# Fault Detection and State Evaluation of Rotor Blades

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# FAULT DETECTION AND STATE EVALUATION OF ROTOR BLADES

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ABSTRACT

The present work has been done within the Joint Research Project Blade Tester, which develops an approach for cost-effective, serial integrity tests of rotor blades. At that, manufacturing faults shall be automatically detected, localized and assessed with respect to their impact on the integrity of rotor blades in operation. Several techniques are involved and discussed in the contribution, such as 3D full-scale geometry measurement, structural modelling by the finite element method and model validation, fibre optical sensing, several non-destructive testing techniques and parameter identification on the basis of static and dynamic tests.

**KEYWORDS :** *rotor blade, fault detection, finite element model, NDT, parameter identification.*

## INTRODUCTION

Wind turbines are usually exposed to intensive dynamic loading for 20 to 30 years of design lifetime. A rapid development of new machines, carrying structures and foundation types in the offshore area causes diverse scientific and technological challenges with respect to structural health monitoring. There exist almost no commercially available and reliable solutions for offshore structures although the so-called condition monitoring systems (CMS) are requested by permission authorities. Structural health monitoring shall increase the availability and efficiency of wind turbines and minimize the operation breakdowns. The aim of monitoring is the early diagnosis and prevention of severe damages or failures. Various CMS solutions for rotor blades, tower or foundation are currently under development and testing.

A typical challenge for all monitoring systems is not only the measurement technique or the measurement process itself but mainly the structural assessment and damage or lifetime prediction. In our opinion, this step is almost impossible without a validated structural model that correctly describes structural response and provides a link between measured data and real physical parameters of interest.

Manufacturing of rotor blades involves still a lot of handwork and faces, therefore, with many production faults. The latter can be more or less critical with respect for structural integrity, but are always costly if they cause operation breakdowns and repair after installation. Detection and elimination of manufacturing faults already on production site meets an understandable and increasing interest of manufacturers. The next question to be answered, if some defects have already been detected, is about their effects on the integrity and durability of the structure. Accordingly, the classification of defects as critical or not causes the necessity to repair them on production site or to accept the risk of a late and costly repair on the operation site.

The present work is dedicated to the evaluation of the manufacturing faults and the virgin state of rotor blades as a reference state for monitoring. The uncertainties of the initial state can strongly handicap further damage assessment, thus, shall be reduced. The work has been done within the Joint Research Project "Blade Tester" financed by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [1]. This project develops an automated approach for cost-effective, serial integrity tests of rotor blades appropriate for production facilities. At that, manufacturing faults shall be automatically detected, localized and assessed with respect to their impact on the integrity of rotor blades in operation. An individual test certificate for each rotor blade after manufacturing shall document the virgin state and serve as initial information for further monitoring and inspection actions.

## 1 INITIAL STATE

Structural health monitoring generally requires a reference state for comparison with the current state during operation or at least information on several structural or material properties to be assessed. Usually, such a virgin state is purely documented. Besides, it is not always clear, which state is suitable to become a reference state: the one after manufacturing or that after installation, or even the state during the early service time, since the availability of the required information is quite limited. Obviously, it is desirable to gather such information at the earliest, for example, on production site.

The approach followed in the present work is to check the rotor blades immediately after and sometimes even during the manufacturing process. Typically, such checks concerns global and local properties, both structural and material ones. Natural vibration frequencies and static deflections under dead weight in various positions and under various support conditions are some typical global properties. Geometry imperfections, the quality of composite texture, layered structure and glue joints are some local characteristics. At the beginning, a list of substantial production defects has been defined among all project partners, including manufacturer, designer, certifier and academic representatives. The list is classified according to the following criteria: appearance rate, effect on structural integrity, detectability, repair cost etc.

All investigations within the project have been done in a testing facility of the Technical University Berlin on a series of rotor blade specimens, the so-called tuners, of 13.4m length (Figure 1), coming from an industrial small-size blade design. Typical manufacturing defects have been integrated into these rotor blades and thoroughly documented.

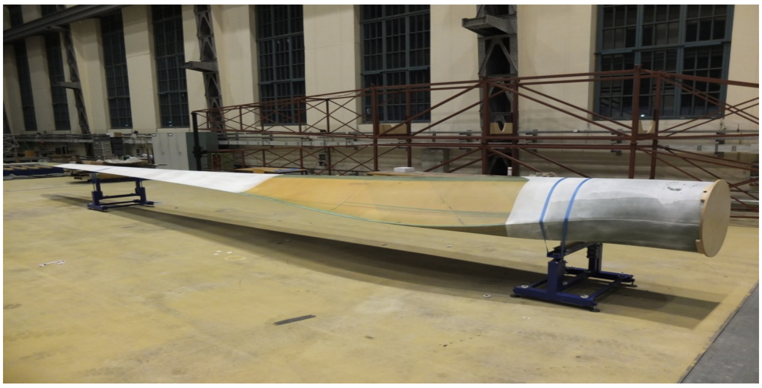


Figure 1: Rotor blade

## 2 3D FULL-SCALE GEOMETRY MEASUREMENT

The first step of the proposed approach contains 3D measurement of the rotor blade geometry and identification of imperfections. Such imperfections can influence the overall aerodynamic efficiency of the wind turbine and, sometimes, give an indication of structural defects visible on the surface. Blade Tester aims, among others, at finding correlations between internal defects and external imperfections.

Geometry measurement of large 3D structures like rotor blades can be carried out by a specialized industrial equipment. In the present study, we use a unique combination of a laser tracker and a 3D white light scanner. While the scanner takes shots of patches of a size of approx. 0.5m², the tracker is able to match these patches in a global coordinate system. Sometimes, it is sufficient just to check the contour accuracy in representative sections. This task can be done by the laser tracker in stand-alone mode (Figure 2, right).

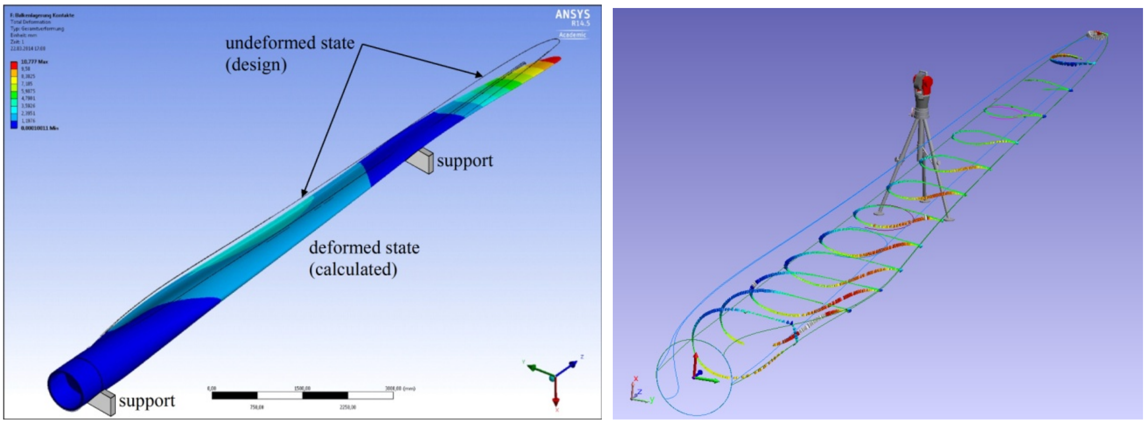



Figure 2: Comparison of design geometry and calculated deformed state under dead weight (left) and contour sections measured by laser tracker (right)

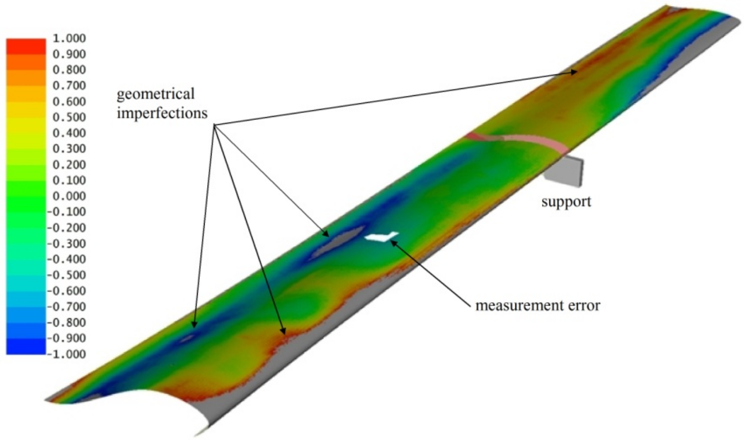



Figure 3: Measured geometrical imperfections on a rotor blade segment

A specific problem is caused by the fact that the measured rotor blade geometry contains essential deflections even under the dead weight; so, it is impossible to compare such measurements directly with the design geometry (Figure 2, left). A solution of this problem suggests a comparison of a numerically simulated deformed state under dead weight, by means of the finite element method, with the measured surface geometry. The corresponding interface and remeshing tools are available or have been developed, respectively. They allow identifying geometrical imperfections along the whole surface within a 1 mm range (Figure 3).

## 3 FINITE ELEMENT MODEL AND ITS VALIDATION

A 3D finite element model of the test rotor blade has been developed within the ANSYS software [2] capable to integrate several manufacturing faults, e.g. inclusions in bonding and delaminations. The FE model consists of approximately 120.000 shell elements, which are simulated as layered composite according to the rotor blade design. With more than half a million degrees-of-freedom, this model exceeds by far the complexity of the models commonly used in structural design.

The model is validated by static and dynamic tests. The static test data includes the measured deflections and strains under dead weight, as shown in Figure 4 for fiber optical strain sensors. The dynamic tests usually provide natural vibration frequencies and mode shapes, as can be seen in Figure 5.

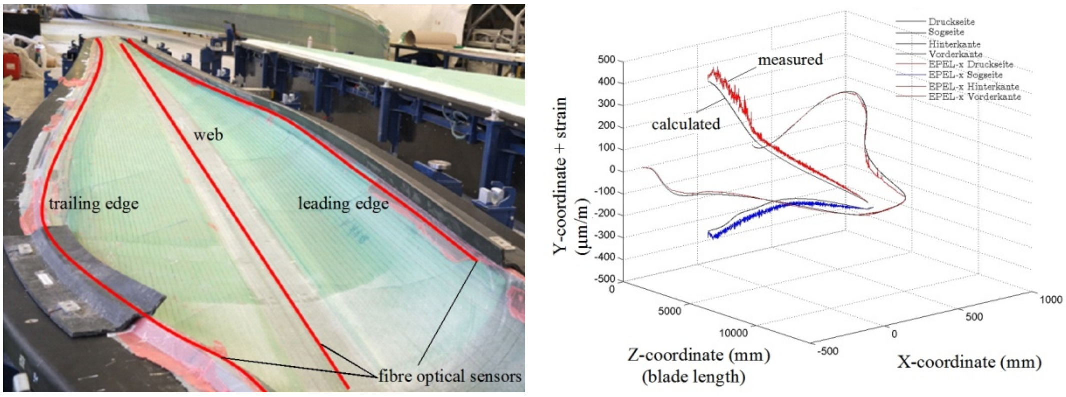



Figure 4: Locations of the fibre optical sensors in the rotor blade (left) and comparison of measured and simulated strains along the fibers (right)

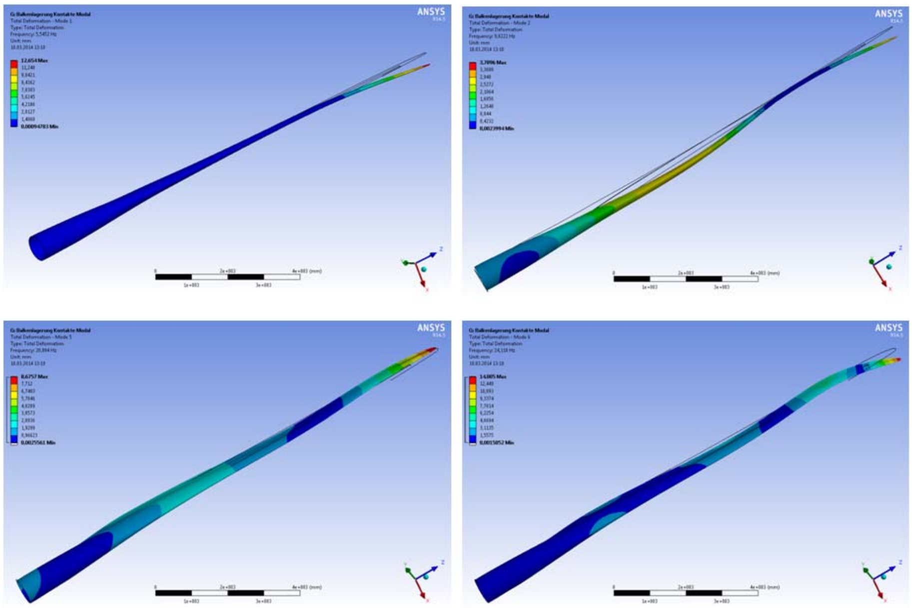



Figure 5: Four natural vibration modes of the rotor blade on two supports according to Figure 2 (simulation)

It is evident, that this computational model will not initially fit to the measured one, since many structural and material parameters cannot be exactly determined in advance. Additionally, several manufacturing faults, which are to be found, can also influence structural response. Thus, the model validation can be performed within a multi-step update process, which basically contains appropriate parameter identification and optimization steps.

Obviously, such processes are computationally very intensive and should be accelerated. It is also obvious that each structural response, simulated as well as measured, is specific with respect to a certain set of boundary conditions, loading, structural and material parameters. The Response Surface Method (RSM) is applied in this work to rationally combine numerical efficiency with required accuracy (s. Section 5.3) in structural optimisation and parameter identification.

## 4 NON-DESTRUCTIVE TESTING

Rotor blades can currently get various manufacturing faults due to handwork in the production cycle. Some of manufacturing defects are less critical and relates to the surface quality and repairs. Some of them can cause even structural failure and, thus, are very critical. In both cases, they cause operation breakdowns and reduce the cost efficiency of the wind turbine. Non-destructive testing (NDT) should help to detect relevant manufacturing defects and to identify the virgin state of the rotor blade.

The main goals of the NDT application are detection, localization and identification of manufacturing defects. This should make possible to assess their effects on the safety and integrity of rotor blades in the second step. For that purpose, various techniques are applied in Blade Tester. The main problem in detection of local defects or damages is that each of them does not significantly influence the global behavior of the rotor blade and, thus, can hardly be measured in the global structural response, both static and dynamic. Therefore, we apply various techniques based on wave propagation, since wave of small length interact well with the local damages or defects. The effects of defects can thus become well measurable.

The applied NDT techniques can generally be subdivided into two groups: those based on electro-magnetic waves and those based on elastic waves. Elastic or mechanical waves are preferable for the present task, since they interact with the mechanical properties of the structure that are in focus. In this contribution, we present the results obtained by the water-coupled mobile ultrasonic device MUSE, which have been adopted for the Blade Tester project. It allows scanning a surface of 300 x 200 mm with the resolution of 1 mm in ca. 15 minutes.

Figure 6 shows a cross-section of a rotor blade with a typical structure consisting of two half-shells, two shear webs and several glue joints. Figure 7 shows a special ultrasonic scan of this blade component with reduced colour resolution for better identification of defects. One can recognize numerous air voids in the glue layers or some surface damages due to poor workmanship.

Figure 6: Cross-section of a rotor blade segment with manufacturing faults

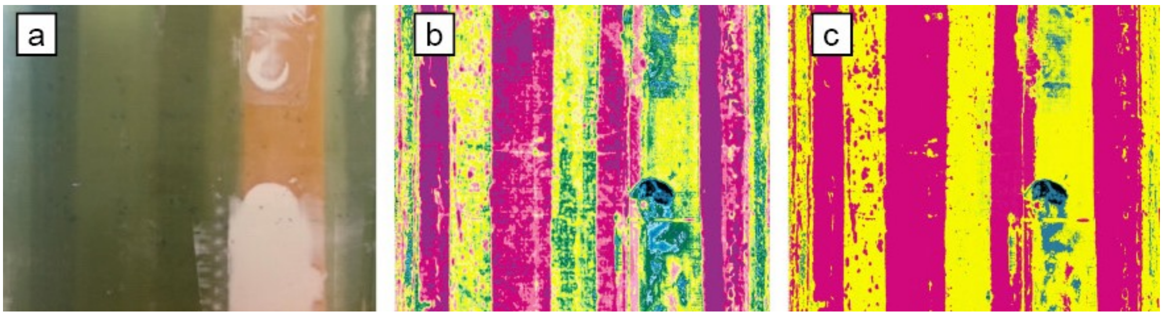



Figure 7: Results of ultrasonic scan on a rotor blade section; a) photo of the test section, b) ultrasonic scan with 64 colours, c) ultrasonic scan with only 5 colour grades giving a better position of manufacturing defects (e.g. voids in glue are red points in a yellow band)

Even the best NDT technique cannot predict the “effects of defects”, which is a typical challenge of structural health monitoring. The main difficulty concerns the way to introduce the measured defects into the global structural model for the purpose of damage or lifetime prediction. Usually, local defects and global integrity require quite different simulation scale. This work is currently in progress.

## 5 PARAMETER IDENTIFICATION

Essential structural and material parameters of a series of rotor blades can significantly vary due to handwork during manufacturing. They could be determined from static and dynamic tests on the rotor blade after production. From the mathematical viewpoint, parameter identification is an optimization task with the goal of reducing an objective function to a minimum. Although simple at a first glance, the procedure can become very costly in terms of computational time when the set of variables increases, which is likely to be the case in real-world applications. Obviously, a first step is to reduce the set of input and output parameters by checking them for interaction, e.g. to eliminate dependent variables. This reduction of the problem's dimension can be done by sensitivity analysis. The efficiency of the main procedure can be increased by capturing the results for a given set of input values from a response surface instead of performing a simulation run in each step. A properly defined response surface hereby allows for interpolation of intermediate values instead of a full simulation.

### 5.1 Sensitivity analysis

Two groups of variables are generally defined for sensitivity analysis: a set of input variables $\boldsymbol{X} = \{X_1, X_2, \dots, X_n\}$, which represent material, geometry and stiffness properties, and a set of state variables $\boldsymbol{Y} = \{Y_1, Y_2, \dots, Y_m\}$, which are physical values of structural response, for example, displacements, strains, stresses or vibration properties.

Sensitivity analysis should help to discover and eliminate dependent variables within each set $\boldsymbol{X}$ and $\boldsymbol{Y}$. The second goal of sensitivity analysis is to determine, what input variables in $\boldsymbol{X}$ exhibit the largest influence on the most important response variables $\boldsymbol{Y}$. A usual procedure for sensitivity analysis involves a total vector of parameters $\boldsymbol{Z} = \{\boldsymbol{X}, \boldsymbol{Y}\}$. By variation of individual input parameters $\overline{\boldsymbol{X}} = \boldsymbol{X} + \Delta\boldsymbol{X}$ and by means of structural simulation, it is possible to calculate several new state variables resulting in $\overline{\boldsymbol{Z}} = \{\overline{\boldsymbol{X}}, \overline{\boldsymbol{Y}}\}$. The dependence of all parameters, both input and state ones, can be estimated by various correlation measures ranging between -1 and 1. For instance, correlation coefficient of (-1) or (+1) means full correlation, negative and positive, respectively. The value 0 indicates no correlation.

Such a sensitivity analysis is carried out in the present study within the OptiSlang software [3], which is coupled with the ANSYS software [2] for structural simulations. The results of sensitivity analysis are visualized by the so-called sensitivity matrix, which contains the correlation coefficients. Since a sensitivity matrix of dimension $(n+m)$ is based on $(n+m)^2$ individual contributions, its calculation can be very expensive for an increasing number of variables. It seems to be rational using the response surface methodology in combination with efficient stochastic approaches, like the Latin Hypercube Sampling [4]. In the present study, we apply a traditional way keeping the number of variables quite limited.

### 5.2 Optimization approaches

Various optimization approaches can be generally applied within the procedure of parameter identification. The goal is to minimize the difference between the measured and simulated response variables $\boldsymbol{Y}$ by variation of the input $\boldsymbol{X}$. The efficiency of parameter identification can be significantly increased by preliminary sensitivity analysis, as described above.

The optimization problem under consideration can generally be described through the goal function

$$\min J(\boldsymbol{X}) \tag{1}$$

with several problem-specific restrictions, which are not discussed here. In the framework of the least squares approach, we define a residual vector as a difference of the simulated and measured response variables

$$\boldsymbol{R}(\boldsymbol{X}) = \boldsymbol{Y}_{sim}(\boldsymbol{X}) - \boldsymbol{Y}_{measured} \tag{2}$$

and the goal function as a scalar residual product:

$$J(\boldsymbol{X}) = \boldsymbol{R}^{\boldsymbol{T}}\boldsymbol{R}. \quad (3)$$

A typical problem arises from the fact that the properties of the goal function are generally unknown in advance. They can be quite complicated and possess several local minima. Thus, a suitable selection of start points and appropriate optimization approaches is required.

In the present study, we apply several approaches for optimization, among others, the trust region approach, the pattern search approach, the evolutionary algorithms and the simulated cooling approach. Details of these approaches can be found, for example, in [5].

Due to numerous local minima of the goal function, it is important to find parameter ranges, where minima exist, at least approximately. This preliminary analysis can be efficiently done by use of the response surface as a meta-model instead of the structural simulation at each step of the optimization process.

## 5.3 Response Surface Method

Response surface is a relationship between input variables $\boldsymbol{X}$ and state variables $\boldsymbol{Y}$ represented explicitly in a *(n+m)*-dimensional space:

$$\boldsymbol{Y} = f(\boldsymbol{X}). \quad (4)$$

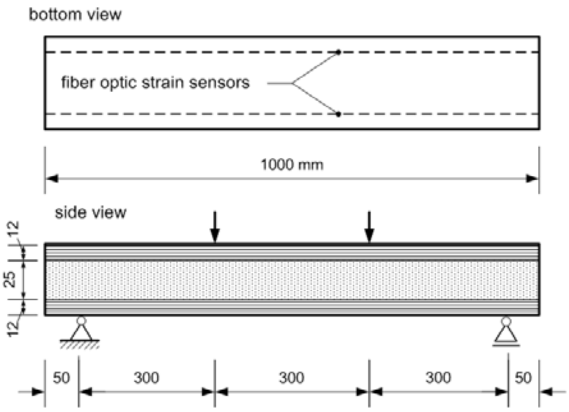
In this sense, it can be considered as a meta-model or an alternative to the structural model.

A relationship between $\boldsymbol{X}$ and $\boldsymbol{Y}$ is usually implicit, but can be calculated using a suitable structural model, at least for some discrete values of input variables $\boldsymbol{X}$. Using a certain number of such response states $\boldsymbol{Y}_i(\boldsymbol{X}_k)$, the so-called response surface points, it is generally possible to approximate this surface by an analytical function. Due to diverse reasons, it is usual to apply second-order polynomials of the form:

$$\boldsymbol{Y_i} = a_0 + \sum_{k=1}^{n} a_k X_k + \sum_{j=1}^{n} \sum_{k=1}^{n} b_{jk} X_j X_k\,, \quad i = 1, \dots, m. \quad (5)$$

## 5.4 Example: sandwich plate

The proposed approach has been already checked on several small-size laboratory specimens. For example, a sandwich plate consisting of two laminate shells and a foam core in between is tested in a four-point bending test according to Figure 8. The plate is instrumented by a fiber optical strain sensor going through the interface of the shell and the core on both sides. The strains on the bottom side are positive and generally proportional to the bending moment (Figure 9, left).



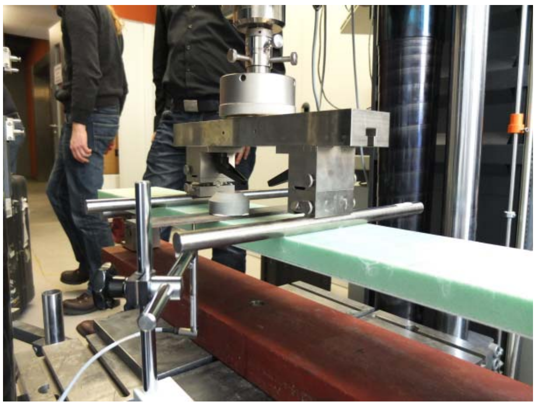



Figure 8: General test setup for sandwich plate

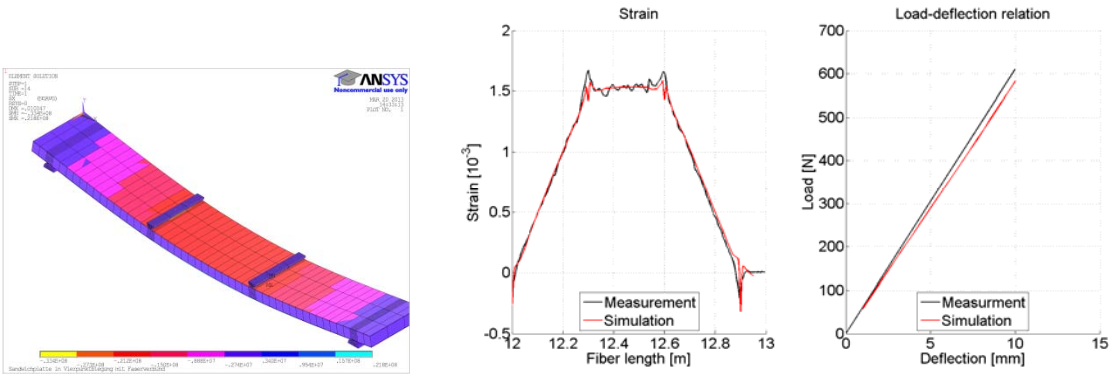



Figure 9: FE model (left); comparison of computational and experimental results (right)

Also the plate exhibits mainly linear response under low load levels, it was difficult to achieve a satisfactory agreement between the measured and calculated strains and deflections, as long as friction effects at supports and load transmission beams had not properly accounted for in the finite element model. In spite of these dominated local effects at supports and load beams, the optimization procedure is able to fit the set of parameters quite well to the measured strain data (Figure 9, right). The input parameters are mesh density, distance between supports, the elasticity modulus of the foam core and the laminate shells, the thickness of the foam core and the friction coefficients at supports and load beams.

## CONCLUSION AND OUTLOOK

The present study shows typical challenges and proposes several approaches for detection of manufacturing faults and virgin state evaluation of rotor blades. This task usually includes geometry measurement and identification of imperfections, finite element modelling and simulation, non-destructive testing as well as identification of essential parameters by means of optimisation.

It is evident that such information about the initial state and a validated computational model is strongly desired for structural health monitoring.

However, even if such information is available, the assessment of “effects of defects” remains a challenge. The main difficulty concerns the way to introduce the measured defects or damages into the global structural model for the purpose of lifetime prediction. Usually, local defects and global behaviour require quite different simulation scales and can generate enormous computational costs. This work is currently in progress.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] www.bladetester.de
[2] *Ansys, Finite-Element Code*, Ansys Inc. Canonsburg USA
[3] *optiSlang Software*, Dynardo GmbH, Weimar, Germany
[4] A. Florian. An efficient sampling scheme: Updated latin hypercube sampling. *Probabilistic Engineering Mechanics* 2(7): 123-130, 1992.
[5] A. Schumacher. *Optimierung mechanischer Strukturen – Grundlagen und industrielle Anwendungen*. Springer Verlag, 2005.