Composite Design of Dynamic-Stability-System (DSS) Foils For A Mini 6.50 Racing Yacht

SESS6039 - COMPOSITES ENGINEERING DESIGN AND MECHANICS

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5000 words (excluding tables, figures, tables, etc.)

Introduction

The Mini Transat is a bi-annual solo transatlantic yacht race where competitors compete in Mini Transat 6.50 class boats [1]. The Mini 6.50 class is a small offshore monohull racing design, with two different categories of boats: the production series boats and the prototypes. The production series boats (called "serial") have clear and defined rules, so the boats remain simple, safe and accessible to everyone, where high-end and expensive materials such as carbon fibres, kevlar honeycombs are prohibited. Additionally, at least 10 of each production boat design must have been produced in order for it to qualify [2]. However, the prototypes are meant to have more freedom in the design rules to allow new innovations to emerge and therefore aims to have the fastest boat of the fleet, with the only requirement being that they must be 6.5m in length [3]. This report focuses on the prototype class where an unlimited number of hydrodynamic control surfaces are allowed, unlike the serials which are restricted to 3 appendices (1 keel, and 2 rudders).

The use of high-end composite materials within the prototype division, such as carbon fibres, allows new innovations in the class. In particular the development of new appendices, such as foils. Currently the two most common foils are T or C foils, which allow the craft to be fully foiling, and Dynamic-Stability-System (DSS) foils, which do not allow the craft to be fully foiling. In this report, a DSS foil is considered.

A DSS is a hydrodynamic lifting surface which uses a retractable hydrofoil that deploys to leeward and creates enough lift force to provide a significant increase in stability, whilst allowing there to be a reduced wetted surface area of the hull to decrease the resistance [4]. Although the overall design is simpler than a T or C foil, a DSS system design remains challenging, where innovations and high-end engineering analysis are required. An example of a DSS system on a Mini Transat 6.50 is shown in Figure 1.

Figure 1: DSS foil equipped Mini 6.50 [20].

Aims and Objectives

The aim of this report is to investigate the construction of a Dynamic-Stability-System (DSS) foil for a Mini 6.50 offshore racing yacht. This will be achieved through the following objectives:

- Determine the loads experienced by a Mini 6.50 DSS foil, and the desirable failure modes.
- Determine how the chosen fibre orientations in the foil affects the adaptive nature of the foil.
- Determine the required final composite layup
- Determine the manufacturing and implementation method of the foil.

The scope of this report is limited to the manufacture of the DSS foil only, meaning that the foil deployment and retracting system will not be including in the structural and manufacture analysis.

Group Roles

Cameron:

- Determination of the DSS foil design, loads, and desirable failure modes. Consideration of End-of-Life.

Louis:

- Implementation of the DSS system within a Mini 6.50, and the associated maintenance and repair aspects.

Andres:

- Structural analysis, manufacturing description and costs discussion.

Design Requirements

DSS Foil Design

The Mini 6.50 class rules state that appendages, defined as 'rudders, daggerboards, foils, fin and any other device aspiring to create a hydrodynamic lift', must be able to fit within the maximum beam of 3m [5]. However, in the deployed state, they can exceed this value.

A DSS foil is a continuous foil meaning the longest the foil can be is 3m, as when retracted it must be able to sit within the 3m beam restriction. It has been assumed that in the fully deployed state, the foil extends 2m from the hull. This means that 1m of the total foil length will remain inside the hull and will support the extended portion of the DSS foil. This is shown in Figure 2.

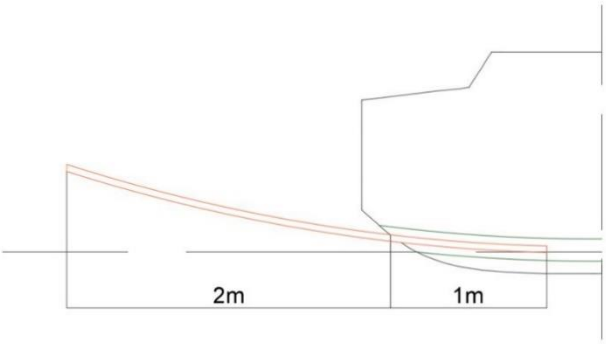

Figure 2: DSS Foil Length

Figure 3 shows a DSS equipped Mini 6.50 on its trailer. As the size of the boat is known, it is possible to estimate the chord, thickness, and likely section shape of the foil.

Figure 3: DSS Equipped Mini 6.50 [20].

From the images the chord was estimated to be 0.4m and the thickness 0.05m. Additionally, the foil shape was shown to likely be a NACA 6412 (shown in Figure 4).

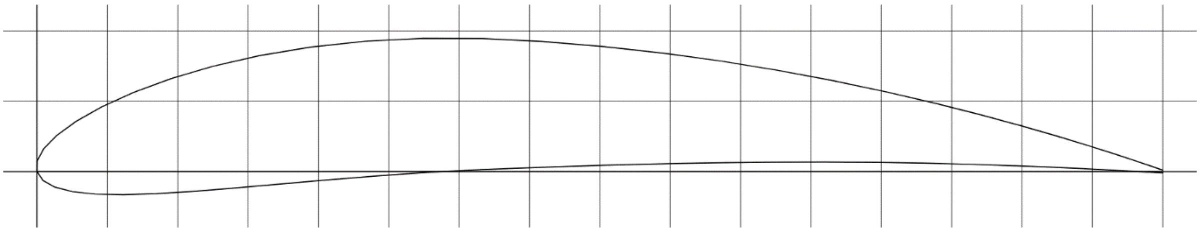

Figure 4: NACA 6412 Profile [19]

Foil Loads

It is assumed that the maximum load experienced by the foil will be maximum weight of the boat, which is 1000kg. In order to facilitate more simple analysis, the strength and response of the foil is going to be assumed to be mostly (80%) dependent on the monolithic core. Therefore, in reality the response may vary slightly.

It is worth noting that for a NACA6412 foil with zero angle of attack, in order to produced lift of 10000N (equivalent to the 1000kg boat weight) a speed of 15 knots is required. However, as the foil location if closet to the water surface, at higher speeds, when the craft is planing, the foil will be at or just above the water surface. This means it will no longer be loaded and producing lift. This supports the assumption that the maximum load experienced by the foil will be the maximum weight of the boat.

In order to perform analysis of the monolithic core, this monolithic core will be treated as a cantilever beam. This is because the foil can be treated as being fixed where it exits the hull. Treating the foil as a cantilever beam allows the problem to be simplified so that CLPT can be used for analysis. The process of simplifying the problem is shown below:

1. It is assumed that the maximum 9810N lift force (1000kg x $9.81ms^{-2}$) would act as a uniform distributed load. As shown in Figure 5.

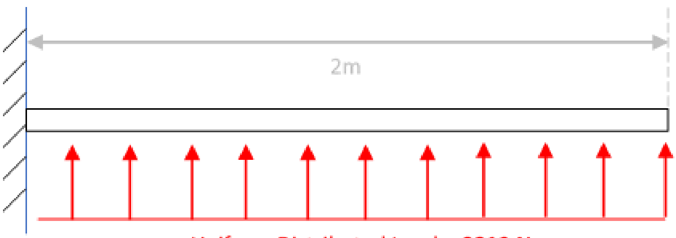

Figure 5: Uniform Distributed Load on Foil

2. It is then assumed that the bending moment (BM) along the length of the beam will vary according to the equation:

$$M_x = {wx^2}/{2}.$$

Where x is the distance along the length of the beam.

The is allow the BM to be plotted along the length of the beam. The red arrow indicates the direction and position of the maximum BM This is shown in Figure 6.

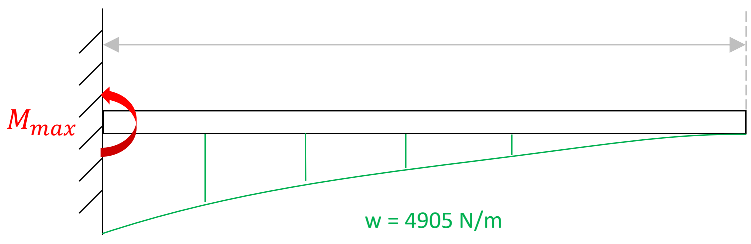

Figure 6: Bending Moment on Foil.

3. It can be seen that the BM is highest at the point where it is fixed as it exits the main hull. For this analysis, the maximum BM will be taken as being present along the whole length of the foil, whereas in reality it can be seen that the bending moment reduces as you move to the end of the foil. The maximum BM is given by:

$$M_{max} = {(4905) \times (2)^2}/{2} = 9810\ Nm$$

It is assumed that the drag force on the foil is much less than the lift force, and that if the foil is designed for the high lift force, it will be sufficiently strong to withstand the drag force acting on the foil. However, this is an area that further analysis will be required in, especially given the desirable failure mode outlined below.

It should be noted that the design of a DSS foil is both a stress and deformation driven problem, as the foil must be designed to withstand the loads that is must produce, whilst also ensuring it does not deflect large amount, as this will reduce performance.

Desirable Failure Mode

The failure of the DSS foil would have a significant impact on the performance of the Mini 6.50, and that if not properly designed, could have a catastrophic impact on the structural integrity and watertightness of the boat.

The most likely cause of failure of the foil will be due to a collision with an Unidentified Floating Object (UFO). As Mini 6.50s spend continuous long periods of time (up to a month non-stop) at sea, their chance of encountering a UFO is higher. To minimise the impact to the main boat when there is a collision with a UFO, it is desirable for the foil to fail at the point where it enters the main hull. As the foil casing within the hull is watertight, failure at this point will result in there being no impact on the structure or watertightness of the boat.

As the foil is tightly secure at the point where it enters the hull, hitting a UFO would result in a shear force being applied to the foil at this point. As such, the foil structure should be designed so that it can withstand the shear forces present during normal operation due to the drag on the foil, but will fail for shear forces greater than that.

Structural Design and Investigation of the Influence of Different Composite Layups

Material choices and composite layup can change a foils behaviour under load and improve hydrodynamics by passive adaptation. The structural beam on the inside of the foil will have the most significant effects given our assumption that it will withstand 80% of the total load, which in this case would be 80% of the maximum BM on the foil. The ideal layup configuration to decrease the angle of attack when the foil is subjected to this maximum BM was investigated. The chosen of laminate fibre orientation were:

$$[0°, -30°, 0°, -45°]_n \quad \text{n=80}$$

Where n means a repetition of the laminate in the same direction, with n=80 the resulting laminate has 320 layers. For example, if n=2 the resulting laminate would be $[0°, -30°, 0°, -45,\ 0°, -30°, 0°, -45°]$.

Anti-symmetric unbalanced laminates, like the one chosen, are prone to twist bend couples. With the simplified load case having a moment applied in the x-direction, the resultant bend along the span will have dampening properties and increase comfort as the foil "arcs" when loaded. This curvature can be observed by applying a tensile load on two laminates or a moment on a single laminate. Figure 7 represents the spanwise deflection of the foil in blue, to obtain deflection a constant moment and resultant k_x value is assumed for the entire length, giving a radius of curvature. Although assumptions for CLPT do not apply in the chord direction (L/t ratio smaller than 20). Figure 8 shows the predicted decrease in angle of attack when under load in red and the black line represents the target reduction in angle of attack by 5°. Before moving to a detailed design, First Order Shear Deformation Theory (FSDT) and FEA for the beam should be analysed to validate the precise change in angle of attack. Having the -30° and -45° layers is critical otherwise a positive angle for these laminates would results in unwanted bending downward increasing the angle of attack.

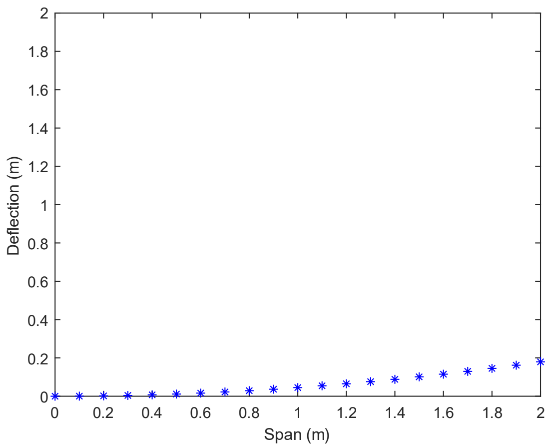

Figure 7: Foil span deflection under load.

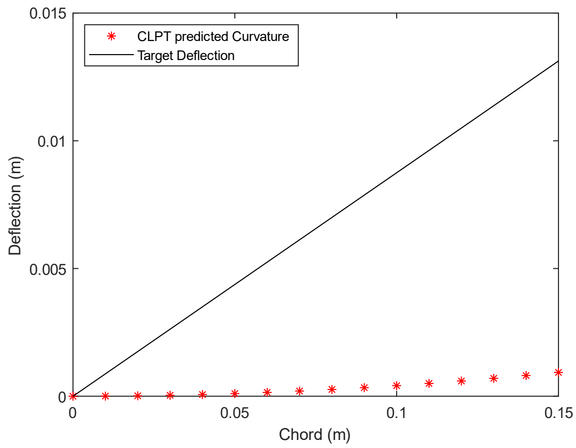

Figure 8: Angle of attack passive adaptation

Once appropriate laminate configuration for the desired twist-bend couple was selected, it was necessary to select materials. The bottom of the foil would be subject to high tensile loads and the top would be in compression. Carbon fibre makes the best option for this application given the reduced space in the NACA section, our loaded beam is restricted to a rectangle of 4 by 15cm. Flax was designated as a structural aide and second moment of area builder between two carbon plates. Flax will maintain the composite behaviour and contribute to the bend-twist couple. The final sandwich is composed of a 1 cm layer of pre-preg carbon followed by 2 cm of pre-preg flax and a final 1cm layer of carbon, both materials with unidirectional patterns. Table 1 provides necessary material properties to evaluate the beam with CLPT.

Table 1: Composite properties for selected Flax and Carbon pre-pregs

Property	**Gurit SE-75 Pre-Preg UD Carbon** [6]	**Evopreg AmpliTex Pre-Preg UD Flax** [7]
$\boldsymbol{E_1}(Composite)$	153 MPa	30.4 GPa
$\boldsymbol{E_2}(Composite)$	5.6 MPa	4.6GPa
$\boldsymbol{G_{12}}(Composite)$	2.57 MPa	2.0GPa
$\boldsymbol{v_{12}}(Composite)$	~0.28	~0.28
$\boldsymbol{Ply\ Thickness}$	0.125 mm	0.125 mm*
$\boldsymbol{X_t}(Fibre)$	2722 MPa	269MPa
$\boldsymbol{X_c}(Fibre)$	1422 MPa	166MPa
$\boldsymbol{Y_t}(Fibre)$	39 MPa	26 MPa
$\boldsymbol{Y_c}(Fibre)$	~117MPa**	~ 111 MPa**

*Assumed value, **Compressive failure assumed to be matrix failure rather than fibre.

Half of the ply's are oriented in the 0° direction this is to aid in the loads parallel to them, the intercalating layers have a slight angle of -30° and -45°, this was done so that an alternating ply sequence would allow for efficient manufacturing and also not fail in the 2-direction. Figures 9 and

10 display the stress experienced by each lamina. The horizontal lines represent the border of flax and carbon.

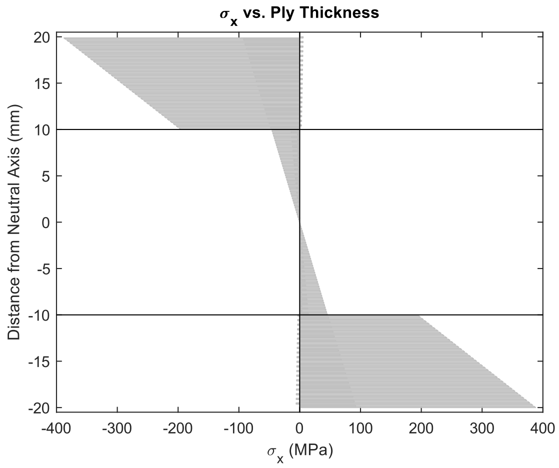

Figure 9: Stress in the x-direction (along foil span)

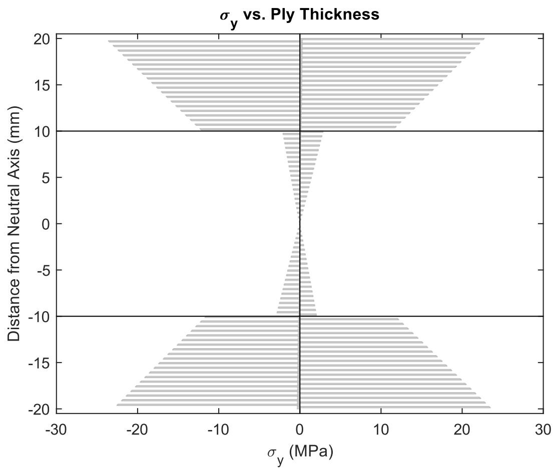

Figure 10: Stress in the y-direction perpendicular to fibres.

Figure 12 shows the stress in the principal direction parallel to the ply's where there is no risk of failure, green bars mark fibre failure loads for flax in both tension and compression. Red bars mark failure loads for carbon. In Figure 11 stress in the direction perpendicular to the fibres we can see at the bottom where carbon is in tension the outer laminates are closer to failure however still have a reasonable margin.

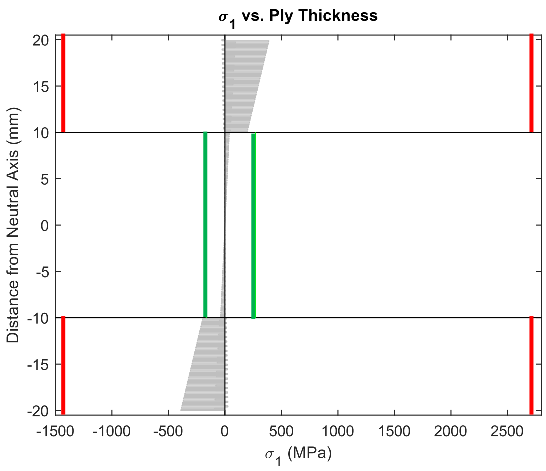

Figure 12: Stress parallel to fibres 1-direction

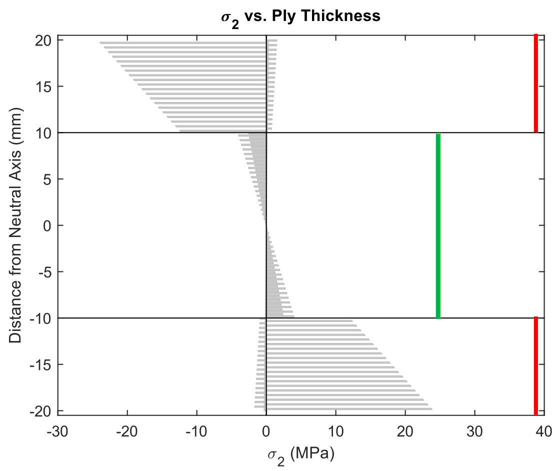

Figure 11: Stress perpendicular to fibres 2-direction

It should be noted that no maximum strains or maximum shear calculations were completed at this stage of the design process, further analysis should be taken to ensure the laminate does not fail for these criteria. Furthermore, flax and carbon were assumed to have the same ply thickness, a study to evaluate different thicknesses should be conducted in future work.

Manufacturing Process

Given the high expected loads along the foil span and the limited volume available within the foil section pre-preg carbon fibre is necessary for manufacturing this DSS arrangement. Four aspects of the layup will be discussed, pre-preg infusion of Carbon and Flax, vacuum infusion, and the autoclave baking process. Lastly assembly and post-curing corrections are explained.

Foil Cross Section Configuration

Given the Figure 13 below. The foil is made of 5 principal components: top foil shell, bottom foil shell, structural monolithic beam, fore shear plate and aft shear plate. The spaces between them are filled with Araldite-2015a adhesive. This specific adhesive was chosen due to its ability to bond with dissimilar materials and high shear modulus, given that the top shell and bottom shell will be in shear due with each other when bended. To further aid shear bonding the V-shaped sections along the leading and trailing edges were added, lap shear strength tests and evaluations of the stress field along the adhesive should be conducted in future work, using the decided manufacturers products and same surface finish. With crosses we can see the PET core, this one can be either machined or cut to size in linear sections with traditional woodworking tools. Although simpler to manufacture, an expanding foam core would make disposal more difficult.

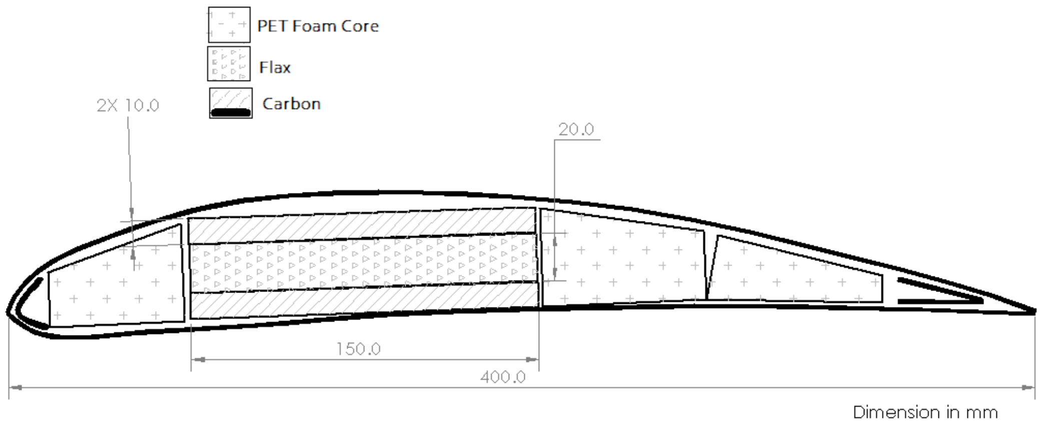

Figure 13: Cross sectional view of the foil's internal architecture

*Carbon is represented both by the diagonal lines in the structural beam and by solid black along the top and bottom shells.

Structural Beam

The load beam is to be manufactured with pre-preg carbon and pre-preg flax, to ensure maximum utilisation of the materials they are ideally cut with a CNC Drag knife (To avoid the repetitive task of cutting 320 sections), there will be 160 straight layers and two different sets of 80 layers cut into a rectangle at their specified angle. A mould should be used to obtain the correct curvature (or flat section). All layers should for optimal properties the beam should be cured in an autoclave at 80°C for 6 hours [6]. Vacuum is necessary to maintain alignment as there will be induced curing stresses during the autoclave process, additionally the vacuum will ensure no voids are present in the laminate.

Since both the flax and carbon matrix combination can be cured at the same temperature this should be a single curing operation. For an optimized structural integrity, the temperature in the autoclave should be increased to 110°C in the last 2 hours of curing [7]. To ensure that the beam will properly bond with other components peel ply should be placed along top and bottom surface to produce abrasions for the adherent.

Foil Shells and Edge Plates

The foil shells being the outermost section of the beam will have to take significant strains due to bending. They will also be subject to hydrodynamic loads, for this reason a study should be conducted to determine monolithic laminate thickness and if using High-Elongation Carbon (HEC) is the best option [6]. For convenience and to minimize the number of manufacturing process' the leading edge and trailing edge shear plates will be made with the same method. If CFD indicates that a cuadriculated surface finish could create parasitic drag, chop strand mat could be the first layer along the mould surface to produce an even finish. All internal surfaces should have a peel-ply finish or abrased via sandblasting.

Assembly and Post Processing

Figure 14 below illustrates the components in the assembly. Starting with the bottom foil shell, liberal amounts of adhesive should be placed along the surface and adjacent components should be aligned before Araldites 2015-1 45minute pot life. Having all surfaces coated with adhesive the top surface should be positioned, excessive adhesive coming from bond lines is expected, minimizing voids is critical because Araldite 2015-1 will shrink in volume by 7% when curing [8]. To maintain geometric stability a clamping jig should be used during the curing of the glue. When assembling PET Core notches may be cut to allow for bending in areas with curvature.

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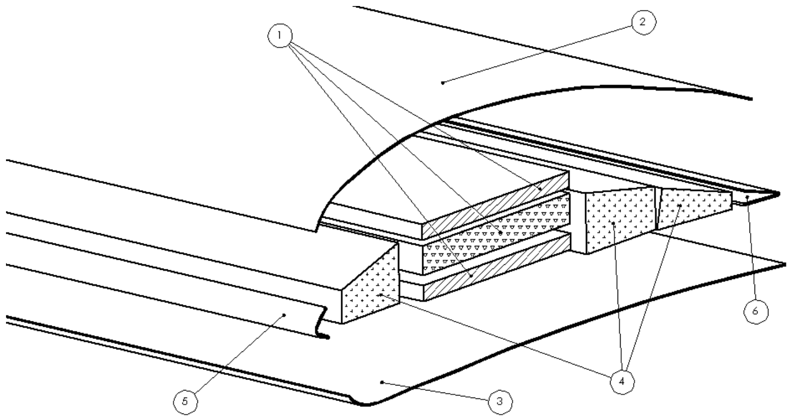

Figure 14: Exploded view of foil components

Legend: 1. Structural Beam and sub-components, 2. Top Foil Shell, 3. Bottom Foil Shell, 4. Structural PET Cores, 5. Leading Edge Shear plate, 6. Trailing Edge Shear Plate.

After all moulding process' excess fibres and resins should be trimmed with composite specific cutting tools to avoid creation of impurities. Special care must be provided to the trailing edge where a sanding will be necessary to give the foil a sharp hydrodynamic exit for flow. To obtain maximal durability the hydrofoil should be coated with a gelcoat-based finish.

Installation of DSS Foils Within a Mini 6.50

Like the Mini 6.50's spirit, the installation for the DSS system attachment to the hull needs to remain simple, cost-effective and accessible. A system with a low number of parts and structural integrity is therefore required. This section introduces a first idea's iteration of how the structure can be implemented within the hull. The only constraints are the materials, which were chosen according to the rules [5]. Another constraint concerns the longitudinal location of the DSS system, as the keel and the mast are primary structures that cannot be modified. Below is a picture of a typical interior for a Prototype Mini 6.50, with the canting keel mechanism, aft of the mast bulkhead, supporting the compressive load applied from the mast and the rig. Therefore, these two key elements cannot be moved, so the DSS system is chosen to be located forward of the mast bulkhead to remain as close to the LCG as possible.

Figure 15 Interior of a Proto Mini 6.50, showing canting keel pendulum mechanism [8]

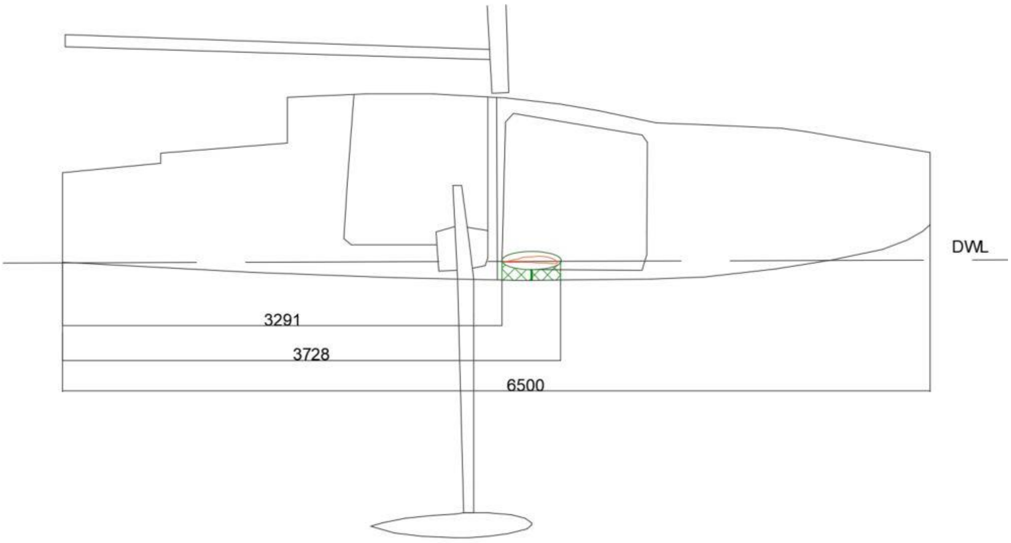

Figure 16: Longitudinal position of DSS

Supporting structures need to be considered as well to support the DSS system and attach it to the hull. A structural-monolithic-carbon foil casing is therefore designed and laid up onto the interior's shell to protect the foil and provides the watertightness. Because the maximum righting moment is found to be at the junction between the foil and the hull, internal structure such as bulkheads and transverses are added to increase the structural integrity of the system. Moreover, only the DSS foil needs to be removed for maintenance, so for the sake of structural integrity, the foil casing and the associated supporting bulkheads are chosen to be fixed and non-removable. Therefore, they are all laid-up and bonded together using adhesive such as Araldite® glue, and wet layup CFRP overlapping. Because this structure would become part of the primary structure, more engineering analysis through FEA would be required for further research to optimise the structure, by reducing the weight and the quantity of materials used, while meeting the design loads requirements generated from the bending moment and shear forces of the foil. Figure 17 shows the first design iteration of the foil support structure.

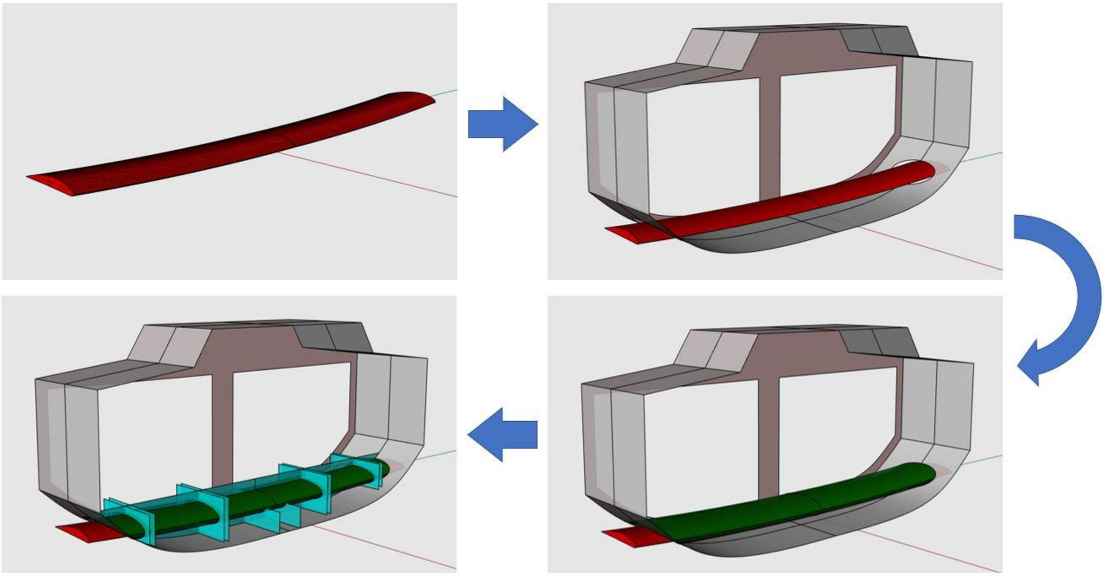

Figure 17: Flow chart diagram of the DSS supporting structure. Looking from forward to aft, the rear bulkhead is the mast bulkhead.

Finally, the last installation required for this DSS system is the pulley system that will control the deployed length of the foil. A maximum length of 2m can be deployed, as it would create sufficient lift to support the vessel's weight. However, the advantage of this system is that the lift can be controlled through the chosen submerged surface area. As shown below, a system of rubber wheels (in cyan) located in between the foil casing and the foil on both sides control the sliding within the foil casing. The central wheels are connected to a sealed bearing system that will allow through a system of pulleys and control lines to rotate them and slide the foil. The outer wheels are set to give direction and compressive forces so the foil remain still and does not slide out of the hull. All the wheels are fixed and do not move transversely.

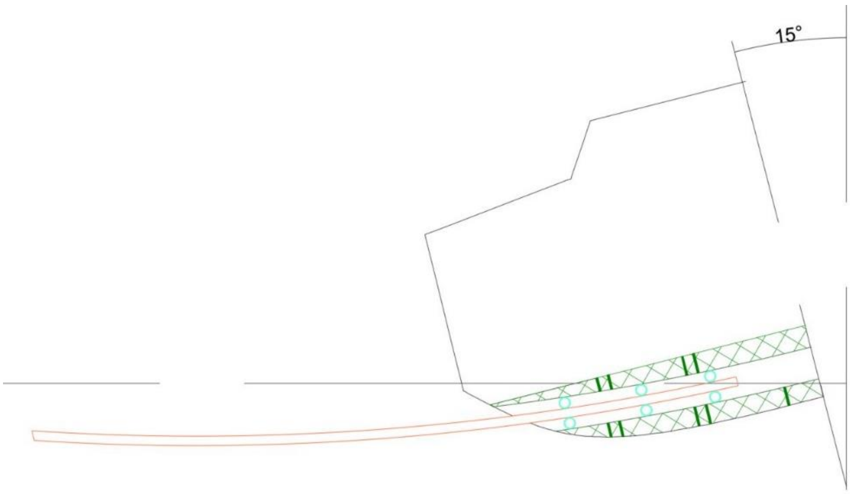

Figure 18: Deployed DSS system and its deploying system at 15° heel angle. Rubber wheels are in cyan.

Cost

Manufacturing the foil with composites is the most economical route in low volumes, however accurately predicting cost requires selecting specific material vendors and service providers which will vary widely by region and number of units produced.

When conducting a detailed cost estimate the minimum expenses it should include are, cost of raw materials (carbon, flax, PET core, adhesive) and excess, rate for drag knife CNC, rate for Autoclave price of necessary vacuum bagging fittings necessary, vacuum bagging sheet, area of the part and perimeter of the part (Tacky tape), cost of tooling (moulds and jigs) and cost of labour and the expected amount of time required to fabricate [9].

If industrially produced the expected cost of the foil to the consumer is ~£6000 based on a geometrical comparison to similar available equipment (Nacra 17 Foil [10]). Given that the Mini 650 prototype class is experimental it is unlikely that a foil could be mass manufactured hence making an aluminium alternative impossible. The manufacturing process for aluminium foils is extrusion. Where dies for a 40cm chord would be costly and minimum production runs due to heavy equipment necessary would likely exceed demand. Aluminium DSS systems do not exist, hence a market demand study and a cost estimation for the novel aluminium foil could prove them successful if enough boats are interested.

Maintenance and Repairs

As mentioned earlier, the most likely mode of failure of the DSS system is an impact at high speed with an UFO. However, other common modes of failure due to continuous loadings and fatigue, such as cracking, fibre debonding, delamination and fibre breakage can occur while being in service. These kinds of failure will not yield to an entire system failure but needs to be promptly assessed before they become a significant issue.

Damage Identification at sea

As the foil cannot be taken nor inspected while at sea, three watertight maintenance hatches as shown below are set on the casing (starboard, port and centreline) to easily access the foil and the rubber wheel system located in between the foil and the casing. Thorough engineering analysis needs to be carried for the casing as fibres would be cut at the hatch's location, affecting the structural integrity.

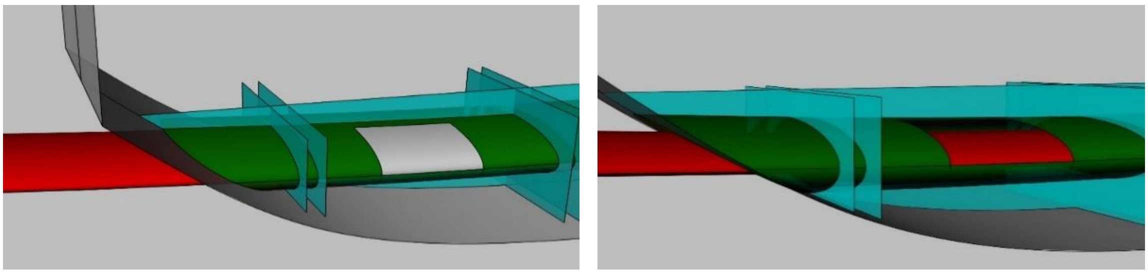

Figure 19: Starboard maintenance hatch (in grey) located on foil casing (green). Closed (left) and open (right)

Equally, these hatches also help to take the foil out for winter maintenance or when lifting the boat on land as rubber wheels can be removed to reduce the compressive load that stops the foil from sliding. Internal fibre or matrix's breakage in composite materials can be complicated to detect by eye so Non-Destructive Techniques (NDTs) have been developed to assess the damage of a composite structure. However, some of these techniques are expensive and need an experimental setup so they cannot be performed when the structure is in service.

Non-Destructive Techniques (NDTs)

In [11], eight different techniques have been found to be useful when assessing the damage within a composite structure. They are listed below:

- Microwave detection (High-Cost)
- Acoustic Laser Detection
- Infrared Thermography (IRT)
- Digital Image Correlation (DIC)
- Piezoelectric transducer methods (PZT)
- X-ray Tomography
- Ultrasonic Testing (UT)
- Strain Gauges and Fibres Optics sensors
- Acoustic Emission Monitoring (AE)

Because Microwave detection, Acoustic Laser Detection and IRT happen to be a high-cost solution, these NDTs should not be considered for a small-budget Mini 6.50 maintenance check. Moreover, DIC, PZT, X-ray Tomography require heavy experimental setups and/or skilled operators, therefore cannot be used by a Mini Skipper due to their lack of accessibility.

Ultrasonic Testing is a broadly-used, low-cost and efficient NDT as it enables to visualize the projection of the transmitted ultrasound through the composite. UT allows to detect a variety of flaws, such as cracks, voids, disbonds and delamination [12] as well as their size and depth location in the structure. No health-hazards are associated with this NDT so even the skipper or any shore team member can use it. Some limitations are however to consider, as UT requires time to assess a whole structure (point scan) and coupling liquid (water) as soundwaves propagate faster in water. Moreover, a skilled operator is required to read the results and set-up properly the damage assessment. Though the advantages significantly outweigh any potential drawbacks, so this technique would be appropriate to assess damage for the foil, the foil casing and the internal structure such as the bulkheads.

Finally, Acoustic Emission Monitoring is also an alternative to assess any damage on the DSS system as it only requires sensors that are adjusted on the structure which convert the stress waves into electrical signals, as in UT. However, it is a relatively slow method, as sensors are usually located around where the operator thinks there is a damage. Assessing the whole structure would therefore take time.

Repairs

One of the advantages of composite structures is their ease of repair. Some repair procedures are outlined below [13]. Most of these methods are usually best-suited when using vacuum bags, as it would reduce the number of voids within the repaired structure. Preparation of the surface is also very important as surface contamination can affect the structural performances.

i) Laminated Patch: most common, simple and low-cost repair that needs the least preparation. This technique is broadly used for "field repairs". However, this usually needs to be retrofitted later with a correctly prepared permanent repair.

ii) Stepped/Tapered Scarf joint repairs: one of the most favoured types of repairs as they usually recover most of the stiffness, strength, flushness and stress-distribution due to the bond area, that increases as the scarf angles increases. Indeed, this joint usually attains its ultimate strength when the average shear stress reaches the adhesive yield stress [14].

iii) Bolted plates: this method, as the patch repair, is usually used when repairing the structure on the field, while being in operation.

iv) Resin infusion/injection: According to [13], this method restores the original part to near-design compressive and shear strength through injecting low viscosity adhesive into a delaminated structure. This method requires more equipment.

Most of these repair procedures rely on the quality of the adhesive, as it becomes a shear-strength driven problem. Therefore, for the DSS foil, as the most expected failure is an impact at high speeds, the outer-layers would be damaged and a tapered scarf joint would be best suited to recover the initial materials properties, where the longer the scarf angle, the better the joint. Common scarf angles in the marine industry happen to be 40-100:1, meaning typical scarf lengths are 40 to 100 times the thickness of the part being scarfed/repaired [13].

Sustainability and Environmental Impact

It is important to consider the end-of-life options for the carbon-flax composite DSS foil outlined in this report. This is because a prototype Mini 6.50 will likely have a relatively short useful life span, due to the rapid advancements in technologies and design, which means that current boats will rapidly become uncompetitive compared to new ones.

The fact that the DSS foil is made from a number of different materials makes recycling difficult unless the foil is able to be split into its constituent materials. If it is assumed that biodegradable epoxy bio resin is used, then recycling becomes much easier. The flax fibres and bio resin are both biodegradable and as such will naturally break down. In order to separate the carbon fibre from the bio resin, it is likely the resin will have to be burnt off; however, this is a fairly energy intensive process and the fumes created do contribute to global warming [15]. The carbon fibre which is left could then be reused in products such as non-woven carbon mat [16]. If the carbon and resin is not separated, then it will have to go to landfill, where it will not biodegrade. If the foam it used is a Polyethylene Terephthalate (PET), then it is 100% recyclable [17]. The quality of adhesive will be small when compared to the other components, and as such the effect is assumed to be negligible in the end-of-life processing. However, it is clear that if the adhesive used were biodegradable, this would be advantageous. Therefore, it is possible to largely recycle the DSS foil, though it is still a labour and energy intensive process. As such, the ease and feasibility of recycling is heavily dependent on the resin system and core material chosen. Finally, a DSS foil for a Mini 6.50 would only be manufactured in very small numbers, most likely just a single one-off foil. As such, the scale of the environmental impact would always be relatively small.

In the future a full Lifecyle Assessment (LCA) should be completed, to gain a better understanding of the environmental impact that the foil has. A LCA would also incorporate the production of the raw materials, manufacturing, and operation of the foil, not just its end-of-life.

It should be noted that extruded aluminium, a possible alternative construction method to the composite ones outlined, would be 100% recyclable, and would also be easy to recycle when compared to the composite option. That being said, creation of aluminium from raw materials is a highly resource intensive process [18].

Conclusions

The composite structural design and engineering of a Dynamic-Stability-System (DSS) foil was analysed in this report to optimise the final layup and its influence on the overall adaptive shape. A preliminary load analysis was performed which found the maximum bending moment to be 9810Nm. It was also found that 2m foil with a NACA6412 section was the most suitable for a Mini 6.50 DSS foil.

A composite layup structure of $[0^o, -30^o, 0^o, -45^o]_n$ (where n=80) was found to result in the desired bend-twist couple and resisted the expected loads. The hybrid 1cm carbon, 2cm flax, 2cm carbon, structural monolithic beam was found to be suitable using CLPT. However, further analysis using FSDT and FEA would be advantageous, as it would remove the assumptions and limitation within CLPT. Moreover, this further analysis would be able to account for the drag on the foil and the resultant shear force. This would also allow for more analysis of the desirable failure mode.

The installation of the DSS foil was analysed to produce a feasible and lightweight structure that will maintain the foil in a tight position. This system was found to be reliable as a small number of parts is required, and maintenance and repair would be easily done by the skipper or the shore team. For structural integrity, the overall engineering system is part of the primary structure around the mast bulkhead. Further FEA would be required to ensure the feasibility of this structure and optimise its weight.

Regarding maintenance, although several methods were highlighted, only the Ultrasonic Method happened to be both efficient and cost-effective, and the “beam” shape of the foil allows repairs to be easily performed. However, the type of the repair needs to be thoroughly chosen so the structural performance of the foil is not affected. The finish of the surface should also be considered for hydrodynamics performance.

Finally, it was found that nearly all of the foil is recyclable if the time and energy is taken to split the foil into its constituent parts. However, to get a better idea of the environmental impact that the foil has over its entire life, a LCA should be completed in future. Although difficult to give an accurate answer there is an idea of the price range for this foil, it will be lower than that of aluminium due to the low volume of production.

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