proceedings

ISEA 2018
Brisbane Queensland Australia
26-29 March 2018
'Engineering of Sport'

MDPI

Proceedings

Composite Design for a Foiling Optimist Dinghy †

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† Presented at the 12th Conference of the International Sports Engineering Association, Brisbane, Queensland, Australia, 26–29 March 2018.

Published: 12 February 2018

Abstract: In April 2017, a foiling Optimist dingy designed entirely by students, was successfully tested under standard sailing conditions in the waters outside Gothenburg. In order to achieve take of wind speeds as low as 6 m/s, a stiff and lightweight design of the dinghy and its foiling components was necessary. There have been few successful attempts to make an Optimist foil in a stable manner, as such there were no standards or recommendations available for the design. Therefore, a simulation driven structural design methodology for hydrofoils, centreboards, centreboard-to-hull connections, and necessary hull reinforcements using sandwich structures was adopted. The proposed design was then manufactured, allowing for a significantly stiffer hull and a 20% decrease in weight over a conventional Optimist. Excluding the rig and sail, the final weight came to 27 kg.

Keywords: carbon fibre reinforced polymer design; Optimist dinghy; foiling

1. Introduction

Velocity predictions based on computational fluid dynamics (CFD) have shown that with a sound foiling concept, an Optimist dinghy can be made to foil at wind speeds from 6 m/s, provided that its total weight (incl. sailor) is below 90 kg [1]. However, to make an Optimist dinghy foil at these low wind speeds, it is important to find the optimal geometrical configuration. It is also crucial to have a design which can withstand the increased loads when foiling.

Although off-shore foiling dates back more than 40 years [2], there are no standards or recommendations available for the design of foiling Optimists. Thus, a simulation driven structural design methodology was adopted (as described in this work). Due to time constraints, the rudder and rudder-to-hull connection was excluded from the design study since loads are higher on the centreboard foil (or centre foil in short). Disregarding the weight of the sailor, the rig, the initial lightweight (9 kg) hull and the rudder, it was considered that a maximum of 6.5 kg of material could be used for the design of the centre foil, the centreboard, the centreboard-to-hull connection and the necessary reinforcement of the initial hull itself.

2. The Design Task

The adopted approach was to design the centre foil and the centreboard to be strong and stiff enough to withstand the foiling forces and maintain hydrodynamic properties. The remaining mass was then to be efficiently distributed to reinforce the hull. As the work was divided into two parallel tracks, separate weight targets were defined. For the structural design of the centreboard and centre foil incl. T-inserts for their joining, the maximum weight was set to 2.5 kg. In addition, to maintain hydrodynamic properties, the deflection of the foil tip was limited to 2.5 mm when foiling. To reinforce the hull such that the dinghy's torsional stiffness was increased by at least 50%, the remaining 4 kg could be added. This also included designing the centreboard casing which allowed for the attachment of the centreboard to the hull.

To provide a conservative design, a general safety factor of two (unless explicitly mentioned) was used throughout. Numerical finite element analyses were performed using ANSYS Mechanical v17.1 [3]. In all cases, converged results with respect to element size were achieved.

3. Loads and Dimensions

The outer dimensions of the centreboard and centre foil necessary to provide optimal foiling conditions were determined in a parallel student project, see [1,4]. These were given as an input to the current design study and could not be altered. In addition, the hydrodynamic forces acting on the components during foiling were calculated (using CFD) in the parallel project. Consequently, these were also provided as input.

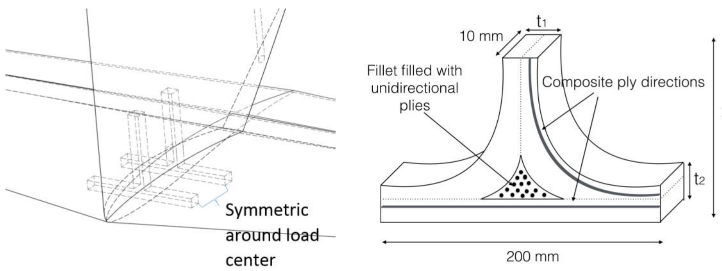
4. Material Selection

The various foiling components as well as the hull reinforcements were designed (and later manufactured) as sandwich structures in order to save both weight and cost. In detail, a Divinycell H60 foam core covered by stiff and strong laminated face sheets of a thin-ply unidirectional carbon fibre reinforced polymer (CFRP) was used. For the face sheets, spread tow TeXtreme® (Borås, Sweden) carbon fibre bundles (50 gsm) were assumed as the reinforcement material and LY556 as the epoxy polymer. For simplicity, a ply thickness of 0.1 mm was used throughout the design process. The material data was provided from the TeXtreme manufacturer Oxeon AB and can be made available on request.

5. Design Method

5.1. T-Inserts

The discontinuity of fibres in the centreboard-foil interface was solved by designing T-inserts within the foam structure as shown in Figure 1a. The inserts were designed using unidirectional plies wrapped over a delta fillet with fibres running through the thickness, see Figure 1b. In order to create a conservative design, it was proposed that the T-inserts should be independently capable of carrying the applied loads induced on the centreboard and foil. As the face sheets are also required to carry the loads a safety factor of 1.2 is used on the T-inserts.



(**a**) (**b**)

Figure 1. An illustration of the T-insert design, where (**a**) shows the placement of the T-inserts inside the vertical centreboard and horizontal foils and (**b**) the geometrical shape of a single T-insert.

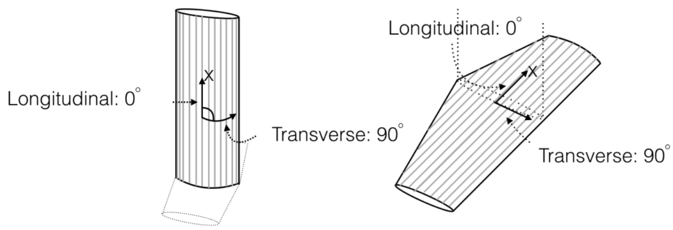
Handbook calculations based on Euler-Bernoulli beam theory (see e.g., [5]) were conducted, considering the resulting surge and sway loads on the centreboard and the resulting heave and surge loads on the foil, to obtain a first estimate of thicknesses t_1 and t_2 (Figure 1b). In these preliminary studies, a simple maximum stress criterion [6] was used, considering only compressive fibre failure (since that is lower than the tensile strength and compressive stresses are higher than the tensile) to estimate the amount of reinforcements needed in the T-inserts.

The T-inserts were then, in a second step, analysed by the finite element (FE) method to get the actual stress distribution and design safety factor. For this purpose, the composite plies on the outside where modelled as layered thick shell elements (the shell has various properties through its thickness to represent the different layers) which were node-by-node connected to solid elements utilised to model the delta fillet. The upper part of the T-insert was fully constrained and the foiling forces were applied to the bottom of the insert. To assess the risk of failure in any ply (initial ply failure), several failure criteria were simultaneously assessed (Maximum stress, Tsai-Hill and Hashin, see [6]). This in order to obtain a conservative design approach were only the most critical criterion, providing the lowest safety factor against initial ply failure, is considered in any point in a laminate.

5.2. Centreboard with Integrated Centre Foil

Initially, handbook calculations were used to propose an initial design for the centreboard and the centre foil. First, the maximum shear forces were determined from equilibrium of forces. With this information available, the shear stress distribution over each cross section could be calculated [5]. In order to do so, the cross-sections of the components were approximated as ellipses (compared to the true NACA and Wortmann profiles [1]). The maximum shear stress was then compared against the shear strength of the core to make sure that the sandwich design was strong enough.

To design the CFRP face sheets, the maximum bending moments and axial forces were determined in each component using Euler-Bernoulli theory [5] and considering each component as an idealised beam. With these moments and forces available, the required number of plies with fibres along the main loading direction, the longitudinal direction as indicated in Figure 2, could be evaluated. As for the T-inserts, the maximum stress criterion for compressive fibre failure was evaluated under the conservative assumption that these plies should be able to carry the entire load. However, in order to account for unforeseen transverse and shear loads and to provide a robust design, plies with 45° and 90° fibre orientations were added in the final design.



(**a**) (**b**)

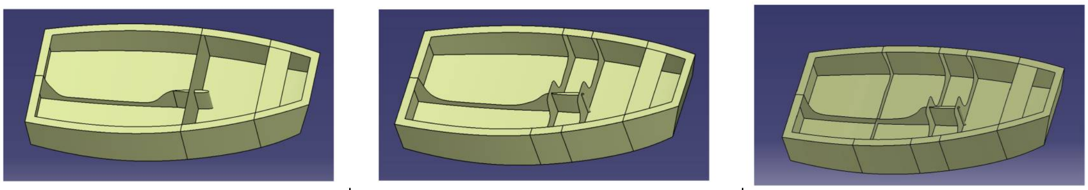
Figure 2. An illustration of main longitudinal directions for (**a**) the centreboard and (**b**) the centre foil.

In the subsequent FE analysis of the centreboard and the centre foils, both components were modelled with solid elements for the core and layered shell elements (cf. above) for the face sheets. Furthermore, the connection between the centreboard and hull was not considered explicitly. Instead, the centreboard top was treated as a completely fixed boundary. This provided accurate results at the foil—centreboard joint, which is a critical area of interest. For the failure risk assessment, the same approach as described above for the T-inserts was used.

5.3. Centreboard Casing and Hull Reinforcement

Under normal (non-foiling) conditions the vertical forces on the centreboard are small. However, when foiling, significant vertical forces from the foil must be transmitted through the centreboard to the hull. This means that, with the increased load from the foil, the attachment of the centreboard must be modified. Furthermore, the centre foil and the centreboard are an integrated component. Thus, it is no longer possible to use the conventional solution where the centreboard is inserted from above through the casing. Instead, the centreboard has to be introduced into the casing from below the hull and is kept in place by the lift force when the dinghy is in the water. As a consequence, the geometrical design of the casing was given the same shape as the upper part of the centreboard (to fully enclose the centreboard) with a lid secured on top. To reinforce the casing and transfer the applied loads to the existing hull, transverse supporting bulkheads had to be designed to be placed on each side of the casing. These transverse bulkheads must also provide the required 50% increase of the torsional stiffness of the hull.

All in all, three concepts for the casing and the hull reinforcements were developed and analysed with respect to stiffness and strength using one, two or three transverse bulkheads. These were, denoted concept A, B and C, respectively (see Figure 3). Concept A uses one supporting bulkhead across the hull, with a height equivalent to the sides. Concept B uses two bulkheads with varying heights that extend above and over the casing. Finally, concept C has an additional bulkhead placed towards the rear of the Optimist. In all concepts there is an additional bulkhead placed in the front of the Optimist. This will be used to secure the mast. To save weight, the casing and the bulkheads were designed as sandwich structures, with the same material as for the foiling components.



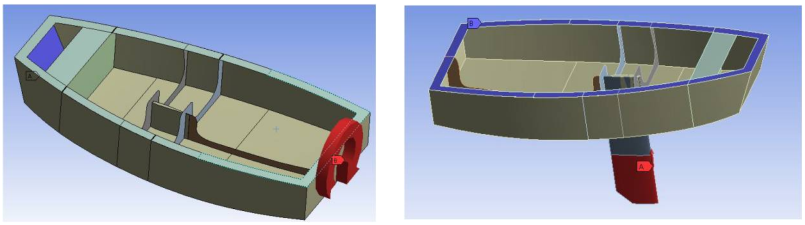
(**a**) | (**b**) | (**c**)

Figure 3. An illustration of the three reinforcement concepts considered: (**a**) A, (**b**) B and (**c**) C.

The complexity of the geometry did not allow for meaningful handbook calculations of the casing or stiffening bulkheads. Instead, different lay-ups for the bulkheads and the casing, respectively, were analysed using FE. In the FE models, the casing and the bulkheads were modelled using layered shell elements only, whereas the hull was modelled with a combination of solid elements for the core and layered shell elements for the face sheets.

Fibre reinforcements oriented along the bulkhead and the casing (oriented along the heave axis) are crucial for sufficient bending stiffness and strength. Furthermore, reinforcements oriented in ±45° to these respective directions are required to carry torsional loads and reinforcements oriented at 90° are necessary to carry unexpected loads. After studying a number of alternative designs, the final lay-ups, for which results are presented below, were obtained as $[0_2/-45/90/45/0/-45/0/45/0/\text{core}]_S$ for the bulkheads and $[90/-45/0/45/0]_S$ for the casing. For the bulkheads, a core thickness of 12 mm was used. This yields an estimated weight increase for the three concepts of 4.0 kg for concept A, 3.9 kg for concept B and 3.8 kg for concept C, all below the required maximum.

To determine the torsional stiffness of the hull for each concept, the front of the FE model of the Optimist was constrained with a fixed support (blue surface) at the same time as a moment M (red arrow) was applied to the aft, see Figure 4a. The resulting rotational deformations, θ, around the surge axis of the Optimist were measured at the point of moment application. The rotational stiffness, k, was then calculated as $k = M/\theta$.



(**a**) (**b**)

Figure 4. Boundary conditions for the FE analysis of (**a**) torsional stiffness and (**b**) strength of the hull design concepts. Blue indicate constrained surfaces and red indicate areas of load application.

A conservative approach was taken in the strength analysis, by defining a fixed boundary on the rim of the Optimist, see Figure 4b where the blue area on the rim represents the fixed support and where the red regions correspond to areas with applied loads. Furthermore, as the centreboard was designed in a separate part of the project, it was here replaced by a steel component with the same geometry, resulting in an even more conservative load case. The contact between the centreboard and its casing was defined such that the centreboard was free to displace within the casing but was restricted to move in the vertical direction. Furthermore, the top of the casing and the centreboard was set as a bonded connection.

6. Results

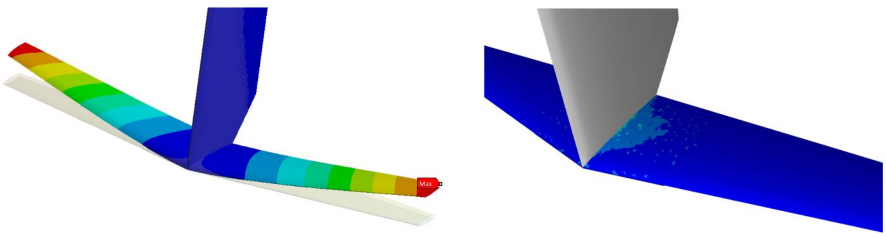
6.1. T-Inserts

The handbook calculations gave that the minimum thicknesses needed for the T-inserts were t_1 = 2.8 mm and t_2 = 10.7 mm, respectively, which corresponds to a minimum of 107 CFRP plies needed to meet both requirements. From the FE analysis, it was clear that the most critical failure mode was delamination between the delta fillet and the surrounding CFRP plies. However, the safety factor against failure initiation was well above 2.

6.2. Centreboard with Integrated Foil

Handbook calculations predicted a maximum shear stress of 130 kPa in the centreboard and 225 kPa in the centre foil, which is well below the shear strength of Divinycell H60 (630 kPa). This was also confirmed by the FE analysis for each component.

The handbook calculations also predicted that the minimum number of 0° plies for the centreboard and the centre foil were 2 and 1, respectively. However, when conducting the FE analyses, it was clear that stress concentration effects lead to that more 0° plies are required for the foil and the centreboard to meet the design criteria. In the end, the required lay-up for the foil were $[90/45/0/-45/0]_S$ for which FE-results are shown in Figure 5. The maximum tip deflection was found to be 2.4 mm and the minimum safety factor according to the Tsai-Hill criterion (most critical), was 2.2.



(**a**) (**b**)

Figure 5. FE results from the analysis of the centreboard and centre foil (**a**) deflection and (**b**) critical failure index.

For simplicity, the same face sheet lay-up as for the centre foil was used also for the centreboard. Also here, the safety factor against failure was larger than 2 in all plies of the face sheets.

6.3. Centreboard Casing and Hull Reinforcement

The stiffness results for the three concepts are presented in Table 1. As can be seen, concept B results in the highest increase in torsional stiffness (70%) which is well above the requirement.

Results from FE analyses of the three design concepts are presented in Figure 6, showing the most critical areas and their safety factor against failure initiation (red indicates most critical areas but does not indicate actual failure). The results show that concept B distributes the stresses most efficiently, while being well above the required safety factor. Also concept A has stress levels which yield safety factors well above the required limit. Surprisingly though, concept C has a drastic reduction in minimum safety factor, even though the difference to A is the addition of a second bulkhead (although at a lower height). To conclude, reinforcement concept B was proposed for the actual manufacturing of the dinghy.

Table 1. Torsional stiffness of the three hull reinforcement concepts.

	No Stiffening	Concept A	Concept B	Concept C
Torsional stiffness [kNm/rad]	31.6	50.6 (+60%)	53.7 (+70%)	48.2 (+53%)

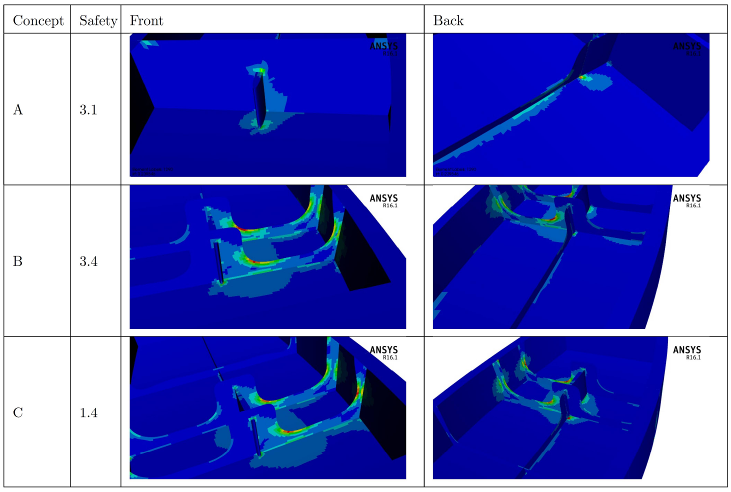


Figure 6. Resulting critical failure index distribution for design concepts A, B and C. The scale is set from dark blue to red where red indicates the highest risk of failure (lowest safety factor).

7. Conclusions

A simulation driven design process of a foiling Optimist dinghy has been presented in this work. It was used to obtain design solutions for the centreboard, a centre foil, the centreboard-hull connection and necessary bulkheads reinforcing an already existing lightweight (but not stiff enough) Dinghy hull (9 kg). For all components, except the centreboard-hull connection, sandwich design solutions were proposed with a Divinycell H60 foam core covered with laminated face sheets of thin-ply carbon-epoxy. The centreboard-hull connection was realised as a pure laminate design with the same CFRP material.

A safety factor against initial failure of at least 2 was achieved for all parts. Also, a reinforced deign of the hull was obtained with a predicted increased of the torsional stiffness of 70%.

The dinghy was later manufactured based on the design specifications form this work. In the end, the total weight (incl. all appendages) was 27 kg, which is more than 20% lighter than a standard Optimist. In early April 2017, a final on-the-water testing was carried out with great success [7].

Acknowledgments: The financial support from the Area of Advance Materials Science at Chalmers is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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