DESIGN METHODOLOGY OF A FLEXIBLE COMPOSITE PROPELLER BY COUPLING STRUCTURAL AND HYDRODYNAMICS SIMULATIONS

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Abstract

CoPropel [1] is a European project which puts forth a holistic approach to develop and mature an innovative composite propeller for next generation vessels. Compared to their traditional counterparts, marine composite propellers have numerous benefits such as less cavitation, reduced noise emission, lightweight and performance. Regarding performance, metallic propellers, due to the rigid properties of the materials, are designed for a single operating condition and not optimal for other speeds or sea conditions while the flexibility of composite makes it possible to adapt the shape to off-design points.

MECA brings its expertise to developed an innovative methodology coupling FEM and CFD models that predict the deformation of blades under hydrodynamic load to be able to design a controlled deformable blade with a wider range of efficiency.
While innovative, these works are coupled with a robust structural and industrial design aimed at providing the marine industry with a mature, certifiable, sustainable and quasi-industrial demonstrator.

This paper will describes the methodology, the results and its outcomes.

1. Introduction

Today, due to the challenges of climate change and new objectives set by International Maritime Organization (IMO), the energy efficiency of vessels is a crucial topic for shipowners and is highly dependent on the performance of propellers. Due to their flexibility, composite propellers offer certain advantages compared to metallic one: less cavitation, dampening of vibration, noise reduction, but also an improvement of efficiency and therefore less fuel consumption and greenhouse gas emissions.
This efficiency improvement come from that metallic propellers, due to the rigid properties of the materials, are designed for a single operating condition and not optimal for other speeds or sea conditions while the flexibility of composite makes it possible to adapt the shape to off-design points.

The European research project CoPropel [1], launched in June 2022 with 9 partners from 5 countries, aims to improve the knowledge in designing, building and testing propellers in composite materials. Within the project, two propellers will be designed and tested, a small-scale to study the behavior in hydrodynamic tunnel and in a towing tank, and a full-scale propeller to evaluate the performance during sea trials. Tests will be also supported by numerical simulations with an objective of improving the existing requirements from Classification Societies.

This paper will present and detail the innovative methodology developed by MECA and Erflow-Engineering within CoPropel's project. Using weak-coupling between FEM and CFD models, with limited computational effort, we work on a range of design points to :

- define a target pitch (difference of deflection between the trailing edge and the leading edge)
- optimize the stacking of layer within the composite blade to target this shape
- robustly size the blade couple with an industrial design

2. Computational Fluid Dynamics (CFD) - Metallic propeller behavior analysis

2.1. CFD - Metallic propeller behavior and efficiency curve

All the CFD simulations were performed with Niceflow software in open water configuration, using automatic remeshing techniques. The software and the results obtained in this configuration have been validated against numerical results obtained with CFX and experimental results (from BSHC Copropel's partner).

Flow structure around the propeller can be visualized using Q criterion collored by helicity as shown in figure 1:

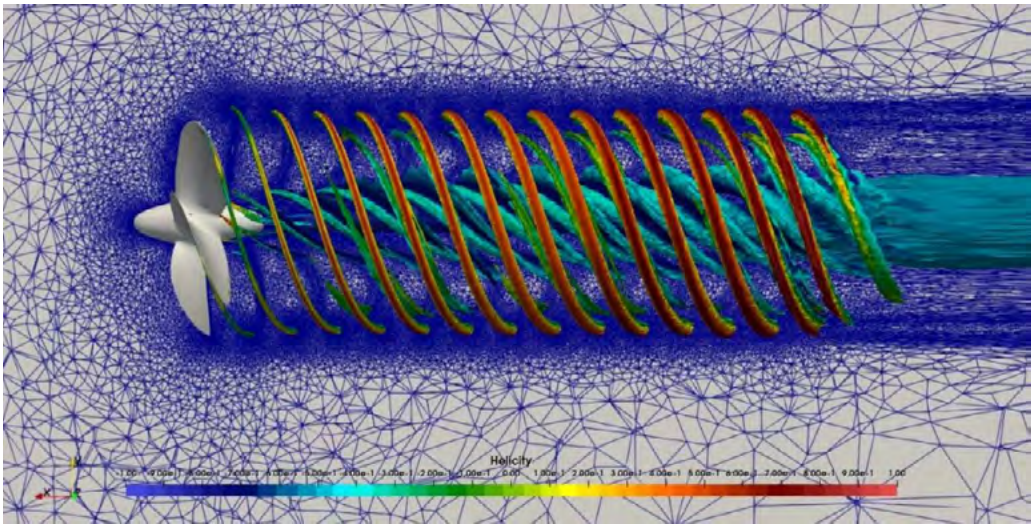

Figure 1. Flow structure and adaptative mesh visualization.

The final computed torque and thrust at different operating points are used to define the adimensional torque and thrust with the flow conditions. The efficiency η is then computed from those variables. The final curves are given Figure 2. In addition to the obtain thrust and torque, estimated (est.) values from the extrapolation mesh convergence study are also given. This should represent the results with no error from meshes:

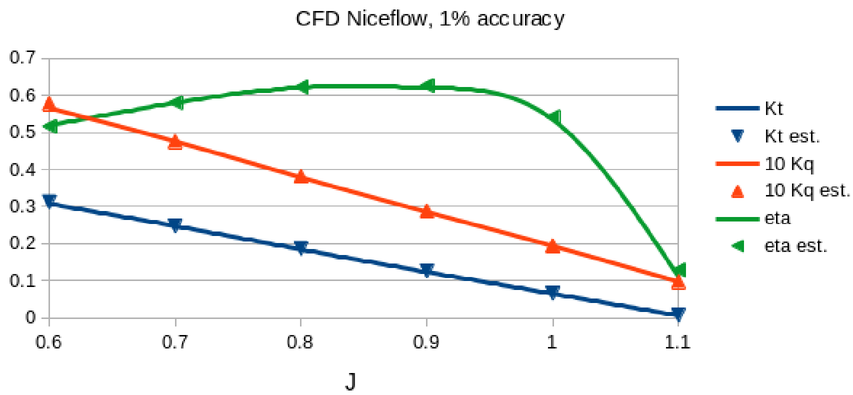

Figure 2. Adimensional coefficients of Le Palais propeller.

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2.2. Operating point definition

The propeller operational conditions can be estimated using the boats engine data given in the data sheet. The power available for the propeller is obtained from the engine power minus the mechanical loss and some losses associated to the sea environment, call sea margin (SM). The sea margin can fluctuate; thus, we choose sea margins ranging from 0 to 30%.

It follows that two extreme operating points can be defined for the further optimization:

- SM 30: J0.88, which is the referent state for which the metallic propeller had been design;
- SM 0: J 0.69, a realistic off design point on which the optimization will be done.

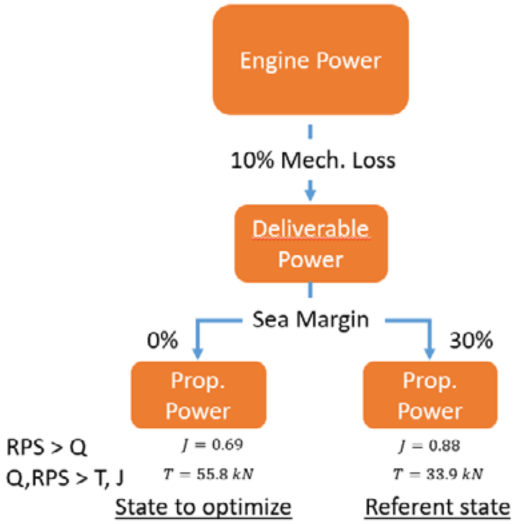

Figure 3. Operating point definition.

Knowing these two operating points, the pressure loads (detailed within Figure 4) applied by the fluid on the blade these two operating points are computed using CFD computation in order to be used as entry data for the mechanical simulation:

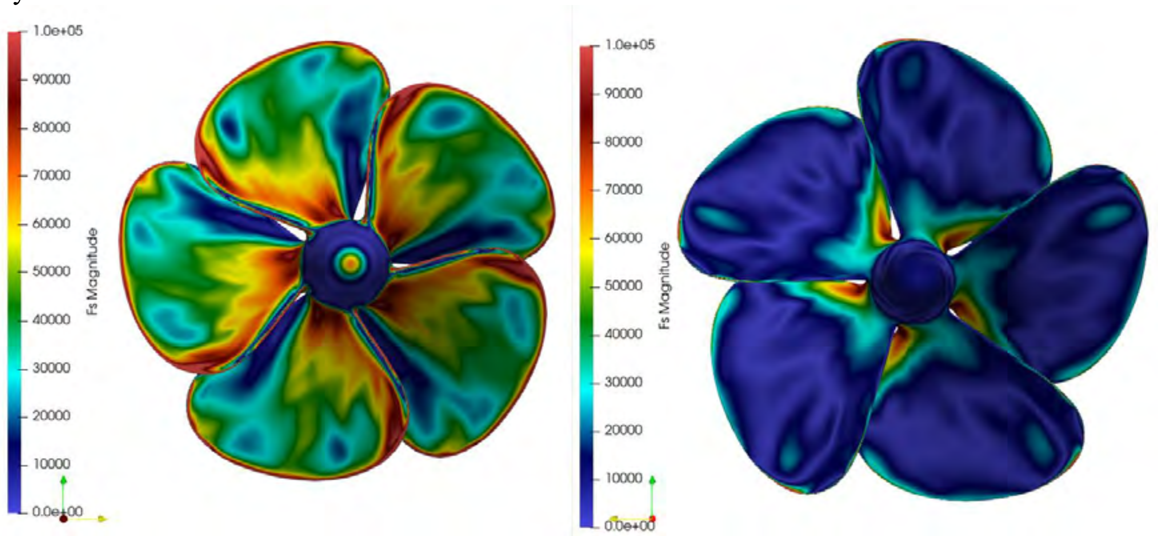

Figure 4. Total surface force applied on the full scale propeller at J=0.88 (sea margin 30).

2.3. Optimal shape computation

Hydrodynamic pitch of a propeller is a key feature of the propeller efficiency and requires specific knowledge and methodology to be defined accurately. Rigid propellers are defined to provide best propulsion for a single design point.

When the propeller is working off-design, its behavior is suboptimal by definition, and efficiency is less than at the design point. The composite blade aims to adapt the given propeller for off-design point to

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provide better efficiency at these sub-optimal regimes, with a blade able to reach a different pitch ratio P/D when the load is different than the design load.

The methodology is based on the adimensional curves of the metallic propeller, see Figure 2. The propeller blade profiles are decomposed in 2D definition to define the geometric pitch, the 2D profile pitch and profile hydrodynamic pitch:

$$P_{hyd} = P_{geo} - P_{2D} \tag{1}$$

P_{hyd}: The hydrodynamic pitch is the effective pitch at r/R when the propeller is rotating at given advance ratio J, i.e.

$$P_{hyd} = \frac{180}{\pi} \operatorname{atan}\left(\frac{J}{r/R\,\pi}\right) \tag{2}$$

P_{geo}: The geometric pitch is the pitch at rest of the profile.
P_{2D}: The 2D pitch of the profile is a standard generally used in polar curves of NACA profiles. It can be used to observe at what angle the profile provide best lift over drag ratio.

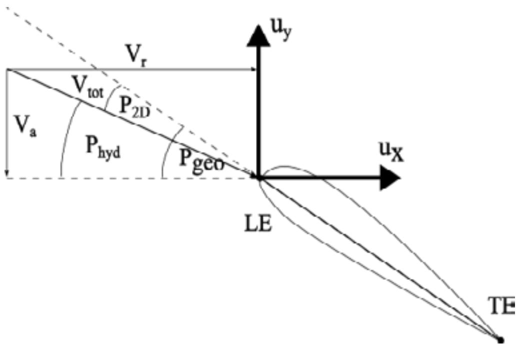

Figure 5. Definition of 2D profiles blade pitches.

One assumes that the best 2D profile angle is not dependent on the flow regime. By subtraction of the hydrodynamic pitch to the rigid pitch at best efficiency point, we obtain the best P_{2D} of the blade's profiles during use.

According to Figure 6, the most important pitch to optimized are those at r/R = .0.8 and r/R = 0.9. It is indeed at the end of the propeller blade where profiles contribute the most to the propeller thrust.

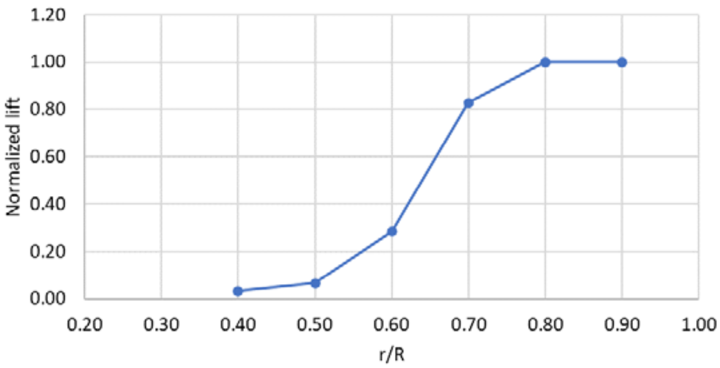

Figure 6. Importance of lift at different radius of the blade.

3. Methodology and optimization procedure descriptions

As defined within §2.2, two realistic operating points (SM30 and SM0) will be used to optimize and size the blade.

All the computation are made on the metal blade geometry (optimized for SM30).

The optimization procedure aims to fit as best as possible the ideal pitch at a given regime. The regime considered is the off-design point considering no loss due to sea margin (SM0) which load has been computed by CFD computation.

Optimization summary:
The objective: The objective of the mechanical optimization is, for a given load (at a given regime corresponding to SM0), to fit as best as possible the ideal 2D pitch P_{2D}.
The variables: The plies angles are the variables of the optimization. Meanwhile the stacking sequence is fixed by manufacturing and design constrains.
Constrains: The strength of the stacking for the sizing load.

After hydrodynamic optimization, mechanical sizing of the blade and compliance to Bureau Veritas rules are checked using design point SM0 which is the more severe load.

Once the optimization and sizing are done, the manufacturing geometry of the composite blade can be defined. By reverse loading, using SM30 loads the composite propeller mold shape is defined such that the deformed shape will match the target optimized shape, when the blade deflects.

4. Mechanical analyses

4.1. Mechanical FE model

A finite element model of one blade is realized, with 2D multilayer shell elements. The lay-up to be optimized is required to be symmetrical, and with a sequence of 1 twill 2/2 for 3 unidirectional layers, following manufacturing constrains. The sand cores with different thickness and plies of bulk resin are modelled to represent the expected profile. The composite plies are dropped from the blade root (maximum thickness) to the edges (ply drop-off) as shown in Figure 7 and Figure 8. One ply of twill 2/2 is layed up along the edge of the blade as a protection sheath (Figure 7 and Figure 8):

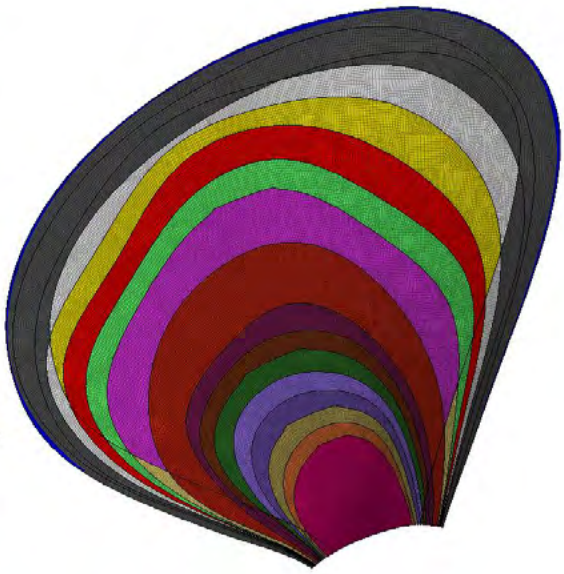

Figure 7. Model thickness discretization and zones definition.

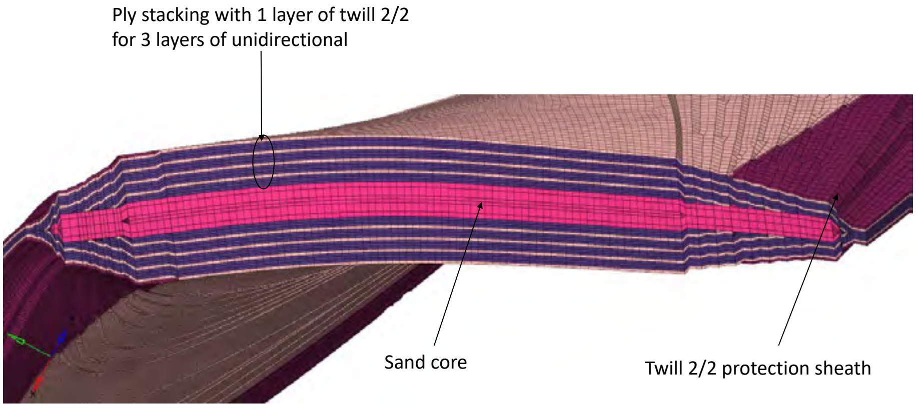

Figure 8. Cross sectional view and stacking of the FEM model.

4.2. Optimization results

The selected optimization algorithm is the Enhanced Dual Optimizer based on separable convex approximation (DUAL2) implemented in Optistruct. Sensitivity analysis of the optimization algorithm, initial configuration, and convergence parameters has been performed. The influence of the weighting factors of the pitch along the span in the objective function has also been analyzed.

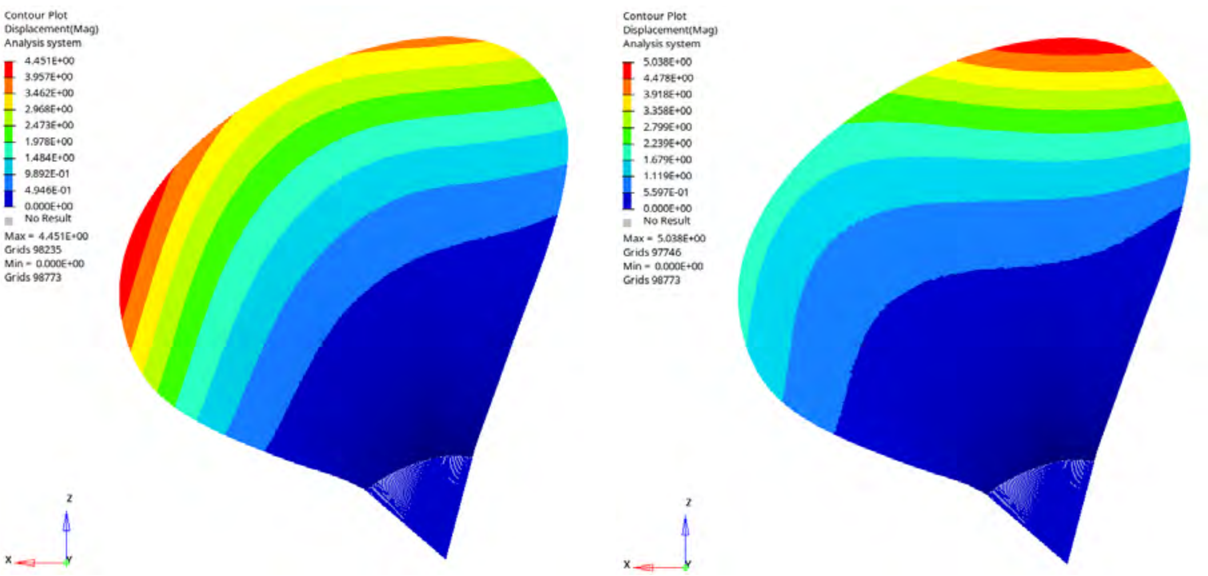

Figure 9. Variation of displacement between reference shape (J = 0.88) and the design shape (J = 0.69) with unoptimized (left) and optimized stacking (right).

With this stacking, the obtained pitch at 0.9R is 21.69° against 22.13° for the initial stacking.

Figure 10 shows the pitch variation for different materials. This figure points that composite material with an optimized layer stacking tends to reduce the difference between the calculated and the ideal pitch variation. Calculation have also been done with the metallic material:

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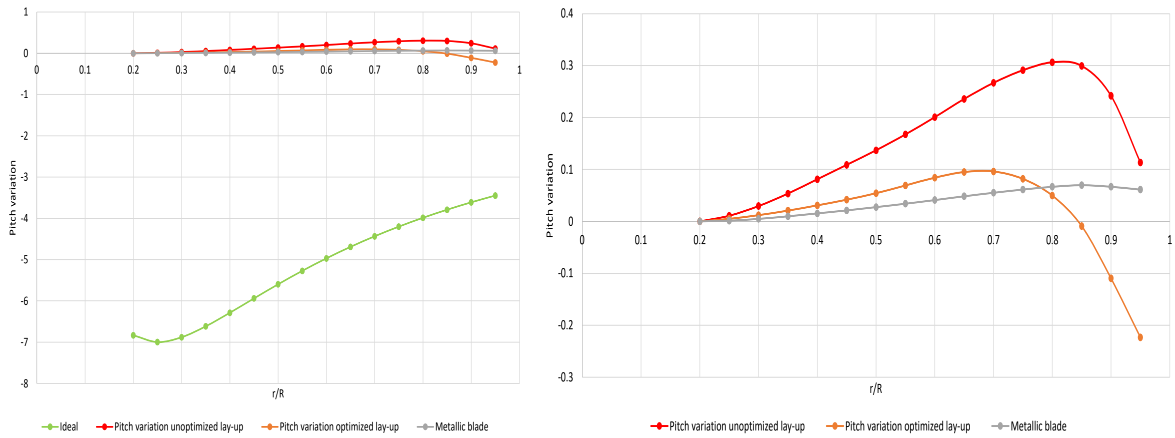

Figure 10. Comparison of the pitch variation for different material: with ideal pitch (left) without (right)

The pitch variation does not reach the calculated ideal one which seems impossible to reach without using a variable pitch propeller. However, the use of composite material with optimized orientation of the lay-up allows to reduce the difference between the ideal and the calculated pitch. The use orthotropic composite material even enable to reverse the sign of pitch angle evolution within the range of design points. This changing of pitch direction can lead to a significant improvement of the pitch variation in comparison with metallic blades at the top of the blade which is the most important area in terms of lift. So, this optimization successfully improves the pitch variation in the region which has the most weight, see Figure 6.

4.3. Sizing results

The minimum safety factor is 3.4, see Figure 11. According to BV NI663 [2], a minimum safety factor of 2.68 is sufficient for static strength consideration, and complementary fatigue analysis must be carried out to ensure the mechanical resistance of the blade.

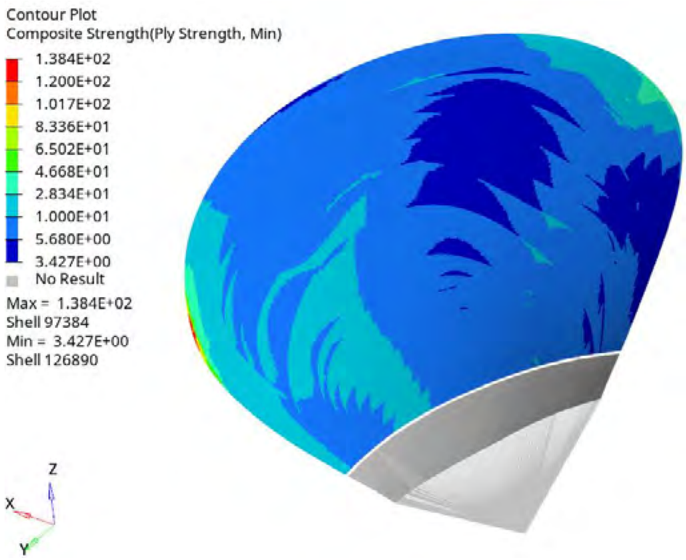

Figure 11. Minimum safety factors SF_CSiapp calculated in each ply

A complementary strain analysis has been made to complete the static verification. The calculated strains have to remain low in order to avoid important deformation that can lead to fatigue failure. Based on a previous study on composite propeller and bibliography, a maximum strain criterion has been determined. The maximum strains of the full-scale propeller are computed and are located on the external plies of the blade (ply 1 and 38) as presented in Figure 12: these strains.

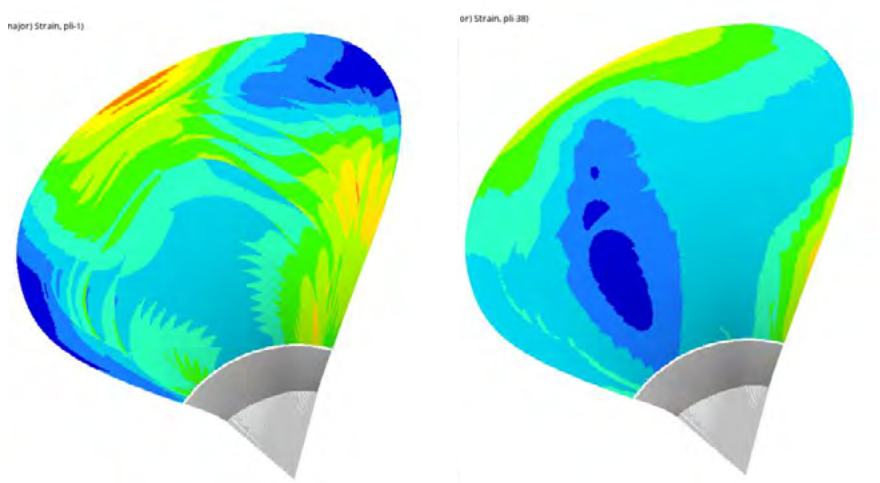

Table 12. Strain field on the blade: extrados (left) and intrados (right).

The strains within the blade are sufficiently low and thus no fatigue damage is expected for the blade proper. For the blade root interface, a dedicated static and fatigue analysis is performed by TWI, and prototype testing is prepared.

3. Conclusions

An innovative methodology coupling FEM and CFD models have been develloped, starting with a reference metallic blade, to propose an enhanced design using composite material.

The procedure includes:

- Obtaining the functional curve of the propeller and the fluid loads with automatic meshing
- Defining the optimal composite stacking within a wide range of design points
- Assessing structural strength according to Bureau Veritas rules
- Providing all manufacturing data, including reverse-loaded shape.

Most of all, each procedure step has been highly optimized and automized, in order to be industry compatible in terms of cost and timeframe.

We have shown that the orthotropic capability of the composite blade can be successfully exploited to improve the change of pitch angle within a ranger of design points, without being detrimental to structural strength.

A full scale test campaign already schedule within the COPROPEL project will aim at demonstrating the benefits of this redesign, including noise reduction, lower vibration and cavitation, but also efficiency gains thanks to the flexibility.

Acknowledgments
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[2] BUREAU VERITAS, NI 663 – Propeller in composite materials, March 2023.