CERTIFICATION APPROACH FOR COMPOSITE PROPELLER WITH DESIGN ASSESSMENT BASED ON NEW TOOL APPLICATION

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Abstract

Today, due to the challenges of climate change and new objectives set by International Maritime Organisation, 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 hydrodynamic efficiency and therefore less fuel consumption and greenhouse gas emissions.

The European research project CoPropel aims to improve the knowledge in designing, building and testing propellers in composite materials. Two propellers will be designed and tested, a small-scale to study the behaviour in hydrodynamic tunnel and in a towing tank, and a full-scale propeller to evaluate the performance during sea trials. Tests will be supported by numerical simulations with an objective of improving the existing requirements from Classification Societies.

The paper will detail the certification scheme proposed by Bureau Veritas in the guidance note NI663 Propeller in Composite Materials. Then, a new tool based on the coupling of Boundary Element Method with Finite Element Model will be presented. Advantages of this tool will be highlighted in the certification process of propeller in composite materials.

1. Introduction

Today, due to the challenges of climate change and new objectives set by International Maritime Organisation (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 hydrodynamic efficiency and therefore less fuel consumption and greenhouse gas emissions.

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 behaviour 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.

In a first part, the paper will detail the certification scheme proposed by Bureau Veritas (BV) in the guidance note NI663 Propeller in Composite Materials. All steps, from the testing qualification, the design assessment methods to construction and in-service surveys necessary for the qualification of composite propeller will be described. Then, a new tool based on the coupling of Boundary Element Method with Finite Element Model (BEM/FEM) will be presented. This tool was used for the design review of two propellers: a small-scale propeller, 250mm diameter, developed within CoPropel project and a full-scale propeller, around 1m diameter, designed from a previous project. Results obtained for both designs will be compared with a two-way hydro-structure coupling performed with Computational Fluid Dynamics (CFD) and FEM for the validation of the new tool. Advantages of this tool will be highlighted for the use in the certification process of propeller made in composite materials.

2. BV Guidance Note NI663

2.1. Introduction

Nowadays, few standards exist regarding the certification of composite propellers. Only three Classification Societies issued guidelines covering this technology. ClassNK, from Japan, was the first and proposes the document *Guidelines for Composite Propellers (Part on Manufacturing/product Inspection)* [2]. The document has been issued in August 2015 and deals with the fabrication process and materials but excludes the design assessment. The note is divided in four chapters:

- Chapter 1: General
- Chapter 2: Application of Composite Material to the Propeller
- Chapter 3: Approval of Manufacturing Process
- Chapter 4: Testing/inspection of the Product

In April 2019, Korean Register issued *Guidance for Composite Propeller* [3] providing recommendations for the manufacturing and the testing.

Bureau Veritas published in October 2020 the Guidance Note NI663 *Propeller in Composite Materials* [4]. The covered scope is larger than ClassNK and Korean Register and the content of the NI663 is detailed in the following sections of this paper.

2.2. Certification Scheme

The certification scheme indicated in the BV NI663 consists in 4 main steps as illustrated in Figure 1 and listed below:

1. Raw certification type approval,
2. Design assessment,
3. Tests,
4. Inspection, Certification.

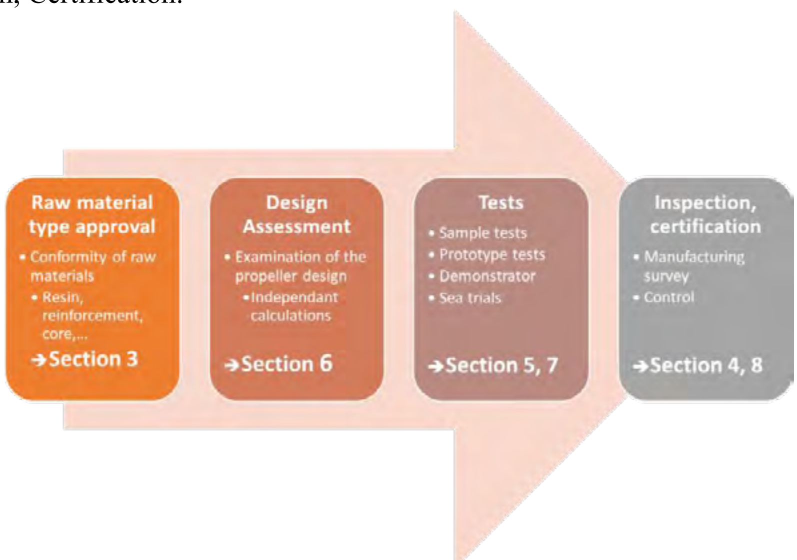

Figure 1. NI663 Certification Scheme.

2.2.1 Step 1: Raw materials certification

The mechanical characteristics of laminates used for composite structures depend on raw materials' characteristics. The raw materials considered are of four main types: resin systems, reinforcements, core materials and adhesives. General information about the main raw materials is given in BV NR546 [5]. Raw materials manufactured in series correspond to HBV product according to BV NR320 [6] and the type approval process of raw materials requests the two following successive phases:

- Design type approval: to review the technical documentation and mechanical characteristics proposed by the supplier in compliance with the rule requirements.
- Work's recognition: to assess the compliance of the raw materials manufactured in series with the design type approval.

In the framework of CoPropel, materials used are not type approved by BV and should be certified by the materials provider in the scope of the certification.

2.2.2 Step 2: Design assessment

The composite propeller design assessment proposed by BV NI663 is based on two assessment methods [7]:

- <u>Cantilever Beam Method (CBM):</u> CBM is an analytical method able to represent the radial distributions of thrust and torque force loading. From these loads, strains and stresses can be calculated.
- <u>Numerical Method (NM):</u> NM is a method combining Computational Fluid Dynamics (CFD) or Boundary Element Method (BEM) for the loading and Finite Element Analysis (FEA) for stresses.

The advantage of the CBM is its ease of use and for obtaining results at a preliminary design stage. However, due to the blade load application in only two points and the limitation of the calculation area below these loading points, stresses calculation is required at only one location, i.e., at 25% of the propeller radius from the root.
Numerical Method is based on the potential flow tool such as Procal [9] or on CFD computations in order to determine the pressure distribution, and on FEA to evaluate stresses. The final validation of the blade design should be demonstrated by applying the numerical method (NM).
The first stage consists of determining the hydrodynamic pressures applied on the propeller using dedicated software. In the second stage, a FEM is to be carried out representing the mechanical behaviour of the blade and its connection to the shaft line. Material properties are to be considered layer by layer according to BV Rules NR546. Boundary conditions should be representative as much as possible to the hub connections.
For both methods, CBM and NM, stresses are to respect BV criteria defined as rules safety factors SF and SFcs for propeller blades made in composite materials.
Two SF are to be considered:

- Minimum stress criterion in layers: $SF \geq \alpha\, C_V\, C_F\, C_R\, C_l$
- Combined stress criterion in layers: $SFcs \geq \alpha\, C_{CS}\, C_V\, C_F\, C_l$

The proposed minimum partial safety factors to be considered for composite materials blades are defined in BV NI663 [4] as follows:

- α : Coefficient taking into the accuracy of calculation method used for the design check.
- C_V: Coefficient taking into account the ageing effect of the composites.
- C_F: Coefficient taking into account the fabrication process and the reproducibility of the fabrication.
- C_R: Coefficient taking into account the type of stress in the fibres of the reinforcement fabrics and the cores.
- C_l : Coefficient taking into account the type of loads.
- C_{CS} : Coefficient for combined stresses in the individual layers of the laminates.

As a rule, fatigue analysis is not required when the safety factor is greater than the minimum calculated as above.

In the framework of CoPropel, the Cantilever Beam Method and the two Numerical Methods using CFD and BEM will be applied and compared. More details on NM are given in section 3.

2.2.3 Step 3: Tests

BV NI663 requires several kinds of tests for the certification of composite propellers as presented with the testing pyramid in Figure 2.

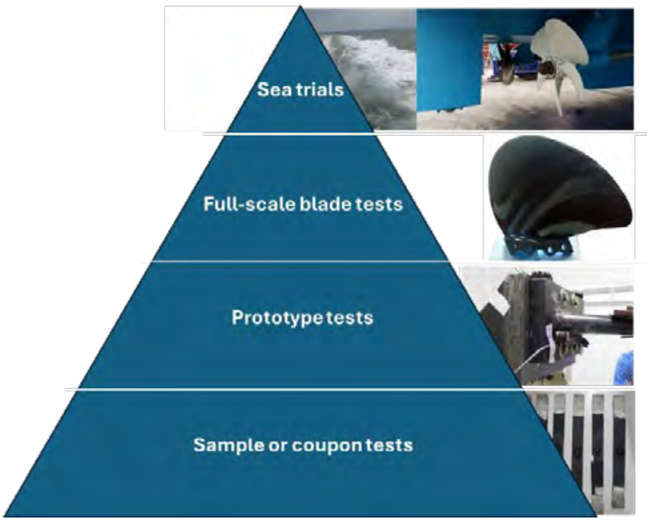

Figure 2. Testing pyramid

- <u>Sample or coupon tests:</u>

Mechanical and physico-chemical tests are to be performed by the propeller manufacturer on coupons representative of the scantling and the process used for the propeller manufacturing. The results of the mechanical tests are to be compared with the theoretical properties of the propeller laminate determined on the basis of the requirements of the NI663 and considered for the structure design assessment. Following tests are to be performed:

  - measurement of density
  - reinforcement content in weight
  - tensile tests
  - bending tests
  - interlaminar shear tests
  - immersion test

Ageing and fatigue tests may be required by the Class Society on a case-by-case basis.

- <u>Prototype tests:</u>

A full-scale static load test is to be carried out by the Manufacturer on one blade or on a piece as much as possible representative of the type of propeller concerned. The first objective is to demonstrate that the prototype under test displays the behaviour provided by the design. The second objective of this test is also to confirm numerical simulations by an experimental approach. The comparison with a Finite Element Model is mandatory by measuring stresses and displacement in two locations, 0,25.R and 0,6.R (where R is the blade radius) considering a load representative of 1,25 times induced bending moment and shear force (generated by maximum thrust and torque in continuous regime). As far as possible, these types of tests must be used for the validation of the blade connection to the shaft line hub. Indeed, the connection to the hub is a critical point for the propeller and the numerical approach may not be sufficient for stresses and strains assessment.
Fatigue tests may be required by the Class Society on a case-by-case basis.

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- Full-scale blade tests:

The full-scale blade tests consist in the following control of each blade:
  - dimensions
  - weight
  - centre of gravity
  - stiffness (modal analysis/eigenvalue).

In addition of these controls, some non-destructive tests (NDT) may be carried out in order to verify the quality of the blade all along the production process.

- Sea trials

The sea trials are intended to demonstrate that the propeller is functioning properly according to the criteria defined by the Class Society. The sea trials procedure is to be submitted to the Society before testing and should include following information:
  - aims of the sea trials
  - organization of sea trials (date, attendees)
  - sea trials conditions (place, weather and environmental conditions…)
  - procedure of test (duration of the tests, checks)
  - control and measurement, measurement results.

The testing procedure shall include tests that are representative of ship maneuvering (i.e.giration, crash stop, maneuvering ahead and astern…).

In the framework of CoPropel, coupons tests, prototype tests, full-scale blade tests and sea-trials will be carried out for the qualification of the propeller. In addition, a small-scale demonstrator will be produced to validate the manufacturing process and will be tested in basin and cavitation tunnel to evaluate the hydrodynamic performances.

2.2.3 Step 4: Inspection, Certification

For composite materials propeller, an external examination of the coating condition is to be carried-out. This examination is to be directed at discovering significant alteration of the coating or contact damages. If any and if deemed necessary, NDT testing might be requested by the Society.
Particular attention is to be paid of the following parts of the blade:
- leading edge
- trailing edge
- connection system

Based on records of NDT tests, a comparative analysis might be performed, where deviations will be submitted to the Class Society for acceptance.

In the framework of CoPropel, manufacturing steps will be surveyed and blade will be inspected.

3. Numerical approach for the design assessment

This section presents the use and the validation of a new Fluid-Structure Interaction (FSI) tool, ComProApp, based on BEM and developed within CRS (Cooperative Research Ships) [10]. Two propellers have been used for this study:
- A small-scale propeller, 250mm diameter, developed within CoPropel project,
- A full-scale propeller, 1.1m diameter, designed from a previous project.

3.1. ComPropApp

ComPropApp is an in-house tool developed by the CRS partners and designed for the hydro-structural analysis of flexible, i.e. composite materials, ship propellers [11]. ComPropApp performs FSI analysis by explicit two-way coupling of the fluid solver, Procal, and the Finite Element solver Vast (Trident) or Nastran (Siemens) with a graphical user interface, see Figure 3. The fluid solver Procal is a BEM solver that is based on the potential flow theory while the structural solver (Vast or Nastran) is a mechanical solver using FEM. The Finite Element solver solves the non-linear problem iteratively by applying the actual external blade load incrementally up to the convergence.

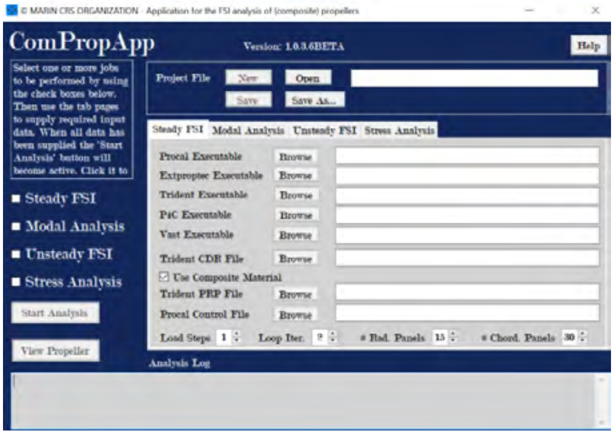

Figure 3. ComPropApp, graphical user interface

3.2. Small-scale propeller

The small-scale propeller geometry is based on the geometry characteristics of the Madara propeller, an inland navigation pusher barge. The original propeller has a diameter of 1960 mm with 4 blades and the pusher barge Madara has 2 symmetrical propellers. The small-scale propeller, designed in composite materials by Meca, a CoPropel partner, has a diameter of 250mm, to be compatible with small-scale tests facilities. Figure 4 shows the geometry of the small-scale propeller, the Madara vessel and the characteristics of the propeller.

Diameter: 0.25 m
Number of blades: 4
Materials: Carbon fibres and epoxy resin

2 operational conditions:

- J=0; 1800 rpm
- J=0.55; 1800 rpm

Figure 4. Small-scale propeller information and Madara vessel

Numerical simulations of the small-scale propeller have been performed by Meca and Bureau Veritas using two methods, CFD/FEM and BEM/FEM (ComPropApp) coupling respectively, for two advance coefficients: J=0 and J=0.55. The small-scale propeller will be experimented in a hydrodynamic tunnel and in a towing tank at Bulgarian Ship Hydrodynamics Centre (BSHC) and blade deformations will be measured.

The maximal displacement of blades obtained by both numerical simulations are presented in Table 1. As tank test has not been yet performed, results are compared between CFD/FEM analysis and BEM/FEM coupling with ComPropApp.

Table 1. Small-scale propeller results.

Blade displacement (mm)	*BEM/FEM (Femap)*	*CFD/FEM*	*Discrepancy*
J=0	2.90	3.40	13.5 %
J=0.55	0.90	1.04	14.7 %

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3.3. Full-scale propeller

The full-scale composite propeller has been designed in the framework of FabHeli, a French research project led by LoireTech and partly funded by the French department of Defense (DGA). The full-scale propeller geometry comes from the small passenger vessel Le Palais and characteristics are presented in Figure 5.

Diameter: 1.1 m
Number of blades: 5
Materials: Carbon fibres and epoxy resin

Figure 5. Full-scale propeller information and Le Palais vessel

Numerical simulations have been performed by Bureau Veritas and Bureau Veritas Solutions by applying the two approaches: CFD/FEM and BEM/FEM. In total 4 calculations have been run:

1. BEM/FEM one-way coupling: ComPropApp with Vast
2. BEM/FEM one-way coupling: ComPropApp with Nastran
3. CFD/FEM one-way coupling: StarCCM+ & Femap Nastran
4. CFD/FEM two-way coupling: StarCCM+ & Femap Nastran

Calculation 1, ComPropApp with Vast, will be the reference for the evaluation of the discrepancy with the other results. Table 2 summarises the maximal displacement obtained for the blade.

Table 2. Small-scale propeller results.

(mm)	*BEM/FEM (Vast)*	*BEM/FEM (Nastran)*	*CFD/FEM (one-way)*	*CFD/FEM (two way)*
Blade displacement	13.6	11.58	12.93	12.74
Discrepancy	/	-14.85 %	-4.93 %	-6.32 %

The comparison of thrust and torque calculated for each configuration with CFD and BEM leads to less than 3% discrepancy confirming the validity of BEM for the evaluation of flexible propeller loads. Regarding the deformation of the blade, the maximal displacement is calculated with ComProApp with Vast and the discrepancy is 6.32 % with the CFD/FEM two-way coupling calculation. Results obtained with ComPropApp with Vast or Nastran are acceptable with this computation method in the studied configuration.
The comparison of time spent for the model preparation, for solving the problem (CPU time) and for the post-processing for both approaches, BEM/FEM et CFD/FEM, shows a non-negligible advantage of ComPropApp. Indeed, CFD/FEM approach requires 10 times more time to achieve one calculation than BEM/FEM.

For information, the vessel Le Palais will be reused within CoPropel project for sea trials. A new optimised propeller will be designed and manufactured by the consortium. Numerical simulations as well as experiments will be carried out next year. Calculation results and measurements at sea will be compared to confirm the validity of numerical approach for propellers made in composite materials. Additionally of displacements, stresses in each ply of laminates will be evaluated and compared with criteria indicated in the BV guidance note NI663.

3. Conclusions

This paper presents steps leading to the certification of propeller made in composite materials. The complete guidance note NI663 issued by Bureau Veritas covers all steps, from the materials characterisation to the installation and in-service surveys. The paper focuses on the design assessment step and especially on the use of ComPropApp, a Boundary Element Method tool developed by CRS members, and able to carry out hydro-structure coupling calculations.
The study compares the results obtained by using two different Fluid-Structure Interaction calculation methods, BEM/FEM coupling and CFD/FEM coupling. In terms of hydrodynamic loads, thrust and torque computed by two methods give a maximum of 5% discrepancy for rigid or flexible propellers. These good results confirm the validity of using Boundary Element Method for the loading of propellers. Regarding the mechanical calculations by Finite Element, a discrepancy of 15% on displacements has been observed between the two approaches. This difference is not too huge in considering the time won by using ComPropApp tool for the calculation. Indeed, ComPropApp is ten times more rapid than CFD/FEM coupling for pretty accurate results. Stresses are also to be evaluated and compared for the validation of the propeller scantling in accordance with Bureau Veritas requirements. This task will be performed within CoPropel project.

In an industrial process, the use of ComPropApp will be useful for a designer, especially at a preliminary design stage to test several laminate configurations and several operational profiles. Similarly, for a Classification Society, in charge of the design review of a composite propeller, ComPropApp will allow to confirm results of the calculation note submitted by the manufacturer. CFD/FEM remains important for the validation of the results at a minimum one operational point.

At this stage, only numerical results have been compared, between CFD/FEM and BEM/FEM. However, as tank tests and sea trials will be performed during CoPropel project, a comparison with numerical simulations and experimental measurements will be possible. This comparison will allow to verify and validate computations and tools.

Acknowledgments
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