Optimisation of a Composite Sailing Wing for a Racing Catamaran

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Abstract:

The development and optimisation of a rigid sail, used in the International C-Class Catamaran Championship (ICCCC), in Falmouth, 2013 is here presented. Two major iterations were done. Firstly, the whole skin is structural. Then, in a hybrid solution, part of the skin was replaced by vinyl film. The whole catamaran was developed and manufactured in Optimal Structural Solutions Lda.

The main focus was to conceive a rigid sail with an exceptional performance for racing purposes. As this sail is rigid, it behaves in a similar way as a wing. This type of sail is more efficient than a conventional one. Due to time constraints, only linear analyses were performed and a unique load case was studied, deemed as most critical (wind at 40kt, 45º from bow).

Structural optimisation was carried out with OptiStruct®, used to determine the laminate of the sail. Initially, all the skin was taken as structural. This lead to a very heavy solution and it was understood that a moderate thickness in the sail skin is needed due to the great span. Therefore, despite using sandwich composites, the aft of the main plane and flap were replaced by vinyl film.

Pre-impregnated carbon fibre and foam were used. Whenever possible, sandwich configurations were used for achieving a greater moment of inertia, with a small increase in the laminate mass.

The sail skin was not damaged during the competition. However, nonlinear analyses and a comprehensive loading envelope should be considered in the future.

Keywords: FEM, ICCCC, laminate composite materials, structural optimisation, sandwich composite materials, CFRP, OptiStruct®.

1. Introduction

The motivation of this work was to develop a close to optimum concept of a catamaran rigid sail for racing purposes. As a race is a competition, thus, for being ahead of the others, each team seeks not only the excellence of sailing but also the best catamaran, by making use of cutting-edge engineering and materials.

This sail was developed by Optimal Structural Solutions Lda., and attended the ICCCC[1], in September 2013, Falmouth, UK.

For having an outstanding performance during the competition, the most lightweight solution is sought, while being structurally reliable. For being light, the catamaran is able to accelerate quicker because the mass to be accelerated is smaller. Likewise, there is an enhanced capability to be manoeuvred, due to the greater influence of the pilots' mass when compared to the catamaran's mass (*i.e.* the centre of gravity is more influenced by the pilots' position if the catamaran is lighter). Moreover, as the catamaran grows heavier, it will sink more, and will become much slower due to the water friction. As reliable, it is intended to be safe and manoeuvrable which can be translated in strength and stiffness requirements, correspondingly.

The desired design will be a balance between mass, whose distribution is related to stiffness, and structural performance. For this project, time is a crucial variable because the sooner the catamaran is ready, the more training hours will be available before the competition. The steps that precede – and lead to – the achievement of a good design are the following (1):

1. formulation of the functional requirements;
2. creating the conceptual design;
3. optimising and
4. detailing.

The first steps for creating the sailing wing are to consider the ICCCC regulations, as geometrical constraints, to infer and investigate the conditions to which the sail will be exposed (for instance, maximum wind speed), and what performance is sought (say desired speed of the catamaran, maximum weight, among others).

Taking into account the previous steps, the conceptual design is created by investigating the aerodynamic loads and choosing a geometry (aerofoil, chord…). In this step, the outer skin geometry closes, as there is the need of freezing the aerodynamic loads. Other geometric features, such as ribs and spars can be changed afterwards, although a first guess should be done at this point.

The following task is optimising the baseline concept, and it is at this point that the present study starts. At this stage, it is crucial to understand 1) what constrains the design (constraints); 2) what can be changed (design variables) and 3) what behaviour is desired in the final solution (objective). This design stage is mainly automated, following adopted optimisation procedures that provide optimal values of certain design variables, considering the design constraints and criteria (load cases, for instance). (1)

[1] ICCCC: International C-Class Catamaran Championship

When the optimisation ends, the final concept of the wing is created, and we have the global laminates defined. The following task is to detail the solution, considering: 1) manufacturing aspects such as the shape of the laminae; 2) the probable need of local reinforcements if any local strength problem is detected. These considerations will turn the concept into a final design, ready for production release. For doing so, it is mandatory to convert the design into moulds and laminating manuals which are used to manufacture the sail.

1.1. Why rigid sails?

Flexible sails have a structural part, the mast, which withstands the aerodynamic loads generated in the flexible parts. Due to the flexibility of the sails, which are made of cloth, these must be triangular because of the attachment at the top of the mast. Conversely, rigid sails have more design freedom, thus, a wing-like solution becomes available. The second has been chosen for our catamaran, as it offers a more effective aerodynamic load, allowing for her to move swifter. The design freedom of a rigid sail is broad; however, the most common solution is to have a structural skin in the front, a film in the rear and interior structures such as ribs and spars. (2) (3)

A rigid sail provides more control over the aerodynamic load, as it almost does not deflect, when compared to flexible sails, made of cloth. Additionally, wing parameters such as camber and aerofoil thickness remain almost unchanged when loaded. Rigid sailing wings also provide advantages that lack in flexible sails: sailing wings skin generally can withstand both bending and membrane loads while being very slender and light.

1.2. Why carbon fibre?

As the sail generates a considerable aerodynamic load, carbon fibre reinforced plastic (CFRP) was set as the main component due to its relatively low density and high strength. The density of this composite material is around 1.5g/mm^3, which is much less than aluminium. The Young modulus varies very much depending upon many factors such as the fibre orientation. A value of 200GPa (comparable to steel) is an achievable Young modulus in the fibre's direction when using unidirectional fibres (UD). As for the woven, it is common to have around 60GPa in both planar directions, which is comparable to the stiffness of the aluminium.

1.3. Contribution to the aerospace engineering

Although this study addresses a naval application, the optimisation of a CFRP component is highly applicable in the aerospace industry.

In the aerospace industry, the savings on the weight are of high interest because it leads to fuel reductions, which impacts both on the environment and in the financial costs per trip. The use of CFRP in structural components on aircraft, most of them being formerly composed of aluminium leads to weight reduction and is an example of the applicability of this study on the aerospace engineering. (4) (5)

1.4. Assumptions

There is the need of assuming a number of suppositions due to the complexity of the problem:

- both main plane and flap do not have twist;
- dihedral and sweep angles are zero;
- the main plane has only one aerofoil (which is symmetric);
- the flap has only one aerofoil, slenderer than the main plane aerofoil, also symmetric;
- lift and drag coefficients of the wings at all span are equal to their aerofoil lift and drag coefficients, respectively;
- main plane and flap are considered as infinite wings (infinite span).

Other hypotheses, more related to the FE modelling were also established:

- fluid-structure interaction is not taken into account;
- the magnitude of the deformation is small when compared to the size of the structure;
- contact between components is not considered;
- the materials have a linear elastic behaviour.

The prepositions in the list above motivate the use of only linear static analyses except for modal and buckling analyses. As for them, eigenvalue problems were set up. Thus, non-linear analyses did not take place within this work.

2. Optimisation procedure

Our optimisation procedure is used for seeking a very good solution, in terms of objective, while obeying all restrictions, by varying the quantities of prescribed variables. All utilised methods are numerical, which is an iterative process that begins with a user-defined initial guess. Instead of obtaining an exact optimum, the procedure finishes when certain criteria are met, indicating that the current iteration is close enough to the true optimum. (1)

Four terms should be clarified hereupon for understanding the following paragraphs. These are the following (1) (6):

- Response

Responses are employed when setting objective and constraint functions. These are structural responses or a combination of structural responses calculated in the finite element analysis. The displacement of a node, the first eigenfrequency of a modal analysis, the mass (or volume) of the structure are typical examples, among others.

- Objective function

The objective of an optimisation problem is usually described by a unique expression, which is a function of the design variables. An objective function can be, for example, the mass of a structure, its compliance, or even the displacement of a node. The aim of this optimisation problem is to find the minimum of this function.

• Constraint function

Seeking the minimum of the objective function may not be sufficient to obtain a feasible design. The problem should thus be constrained. These constraints are also function of the design variables. Typical constraint functions can call, for example, natural vibration eigenfrequencies or the displacement of a node.

• Design variable

The design variable depends upon the type of the optimisation procedure being performed. It can be, for instance, the thickness of a component. The way of seeking the objective, obeying the constraint functions, is to change these variables.

The aim of the optimisation throughout this thesis is always to find the minimum of a single objective function (mass, compliance or displacement, for example). The following equations describe this type of optimisation problem, in which *n* is the number of design variables and *m* is the total of constraint functions:

$$\min\left(f(x_i)\right), \qquad i = 1, 2, \dots, n \tag{2.1}$$
$$g_j(x_i) \leq 0, \qquad i = 1, 2, \dots, n, \quad j = 1, 2, \dots, m \tag{2.2}$$
$$x_i{}^L \leq x_i \leq x_i{}^U \tag{2.3}$$

With equation (2.1) we seek the minimum of the objective function *f*, which is a function of the design variables vector $x=(x_1,\dots,x_n)$. These design variables should have upper and lower bounds (equation (2.3)). For example, the thickness of a structure cannot be less than zero nor greater than a prescribed value. The optimisation is subjected to constraint functions, described in equation (2.2).

All of the optimisation work was done using exclusively RADIOSS™ (Bulk Data Format) and OptiStruct®. These two programs are solvers that analyse structural components using the finite element method.

The sailing wing was meshed using 2D elements. The combination of all skin nodes, also called grid points, creates the shape of the wing as it defines chord, aspect ratio, taper, among others. For this reason, these nodes cannot be moved or replaced because it would lead to a different aerodynamic behaviour.

Thus, among the optimisation methodologies available within OptiStruct®, the ones where the location of the nodes is a design variable were not used. Methodologies using the SIMP method (7)[2], as the OptiStruct® topology optimisation, was also discarded. This method avoids smooth skin thickness transitions, that are otherwise acceptable and desirable when creating a component by laying up carbon (or other fibres) laminae.

Three methodologies were used: free-size optimisation, size optimisation and ply stacking sequence optimisation. The first methodology is well suited to generate a concept. This concept should be then fine-tuned with the second methodology. Then, a final loop is used for achieving a better performance. The use of these three methodologies in sequence is recommended by the OptiStruct® User's Manual.

The following chart (Figure 1) evinces the adopted procedure.

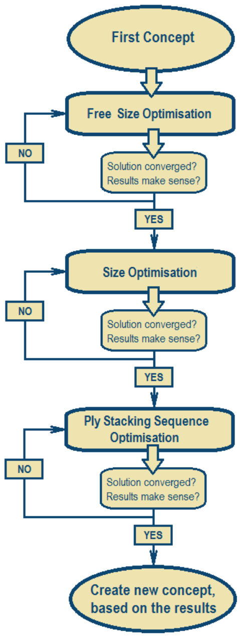

Figure 1 – Optimisation flow chart.

2.1. Free-size optimisation

Free-size optimisation allows 2D (shell) component to vary its thickness between an initial value and a minimum value, typically zero. This initial guess should be, thus, oversize, as the solver will simply remove material from certain elements of the component, as it iterates. The aim of this first methodology is to determine the material thickness at each different orientation, at each location, disregarding the lay-up sequence.

Both material properties (fibre orientations) and geometry (thickness) are simultaneously optimised. The fibre orientations are optimised as the solver chooses the shape and location of the bundles[3].The geometry is optimised as the thickness of each bundle is adjusted.

The solver outputs not only the responses values at each iteration but also a deck file[4] that will be used as baseline in the next optimisation methodology.

It is relevant to note that, rather than defining one laminate per element, in this whole process, each lamina is taken as a whole. Thus, during the optimisation methodologies, each lamina is taken as continuous, providing a better insight of the global behaviour.

[2] SIMP method – Solid Isotropic Material with Penalisation. This method uses penalties in the Young Modulus for intermediate densities. (7)

[3] Here, a bundle is denoted as an unrealistic thick lamina, that will correspond to a group of laminae with the same orientation.

[4] A deck file contains all the finite element analysis information to be submitted to the solver.

2.2. Size optimisation

The bundles created in the free-size optimisation that are outputted in the generated deck file should be reviewed and edited, as needed, in the pre-processor. The purpose of this stage is to fine tune the thickness of each lamina.

In a similar way as before, a deck file, prepared to be submitted for the following methodology, is created by the solver. Also, the quantities of all responses at each iteration is logged.

2.3. Ply stacking sequence optimisation

In this methodology, the ply stacking sequence is optimised by shuffling the laminae. As the mass does not change, it is a common practice to set as objective the minimization of the compliance for achieving a better performance for the same laminate distribution.

There are several constraints available within the solver, regarding the lay-up sequence and related to manufacturing constraints. One can define the maximum number of successive laminae with the same direction. This option is useful to avoid too many consecutive unidirectional fibres because this situation is prone to interior fractures of the fibre during the curing. Another option is to impose that certain orientations are followed by another orientation; for instance, a UD aligned in +45º usually should be followed by another rotated 90º.

As output, the solver generates an HTML file with the specification of the stacking, lamina by lamina.

3. Preliminary work

After receiving the geometry of the baseline concept, the finite element model was generated. Materials and properties were assigned, as well as loading conditions and boundary conditions.

The model was subjected to several quality checks, such as free-free normal modes analysis. The finite element model is depicted in Figure 2.

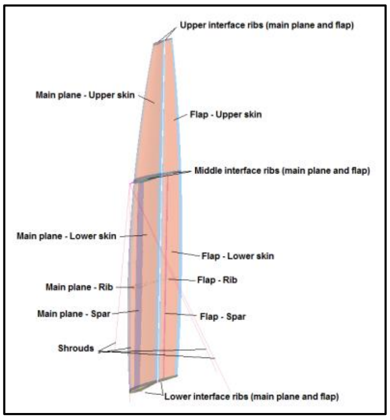

Figure 2 – Finite element model.

In Figure 3, the detail of the loads applied in the finite element model.

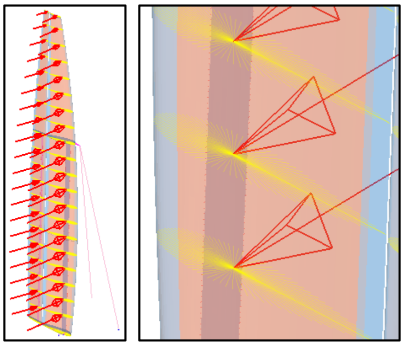

Figure 3 – Loads in the finite element model.

Due to time constraints, only one load case was regarded in the optimisation procedures, which was extrapolated from the loading conditions of the aerodynamic loads. It was assumed a maximum true airspeed of 40kt, which already includes a safety factor. The load case is a wind from port bow with an angle of 45º. The main plane has an angle of attack of -10º. Assuming that the fluid is deflected -10º after passing through the trailing edge of the main plane, the angle of attack of the flap is -10º. For a full understanding of this, Figure 4 should be observed carefully.

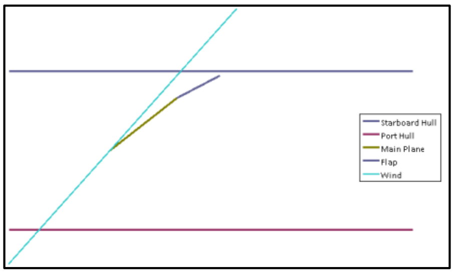

Figure 4 – Load case configuration.

The aerodynamic loads are shown in Figure 5.

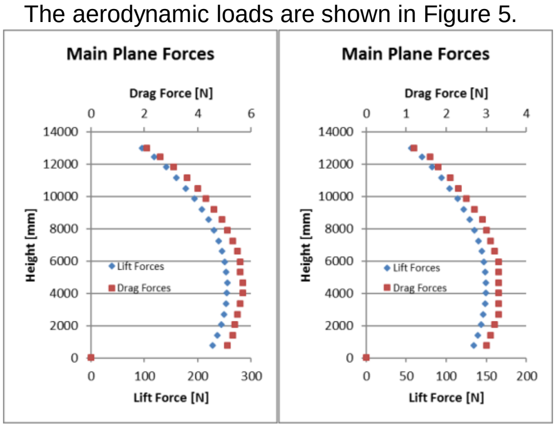

Figure 5 – Aerodynamic loads.

Several laminates were tested in order to provide an initial insight on the component's behaviour.

4. Optimisation procedure

The rigid sail is intended to withstand the aerodynamic loads without damaging, or experiencing too much deformation, and without suffering stability problems. Accordingly, the composite materials should not fail. Hoffman failure theory is used, and the whole structure must not present values above 1.0. The structure must not displace more than 300mm. When subjected to buckling analysis, the rigid sail should not present any eigenvalue under 1.5, as an extra safety factor is requested, related to the uncertainty of the linear buckling analysis when compared to a non-linear analysis.

4.1. First loop

Prior to submitting the free-size optimisation, three general laminates were created. One is monolithic and is applied in zones with more curvature and other zones where foams cannot be applied. Sandwich laminates were used in the remaining zones. The internal components are made of exclusively cloth carbon fibres and the skins are also composed of unidirectional fibres.

Only one property can be optimised at each run if one desires to generate the deck file for the next optimisation step automatically. For this reason, only the sandwich with unidirectional fibres is going to be optimised. Table 1 shows the composition of the laminate that will be subjected to optimisation.

Table 1 – Laminate definition (super-plies).

Ply material	UD	Cloth	Core	Cloth
Ply orientation	0º	±45º	---	0º/90º
Ply thickness [mm]	0.744	0.46	10	0.46
Corresponding no. of plies	4	2	2	2

Instead of declaring laminae with actual thickness, and as long as the free-size optimisation does not take into account the lay-up order, super-plies are defined. This configuration was analysed and respected all prescribed requirements.

For the free-size optimisation, the objective was to minimize the compliance, while keeping the maximum displacement under 200mm and assuring a mass decrease of at least 35%. The optimisation converged after 10 iterations, retrieving a maximum displacement of 194mm and a mass decrease of 35%, corresponding to 130.7kg of optimised composite material. Two local buckling modes were found, in a monolithic zone, near a load concentration (where there will be a metallic insert).

The deck file retrieved from the free-size optimisation was edited, as the bundle boundaries needed to be adjusted. After doing so and launching the size optimisation, the optimised composite material became with a mass of 97kg, corresponding to a total mass of 132kg. The objective set was to minimize the mass, while constraining the maximum displacement (300mm) and the minimum 1st eigenfrequency (1.5) for the linear buckling.

The size optimisation results are not satisfactory, as the mass did not decrease as much as expected. Thus, the third optimisation step was skipped and the whole concept of the sail geometry was reviewed. Before reviewing the geometry, a new loop of optimisation was done, using trial and error, having in mind the insight given by the previous optimisation. The maximum obtained displacement is of 200mm, no buckling eigenvalues under 1.5 were found and the total composite mass was 74kg (a considerable save of 24kg). CFI was also taken in consideration. The considerable weight decrease was mainly due to two reasons: 1) the optimisation of other components which were not optimised previously (monolithic skin, spars and ribs) and 2) the addition of two extra spars.

4.2. Second loop

The results obtained in the section 4.1 are not as good as expected. The thickness of the skin was strongly affected by the buckling analysis. As previously stated, buckling is prone to happen in long slender shells. Considering this, another design was created and tested, in order to assess whether it provides a lighter structure.

The new design is similar to the previous, with more interior components, and part of the skin will be non-structural. By doing this, the structural part of the need to have a thicker skin is due not only to the geometrical instability but also to the structural strength. In principal, this solution will lead to a lighter solution. The addition of multiple ribs is motivated both for structural reasons and for keeping the aerofoil shape in the non-structural skins.

The new geometry is depicted in Figure 6. As one can see, many ribs were added; one spar was included to the upper parts of both main plane and flap; a new spar, at the rear of the pre-existent was also added in the lower part of the main plane.

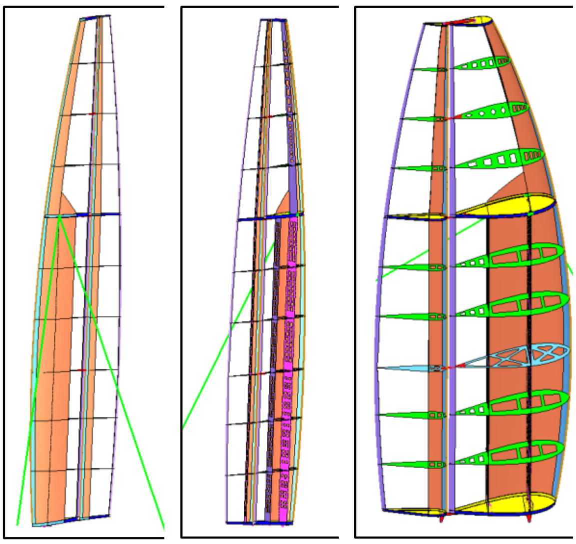

Figure 6 – New geometry.

The baseline laminates are chosen in a similar way that was carried out in the previous loop. However, this time, all the sandwich laminates in the model will be optimised. Their integration will be done only in the size optimisation because unidirectional fibres are desired in the skin but not in the interior components. Three components will not be optimised: trailing edges, monolithic zones of the skin and interface ribs.

The trailing edge is prone to buckle because in the model the membrane effect of the film is not considered, thus an unrealistic (dummy) thick laminate was used. This decision is not dangerous for the structure because we can allow for the trailing edge to buckle without endangering the structure. The function of the trailing edge is to transfer the membrane loads from the vinyl film to the ribs.

The free-size optimisation procedure was carried out with the same conditions as previously. The optimised structure showed a maximum displacement of 140mm, a mass decrease of 35% and a number of potentially catastrophic buckling modes.

Before continuing, the core thickness is imposed as 5mm all over the design area so as solve or, at least, mitigate the buckling problems. The all buckling modes with eigenvalues less than 1.50 are local and negligible.

As previously, the bundles created by the solver were revised. The laminate of the interior geometry, namely spars and ribs, was also included as design variable. Each laminate is independent from one another in the point of view of the stacking.

The size optimisation methodology was divided into two steps. As a first attempt, each ply was allowed to have any thickness, if the total thickness per bundle satisfied prescribed constraints related to maximum and minimum lamina thickness. With this, it was observed the tendency of each bundle to be thicker or thinner (or even disappear). After this step is concluded, the thickness of each ply is injected in the subsequent run, in which each ply thickness would have a discrete (manufacturing realisable) value.

Besides the linear static analysis, the linear buckling analysis was also considered at this stage. The objective of the size optimisation was set as minimizing the mass. As constraints, a maximum displacement of 20mm was set (controlling the bending helps preventing instability problems) and the 1st eigenfrequency should be greater than 1.0 (although eigenvalues under 1.5 are unacceptable for global eigenmodes). This decision was taken because it is understood that normally the first modes are local and thus may have a reserve factor under 1.5.

The analyses converged after 7 iterations, achieving a feasible design. A total composite mass of 51.3kg was obtained, disregarding trailing edge. The mass of the optimised areas is 33.8kg. The maximum displacement has a magnitude of 140mm. Regarding the buckling subcase, only local modes are found for eigenvalues below 1.5.

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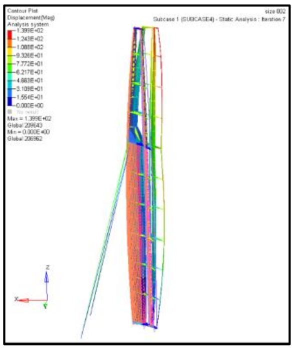

Figure 7 – Displacement plot after size optimisation [mm].

The graphs in Figure 8 show the results at each iteration, for the first buckling frequency and for the total mass.

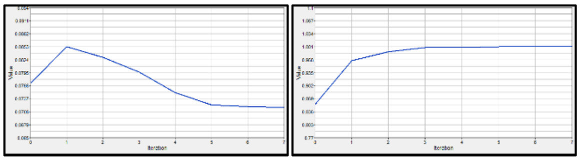

Figure 8 – Left: Total mass. Right: First buckling frequency.

Using the results in the previous table for the following optimisation step in which the ply thickness will change in a discrete (realisable) way, and keeping all the other data unmodified, the optimisation converges after 4 iterations, with an unfeasible design, due to the first buckling eigenvalues. The total composite mass is of 45.9kg. Removing non-optimised composite materials, a total mass of 31.4kg is achieved.

As per the obtained the results, the maximum displacement is 185mm. Buckling eigenvalues less than 1.5 are found although the result is acceptable because the modes are not global.

The graphs in Figure 9 show the results at each iteration, for the first buckling frequency and for the total mass.

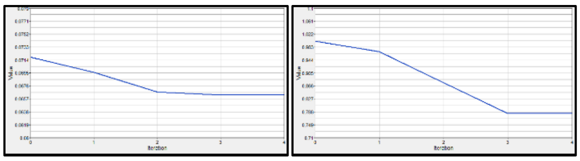

Figure 9 – Left: Total mass. Right: First buckling frequency.

Many attempts were carried out regarding the ply stacking sequence orientation but none of them retrieved a satisfactory result. The baseline configuration is the one explained in the previous paragraph. The objective was set to minimize de compliance. The design constraints which are common to all attempts are the following: 1) Eigen buckling values should be greater than 1.0 (although global buckling modes with values under 1.5 are not acceptable); 2) the maximum displacement of the structure should not exceed 200mm. the attempts regarded solely the constraints associated to the lay-up rules. The following picture (Figure 10) is an example of the HTML generated as output.

Stacking sequence for STACK 1

Iteration 0	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8
13101	11301	11301	11301	11301	11301	11301	11301	11301
13102	11401	11406	13101	11402	13102	11402	11406	11406
14101	13101	11405	11403	11401	11404	11401	11404	11404
11301	14101	11404	13102	11406	11405	11406	11405	11405
13301	11402	11403	11404	11403	13101	11404	11403	11403
11401	13102	11402	11405	11404	11403	11405	13101	13101
11402	11403	11401	14101	11405	14101	11403	11401	11401
11403	13301	13101	11406	13102	11406	13101	11402	11402
11404	11404	13401	13301	13101	11401	13102	13102	13102
11405	13401	13301	11401	13301	11402	13301	13301	13301
11406	11405	13102	11402	13401	13301	14101	14101	14101
13401	11406	14101	13401	14101	13401	13401	13401	13401

Legend
90.0 degrees
20.0 degrees
0.0 degrees

Stacking sequence for STACK 2

Iteration 0	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8
22101	22101	23102	23101	23101	23101	23101	23101	23101
23101	23101	23101	22101	22101	22101	22101	22101	22101
23102	23102	22101	23102	23102	23102	23102	23102	23102
24101	24101	24101	24101	24101	24101	24101	24101	24101

Legend
90.0 degrees
45.0 degrees
20.0 degrees

Figure 10 – Ply stacking sequence optimisation

Further efforts were made. Fine-tuning and trial and error was applied with the knowledge and insight acquired during the optimisations. Specially, the monolithic zones were not optimised by the solver. The final optimised composite material is 39kg.

5. Conclusions and remarks

Due to the loading conditions and to the fact that a great span is needed, thin skins tend to be a bad option as they are very prone to buckle. Thus, the skin requires a greater moment of inertia to meet the needed structural strength. To do so, the thickness would have to increase. Increasing the thickness with little weight addition is possible when using structural sandwiches.

At the first iteration, the whole skin was intended to carry load. After optimising, the total mass of the optimised skin was 97kg, which is much more than expected. Consequently, the concept was reviewed and a hybrid solution was chosen. The aft skin portions of both main plane and flap were replaced by vinyl film. In order to guarantee the sectional shape along the span, many light ribs of sandwich construction were used. The load is intended now to flow by a smaller and more reinforced area. A strong reason for the need of reducing the structural area is that, as the total area is quite large, even having a single ply of cloth at each side with a core in the middle would lead to a mass of 54kg, only for the composite material.

The second iteration retrieved a composite mass of 51.3kg which is less than the virtual minimum mass of the first concept. By the end of the computational optimisation process, there was still time to try further optimisation by hand. A small amount of a better carbon fibre also became available. These two circumstances led to a lighter solution, with 39kg of composite material. This solution also delivered more confidence because more load cases were regarded.

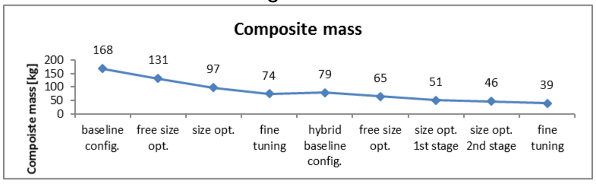

Figure 11 – Composite mass evolution.

The considerable mass saving from the first to the second conception (see Figure 11) is related to the fact that considering the whole skin as structural is an over dimensioned solution regarding stiffness and strength but is underestimated in the stability point of view due to the very thin skins. If one intends to balance these two aspects (strength and stability), a hybrid solution should be sought. This hybrid solution is the one created in the sections 4.2 due to the use of vinyl film.

6. Future work

There are two aspects to keep in mind for improving the procedure in future catamarans and competitions. Attending to the magnitude of the sail span and the expected, a linear static analyses may be adequate for first iterations. However, before closing the design, a geometric nonlinear analysis would be an appropriate way to confirm the results. The second aspect is related to the considered load cases. Regarding different loadings would affect the finite element mesh because the position of the flap with respect to the main plane would be different. For this reason and due to the lack of time, only one configuration was considered and thus only one loading condition was analysed. In the future and in case time issues are not so serious, an envelope of loads and configurations should be considered. As for the finite element model, perhaps modelling the core foams with solid elements, and then optimising the shell elements at each side of the foam would lead to better and quicker results.

Although none of the solutions are desirable or acceptable, they provide an insight regarding the behaviour of the structure. The optimisation using OptiStruct® is now finished, although with less than desirable results. No more efforts are going to be carried out with the ply stacking sequence optimisation.

7. References

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