the centre of the fin to avoid layer overlapping, especially at the leading and trailing edge of the fin.

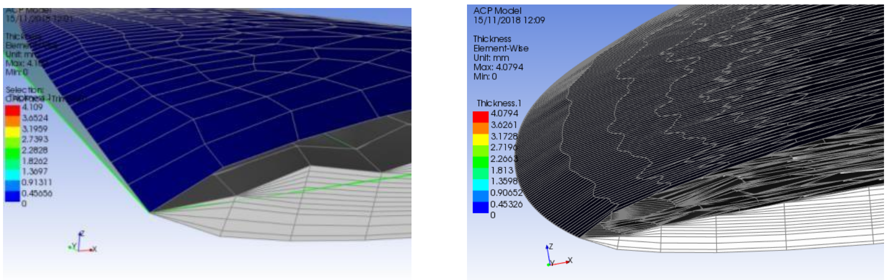


Figure 40 – Left - Layers on the bottom side of the fin overlapping with top layers – Green plane delimitates the centre of the fin, Right - Layers on the bottom side of the fin cut by the section cut plane [21]

The second correction and critical one was only made after running the first simulation. ANSYS post-processing allows the user to create section cuts and see the interior of the part modelled, and it was observed that the gap between the two sides was too high compared with the fin surfaces. In the end, it was discovered that the thickness of layer nº 2 and nº 3 from both sides had the thickness of the 100g CW cloth instead of the 200g which increased the overall thickness by 0.84 mm. After running some simulations, it was concluded that this thickness variation wouldn´t change the results significantly.

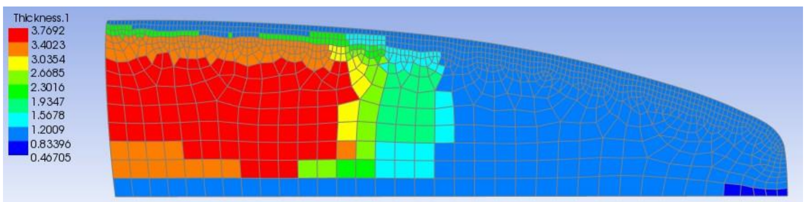


Figure 41 – Overall thickness before correction [21]

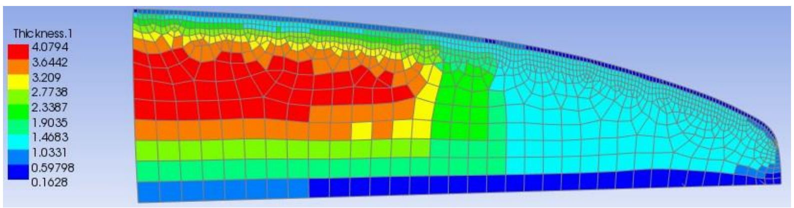


Figure 42 - Overall thickness after correction [21]

5.2. Application of line load to confirm cavitation tunnel results

The deflection of the fin was experimentally studied at the Emmerson Cavitation Tunnel [4]. Unfortunately, their methodology to measure the fin deflection didn´t work as planned, and the fin deflection was only obtained using photogrammetry. A camera was placed underneath the water channel to track the tip deflection and give an estimation of the values experienced. For comparison purposes, an FE simulation was conducted which consisted of distributing a force of 250 N over a quarter chord line from the leading edge. This location is considered the centre of pressure of air foil shapes just like the windsurf fin. A stationary image was captured for each angle to compare the images. The tip position was measured to find out how much they had moved in respect to their background grid and the ratio between the deflection of the tip. The experimental results are expressed as a trendline which relates the gathered data during the experiment as shown in Figure 43

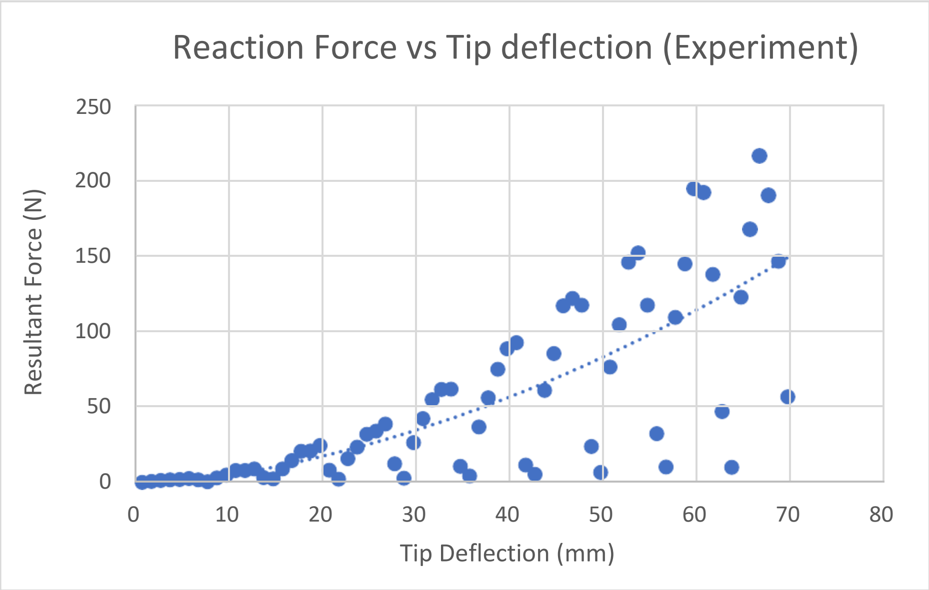


Figure 43 -Tip deflection results obtained experimentally

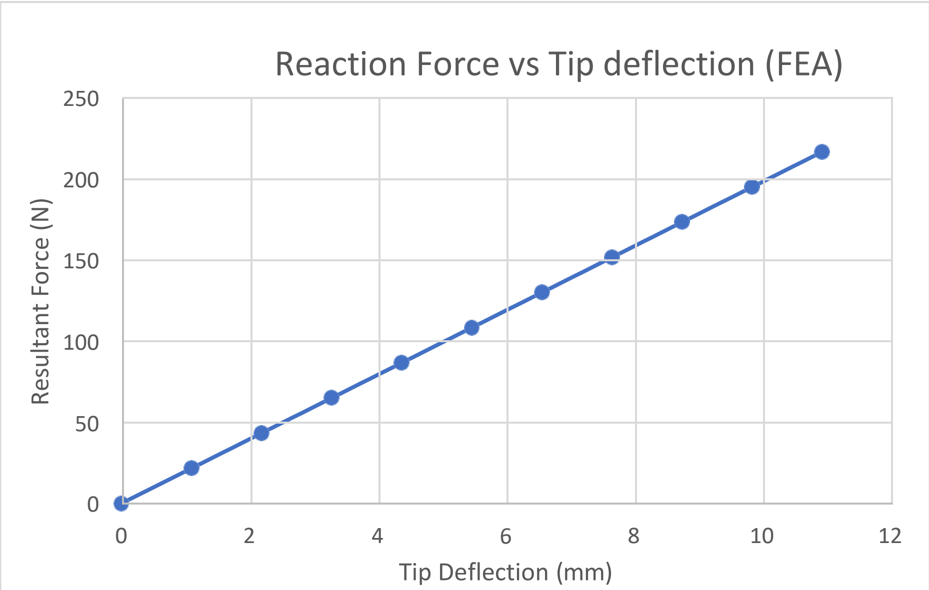


Figure 44 -Tip deflection results obtained with FEA

The reaction force is almost the same, but the deflection measured experimentally is much higher than the FEA results. The FEA results show a maximum deflection of approximately 11 mm at 220 N of force, whereas the deflection obtained experimentally was almost 80 mm. From Figure 12, which shows the results of the structural experiment conducted at the hydraulic machine, it can be observed that at, 220 N of reaction force, the deflection is between 5 to 6 mm. This dissimilarity between the results are expected due to the difficulty of taking the experimental measurements on the cavitation tunnel.

5.3. Parametric study – Varying hydrodynamic properties

The initial simulations consisted in measuring the tip deflection and twisting angle at three locations over the spanwise length of the fin with the variation of velocity and Angle of attack. This initial experiment is fundamental to understand how these two parameters affect the structural behaviour of the fin and to select a range of velocities and AoA to fix during the following experiments where other variables such as fibre orientation and the material will be varied. This experiment is primarily needed to narrow the range of variables and minimise the number of times the experiment needs to be run to get significant results.

5.3.1. Variation of Tip deflection with Angle of AoA

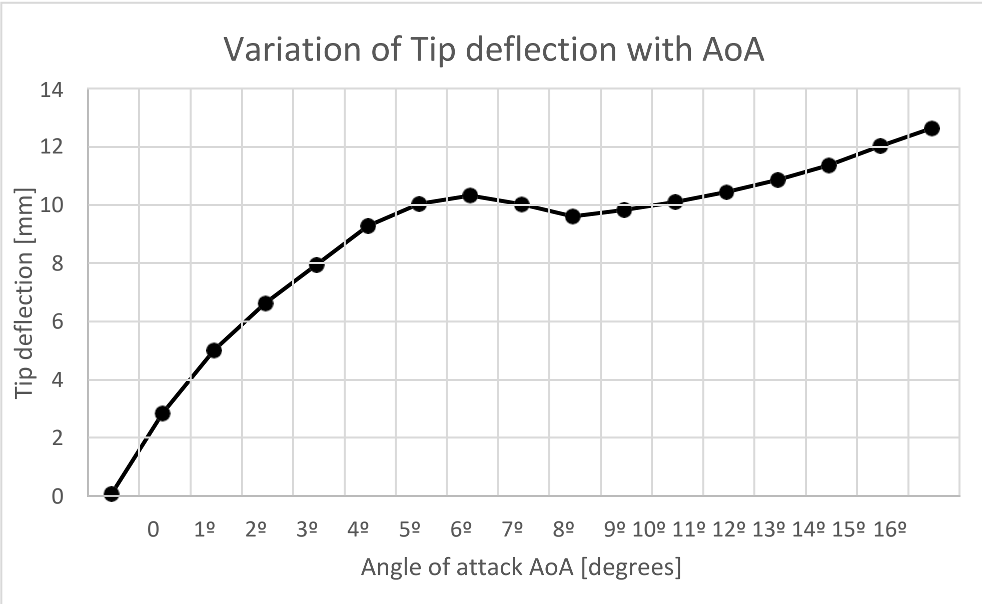


Figure 45 – Variation of Tip deflection with AoA

The velocity was kept fixed at 8 Kn, and the AoA was changed from 0º degrees up to 16º. From the experimental and CFD studies [4][3] it was observed that the C_L increases almost linearly with the angle of attack α which reaches approximately α = 7º and then starts to decrease when it stalls. Since the lift force acts on the fin and is characterised by the pressure distributions imported into ANSYS, it is expected to observe a curve with the same shape as the coefficient of lift vs AoA curve. From a theoretical background, it is known that the fin angle of attack rarely goes beyond 6º, which means that for this investigation the range of AoA chosen is between 0 and 6 degrees.

5.3.2. Variation of Twisting angle with AoA

The geometric twist experienced in slalom fins is expected to be low due to the absence of rake (swept back geometry). For measurement purposes, the deformed geometries were exported to the CAD software Rhinoceros, and three equally spaced planes were placed along the fin. With the intersection of these planes with the fin geometry, it was possible to measure the twisting angles as shown in the figure below.

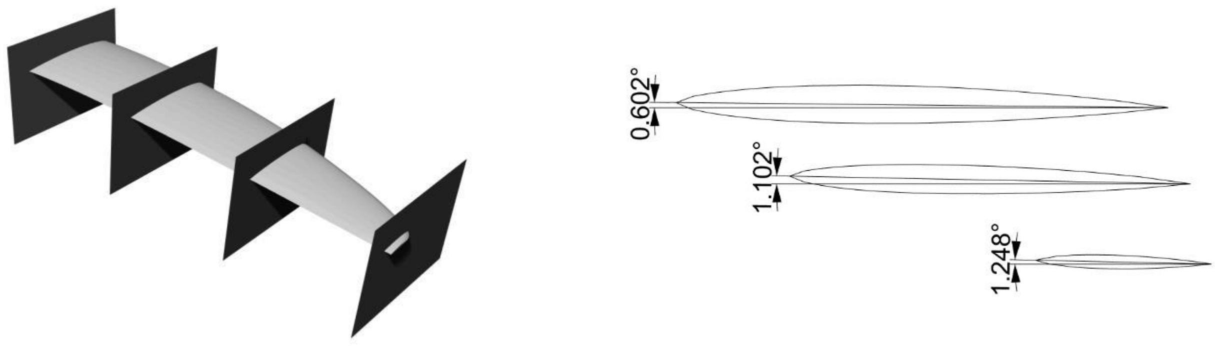


Figure 46 – Left - 3D deformed geometry of the fin - V=10 Kn AoA 4º, Right - Front view of the Intersection cut at the three planes

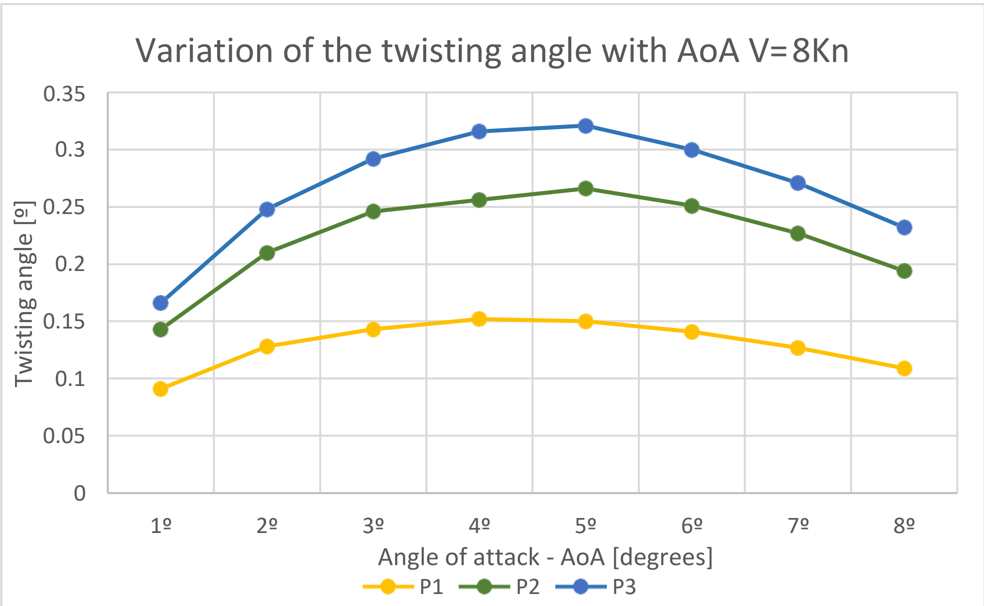


Figure 47 - Variation of Twisting angle with AoA V=8 Kn

The twisting angle increases up to an AoA of 5º and then decreases, showing a similar trend of the tip deflection. Again, the twisting angle of the tip is closely related to the pressure distribution, which increases up to approximately α=7º and then starts decreasing. At location P_1(closest measurement from the root of the fin) the maximum twisting angle is approximately 0.15 degrees whereas, at the tip, the twisting angles is higher than 0.3

degrees. This significant difference is expected as the root is prevented from being rotated due to the fixed support to the board and because the root has the thickest section of the fin. The angles magnitude may seem insignificant but for such low velocity, each decimal makes difference in the sailing performance. A twisting angle of 0.35 degrees when sailing on a board with the fin AoA=5º represents 7% of the total AoA which ends up making a high impact on the fin performance

5.3.3. Variation of Tip deflection with velocity

Increasing the velocity increases the magnitude of the variables twisting angle and tip deflection. If the 3D effects would be considered, scaling the velocities wouldn´t have been possible as the shape of the curve wouldn´t be the same. For comparison reasons, two AoA were plotted against velocity.

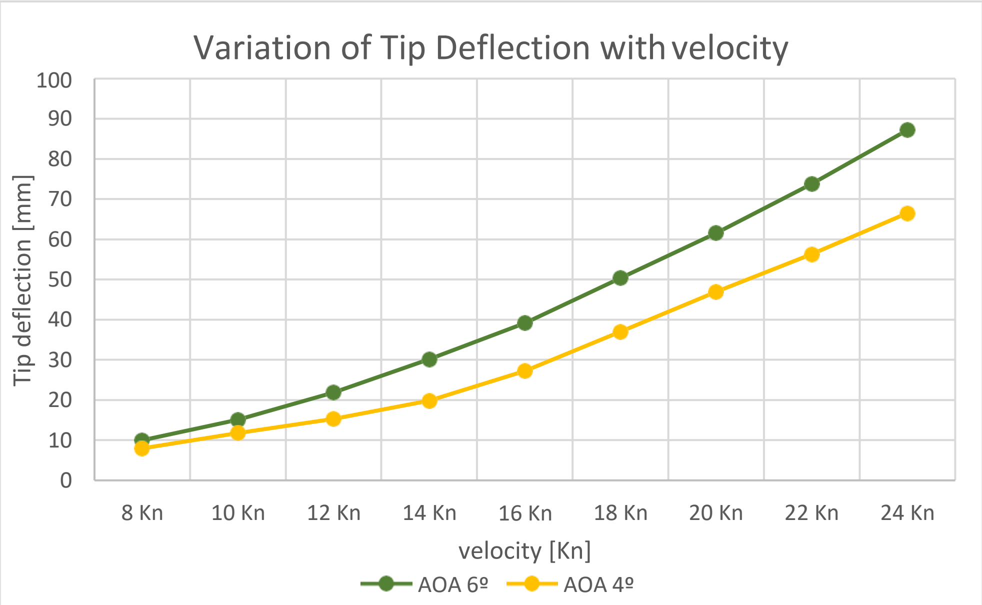


Figure 48 – Variation of Tip deflection with velocity for two AoA = 4º,6º

The curve in Figure 48 shows an initial exponential relation between the velocity and the tip deflection and then it becomes almost linear. At α =4º the tip deflection slightly increases until 14/16 knots and then it grows linearly at a rate of 5 mm/kn. At α =6º the relation is the same but with higher magnitude.

5.3.4. Variation of Twisting angle with velocity

The variation of twisting angle with velocity follows a similar trend of the variation of the tip deflection with velocity. At low-velocity values, the angle is very low in the range of 0.5-1 degrees whereas at higher velocity values it goes up to 2.6 degrees.

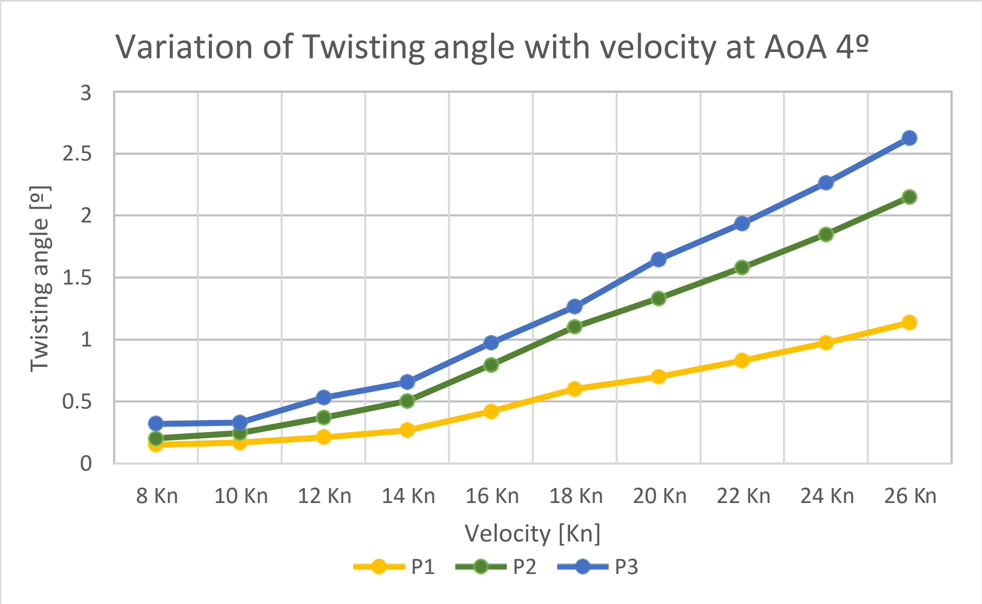


Figure 49 - Variation of Twisting angle with velocity for two AoA = 4º,6º

5.3.5. Variation of Twisting angle and tip deflection at higher velocities

The velocities at competition levels are much higher than 26 Knots. For that reason, it is important to understand how these two variables change at higher velocities. At slalom windsurf races the average speed is at approximately 28/29 Knots. It rarely falls below than 20 Knots, but it easily goes up to 35/40 Knots in extreme wind conditions. To evaluate the fin deflection and twisting angle at high velocities, 4 additional simulations were conducted at 26/32/38 and 44 knots at α=2º.

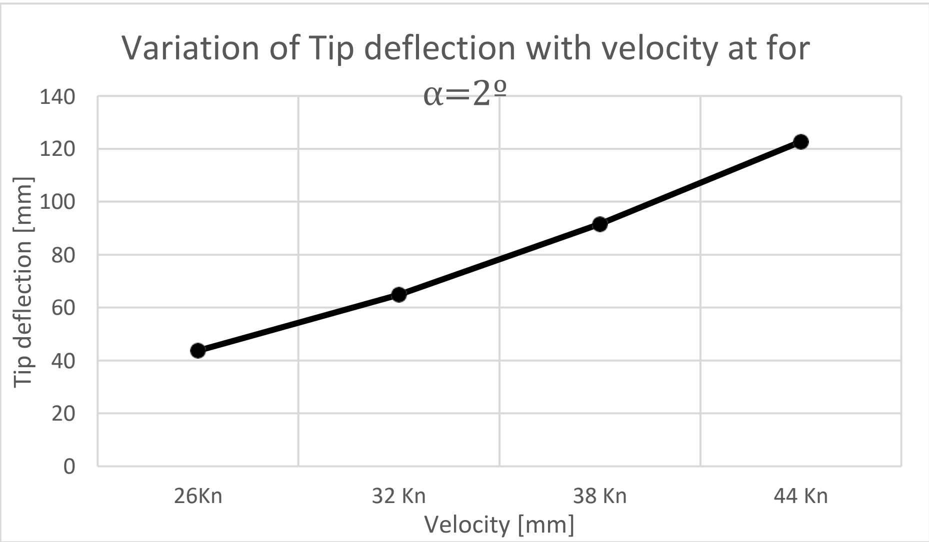


Figure 50 -Variation of Tip deflection with velocity at for α=2º

The tip deflection is much higher than in the previous experiments but is still between an acceptable range. No practical experiments were conducted to find out the elastic limits of the fin yet, but 120 mm should not be very far from the limit. The fin presents excellent flexible properties and is expected to flex this much and even more for higher angles of attack at velocities higher than 40 knots.

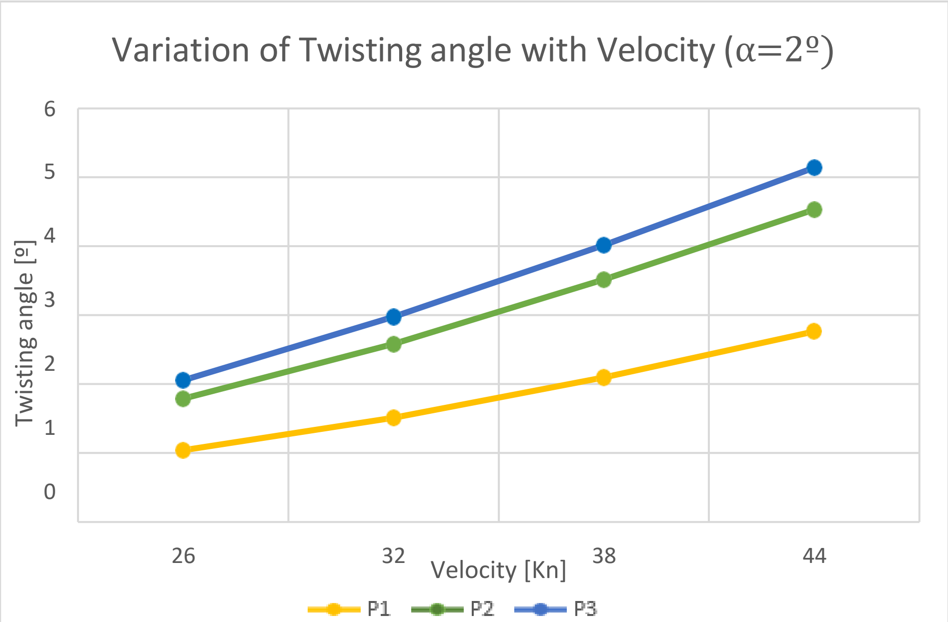


Figure 51 - Variation of Twisting angle with Velocity (α=2º)

The twisting angles are way too high and indicate that the velocity range cannot be so high for the following parametric study. The twisting angles are higher than the angle of attack, which means that the fin wouldn´t be generating any sailing counterforce but would be doing the opposite. The minimum acceptable is a twisting angle equal to the angle of attack at the tip in the most extreme cases.

There are many reasons that can explain such effect, but the main one is that the pressure distributions at higher velocities were kept equal to the highest obtained one in XFOIl and the 3D effects were not accounted. At such velocities scaling a 2D pressure into 3D pressure, the distribution may lead to very inaccurate and far from reality results and for that reason, a new approach to finding the maximum velocity giving reliable results was developed. The following approach is not presented but consisted of running a series of simulation at a fixed angle of attack of α=6º and increasing velocities until the maximum twisting angle was achieved.

Based on the runs simulated before for high and low velocities at different angles of attack it was decided to select the four-velocity-AoA combinations that showed more reliable and trustable results based on the information gathered from the windsurf mechanics and other resources.

Parametric Design study set-up		
Nº	Velocity [Kn]	AoA [º]
1	14	2
2	14	6
3	26	2
4	34	6

Table 4 - FEA Velocity and AoA set-up chosen for the refinement study

5.4. Parametric Design study - Varying material properties

The design tool developed during this research can be used by windsurfing manufacturers to conduct parametric studies on their fin models. From the literature review and theoretical background, it can be noticed that understanding and setting up correctly the input parameters is a fundamental step for achieving accurate results. The input parameters used in this study are in the expected ranges but were not validated with real-life experiments, and for that reason, some results may be out of the real-life range in terms of their magnitude. It is very difficult to measure and analyse what is going on under the board when a sailor is windsurfing, and the input parameters must be approximated as possible to, at least, understand the how a change on an input variable affects the output which is the structural behaviour of the fin. The two main input variables that may be changed are the fibre orientation and the material, and an experiment for each of these parameters was conducted, and the results are below.

5.4.1. Variation of fibre orientation angle

Based on the literature review and theoretical background mentioned before, an experiment to test the FEA model and the ACP module set-up was conducted. The goal of this experiment was to verify if the ACP tool of ANSYS was working properly and to be fully confident about the theory behind the bend- twist effect explained before.

The ultimate goal of this section is to characterise beam behaviour when fibre orientation is varied for the development of accurate models of the fin.

The model consists of a rectangular beam with small dimensions meshed with quadrilateral elements, fine enough to visually verify if the bend-twist effect is present. The model has 5 layers of UD carbon fibre aligned with the reference line, which then shifts 30º off it to simulate the bend-twist effect.

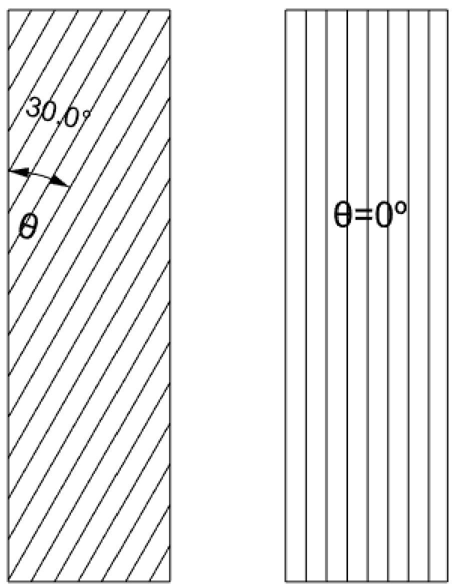


Figure 52 – Fibre orientation of the two beams simulated in ANSYS. At the left side, the beam with the fibres misaligned 30º from the reference line, and at the right side, the fibres are aligned with the reference line. [35]

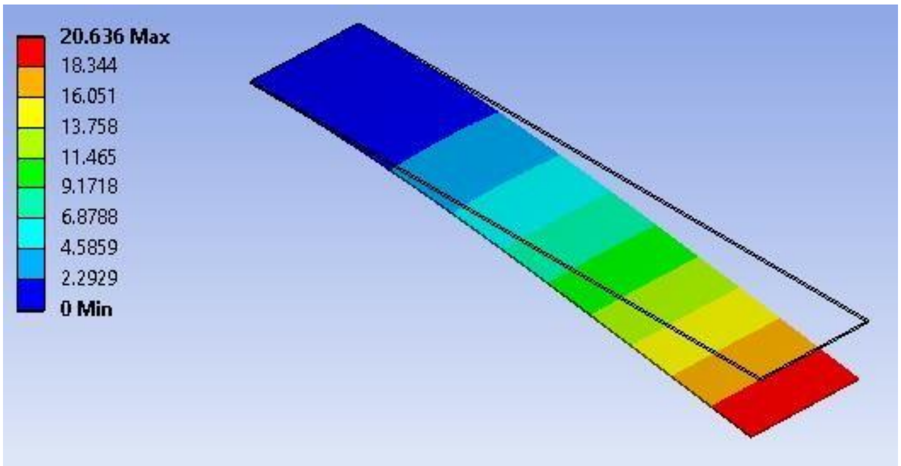


Figure 53 – Beam with the fibre orientation θ=0º - parallel to the applied load – Only bending, no twisting[21]

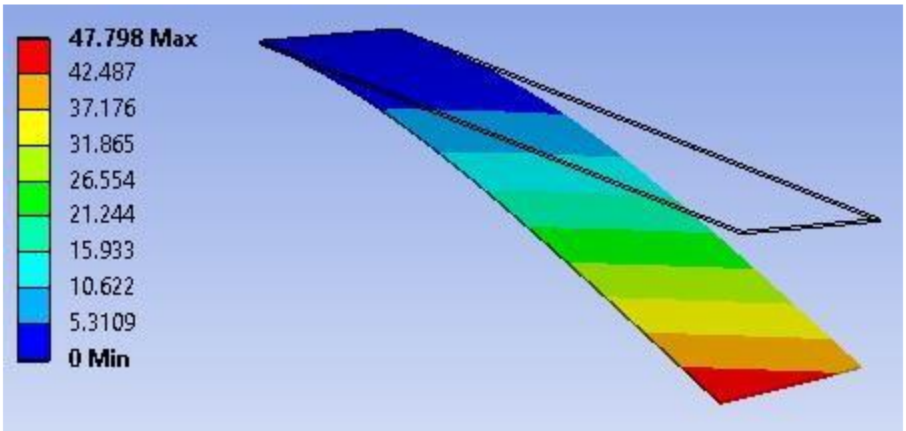


Figure 54 - Beam with the fibre orientation θ=30º - bend-twist effect [21]

In Figure 53, the applied load is in the direction of the fibres, and for that reason, the beam bends but doesn´t twist. The deformation of the beam gradually increases, but it's the same at the two edges. This beam acts just like an isotropic beam when a single point end load is applied. In Figure 54, the contour bands clearly show that the edge on the left side deflects more than the edge on the right side. The load tends to follow the path of highest stiffness, and for an anisotropic disposition of the fibres, asymmetrically oriented, this results in shear strain for the bent plate.

This result conforms with an experimental test conducted at the University of Washington [36] where a carbon fibre UD laminate was cut in different directions creating the beams with fibres oriented 10,20 and 30 degrees. The beams with fibre angles that deviate more from 0º deflected more but also twisted more. The FEA results show the same results, which indicates that the bend-twist behaviour occurring on a single beam also occurs onto the fin, and this may be used to exploit new designs that might require different responses.

5.4.1.1. Deflection

From the pressure distribution applied to the windsurf fin surface, it was observed that the fin tends to twist in the clockwise direction. This twisting affects that maximum tip deflection when the fibres are oriented asymmetrically. For this case, four experiments were conducted at 0, 30 and -30 degrees to understand the effect of varying the fibre orientation on the deflection of the fin.

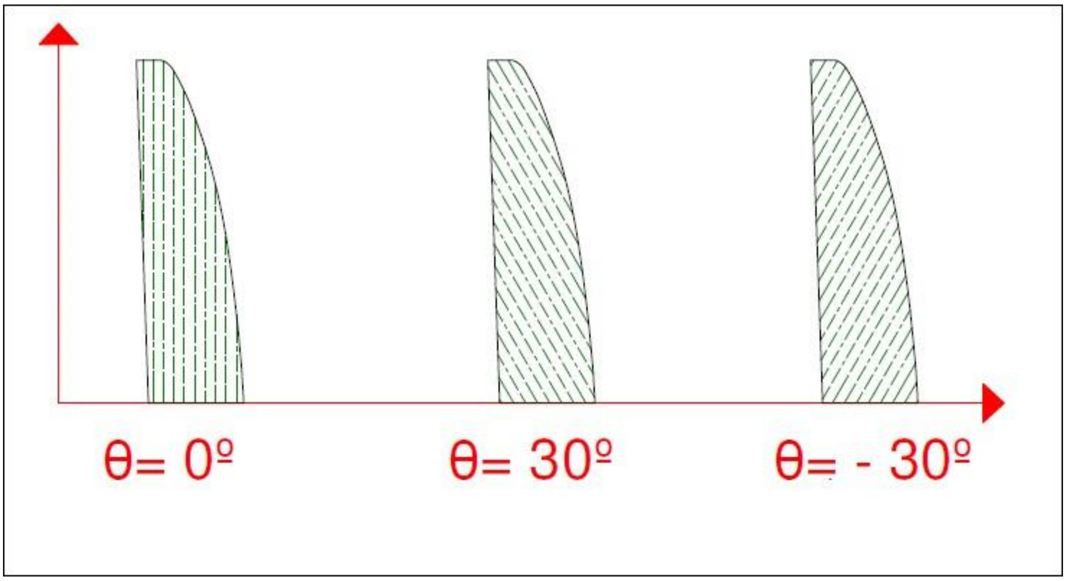


Figure 55 - Schematic of different lay-up schedules

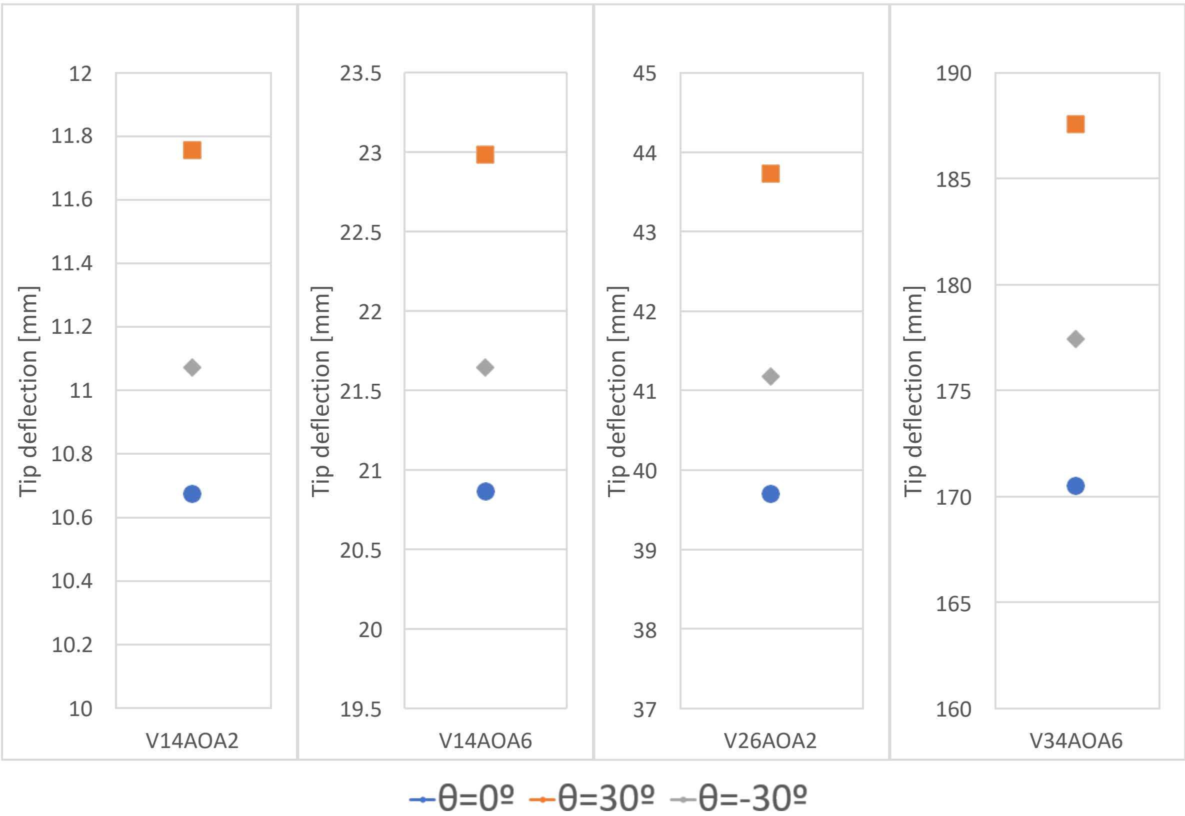


Figure 56 - Maximum deflection of the tip with fibre orientation of 0, 30 and -30 degrees

The results in Figure 56 show that the case where the fibres are oriented with an angle of θ=30º towards the leading edge is the case that presents higher deflection. The case with less deflection occurs when the fibres are aligned with the load direction. For the case with the fibres oriented towards the trailing edge θ= - 30º, the fin deflects less than with the fibres oriented towards the leading edge. The cause for the different deflections when the fibres are shifted the same amount to opposite sides occurs due to the non-symmetric geometry of the fin.

5.4.1.2. Twisting

The twisting angle was measured at the same 3 positions mentioned before, and the following results were obtained. The plots of the 4 experiments show the same result, which is in agreement with the bend-twist results obtained in the foil and shafts researches mentioned before [27], [28],[36]. Only the two most different cases out of the four experiments are mentioned below since they present the same relationship.

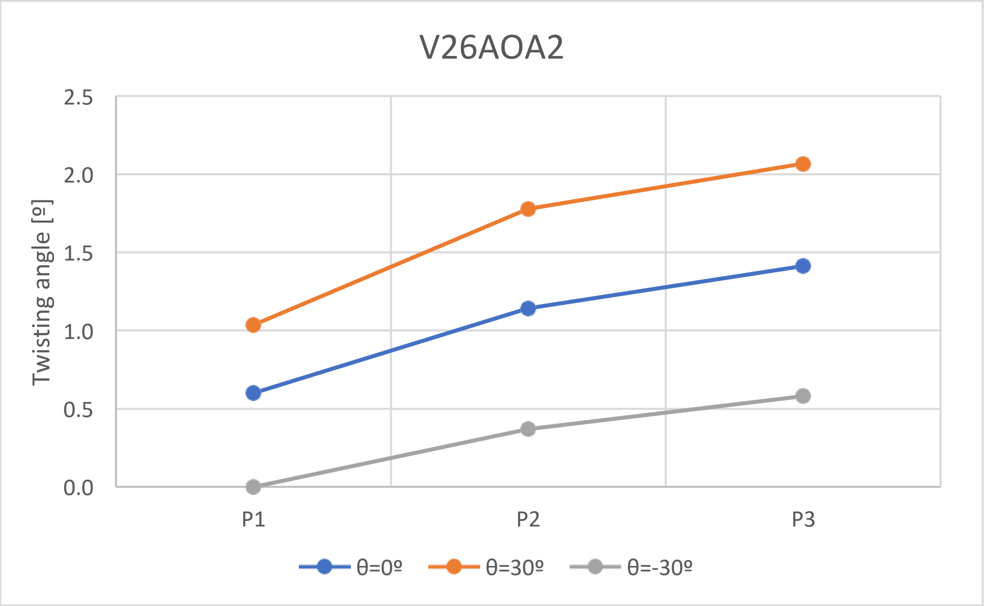


Figure 57 – Variation f twisting angle with fibre orientation of 0, 30 and -30 degrees at V26Kn and AoA2

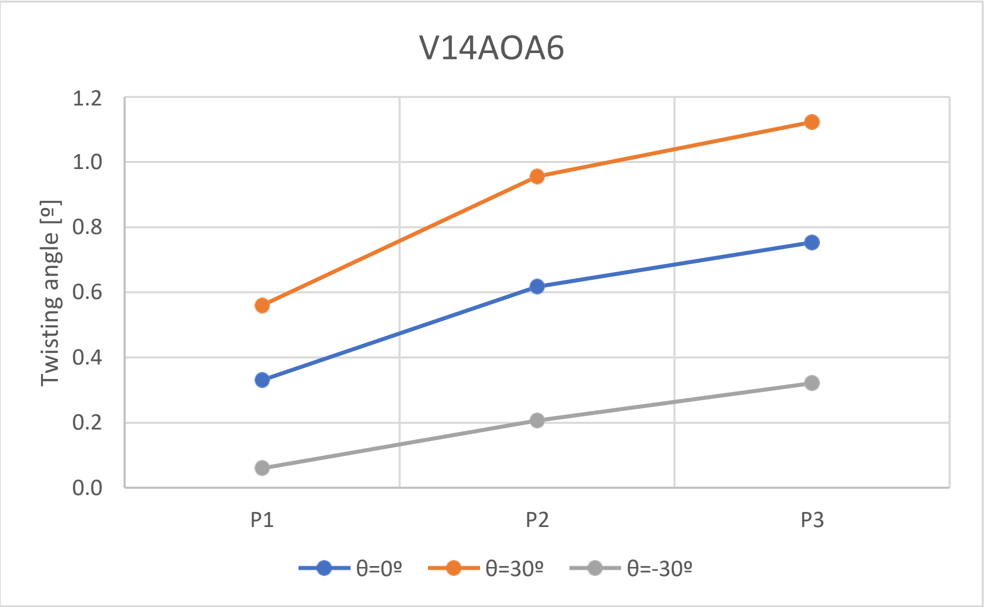


Figure 58 - Variation of twisting angle with fibre orientation of 0, 30 and -30 degrees at V14Kn and AoA6

The first and main remark of the plots is that the twisting angle does not change as the deflection with fibre orientation. The misalignment of the fibres only enhances the twisting behaviour of the fin (especially at the tip) when the fibres are shifted towards the leading edge or rotated 30º counter clockwise. This variation results in an increase of approximately 0.4 º at V14 and .7 º at V26. On the other hand, when the fibres are oriented towards the trailing edge (shifted 30 º clockwise when the fin leading edge is facing the right side) the twisting angle decreases. Due to the geometry of the fin, when the fibres are aligned with the reference direction (θ=0º, perpendicular to the fin root), the fin tends to twist as it was observed in chapter 5.3.3. When the fibres are shifted 30 degrees towards the trailing edge, the normal twisting behaviour of the fin is counteracted by the stiffness of the fibres which is higher in the direction of the twisting direction.

5.4.2. Variation of material

Windsurf fins are expensive pieces of equipment due to the fabrication costs but mostly because of the materials used. The reinforcements and resins are costly, and this tool may be used to replace some of the layers with expensive fabrics such as carbon fibre to other cheaper materials such as fibreglass. The variation of materials is slightly more complicated than the variation of the fibre strand orientation because of the different material properties. FRP fabrics present different densities and different grammage, which means that the FVF also changes, which in turn changes the ply thickness.

To make sure that the thickness of the fin was not compromised, the 8 inner layers 100 g carbon UD (nº7 to nº14) were substituted by 5 layers of 200 g UD E-Glass. All the changes are performed in the excel exported sheet and then imported again with the new lay-up schedule. The user only needs to check if the file was imported accordingly visually. The experiment was conducted with V = 26 Kn and α=2º.

8	name	id	oriented_selection_set_1_id	ply_material	ply_angle
9	1.TOP	1.TOP	OrientedSelectionSet.TOP	fabrics/Cw 100g	45
10	2.TOP	2.TOP	OrientedSelectionSet.TOP	fabrics/Cw 200g	45
11	3.TOP	3.TOP	OrientedSelectionSet.TOP	fabrics/Cw 200g	45
12	4.TOP	4.TOP	OrientedSelectionSet.TOP	fabrics/Cud	0
13	5.TOP	5.TOP	OrientedSelectionSet.TOP	fabrics/Cud	0
14	6.TOP	6.TOP	OrientedSelectionSet.TOP	fabrics/Cud	0
15	8.TOP	8.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
16	10.TOP	10.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
17	12.TOP	12.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
18	13.TOP	13.TOP.2	OrientedSelectionSet.TOP	fabrics/Eglass	0
19	14.TOP	14.TOP.2	OrientedSelectionSet.TOP	fabrics/Eglass	0
20	15.TOP	15.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
21	16.TOP	16.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
22	17.TOP	17.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
23	18.TOP	18.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0
24	19.TOP	19.TOP	OrientedSelectionSet.TOP	fabrics/Eglass	0

Figure 59 - Excel tool that allows for lay-up schedule variation

5.4.3. Deflection

The load is applied perpendicularly to the fibre direction, and the fin experiences tensile forces on the upper side and compressive forces on the bottom side. The overall thickness and geometry of the fin are the same, but instead of 19 layers in each side, it's only made up of 16 layers with higher thicknesses. The young modulus in the direction of the fibre orientation dictates the material behaviour, as mentioned in the previous results. The young modulus of UD carbon in the direction of the applied load used in the manufacturing process of the fin is approximate, $\varepsilon_x = 5.8 \times 10^{10}$ whereas the young modulus of the E-glass fabric is $\varepsilon_x = 1.2 \times 10^{10}$.

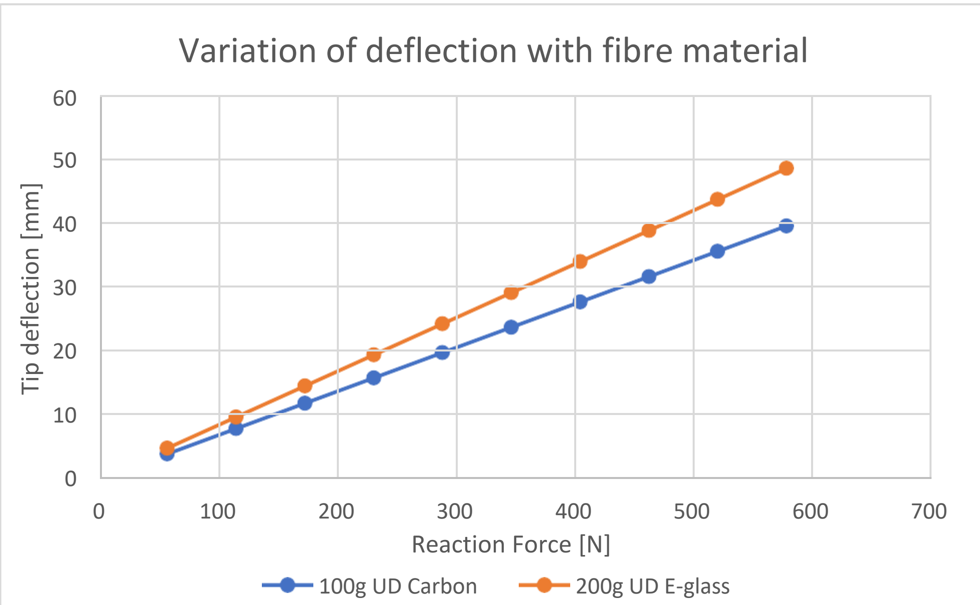


Figure 60 - Variation of deflection with fibre material

Substituting the carbon fibre with E-glass increases the maximum deflection of the fin by approximately 9 mm. The carbon fibre UD plies are 5 times stiffer than the E-glass in the direction of the applied load, which causes this deflection differences. This change could be one of the choices to consider when increasing the flexure behaviour of the fin is required. The deflection increases gradually along the spanwise length of the fin, but this could be controlled by having a ply with different spanwise layers. It is not a standard feature, but it could be tested to see how the fin behaves in such conditions.

5.4.4. Twisting

Apart from controlling the flexibility of the fin, it is also important to be able to change its twisting behaviour of using different materials. The manufacturer may desire to build a new fin with more flexibility and the same strength and stiffness of the initial lay-up schedule but with a smaller or higher twisting angle.

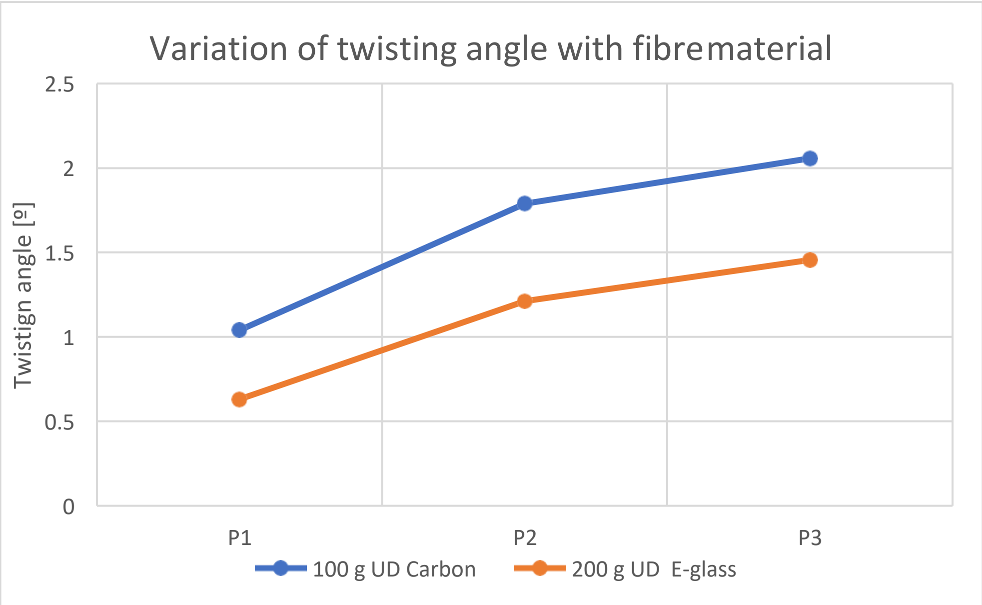


Figure 61 -Variation of twisting angle with fibre material

The figure above shows that the fin modelled with carbon layers possesses higher torsional stiffness than the fin with the E-glass layers and has a maximum twisting angle of approximately 0.6 degrees. This change of material would be a great choice if the manufacturer or rider would like to have a more flexible fin but with a smaller twisting angle. If only the flexure property was desired the fibre orientation of some layers could be changed towards the transverse axis and it would be possible almost to achieve the desired performance from the fin.

6. Conclusion

The information and know how on windsurf fin hydrodynamics and windsurf fin structural analysis was very little at the begging of this project due to the low content available. The information on the windsurf physics is spread over different papers, and it is not easy to understand and relate. The literature review of this project covered most if not all the previous researches on this topic to allow the reader of having a general background of what has been researched previously and use it in the parametric design toll in future works. It was fundamental to review what was discovered before to develop the parametric design tool. Combining the general background literature review with the specific research on the 37 RS F-Hot windsurf slalom fin allowed to understand what was lacking on this topic: A study which combined the hydrodynamics and structural analysis of the fin.

The result of this project is a parametric design tool prepared for investigating slalom windsurf fin structural behaviours when subjected to different hydrodynamic loading conditions. The MATAN program also developed throughout this research was not in the initial plans of the project but ended up being very important for the design tool. The design tool can work independently without the MATAN tool by applying a single point load but important effects such as the twisting of the fin tip won´t be visible in such conditions, and for that reason it is strongly recommended to use both tools together as it was explained before for a complete and more realistic parametric study.

The lack of data was and still is one of the drawbacks of this tool. It was challenging to find information on the correct or realistic ranges of angles of attack and velocities. The results clearly show that the maximum deflection and twisting angle are directly based on the hydrodynamic loading type and magnitude. If the combination of the angle of attack and velocity is not realistic the results would follow the same path and not be realistic too. With the help of experts in the field, it was possible to find that the AOA range was between 1-6 degrees and velocities between 25 to 40 Knots. More important than knowing these ranges was to relate them. Associating a range of velocities to specific angles of attack.

The first parametric study was performed to address this matter and eliminate cases where the outputs (maximum deflection and twisting angle) would be out of the acceptable range. This parametric study consisted of a series of simulation where the maximum deflection and tip twisting were evaluated based on the AoA and velocity. The selection of the 5 cases was based on the information gathered in the literature review and theoretical background, which presents the relation between the angle of attack and velocity. In addition to this, it was also decided to select different cases and a specific non-realistic case to represent the worst-case scenario in terms of maximum deflection and twisting angle which is at 34 kn and AoA of 6 degrees.

From this study, it can be concluded that the maximum deflection increases almost linearly with the velocity. When comparing the tip deflection with the angle of attack, it can be seen that the tip deflection is closely related with the hydrodynamic loading as it presents the same curve shape. In terms of twisting angle, the angle increases up to an AoA of 5 degrees and then starts decreasing. The reason behind the decrease of twisting angle after 5 degrees may be due to the stall angle, which is in that range (5-7 degrees).

From the bend-twist simulation with a rectangular plate, it was concluded that the fin deflects and twists more when the load is not oriented with the fibre alignment. If for instance the fibres are shifted towards the leading edge by 30 degrees, the trailing edge will experience maximum deflection and maximum twisting angle. This is an important fact especially because it showed that the FEA model was giving accurate results and because it may allow for varying the flexing and twisting properties of a fin by simply changing the fibre orientation of a lamina.

Configuring the material also has an impact on the structural behaviour of the fin. It may enhance flexibility or no depending on the materials chosen. The material parametric study is not as flexible as the fibre orientation one because of the thicknesses vary with the material density. This change may result in changes in internal lamination application, which cannot be done so fast using the parametric design tool. The advantage of using the parametric design tool and different materials is to change different materials and keeping the same properties but decreasing the manufacturing cost.

In general terms, all the objectives were accomplished, and the tools are ready to use in more profound parametric studies. The two design studies presented are simple and were used solely to test the tools developed. There is much more work that can be done in this area, specially in the combination of the hydrodynamics and structural analysis studies using the same simulating packages. This advancement would not only decrease the simulation time but increase the accuracy of the model.

7. Future Work

The design tool developed for investigating lay-up schedule designs of the fin as proved to work but it must be accompanied by more experimental work to increase its accuracy. The cavitation tunnel experiment may be one step forward in this investigation if they manage to increase their velocity range. Using photogrammetry during the cavitation tunnel experiments will allow investigators to get accurate measurements of the fin tip deflection, which can be used for comparison purposes.

The other future work that will impact this investigation and further investigations on windsurf fins is to combine all the analysis into a single software. This action will improve the whole project in the following aspects:

1. Decrease the number of licences required
2. Decrease the compatibility problems often seen between different simulation software's
3. Decrease the problem complexity
4. Turn the design tool into a more friendly-user tool that any fin manufacturer or windsurfer can use
5. Decrease the running time of each simulation and eliminating intermediate steps (converting/transforming data)
6. Turn the program more adaptable for quick changes in the hydrodynamics or lay-up schedule of the fin.

There are already a series of simulation packages that combine the CFD and FEA analysis, and that allows the user to import/export information from one analysis to another. There is a recent investigation approach called Fluid-structure interaction or FSI, which consists of the analysis of Multiphysics problems. Modern products are complex and often are influenced by diverse physical laws. When a sailor is windsurfing, the fluid flow causes deformation of the fin to balance the forces, which subsequently causes the flow pattern of the surrounding water to change. Isolating these forces and examining them separately may not give an accurate prediction of the fin behaviour.

Traditional CFD simulations don´t account for this interaction and may lead to inaccurate and incomplete results. Nowadays, there are innumerable software packages that offer FSI analysis. ANSYS, which is one of the most known simulation programs in the world, offers FSI solutions and has been used widely in the aerospace and marine industry.

A good example of the FSI application in the real-world marine industry are the developments that the America´s Cup New Zealand (ETNZ) Team have done in their wing design using ANSYS FSI [37]. ENTZ combined ANSYS fluid-structure interaction (FSI) Multiphysics with composites simulations to perform hundreds of simulations early in the process to optimise the geometry and laminate structure to achieve target shapes and to minimise the weight of the structure while ensuring that it could withstand the loads expected during a race.

Once the aerodynamic predictions for a wide range of twisting angles of the three main wings were completed the structural simulation took place. The engineers started by building the structural finite element model of the wing using ANSYS workbench. The flaps are made of lightweight composites, and so the complete layup schedule was designed and optimised using ANSYS Composite Pre-post. In parallel with the FEA work, CFD engineers were running CFD simulations and gathering the data for different aerodynamic situations. With their outputs and to set up the FSI simulation, the pressures distributions from the many CFD analysis were imported and mapped onto the structure. Coupling the aerodynamic analysis with the analysis of structural integrity of the wing resulted in a better prototype which avoided expensive and time-consuming redesigns.

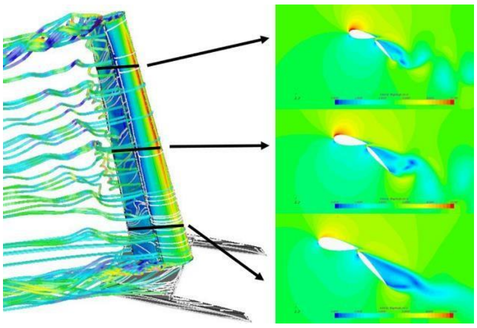


Figure 62 – CFD analysis of the ETNZ wing

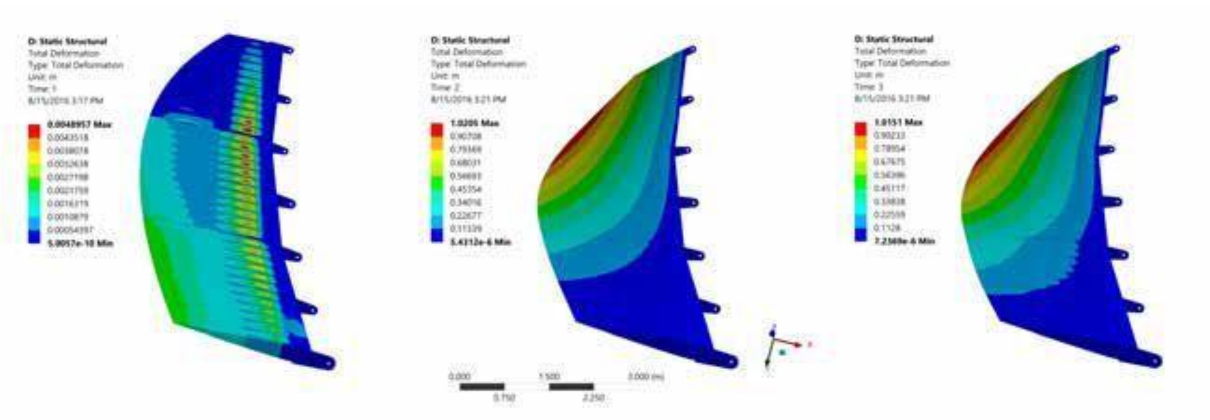


Figure 63 - FSI analysis of the ETNZ wing

There are different ways of performing FSI simulations, and it requires much knowledge to be able to couple the fluid with the structure physics of the material and obtain a reliable design of a wing or a windsurf fin. ETNZ engineers are already in the process of creating a more comprehensive model that includes the main elements and its connection to the yacht. They started by sampling importing pressures from CFD analysis and are already taking into another level.

At the initial stage of this project there was no data of the pressure distributions around the 3D fin geometry and for that reason it was attempted to prepare a CFD model, run a simple simulation with the help of the authors of the hydrodynamic study of the fin using XFOIL and understand how ANSYS CFX or Fluent could be coupled with FEA. This attempt was conducted to test if FSI could be applied to this case and to create a simple model which can be used for future investigations. The project schematic and respective files are available in the project folder.

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