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Finite element modelling and model updating of small scale composite propellers

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Abstract

The application of composite materials in marine propellers is a relatively recent innovation. Methods have been presented to analyse the hydro-elastic behaviour of these type of propellers and in some studies these methods have been validated as well. Differences between measured and predicted responses are typically explained from inaccuracies in structural or fluid modelling. It is beyond all doubt that for an accurate finite element (FE) model a correct modelling of the fibre orientations and material properties is required. Both subjects are addressed in this work. An approach is presented in order to accurately define the element dependent fibre orientations in doubly curved geometries like (marine) propeller blades. In order to improve the structural response prediction this paper presents an inverse method based on experimental and numerical results which can be used for structural identification and FE model updating. In the developed approach the residual between measurement results obtained with static experiments and results obtained with an FE model is minimized by adapting the stiffness properties in the FE calculation. This method has been successfully applied to two small scale composite propellers. The obtained material properties have been determined with a relatively high confidence level. A verification by means of measured and calculated eigenfrequencies show also that accurate results are obtained with the inverse method. Therefore, this paper gives a positive answer on the research question whether it is possible to determine the stiffness properties of small scale composite marine propeller blades from a static experimental data.

Keywords: Composite Propellers, Finite Element Modelling, Model Updating

1. Introduction

The strength and stiffness of polymer composite structures depend on the orientation and distribution of fibres in the material. For that reason composite forming simulations have been developed in order to establish the orientation, distribution and wrinkling of fibres after draping into moulds, see for instance [1], [2] and [3]. For an accurate response estimate of a composite structure the actual fibre orientation and distribution have to be correctly represented in a structural model. Correct modelling of the fibre orientations has been addressed in [4]. It has been proposed to develop a solid element model by extruding a shell element model with correct orientations. This method has been applied for the calculation of stresses in a gas turbine engine vane. The results show the significant effects of an accurate definition of fibre orientations in the FE analysis of (doubly) curved geometries. The necessity of a FE solver with extrusion functionality and an existing shell element model with correct orientations seems to be limitations of this method. This paper aims to present an accurate method without the aforementioned limitations, applicable to determine the material orientations in doubly curved solid FE models, like marine propeller- and wind turbine blades.

Another important factor for accurate FE modelling is the use of correct model input parameters. When destructive measurements are undesirable the input parameters could be deduced by solving an inverse problem. In the inverse problem model input parameters are obtained by combining experimental and model results. This special application of inverse methods is known as a mixed numerical-experimental technique (MNET). Since the nineties many papers have been published on the application of MNET's for mechanical problems, but can be used for any other field if an accurate and sensitive experimental method is available and a good theoretical model exist [5]. Many different approaches are presented in literature for model updating by using MNET's, see for instance the references made in [6], [7], [8] and [9]. According to [10] all the different approaches for model updating can be divided into two main categories: deterministic methods and probabilistic model updating methods, where the first one is the most common approach [6]. An important drawback of the deterministic approach is the non-uniqueness of the solution which might occur especially when having a large number of updating parameters and an insufficiently large data set. A drawback of probabilistic methods is the mathematical complexity, but these methods can handle the non-uniqueness of the solution [6]. Examples

of applications of model updating by means of deterministic and probabilistic approaches can be found in respectively [11], [12], [13], [14], [15] and [16]. Another overview of MNET approaches can be based on the type of the experiments, either static or dynamic. Dynamic experiments seems to be preferred in literature. This could be attributed to the fact that with dynamic experiments eigenfrequencies can be efficiently obtained which are much more sensitive parameters than output parameters obtained from static experiments, according to [5]. However, with dynamic testing one is restricted to a global structural response, while static tests can be used to determine parameters that influences both global and local structural behaviour [17].

In [11] modal analysis measurements have been performed on a composite blade of a small sized wind turbine. An optimisation algorithm has been used to minimize the residual between measured and calculated eigenfrequencies and modes by adjusting the material properties. A similar approach, but on a much larger scale has been presented in [14]. In comparison to [11] and [14], the blades considered in this work are of much smaller size and static measurements instead of dynamic experiments are conducted. The following research question will be addressed: is it possible to determine the stiffness properties of small scale composite marine propeller blades by making use of an MNET based on static experiments and a deterministic approach?

2. Propellers

The two considered propellers, see Figure 1, have a diameter of 0.34 m and the same geometry and glass-epoxy laminate lay-up, but differ with respect to the laminate orientation of the composite blades. For identification the propellers and the blades have been numbered as follows:

- Propeller 45: $[+45^\circ/-45^\circ]$ laminate lay-up.
- Propeller 90: $[0^\circ/90^\circ]$ laminate lay-up.
- Blade number 1 and 2 are designated to the uppermost and bottommost blade respectively, see Figure 2.

The 0° direction of the laminae is parallel to the z-axis of the propeller blade coordinate system, see Figure 2. All the results presented in this paper are according to this reference system.

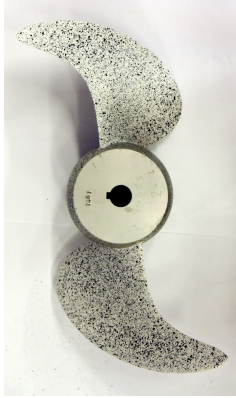


Figure 1: Picture of one of the two-bladed propellers.

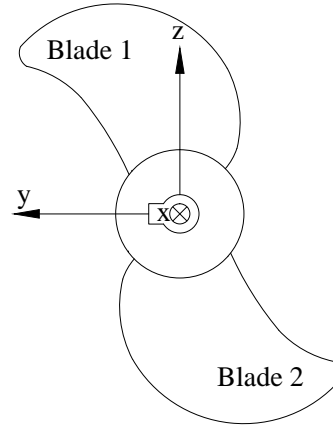


Figure 2: Propeller blade coordinate system; x-, y-, z-axis positive to upstream, portside and top respectively.

3. Experiments

This section describes the experiments which have been executed to obtain a dataset to be used in the mixed numerical experimental technique as presented in Section 5.

3.1. Selected type of experiments

For this work static experiments have been selected for the following reasons:

- Results of the sensitivity study presented in Section 4.4 show that output parameters obtained from static experiments could be very sensitive.
- There were uncertainties on the practicability to obtain sufficient and accurate data with dynamic tests.
- Local information of the tip region can be more easily obtained with static experiments. It can be expected that the stiffness of the tip region will dominate the blade structural response since the propeller tips are very flexible compared to the stiffness of the blade body part.

3.2. Test setup

For the static experiments a turning lathe was used as test setup, (Figure 3). The propellers were mounted on a shaft clamped in the fixed chuck jaws. On the carriage of the turning lathe a load cell with a PVC ball was mounted, such that by moving the carriage a force was applied on the propeller blades by the PVC ball. With Hertzian contact theory a design for the PVC ball has been made such that the contact stresses of the propeller blades would not exceed the maximum allowable compressive stress. For a radius of 20 mm this criterion was satisfied.



Figure 3: Experimental setup for the static tests.

3.3. Measurement techniques

During the static tests the applied force and the structural response of the blades have been measured. The force was measured with a 1 kN force transducer with an accuracy of 0.4 N. The spatial distribution of the suction side propeller blade structural response has been measured with a digital image correlation (DIC) technique. With a DIC technique a very accurate recording of the blade displacement could be achieved. A general value for the 95% confidence interval of the measured displacements is 25 μm . DIC is a full-field image analysis method, based on grey value digital images that finds the displacements and deformations of an object in three dimensional space [18], [19]. During deformation the method tracks the grey value pattern from which the displacements of the object are calculated using the Vic3D software. In the post-processing of the image data a procedure was for blade

displacements induced by deformations and displacements of the shaft. In order to use the DIC technique, the object surface needs to contain a random speckle pattern with no preferred orientation and sufficiently high contrast. In Figure 1 one of the speckled propellers is shown.

3.4. Selected loading conditions

As shown in Section 4.4 only the in-plane material properties are sensitive parameters and could be determined with an MNET. To identify the four in-plane material properties at least four responses with their variation directly attributing to the variation of these parameters are necessary. To be on the safe side two additional loading conditions have been selected. The tip region is the most interesting blade part to investigate since the stiffness of the tip will dominate the blade structural response. The six loading conditions have been selected such that on average the tip structural response dominates, being sensitive to all the in-plane material properties, according to the results presented in Section 4.4. The selected points are depicted and denoted in Figure 4.

The maximum loads have been determined such that the propeller blade stresses are below the maximum allowable stresses and that the responses obtained for different loading conditions have similar magnitude in order to avoid biasing of one of the loading conditions.

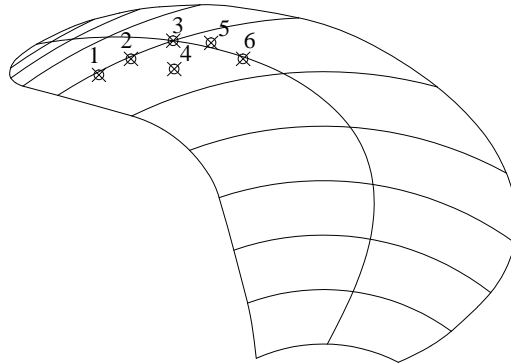


Figure 4: Selected points for the six loading conditions.

4. FEM modelling of the propellers

This section describes how the propellers are modeled in FE. Special attention is paid to define the material orientations. A new approach is

presented to model the material orientations in the propeller blades.

4.1. Geometric representation of the propeller

For FE modelling and calculations MSC Marc/Mentat has been used. The FE models consist of one propeller blade without the hub part. The stiffness contribution of the hub has been modeled by a full clamping of the propeller blade at the blade-hub interface. The underlying assumption is that the stiffness of the hub is much higher than the stiffness of the blades, [20], [21] and [22]. Still, a better approach would be to model the whole setup.

The propeller blades could be discretised using solid or shell elements. A disadvantage of a shell element model is that interlaminar stresses cannot be obtained, in contrast to solid elements. Another advantage of solid elements is that a better description of the actual geometry can be obtained.

In the FE models presented in this paper quadratic solid elements have been applied. Quadratic solid elements were preferred over linear elements since linear elements require many elements in through-thickness direction in order to accurately model the bending dominated blade response.

For the computations presented in this paper a $116 \times 60 \times 4$ element distribution was used. This means that 116 elements are placed along the chord of the propeller (58 elements on both sides), 60 panels in radial direction and 4 elements in through-thickness direction. From convergence perspective a $58 \times 30 \times 4$ mesh would be sufficient. However, the finer mesh with four times more contact nodes was used in order to obtain a smoother representation of the structural response in the FE contact analyses.

4.2. Material orientations

In Section 1 the importance of a proper material orientation for doubly curved structures has been described. Standard commercial FE software packages are usually not able to define unambiguously the material orientations in complex geometries [4]. Local element coordinate systems are usually available in FE software packages. With this feature the through-thickness material orientation can be directed perpendicular to the outside surface of the elements. However, the alignment of the two other material axes will depend on the orientation of the element itself (Figure 6a). This can result in an erroneous material orientation and a misprediction of the structural stiffness. To determine for each element the material orientation a new approach has been developed in which the following steps have been taken.

The first direction is the through-thickness material orientation which is the normal to the element surface, (Figure 5). The second direction is in plane of the element surface. A second plane has to be found which will contain the second material direction. For a propeller in the blade coordinate system (Figure 2), it can be assumed that one of the principal material directions will be in the x-y plane (Figure 5), since the blade is slightly curved in radial direction. Then, the second material direction is the intersection between the plane of the element surface and the x-y plane. This is in essence the projection of the 90° direction unto the element. In case of a single curved geometry this approach results in the correct orientations. In case of doubly curved geometries it depends on the assumption of the second plane. The developed element dependent material orientation is, if not explicitly stated, used for all the FE calculations presented in this paper.

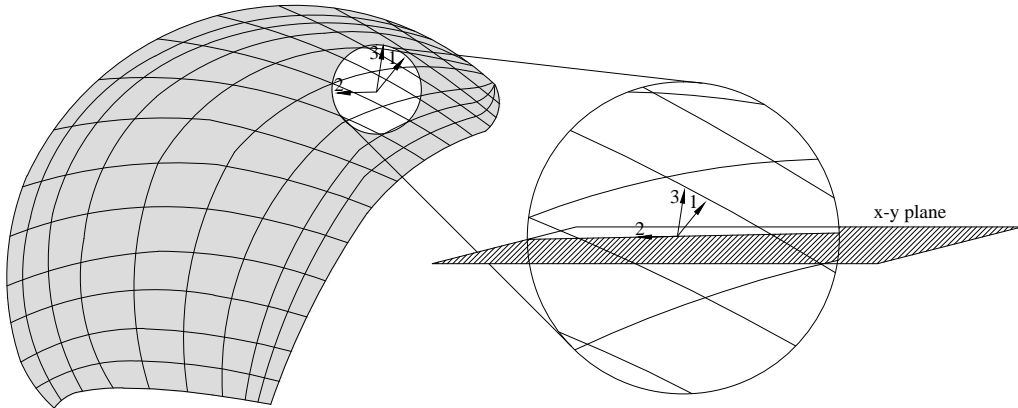


Figure 5: Determination of the material orientations.

A small comparative study has been performed between a FE model with the material orientations based on the local element coordinate system and the developed element dependent material orientations. The typical difference between these two material orientations has been sketched in Figure 6.

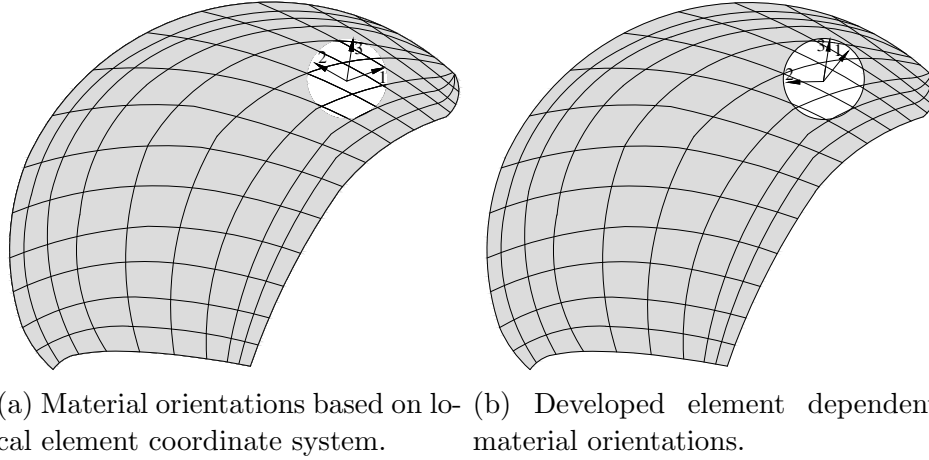


Figure 6: Differences between the two material orientations.

Results of calculated eigenfrequencies of the FE models with the two different material orientations are presented in Table 1. Relatively large differences in eigenfrequencies are obtained for the first two modes. Depending on the meshing procedure, larger differences could be expected when the propeller geometry contains more skew or when the material is more anisotropic.

Mode	Local material orient.	Developed material orient.	Difference %
1	495	474	4.4
2	704	654	7.6
3	1283	1267	1.3

Table 1: Eigenfrequencies [Hz] for propeller 45 calculated with the two different FE models.

4.3. Load cases and boundary conditions

Contact analyses have been selected to model the experiments in FE. The PVC ball which was used to apply static loads on the blades has been modeled as an undeformable body. Analyses have been performed with and without friction. A friction coefficient of 0.3 has been adopted for the analyses including friction as a common value for friction between two polymers. Displacement constraints in y- and z-direction were applied on the PVC ball, because the static load was only applied in x-direction. On the blade itself,

displacement constraints are put on the intersection area between blade and hub in order to model the clamping.

4.4. Sensitivity study

Sensitivity studies have been performed with the FE models in order to select different loading conditions which show high sensitivity for at least one stiffness parameter, such that all the stiffness parameters are sensitive in at least one loading condition. The sensitivity study has been conducted to investigate the differences in sensitivities between eigenfrequency results and static test data as well.

In this sensitivity study the different stiffness parameters are systematically changed in order to investigate their dependency on the response of the FE model. The sensitivities are approximated using a forward finite difference technique. This is performed by using the results of two FE analyses for two states of a stiffness parameter P_j :

$$S_j = \frac{R_j(P_j + \Delta P_j) - R_j(P_j)}{\Delta P_j} / \frac{R_j(P_j)}{P_j} \quad (1)$$

In this equation S_j denotes the relative variation of the output (displacements or eigenfrequencies) due to a relative difference of an input parameter P_j . In this work the relative sensitivities are used instead of the actual sensitivities $\frac{\Delta R_j}{\Delta P_j}$ since the sensitivities of different calculations (eigenfrequency analysis and contact analysis) with different output parameters have to be compared. The output parameters for the eigenfrequency analyses are the first six eigenfrequencies. The output parameters for the contact analyses are the norm of the structural blade response $\|\mathbf{u}_i\|$ for the six loading conditions i defined in Section 3.4.

The sensitivities of the eigenfrequencies and the static output parameters of propeller 45 and 90 are presented in Figure 7 and 8 respectively. The following conclusions can be drawn:

- The out-of plane properties (E_{33} , G_{23} , G_{13} , μ_{23} , μ_{13}) of the laminate are hardly sensitive. Therefore, the sensitivities of these material properties are not shown in Figure 7 and 8. It can be expected that the out-of plane properties cannot be accurately deduced with an MNET using the selected loading conditions.

- The in-plane Poisson ratio (μ_{12}) of propeller 90 is hardly sensitive, it is expected that this stiffness property cannot be accurately determined with an MNET using the selected loading conditions.
- The average sensitivities of the in-plane stiffness properties for the contact analyses are larger than for the eigenfrequency analyses, especially for propeller 90. In contrast to what is stated in [5] that advocates the use of static data in the MNET.

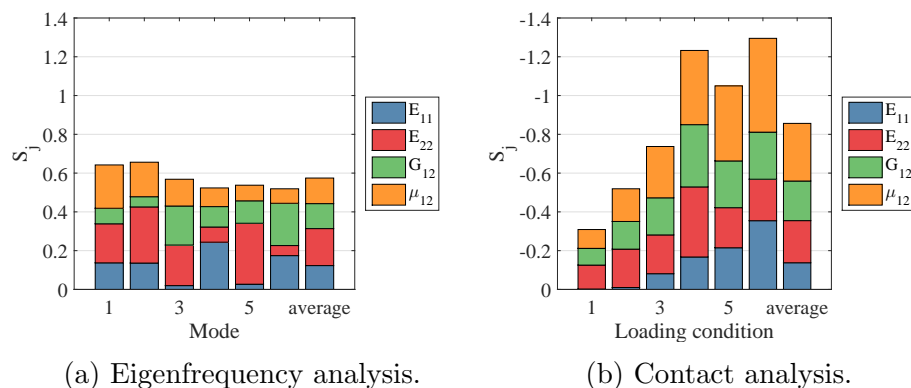


Figure 7: Relative sensitivities of the in-plane material properties for propeller 45, an increase of stiffness results in an increase of eigenfrequency and a decrease of displacements, indicated by respectively the positive and negative sign.

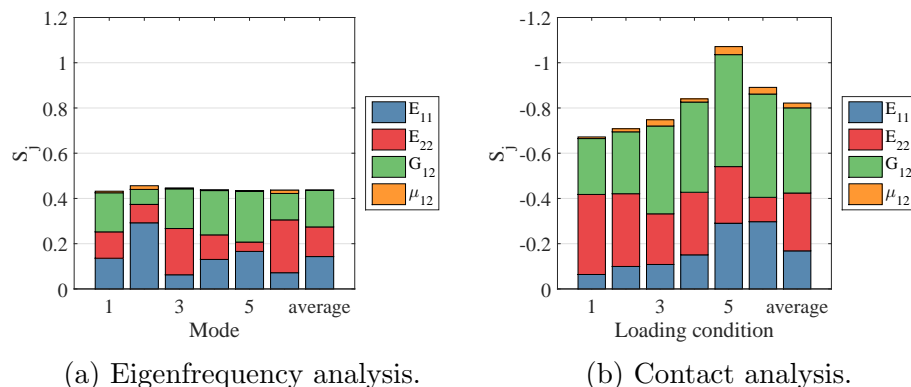
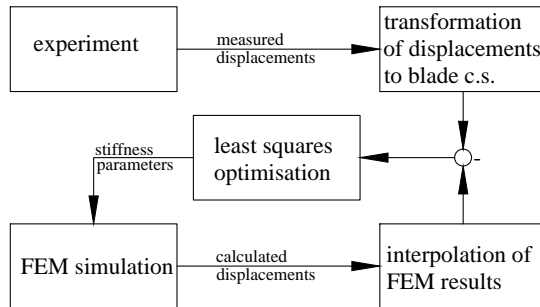


Figure 8: Relative sensitivities of the in-plane material properties for propeller 90, an increase of stiffness results in an increase of eigenfrequency and a decrease of displacements, indicated by respectively the positive and negative sign.

5. The mixed numerical experimental technique

A deterministic model updating method has been developed in order to identify the stiffness parameters of the propeller blades, see Figure 9. In the mixed numerical-experimental technique (MNET) the experimental data obtained from the static tests have been combined with the FE model as presented in Section 4. After measuring of the structural response the results have to be transformed to the blade coordinate system. Before calculating the residual between measured and calculated displacement field the calculated displacement field has been interpolated. Subsequently, an optimisation algorithm of Matlab is used to minimize the residual by varying the stiffness parameters until a converged result is obtained. The interpolation of the FEM results, the transformation of the measured displacements and the optimisation algorithm will be explained in more detail in the next subsections.



centering

Figure 9: Flow chart of the applied mixed numerical experimental approach.

5.1. Interpolation of the FEM results

Considering the contact non-linearity in the structural response, a cubic spline interpolation has been applied in order to obtain the calculated displacements at the same load sampling points as the measurements. In the order of 10^3 points describe the calculated displacement field, compared to $10^5 - 10^6$ points for the measurements. In order to exploit the resolution of the measured displacement field, a second interpolation has been applied to increase the resolution of the calculated displacement field with one order of magnitude. This increase of the resolution show an improvement of the results obtained with the MNET (i.e. the 95% confidence interval are smaller).

5.2. Transformation of the measured displacements

By post-processing the DIC images the measured displacements have been defined in the image correlation coordinate system. However, the relative position and orientation of this coordinate system to the blade coordinate system is not known. Therefore, the measured undeformed blade geometry has been mapped on the design geometry as drawn in the blade coordinate system. The mapping problem has been formulated as an optimization problem in which the transformation between the two coordinate systems is determined by minimizing the objective function $f(\mathbf{x})$:

$$\min_{\mathbf{x}} f(\mathbf{x}) = \sum_i F_i^2(\mathbf{x}) \quad (2)$$

In this case the objective function is the sum of squares of the differences between the coordinates of the sampling points in the undeformed measured geometry and design geometry as drawn in the blade coordinate system $\sum F_i^2(\mathbf{x})$.

5.3. Optimisation algorithm

For the mapping problem and in the MNET the same optimisation algorithm of Matlab has been used. Both problems are very similar; either a residual between two geometries or a residual between two displacement fields has to be minimized. In case of the MNET the term $\sum F_i^2(\mathbf{x})$ in Equation 2 is the sum of squares of the residuals between measured and calculated displacements at the sampling points. The 'lsqnonlin' algorithm available in the optimization toolbox of Matlab has been used to solve the minimization problems. This algorithm is dedicated to solve non-linear least-squares problems with a vector of residuals to be minimized rather than the sum of squares.

6. Results

Results of three different analyses performed with the MNET will be presented in this section, see Table 2 for specification. The results of the analyses will be compared to each other with respect to the final l^2 norm of the residual. Furthermore the l^2 norms of the results will be compared to the l^2 norms obtained with the design stiffness properties. Finally, the model updating with the MNET will be verified by comparing measured and calculated eigenfrequencies of the blades.

Analysis	No. of optim. variables	Friction
A	4	Yes
B	3	Yes
C	3	No
D	0	No
E	0	Yes

Table 2: Analysis A to C specifies the different MNET analyses, analysis D and E are calculations with the design material properties.

6.1. Results of the MNET analyses

Based on the results of the sensitivity study it has been decided to perform MNET analyses with the in-plane Young's and shear moduli as optimisation variables and also analyses with the in-plane Poisson ratio as additional variable, both analyses with friction included. For the stiffness parameters not used as optimisation variables the design values have been adopted. In order to check the influence of friction on the estimated stiffness properties, an analysis without friction has been conducted as well. The results of the different analyses are presented in Figure 10 and 11. The results show that:

- The 95% confidence bounds are generally between the 5% and 10% of the estimated mean values, except for the Poisson ratio. Especially for propeller 90 the confidence bounds for the Poisson ratio of propeller 90 are relatively high. This was already expected from the results of the sensitivity study.
- The estimated parameters for the different blades of propeller 90 are very similar, generally the difference is smaller than 10%. The differences between the results obtained for the blades of propeller 45 are larger.
- Friction results in a totally different estimate for the mean values, the results obtained with and without friction included differ approximately 20%.
- The estimated parameters obtained from the analyses with 3 and 4 optimisation variables and friction included are very similar.

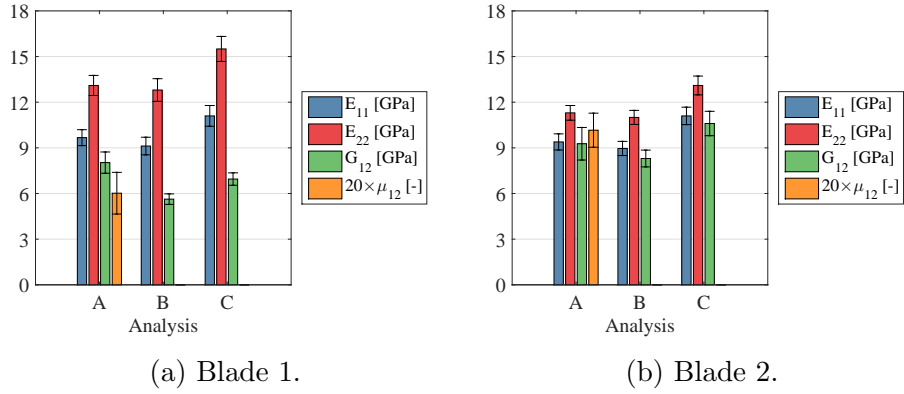


Figure 10: Mean values and 95% confidence bounds obtained for the in-plane stiffness properties of propeller 45 for three different MNET analyses.

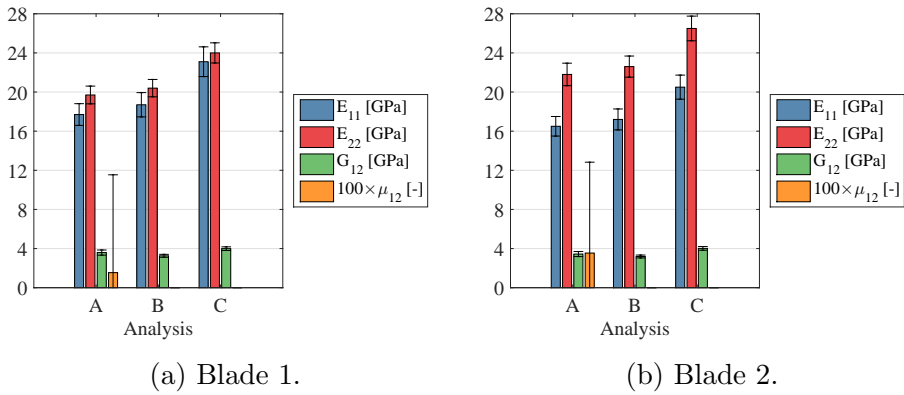


Figure 11: Mean values and 95% confidence bounds obtained for the in-plane stiffness properties of propeller 90 for three different MNET analyses.

In order to show the improvement of the resemblance between measured and calculated response the bending and pitch/twist deformations of propeller 90, blade 2 are depicted for the maximum load at each loading condition in Figure 14. This figure shows that the response calculated from the design material properties is already close the measured response, but a further improvement is obtained with the results obtained from the MNET.

6.2. Comparison of the results

The l^2 norms of the residuals between calculated and measured responses for different analyses are presented in Figure 12. The results show that the l^2 norm of the residuals for the calculations based on the design parameters with friction included, are significantly smaller than without friction, meaning that neglecting friction seems to be unreasonable. The l^2 norms of the residuals obtained with the different MNET analyses are very similar. The improvement of the resemblance between measurements and calculations is the highest for blade 2 of propeller 90. In order to explain this, the difference in l^2 norm of the residual between analysis B and E has been presented for each loading condition in Figure 13. Overall an reduction in l^2 norm is obtained by applying the MNET. However, for all the four blades one or two loading conditions show individually an increase in l^2 norm, while this increase in l^2 norm is the smallest for propeller 90, blade 2. Larger inaccuracies in the static experiments of the other blades is a possible explanation for the highest reduction in l^2 norm of the residual of propeller 90, blade 2.

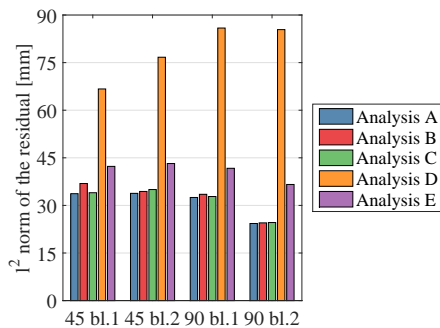


Figure 12: l^2 norms of the residuals between calculated and measured responses for analysis A to E.

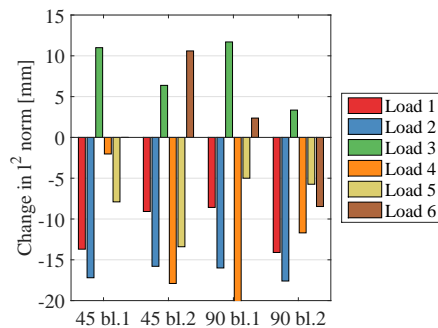
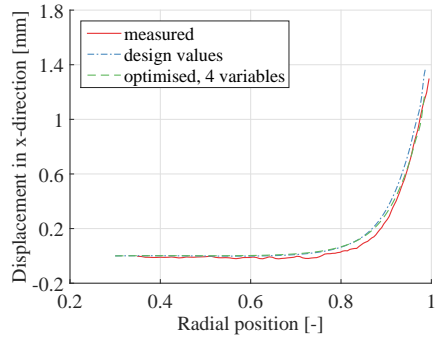
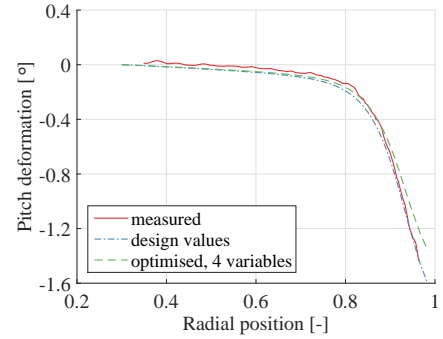


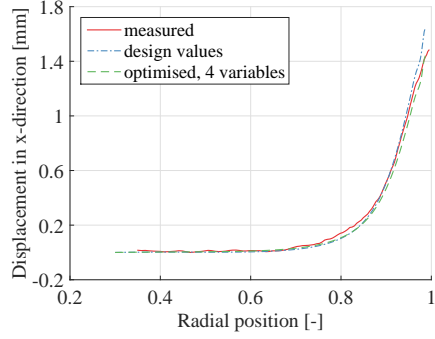
Figure 13: Difference in l^2 norm per loading condition between analysis B and E.



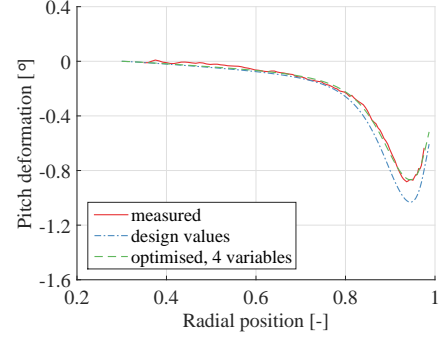
(a) Bending deformation, loading condition 1.



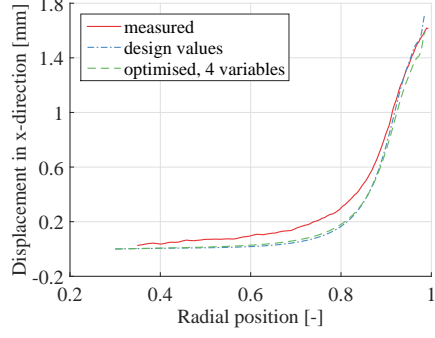
(b) Pitch deformation, loading condition 1.



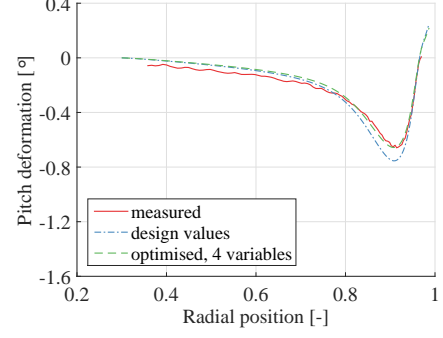
(c) Bending deformation, loading condition 2.



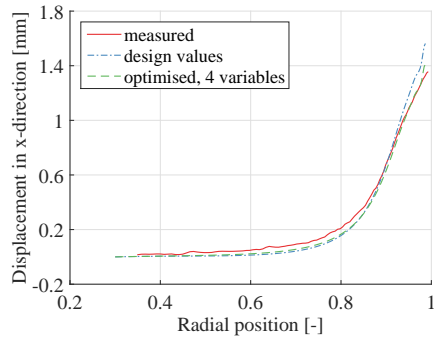
(d) Pitch deformation, loading condition 2.



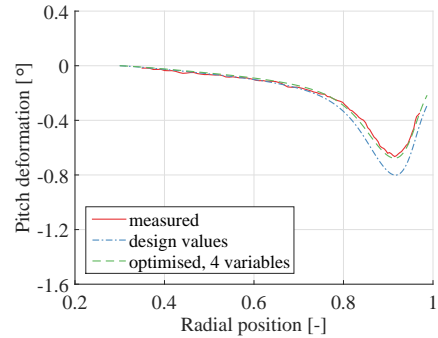
(e) Bending deformation, loading condition 3.



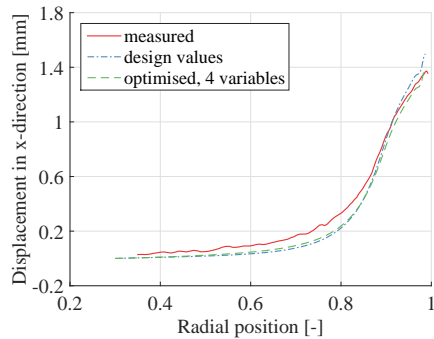
(f) Pitch deformation, loading condition 3.



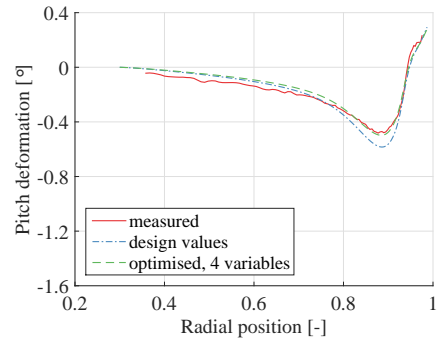
(g) Bending deformation, loading condition 4.



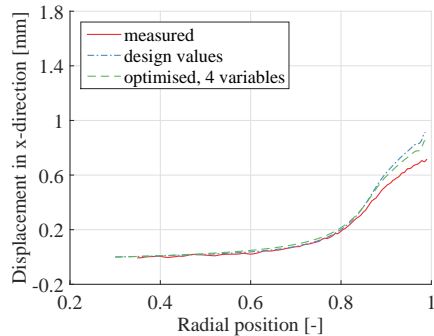
(h) Pitch deformation, loading condition 4.



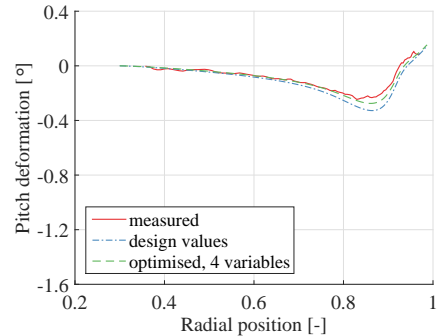
(i) Bending deformation, loading condition 5.



(j) Pitch deformation, loading condition 5.



(k) Bending deformation, loading condition 6.



(l) Pitch deformation, loading condition 6.

Figure 14: Comparison of measured and computed bending and pitch deformation of propeller 90, blade 2. Simulations were conducted with design material properties and material properties obtained from analysis A.

6.3. Verification of the results

In order to verify the results obtained with the MNET, measured blade frequencies have been compared to calculated eigenfrequencies from FE models with the design material properties and the material properties obtained from analysis A. For propeller 90 only the first eigenfrequency was experimentally determined. For propeller 45 two eigenfrequencies were measured. The results in table 3 show that the calculated frequencies are close to the measured frequencies. This confirms what is stated above that the actual material properties are close to the design material properties. More importantly, the small differences between measured eigenfrequencies and eigenfrequencies calculated from the material properties as computed with the MNET show that good results are obtained with the MNET.

Propeller	45				90	
Blade	1		2		1	2
Frequency of mode	1	2	1	2	1	1
Experiment	473	686	473	686	460	487
Design material properties	100%	95%	100%	95%	108%	102%
4 optim. variables	100%	102%	104%	102%	112%	105%

Table 3: Calculated blade eigenfrequencies as a percentage of the measured blade frequencies in [Hz].

7. Conclusions

This paper presents the FE modelling, a model updating method by means of an MNET and results for two small scale composite propellers. For the FE modelling of the blades an approach to determine the element dependent material orientations in doubly curved geometries has been developed. The advantage of the presented approach is that the in-plane material directions are independent of the orientation of the element itself, in contrast to material orientations aligned to the local element coordinate system. Eigenfrequency calculations show a significant difference between results obtained with the material orientations aligned to the local element coordinate system and the presented element dependent material orientations. The FE calculations have been combined in an MNET approach with an experimental static dataset in order to deduce non-destructively the blade

(in-plane) material properties by minimizing the residual between measured and computed structural response. A sensitivity study has been performed to identify the differences between dynamic and static output parameters and to be able to select the loading conditions for the MNET analyses.

This paper shows that a positive answer can be given on the research question presented in the introduction whether it is possible to determine the stiffness properties of small scale composite marine propeller blades by making use of an MNET based on static experiments and a deterministic approach. More specifically the following conclusions can be drawn: First of all, the MNET analyses result in reliable estimates for the in-plane material properties of the blades. This is also confirmed by the verification study in which calculated and measured eigenfrequencies are compared. Secondly, by using the material properties obtained with the MNET, an improvement of the resemblance between measured and calculated result is obtained for the static experiments. This improvement is relatively small because the design material properties are already close to the actual material properties. Thirdly, the results show that friction has an important influence on the estimated results and therefore cannot be neglected. Finally, the results of the sensitivity study show that static output parameters could be more sensitive parameters than eigenfrequency results.

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