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

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Abstract: Windsurfing is a relatively young water sport that is seeing a newfound resurgence with the development of new equipment and new disciplines over the last decades. The different windsurfing components have undergone several changes since the early days of this sport and the new records and new racing disciplines are forcing manufacturers to create new innovative equipment year on year, for leisure and competition purposes. This present study focuses on the smallest but most important part of the equipment – the fin. The study presents a design tool for investigating lay-up schedule designs of a composite slalom windsurfer fin. The tool allows the user to approximate and input certain environmental conditions usually experienced by slalom windsurf fins and to analyze the fin structural response for different fin structure designs.

1. INTRODUCTION

Fibre-reinforced plastics (FRP'S) materials have been widely used in the marine industry and are the only practical selection for fin manufacturers. The construction of these fins involves laying up multiple layers of fiberglass cloth and resin on two molds (one for each side) that are then compressed into one single piece. FRP's are light, strong and stiff and most importantly they can be manufactured in many different complex seamless shapes with different mechanical properties. This versatility shown by the fiberglass material makes it ideal for fin manufacturing. The drawback of fiberglass fins is the long manufacturing time because of the detail and attention that needs to go into making these by hand and the cost associated with it. In the design and development stages, it is sometimes required to manufacture and test many different fins with different flexural properties, which may lead to project delays and excessive prototyping and development costs and time.

The previous research on windsurf fins can be divided into two distinct periods. The initial research conducted at the beginning of 1990 that cover mostly the hydrodynamics of the fin and its performance.(Broers C.A.M. et al. 1992; Chiu T.W. et al. 1992; Fagg and Velay 1996; L. Sutherland & P.A. Wilson 1991; Sutherland 1993), and the second most recent research that started in 2016 and is still ongoing. The new technology that was brought into the water sports lately created the need to develop new fins, foils and other equipment. To accomplish that and to improve the existing windsurfing equipment it was needed to add some research on the previous studies using more advanced methodologies and new concepts that at the time were not as available as they are now. The following recent studies on windsurf fin, both on the structural and hydrodynamic fields are opening new windows for further fin improvements. (Banks et al. 2017; Nascimento, Sutherland, and Garbatov 2018; Santos 2018; Tansley 2018). The complex nature of the internal structural arrangement of a fin and the very chaotic hydrodynamic conditions that a fin is subjected to make the fin performance tests very complex and challenging to replicate in real-life testing. The new simulation packages and finite element analysis software's are now being implemented in diverse fields, exactly to overcome that problem.

The fins studied in this research project are fabricated by F-Hot fins and are used by top international sailors and even world champions. These fins are very expensive and are extensively tested over the years by the top sailors of the world to achieve the optimum set-up for breaking the records year by year. For reducing the testing period and increase the design changes of the fins, it was necessary to develop a tool to approximate and simplify the hydrodynamic environment that allowed to analyse the fin response and all the essential parameters that affect the fin performance. Hence, the aim here is to develop a design tool for investigating lay-up schedule designs of an actual windsurfer fin and to conduct a parametric study to evaluate the tool and to arrive to some conclusions regarding the relationship of some input variables to the fin response such as the fibre orientation angle effect on the maximum fin twisting angle and maximum fin deflection.

The 37 RS F-hot fin is one of the latest slalom windsurf fins commercially available, and it has shown to be one of the top slalom fins in the market. The studies conducted so far on this fin started in 2016 with the development of a Finite Element(FE) simulation program using a commercial FE software.

This program allows to apply approximated loads to a fin and evaluate its maximum deflection and maximum stresses. The FE model was later calibrated and validated with experimental tests conducted on a servo-hydraulic test machine to make sure that the theoretical tests were in convergence with the real-life tests. Following this research, the same fin used for calibration was used to gather real data from a cavitation tunnel. The results were satisfactory, but additional work must be carried out primarily in increasing the tunnel fluid velocity range and in the application of photogrammetry to analyse the real maximum deflection and twisting angles that the fin experiences under an average sailing load.

The latest research on the F-Hot fin was the Hydrodynamic analysis of wave-induced loads on the slalom fin. This research was conducted in parallel with this work and resulted in pressure distribution data, which was then used to approximate the 3D pressure distributions on the FE design tool in this study.

Each of these three studies on the 37 RS F-Hot fins presented before were essential for the generation of this design tool as they provided valuable information during the design tool development (Nascimento, Sutherland, and Garbatov 2018; Santos 2018; Tansley 2018).

2. F-HOT FIN FE MODEL

The 37 Rs F-Hot fin is a composite slalom windsurf fin composed by 38 layers of fabric divided into a “Top” and” Down” section. Figure 1 shows only half of the fin side.

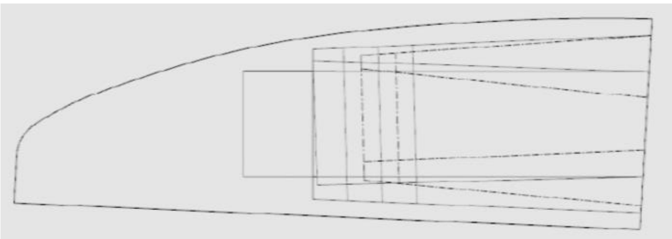

Figure 1 - Lay-up schedule plan

The lay-up plan includes woven and unidirectional carbon and E-glass reinforcements. The initial FE model shown in Figure 2 was developed previously (Nascimento 2017). All the mechanical properties such as layer thicknesses, FVF, and mechanical properties of the fabrics as well as the FE model set-up used for the development of this design tool were used just as developed before. This FE model was calibrated and validated and was prepared for further development in terms of adding new features.

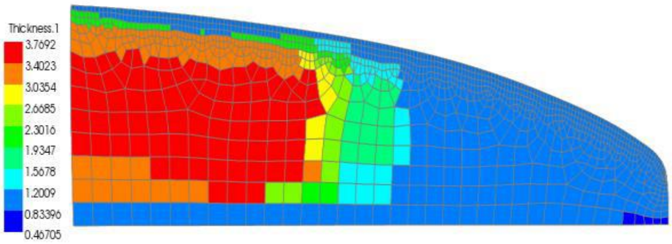

Figure 2 – Thicknesses Plot

Figure 2 shows the thickness distribution over the entire fin. The root of the fin is thicker and hence has more plies since it is the most stressed area. One of the corrections made in this study consisted of changing one of the layer thickness that was not correct and was overlapping to the other side of the fin. To verify if this change would affect the results obtained before, a simulation was run, and it was verified that the maximum defection only varied by 0.0254 mm.

3. MATAN PROGRAM

To approximate in the best way possible the pressure distributions that act on the fin, the results from the hydrodynamic research (Santos 2018) were exported into the Finite Element Analysis (FEA) program. A MATLAB code-named (‘MATAN – MATLAB – ANSYS’) was developed here to generate this simplified hydrodynamic load which imports the XFOIL results from an (*.xlsx) file in the form of pressures P at 80 2D x, y coordinates along the chord of the fin and maps this data to x, y, z, P coordinates over the entire top and bottom surface of the 3D geometry.

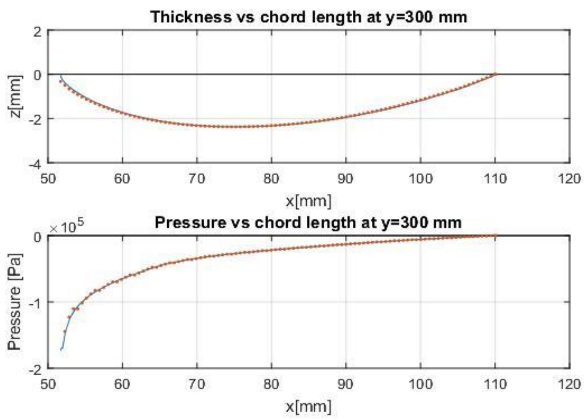

Figure 3 - 2D pressure distribution Plot

The program starts by importing and scaling the x,y coordinates and respective pressure values from a non-dimensional cross-section of the fin (Plot on the top of Figure 3),then it generates a mesh over the entire top and bottom surface and computes an interpolation of data using a specific interpolation function for this purpose based on the nearest neighbour method.

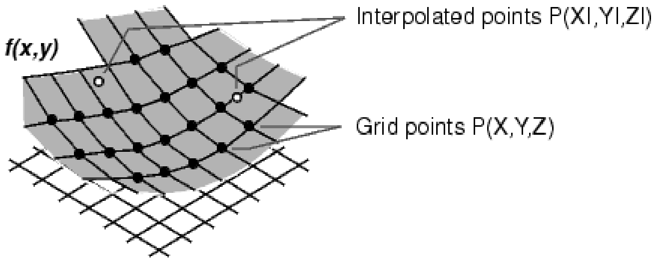

Figure 4 – Neighrest neighbour method

The output of this program consists on a graphical 3D plot of the fin showing the pressure distribution over the entire surface (Figure 5) and a table of loads that may be automatically imported into the design tool for running the FE simulations. This program was exclusively created for this fin but can be adapted to other projects such as wings, foils or any other FSI (Fluid-Structure Interaction) projects.

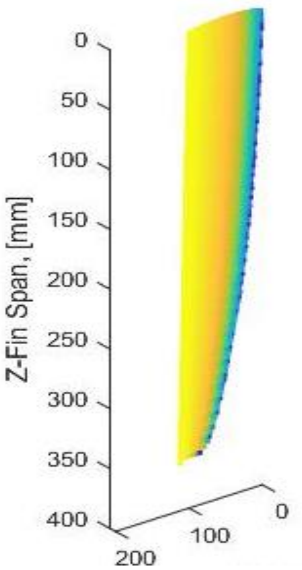

Figure 5 - 3D Pressure distribution x,y,z,P

4. DESIGN TOOL

The design tool was developed using the commercial software ANSYS WORKBENCH 18.2. In addition to the typical project schematics such as geometry, engineering data, solution and results that are commonly present in FE projects, this tool has two more features that allow the execution of parametric studies. The first feature fundamental for this design tool consists of importing the table of loads generated using the MATAN program. For this case, there is a specific 'userbox' where the coordinates and pressure units are specified. ANSYS automatically imports and reads the same file which means that every time the MATAN program is run, the table of loads in the design tool is automatically imported and only needs to be updated.

The other feature added to the FE model is inside the ACP (Ansys composite PrePost). This feature was already integrated into the previously developed FE model but was not being used.

The definition of the lay-up schedule plan is a long process on composite FE analysis. The layers have to be defined one by one; the fabric type and thicknesses have to be attributed to each layer as well as fibre orientation. The layer boundaries must be defined, and this process is lengthy. To overcome this and develop a quick tool where the user could make quick changes and evaluate results relatively fast, only one initial lay-up plan must be defined. Once this is defined, a table with all the information can be exported and manually changed in excel, as shown in Figure 6 6. One of the main advantages of this feature is that if there is a single change that must be applied to all layers the user only has to change it once and then copy and paste the cells for the other layers.

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 6- Lay-up schedule plan exported from Ansys

5. WINDSURF FIN

There is a wide range of fins in the windsurf industry. For each discipline, there is a specific model which has a specific outline shape, and the same model is often manufactured for different sail sizes and sailor weight. This project focuses on windsurf slalom fins which are similar to race model fins but are slightly shorter, slimmer and stiffer. Slalom windsurf fins tend to bend (flex) and twist along their longitudinal axis when they are under hydrodynamic loading. The previous structural related research on the fin (Nascimento, 2018) enabled analyses of maximum deflection and maximum stresses of the fin but did not allow analyses of the twisting angles of the tip of the fin because only a concentrated load at one single point was considered which did not generate any off-axis rotation.

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 freeride 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 to have the windsurfer can maintain better the angle of attack of the fin whereas having twist allows to depower the fin to some extent but makes the board less directional stable (Hanke 2018). In addition to these effects that directly affect sailing performance, twisting may also be used to avoid spin-out momentarily. 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 and delays stall. Fin twisting reduces the fin tip vortices and therefore induced drag providing more control.

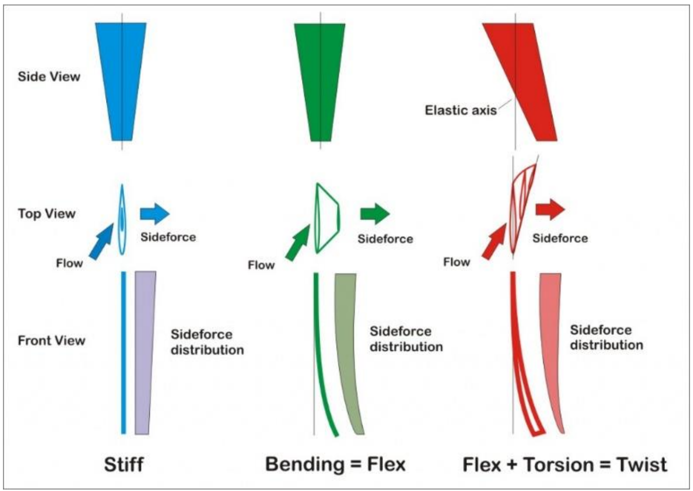

Figure 7 - Different behaviours of the fin under hydrodynamic loading (Hanke 2018)

6. IMPACT OF HYDRODYNAMIC PROPERTIES

The initial simulation investigated the dependency of fin tip deflection and twisting angle at three equally spaced locations over the spanwise length of the fin with the variation of velocity and Angle of attack. This first experiment was conducted to understand how these two parameters would affect the structural behaviour of the fin and to select a suitable range of velocities and AoA to use during the following experiments where other structural properties of the fin are varied.

In this initial experiment, the velocity was fixed at 8 Kn, and the AoA was varied from 0º to 16º. From the experimental and CFD studies (Santos 2018; Tansley 2018) it was observed that C_L increases almost linearly with the angle of attack α which reaches approximately α = 7º and then starts to decrease when the stall occurs. Since the lift force acts on the fin and is characterized 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 the 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 selected is between 0 and 6 degrees.

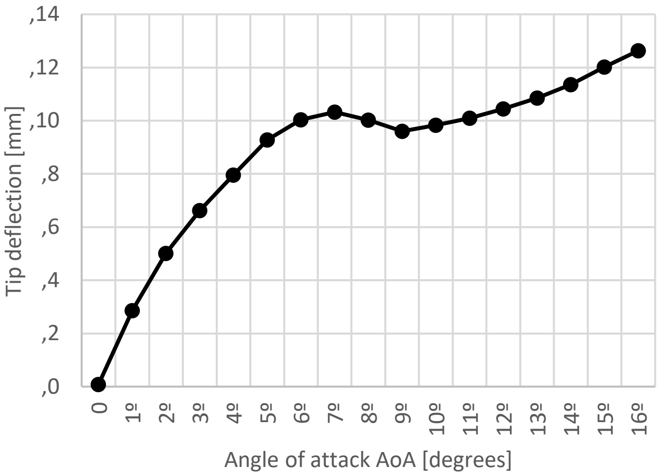

Figure 8 - Variation of tip deflection with AoA

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 figures below.

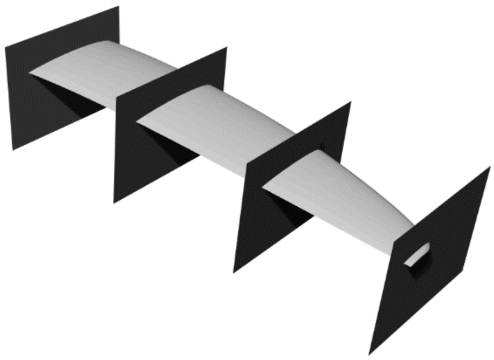

Figure 8 – 3D Deformed geometry of the fin (deflection and twisting present)

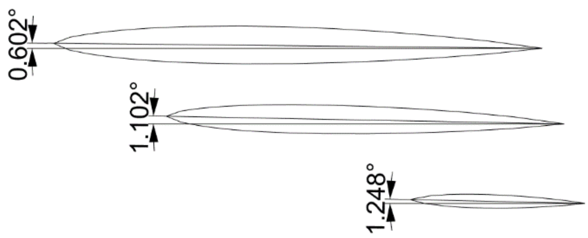

Figure 9 - Front view of cross-sectional cuts of deformed shape

From Figure 10, it can be observed that the twisting angle increases up to an AoA of 5º and then decreases, showing a similar trend to that of the tip deflection plot – Figure 8. The twisting angle of the tip is closely related to the pressure distribution, which increases up to approximately and AoA of 7º and then starts decreasing.

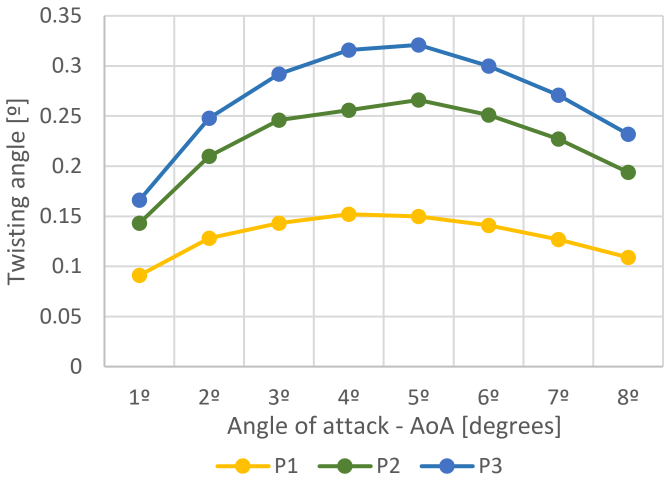

Figure 10 – Variation of twisting angle with AoA

At location P_1 (closest to the root of the fin), the maximum twisting angle is approximately 0.15 degrees whereas, at the tip the twisting angles reach 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 is the thickest section of the fin. The magnitudes of these twist angles may seem insignificant, but for such low velocity each decimal makes a difference in the sailing performance which is highly sensitive to twist angle. A twisting angle of 0.35 degrees when sailing on board with the fin AoA=5º represents 7% of the total AoA, which results on a high impact on the sailing performance.

The variation of twisting angle and maximum deflection with an increase of velocities were also performed. From this second parametric study, which is similar to the one presented above, it was concluded that both the deflection and maximum twisting angle increase with velocity.

The range of velocities was dependent on the study on the hydrodynamics of the fin (Santos 2018). The velocity available from the CFD study was between 8 and 14 Knots, which is a small range. During slalom windsurf races the average speed is approximately 30 Knots, and velocity rarely falls below 20 Knots, and can easily be up to 35 to 40 Knots in extreme wind conditions. To evaluate the fin deflection and twisting angle at higher velocities, four additional simulations were conducted at 26, 32, 38 and 44 knots at α=2º.

Figure 11 shows that the tip deflection is obviously 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 other sources (Hanke 2018) indicate that 120 mm should not be very far from the limit.

For higher velocities, the twisting angles obtained were unrealistically high and indicated that the velocity range could not be so high for the parametric study to follow. The twisting angles are higher than the angle of attack, which would mean that the fin would not generate any lateral forces. The minimum acceptable twisting angle is equal to the angle of attack at the tip in the most extreme cases when the tip would become unloaded.

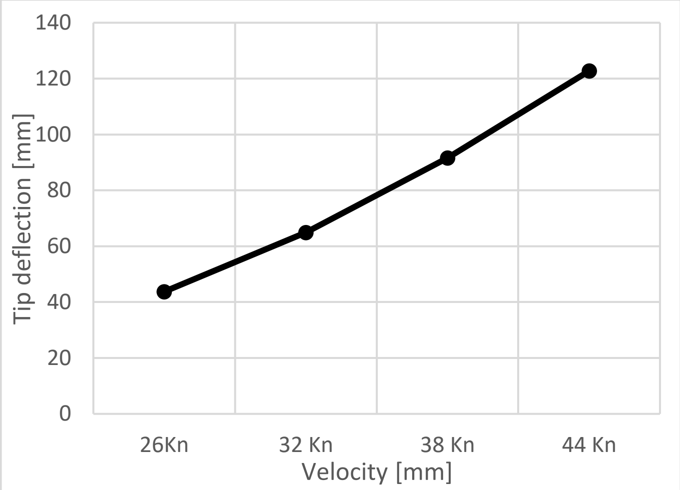

Figure 11 -Variation of Tip deflection with higher velocities at α=2º

There are many reasons that can explain such an effect, but the main one is that the pressure distributions at higher velocities were kept equal to the highest obtained by XFOIL and that the 3D effects were not accounted. At such velocities scaling a 2D pressure into 3D pressure, the distribution may lead to inaccurate and unrealistic results, and hence a new approach to finding the maximum velocity giving reliable results was developed. This procedure is not described herein detail for brevity but consisted in running a series of simulation at a fixed angle of attack of α=6º and increasing velocities until the maximum twisting angle was achieved.

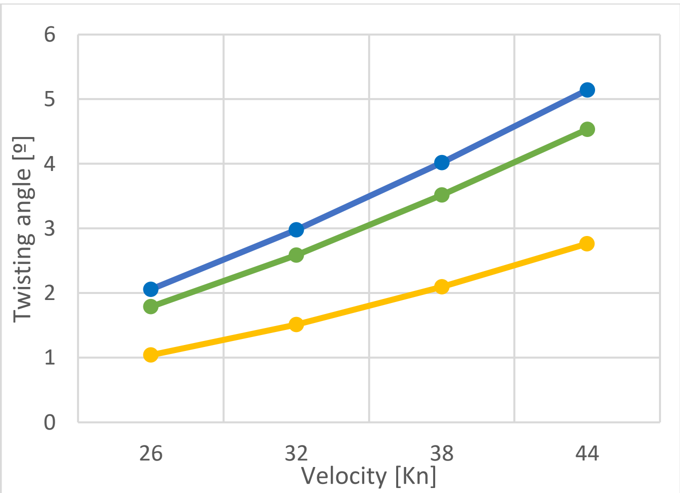

Figure 12 – Variation of twisting angle with higher velocities

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 theoretical background.

Table 1 - FEA Velocity and AoA set-up chosen for the refinement study

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

7. IMPACT OF 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 theoretical background, it can be understood that setting up correctly the input parameter is one the fundamental steps 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 hence some results may only be considered as good approximations. It is challenging to measure and analyse what is going on under the board when a sailor is windsurfing, and the input parameters must be approximated, as far as possible, to at least understand how a change in an input variable affects the output (the structural behaviour of the fin). The two main input variables that may be changed are the fibre orientation and the material. For this study an experiment for each of these parameters was conducted, and the results are below.

Before running the parametric simulations and changing the fibre orientation angle, it was decided to run a simple simulation to confirm some already expected structural behaviours. For this experiment, a simple rectangular beam meshed with quadrilateral elements finely enough to visually verify if the bend-twist effect was modelled.

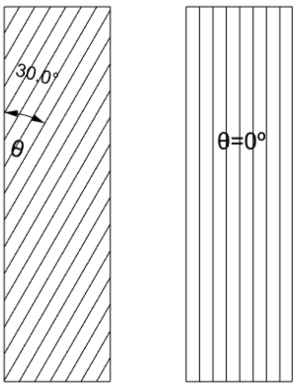

Figure 13 – ANSYS models

Figure 14 shows that when the load is applied to the beam with fibres at 0 degrees to its length, the beam does not twist. The deformation of the beam gradually increases along the length, but this deflection is the same at both edges.

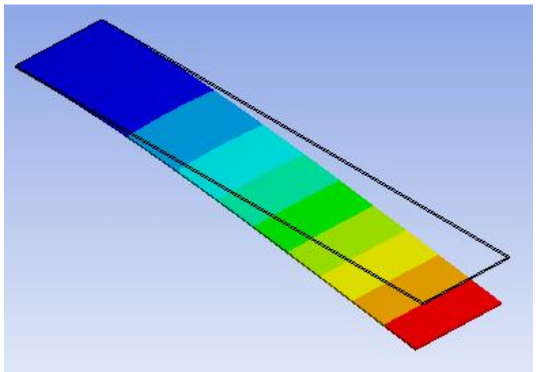

Figure 14 – Deformation of the beam with fibers oriented longitudinally

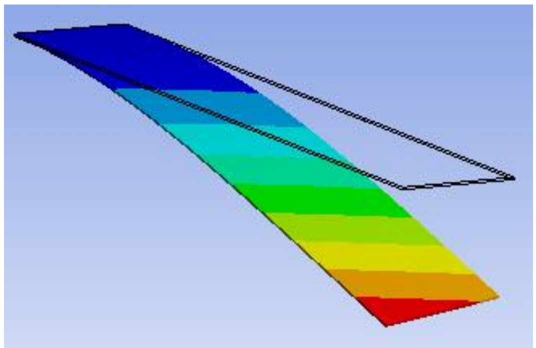

Figure 15 – Deformation of the beam with fibers oriented diagonally about the longitudinal axis

In Figure 15 for fibres rotated by 30 degrees, the contour bands clearly show that the edge on the left side deflects more than the edge on the right side. The same results obtained here can also be seen in similar work for other applications such as wind generator blades (Babuska 2017; Banks et al. 2017)

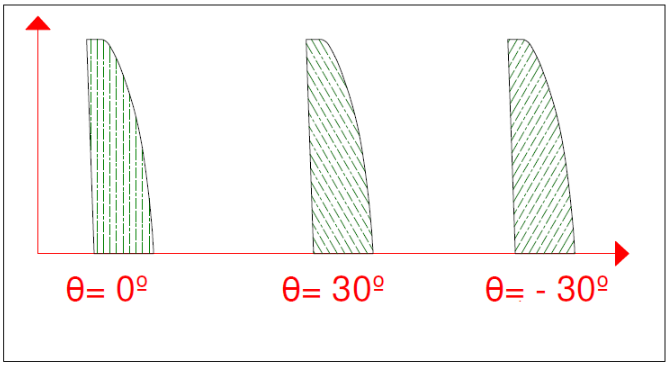

Figure 16 – Fiber orientation of the fins modelled

Figure 15 shows that the fin tends to twist in the clockwise direction for a rotation of the fibres of 30 degrees (Only the five full outer layers on each side were rotated). To further understand the effect of varying the fibre orientation on the deflection of the fin, three cases were simulated: 0, 30 and -30 degrees (Figure 16).

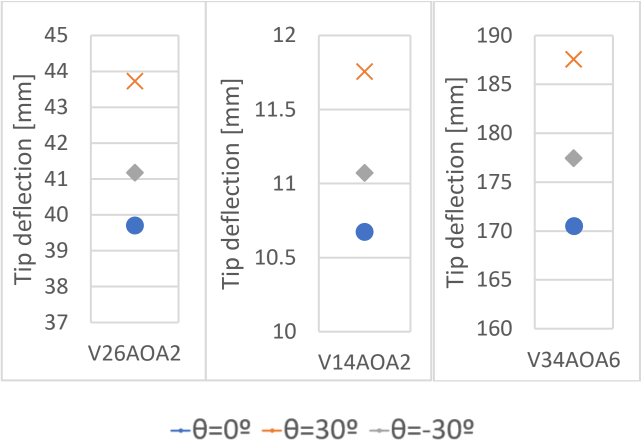

Figure 17 - Maximum deflection of the tip with fiber orientation of 0, 30 and -30 degrees

The results in Figure 17 show that the case where the fibres are oriented with an angle of θ=30° towards the leading edge is that which gives higher tip deflections. The case with less tip 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 (perpendicularly to the fin root).

The twisting angle was measured at the same three positions as described in Figure 8, and the following results were obtained. The plots of the four experiments show similar trends to bend-twist results obtained in other research (Babuska 2017; Banks et al. 2017; Rohde et al. 2015). Since the same trends were seen in each of the four experiments, only one case is described below.

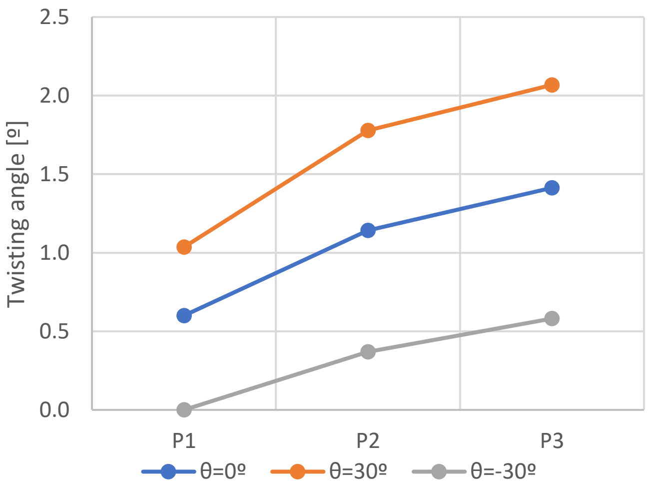

Figure 18 - Maximum twisting angle with fiber orientation of 0, 30 and -30 degrees

Windsurf fins are expensive pieces of equipment both due to time and fabrication costs and also because of the raw materials costs. The reinforcements and resins are costly, and this tool may be used to investigate the possible replacement of some of the expensive carbon fiber layers with other more economical materials such as fibreglass. The variation of materials is slightly more complicated than the variation of ply orientation because of the need to change the material properties. FRP fabrics may be of different densities and different grammages, and the FVF (Fibre volume Fraction) also changes, which in turn changes the ply thickness.

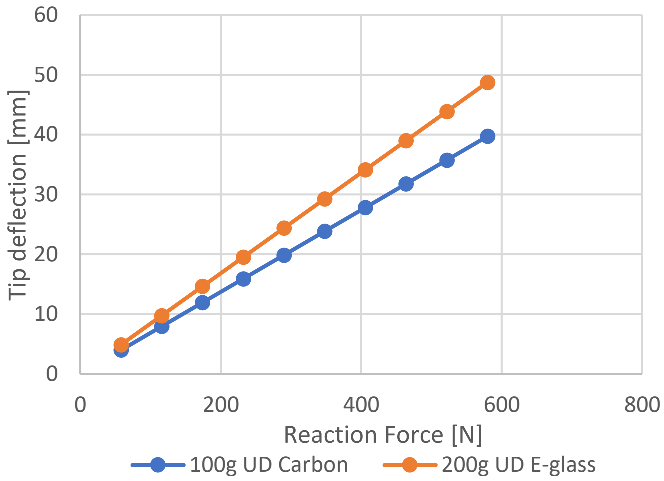

Figure 19 - Variation of tip deflection with fiber material

To make sure that the thickness of the fin was not compromised, the eight inner layers 100 g carbon UD (plies 7 to 14) were substituted by five layers of 200 g UD E-Glass. All the changes were performed in the excel exported sheet and then imported again with the new lay-up schedule. The experiment was conducted with V = 26 Kn and α = 2º.

Figure 19 shows that substituting the carbon fiber with E-glass increases the maximum deflection of the fin by approximately 9 mm. The carbon fibre UD plies are five times stiffer than the E-glass in the direction of the applied load, which causes this increase in deflection. It is worth noting that this change could be a positive one if increasing the flexure deflection of the fin is required.

The deflection increases gradually along the spanwise length of the fin, but this could be controlled by using plies with different spanwise extents. If the deflection of the fin is already optimised and the manufacturer or rider desire 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, the fibre material may be changed.

From Figure 20, it can be observed 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 were desired then the fibre orientation of some layers could be changed towards the transverse axis, and it would be possible to achieve any desired performance from the fin.

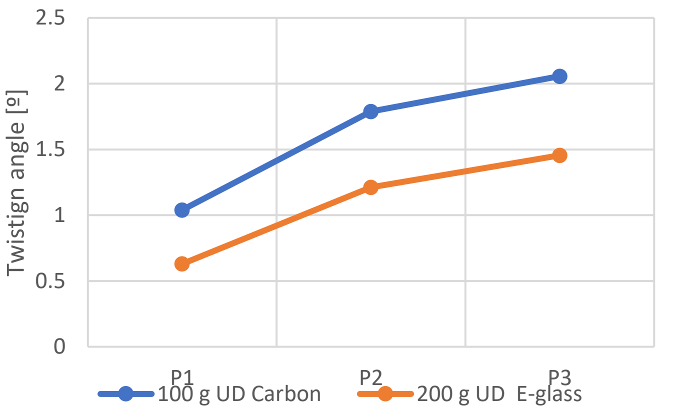

Figure 20 - Variation of twisting angle with fiber material

8. CONCLUSIONS

The study presented here coupled the hydrodynamic and structural analysis conducted before by other researchers into a design tool that is capable of generating different design solutions to improve the fin performance and to reduce development and experimental costs and time.

The previous FEA design tool (Nascimento 2017) was corrected and adapted for the generation of this design tool. These changes were mainly applied to the fin structural properties and not to the geometry.
The MATAN tool initially developed to transform data from the hydrodynamic research into FE design tool can be used for other studies by varying the geometry data points and functions. The same applies to the design tool. The first parametric study facilitated to select a range of parameters in the following simulations. Unfortunately, there are no available databases giving typical velocities and angles of attack of windsurfing fins, and for that reason the little information found was merely based on previous studies and from information gathered from windsurfing websites and books.

From the parametric studies 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 concluded that the tip deflection is closely related to the hydrodynamic loading as it presents the same curve shape. In terms of twisting angle, this increases up to an AoA of 5 degrees and then starts decreasing. The reaction force behind the decrease of the twisting angle after 5 degrees may be due to the stall angle, which is in that range (5-7 degrees). From a bend-twist simulation using a simple rectangular beam, which was conducted just before the parametric studies, it was concluded that the fin deflects and twists more when the load is not oriented with the fibre alignment. Changing the material of specific plies also has an impact on the structural behaviour of the fin. It may enhance flexibility or not depending on the materials chosen. The material parametric study is not as flexible as the fibre orientation one because the ply thickness varies with the material density. This may require changes to the internal lamination lay-up to maintain fin thickness, which can be time-consuming. An advantage of using the parametric design tool to investigate alternative materials could be to try to maintain the fin mechanical properties while optimising the cost of manufacturing.

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, especially in the combination of the hydrodynamic and structural analysis studies using the same simulating packages. This advancement should decrease not only the simulation time but also increase the accuracy of the model.

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