Investigations on fatigue, fracture mechanics and ultimate limit state of a wind turbine rotor blade – Full scale testing, failure analysis and FEM simulations

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Abstract

Rotor Blades (RB) are key components for wind energy generation. They convert the kinetic energy of wind into a usable torque at the turbine and their design of RB directly decides on the performance of a wind turbine. For this reason, no manufacturer discloses all design data being necessary for a complete finite element method (FEM) model. This is the reason why no complete construction documents of RB are available, also not for research purposes. However, within a research project “Multivariate Structural Health Monitoring for Rotor Blades” (MultiMonitor RB) all design data will be available for modelling purposes.

During the entire life cycle of a wind turbine, a large number of cyclic dynamic loads act on RB that can lead to material fatigue until failure. Structural Health Monitoring (SHM) systems can ensure the functionality and safety as they continuously measure stresses and strains. Unfortunately, for damage monitoring there are currently no clear limit values. The damage event has to be recorded based on the reduction of the RB stiffness. However, without knowledge of loads and design data there is no information about the ultimate limit state or the remaining lifetime.

Within the research project MultiMonitor RB, a consortium consisting of two institutes of the Leibniz University Hannover, two Fraunhofer Institutes and two companies (Wind MW and Woelfel Engineering) will design and manufacture a full-scale rotor blade were all construction documents are available for building a complete FEM model. In addition, hardware and software methods for SHM will be developed. The RB will then be instrumented and tested to investigate the performance of the monitoring system. At the same time, the FEM model of rotor blade and test rig will be verified with test results. Furthermore, methods for calculating fatigue damage of fibre-reinforced plastics and investigations in the fracture mechanics of RB are also considered.

1. Introduction

Rotor blades (RB) are among one of the main and most expensive components of a wind turbine. RB act as the interface between the highly unsteady wind loads with gusts and turbulences on the one hand and a power generation technique tending towards linearization on the other hand. The RB convert the kinetic energy of the wind into rotation and a mechanically useful torque. To fulfill this task, all loads from
aerodynamics, dead weight and operation must be transferred safely. In addition to the mechanical task, RB also have an aerodynamic task, because the profile of the blade decides about the conversion performance, meaning how much wind energy can be converted into torque and ultimately into electricity. Robert Gasch, author of the leading German textbook on wind turbines, tags the RB as the “heart of a wind turbine” (1).

In the fiercely competitive wind energy market, energy yield and longevity are important criteria for a purchase decision. Simulations are a proven tool to gain a deeper understanding of failure mechanisms and possible remaining lifetime. For the building of a complete FEM simulation model, blueprints, material data and all other parameters are necessary. Because of the above-mentioned relevance of RB for the performance of a wind turbine, manufacturers are not willing to provide all required information, also not for research purposes. However, research and improvements on structural health monitoring systems, lifetime prediction and fracture mechanics, urgently needs reliable and verified FEM models.

In the near future, the demands on SHM system for RB will continue increasing, so that not only a warning of a damage will be issued, but also an automatic assessment of the damage will be take place. Nowadays, a warning from a SHM system about a blade damage must be checked and evaluated manually by service employees. Based on their inspection results, it can be decided whether a rotor blade has to be repaired immediately or whether it can be operate safely for another time. SHM systems of the future will also have to make statements about the remaining load capacity and the remaining service life. Such evaluations are only possible based on verified FEM simulations. Therefore, SHM systems of the future will be model-based and able to make an automatic assessment on fatigue and fracture mechanics of the blade.

2. Research Project MultiMonitor RB

For the further development of SHM systems and detailed investigations of lifetime prediction, fatigue and fracture mechanics of rotor blades, the German Federal Ministry for Economic Affairs and Energy (BMWi) has approved the research project MultiMonitor RB, which started recently a few months ago. Within the project, a full scale RB, from which all information are known, will be designed and manufactured to overcome the above-mentioned problems regarding confidentiality and to build a detailed FEM model. This article gives an overview of all important research contents within the project.

2.1 Current Technical Development of the Main Component Rotor Blade

Within the last 25 years, the hub heights of wind turbines has increased from 30 meters to actual 120 meters and more. In the same time, the rated power has increased from 300 kW to more than 3 MW. This evolution is accompanied by an enlargement of the rotor diameter to over 100 meters, meaning that a single RB has a length of more than 60 meter, all for onshore turbine design. For offshore wind turbines, the size increases are even greater. Figure 1 illustrates the impressive increase in dimension. The increase
of RB size has also significant influence on the mechanical loads. Doubling the rotor length means a wind attack surface multiplied by 4 and a bending moment at the root multiplied by 16!

![Past & Present Wind Turbine sizes](image)

**Figure 1: Growth of wind turbines since 1980 (2)**

The manufacturing process of RB is characterized by a large amount of manual work. Therefore, and because of the size of the blade and the enormous cost pressure, deviations from the ideal shape and manufacturing errors are inevitable! There are always considerable discrepancies between ideal design of the blade and the manufactured real counterpart. The most common and influential problems of blades are:

- defects of the raw material like missing roving
- manufacturing defects like wrinkles, delamination or dry fibers
- uncleanliness like foreign material inclusion
- geometry deviations
- defects in bonding

However, deviations of weight in the range of ≤ 5% are within the tolerance range for some manufacturers. Figure 2 shows a schematic cross section of a typical RB with shear web (blue), belts (dark grey), sandwich (brown), adhesive (green) and aerodynamic shell (black). In general, a RB consists of several individual manufactured parts that are jointed together, mostly by adhesive. This joining process is crucial for the performance and lifetime of a RB because many mistakes can happen here.
RB are components experiencing extremely high dynamically loads. The base load provided by the wind follows a stochastic Weibull distribution leading to vibration excitation. This base load is superimposed by periodic and transient oscillations such as gusts, the altitude profile of the wind field, windward wind effects within a park, pitch and yaw movements of the blades, brake maneuvers, slant flow, stall due to the tower-blade passage, mass and aerodynamic imbalance, etc. Figure 3 depicts some of them.
Wind turbines are typically designed for an operating time of 20 up to 25 years. As shown in Figure 4, wind turbines and their components experience a very high number of load cycles during this lifetime, round about $2 \times 10^8$ cyclic loads. This makes RB of wind turbines to one of the most stressed technical components of all, even more than those of helicopters.

![Figure 4: Wind turbines are among the most stressed technical components](image)

Manufacturing defects in varying degrees occurs to approximately 70 % up to 80 % of all RB. Additionally, the high number of dynamic loads leads to progressive fatigue. Manufacturing defects are imperfections in the structural texture and often the origin of damages and failure. At these points, the acting forces in direction and magnitude may exceed the maximum requirements imposed by the design. In the end, the high dynamic load result in a loss of bearing capacity and thus to the total failure of the blade.

Offshore wind turbines require special precautions from several points of view. Offshore implies very high investments due to the particularly aggressive maritime environmental conditions. In addition, the accessibility of offshore facilities is restricted to appropriate weather and sea conditions. Therefore, it is necessary to detect damage at an early stage and foresee a failure in order to initiate necessary repair work of structural damages of RB in a timely manner. Furthermore, offshore turbines and blades are larger, meaning also more expensive in production. From this point of view, a SHM system for rotor blades therefore has a great significance!

### 2.2 Economic Aspects

Also from economic considerations, a SHM system for rotor blades will has great relevance. In Germany, the share of renewable energies in primary energy consumption is to be significantly increased in accordance with the Renewable Energy Sources Act. In order to achieve this goal a significant increase of wind turbines will be necessary in
addition to other measures. Further motivation comes from the cost discussion, which forces increases in the efficiency of wind turbines. That is one of the reasons for the huge size growth of wind turbines over the last 20 years. The RB play an important role as their failure leads to standstill times of weeks and months. Particularly serious is a standstill due to problems with RB in offshore installations. Due to the limited availability of ships and floating cranes and because of the necessity of appropriate weather and sea conditions, costs in the region of several million Euros are quickly incurred. Although rotor blades are not the number one concern in terms of frequency of damage, they are among the leaders in terms of the duration of the downtime caused and the repair costs (3).

3. Objectives of the Research Project MultiMonitor RB

In the near future, simulation models will form the basis of SHM systems. An FEM model of the object to be monitored should enable concrete statements about the remaining service life and the possible course of damage. The project aims to develop components for SHM systems of the future. Main goals of MultiMonitor RB are the development and testing of global and local SHM processes for RB of wind turbines and their combination. In the sense of a multivariate approach, various structural mechanical and acoustic approaches that can capture different characteristics and damages are taken into account. The SHM procedures are designed to ensure automated and reliable detection and classification of structural damage at an early stage. To the best of our knowledge, MultiMonitor RB is the first project to carry out all investigations on a well-known full-scale blade for detailed research. This allows a comparison between both, the simulated and real RB, for investigations on a digital and a physical twin.

Central idea of the project is the combination of numerical simulation models with measurement-based SHM methods. This allows the integration of rotor blade data into the development of SHM routines as well as into the system hardware themselves. This includes geometry data, material data and information on the manufacturing process. Based on the geometry and material data of the RB, a numerical model is created which enables the development of model-based SHM methods and is used for the simulation of material fatigue, damage development and residual strength assessment can. Subsequently, numerical models can validate the results in a destructive blade test and by measurements under operating conditions in a real WT.

![Figure 5: Typical layer structure and thickness distribution](image)

The research project has the following scientific and technical objectives:
- Design and production of a 40 m rotor blade and preparation of a test specimen
- Development of different local and global SHM methods including device technology and routines for signal analysis
• FEM simulation model of the blade using all available data (in the case of commercial RB, there are generally serious limitations of the model with regard to the availability of data)
• Instrumentation of the test blade with all SHM methods being developed within the project
• Full monitoring of the load test with established methods
• Maximum load test until the blade brakes
• Further development and optimization of algorithms for vibration-based SHM based on simulation and measurement data
• Further development and optimization of algorithms for acoustic detection and localization
• Further development of SHM algorithms by means of ultrasound emission
• Performing simulations using a fatigue damage model for fibre-reinforced composites, model-based SHM and model validation
• Simulation of the fracture mechanics using new numerical failure models of the laminate and fracture mechanics investigations
• Simulation of the effect of certain leaf damage on the change of measurement data
• Assessment of the residual load capacity of the RB
• Final test of SHM methods in an offshore wind farm and linking the SHM routines with damage statistics of the wind farm
• Assessment of practicality and giving optimization advice

3.1 Design of Experiments

For the large-scale test, the produced RB will be equipped with all newly developed components of the SHM system. In the large-scale test stand of the Fraunhofer IWES, shown in Figure 6 (right), the blade will be tested until failure. Usually, destructive tests under normal load conditions are very time-consuming since failure due to fatigue requires many load cycles. Therefore, overloads are applied to induce accelerated aging. But this requires large forces and large strokes.

![Figure 6. Time consuming testing with overload (left), Blade test with hydraulic actuators at the premises of IWES](image)

A fixed coupling to a hydraulic force transmitter enables the necessary loading to be initiated. However, the fixed coupling to the hydraulics prevents the rotor blade from
vibrating freely. The SHM system from Woelfel is based on vibration monitoring in which it measures the structural response e.g. be excited by wind and the rotation of the turbine. Therefore, after a period of applying high loads, the hydraulic coupling must be removed for measuring the structural response of the free vibrating blade. In reality, the vibration excitation comes from wind loads, rotation of the rotor and other operational conditions. In the test stand, this is imitated by applying electromechanical shaker in horizontal and vertical direction, shown in Figure 7, which are constantly attached to the rotor blade. Using the shaker for vibration excitation, white noise can be initiated allowing measurement with the SHM system.

![Horizontal and vertical shakers on the rotor blade](image)

In order to verify the measurement results, comparative independent measurement methods like strain gauges, high-speed camera, infrared camera etc. are used within the destructive blade test.

### 3.2 Finite Element Simulation

In addition to practical and experimental work, Finite Element Modelling (FEM) simulations accompany the project. First, the RB will be modelled in all details in a FEM simulation, starting from the precise laminate structure to the exact knowledge of all geometric dimensions up to the specific material characteristics.

Usually, the manufacturing process of rotor blades is characterised by a large amount of manual work and there exists no "perfect" blade. All of them have larger or smaller deviations from the aspired design. Figure 8 and Figure 9 picture typical imperfections like wrinkles, dry spots or missing adhesive. These inevitable fabrication defects and flaws will also be considered within the simulation since they are mostly the source of the structure's failure. Therefore, an authorized expert will inspect the RB direct after fabrication in order to assess the positions and characteristics of all imperfections.
Figure 8: Wrinkles are a misalignment of fibers within the laminate structure (left). Massive appearance of wrinkles (number & size) in a real rotor blade (right). (4)

Figure 9: Dry laminate and glass fibers (left), missing adhesive at the sheer web flange (right) (4)

Within the research project MultiMonitor RB we fundamentally investigate the failure mechanism of a full scale, 40 m long RB in a destructive large scale test. Therefore, the found imperfections should be modelled and included in the FEM simulation. It should be tried to use those models for investigations in the field of fracture mechanics. Second, the complete test rig with rotor blade and loading equipment (shaker, hydraulic coupling) will also be modelled and calculated. At the end geometry and material data of the blade as well as boundary conditions and the load history are modelled. To sum up, this allows the complete computer-aided tracking of the real process of a RB failure.

3.3 Development of Methods and Algorithms

The central new idea of the research project is the combination of numerical simulation models with measurement data-based SHM methods and the integration of real data of the RB (geometry, material data, boundary conditions) into the development of new SHM methods and systems themselves. Therefore, in MultiMonitor RB two different approaches will be pursued for the development of methods and algorithms:

1. Improving the signal analysis of the SHM systems:
   In general, no sensor is available that can measure damage directly. Therefore, for the development of a successful SHM system, it is crucial to find measurable physical quantities that change with damage. As the name suggests, a vibration-based SHM system detects changes in the vibration behaviour of a structure. In principle, all modal parameters are monitored: vibration velocity, accelerations, frequencies, amplitudes, phases, damping, etc. In order to detect even the
smallest changes, on the one hand, the sensors must be very sensitive and on the other hand, the signal-to-noise ratio must be as large as possible. For modal parameters, changes $> 0.3\%$ should be detected, with respect to sensitivity the minimum is $0.005$ Hz (6, 7).

2. Simulation of fatigue and fracture mechanics:
   Developing methods, algorithms and models for FEM simulation. In detail, these are a fatigue-damage model (ESM, based on the German word “Ermüdungs-Schädigungsmodell”) and a model for fracture mechanic investigations.

3.4 Experiments

After manufacturing and inspection, the RB will be probed on a test stand with a defined procedure until total failure and break. During this test, the RB is equipped with the now commercially available monitoring system SHM.Blade® from Woelfel (5, 6), supplemented with additional strain sensors, accelerometers and others. The signal analysis relies on methods of statistics, pattern recognition, self-organizing maps, neural networks and machine learning. The extended sensor technology promises an extensive data basis and leads to the further development of advanced damage indicators based on modal parameters.

Besides SHM.Blade® System from Woelfel, the Leibniz Universitaet Hannover installs an additional vibration and model based SHM-Systems during the test for comparison and verification purposes (7, 8). Moreover, additional sensors further extend the data basis, which allows the application of new algorithms based on big data analytics. The experiments on the test stand are accompanied by another SHM-System from the University is using acoustic emission based on airborn sound (9). Fraunhofer IWES provides an acoustic emission monitoring system (10), which is specially designed for blade testing.

Overall, various monitoring systems will be used during the large-scale test until failure. This provides an extensive data basis for the development of algorithms an exhibit new insight in damage mechanics. Comparing measurements and simulation allows the verification of the FEM model. Numerically established fatigue and failure models for laminates are also included in the calculations. Finally, general criteria for the evaluation of the load bearing capacity of RB are derived. The combination of simulation and measurement total failure promises fundamentally new insights, especially with regard to the transferability to other types of RB.

4. Conclusions

To sum up, essential goals of the research project "Multivariate Structural Health Monitoring for Rotor Blades" (MultiMonitor RB) are the development, combination and test of global and local SHM methods for rotor blades of wind turbines. In the sense of a multivariate procedure, different structure-mechanical and acoustic approaches, which are able to capture different indicators and damage parameters, will be considered. The SHM methods are to guarantee an automated and reliable detection and classification of relevant damages during an early stage.
The development of new methods and algorithms based on stochastics, statistics, pattern recognition, self-organizing maps etc. for damage detection in the laminate as well as obtaining information about the limit load-carrying capacity by coupling measured data with the FEM macro and material model are essential for the future of the vibration-based SHM system. In the course of a destructive test of the rotor blade, it will be possible to compare measurement and calculation and herewith conduct a model update.

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