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Preface

This report together with the MS Excel spreadsheet "RED blade failure database.xlsx" is deliverable 3.2 of the project "Wind turbine rotor blade testing technology research and platform construction". The project is supported by the Renewable Energy Development (RED) programme in which the Chinese and Danish governments are cooperating and aiming at institutional capacity building and technology innovation for renewable energy development.

This particular project is a partnership between the Chinese Baoding Diangu Renewable Energy Testing and Research Co., Ltd., a national wind and solar energy key laboratory for simulation and certification and from Denmark the Department of Wind Energy, Technical University of Denmark, a Danish wind energy research department that has provided a major part of the wind energy research in Denmark and is one of the leading wind energy research institutions in the world.

The project will focus on research for on-site, full-scale and down-scale structural testing of wind turbine rotor blades. An advanced blade on-site monitoring platform and full-scale testing platform will be constructed to strengthen the capacity of wind turbine blade testing and demonstrated in Baoding, city of Hebei Province in China.

The project will provide the manufacturers with the possibility to do comprehensive blade testing in order to achieve test data for fulfilling requirements of standards and in order to obtain better and more optimized blade design. Meanwhile advanced experiment tool and valid test data can also be provided for the research and certification institutions in order to develop better design methods and certification guidelines and standards.

The project has three main parts. The first part is research in full-scale and down-scale structural testing of wind turbine blades as well as condition monitoring for on-site testing of whole wind turbines. The next part is construction of platforms in China for full-scale fatigue testing of blades and on-site condition monitoring of wind turbines. Finally, the last part is to demonstrate the full-scale fatigue testing and the on-site condition monitoring.

Roskilde, Denmark
December 2014

Content

Summary

This report deals with the importance of measuring the reliability of the rotor blades and describing how they can fail. The Challenge is that very little non-confidential data is available and that the quality and detail in the data is limited.

1. Introduction

Catastrophic failure of wind turbine blades, due to excessive loading or fatigue damage, can lead to the destruction of the entire machine. This can cause not only a significant economic loss, but also a risk for the safety of the surrounding areas. It is therefore important to ensure that the blades can endure the loading they are exposed to throughout their lifetime.
In this respect it is important to measure the reliability of the different components and understand why they fail. The Challenge is that very little non-confidential data is available and that the quality and detail in the data is limited.

2. Reliability statistics of wind turbines and subsystems

There have been several reports in the last decade investigating the availability of wind turbines using several different databases. These databases include the primary European databases which started in late 1980's and more recent databases started in USA. Table 1 shows the databases available for investigation of wind turbine availability around the world. Most of these databases are related to wind turbines and farms in Europe.

Using these databases several studies have been conducted to estimate the availability of wind turbines. Most of these databases include the reasons of unavailability, which can be a number of different reasons including blade faults. Since the focus of this report is on the blade failure only, the other causes of unavailability are not discussed further in this report.

Table 1 Available databases for investigation of wind turbine availablity

Database	Country	Number of Turbines	From year	To year
WMEP	Germany	1500 Onshore	1989	2006
LWK	Germany	>650 northern Germany	1993	2006
VTT	Finland	~72	1992	tbc[1]
Vindstat	Sweden	~800	1988	tbc
WindStats Newsletter	Europe	~30000	2012	tbc
ReliaWind	Europe	~350	2008	2011
WMEP Offshore	Germany	~300	2007	2011
CREW	US	900 above 1MW	2011	tbc
DNV-KEMA and GL Garrad Hassan for NREL	US	10 GW combined data		tbc

[1] To be continued.

Unavailability of a wind turbine in time caused by blade failure does not directly give the probability of blade failure. The downtime for each failure also needs to be considered. In some of the databases failure events are also registered.

One of the most extensive databases is WMEP which includes more than 1500 onshore wind turbines from 1989 to 2006. In a presentation from Peter Tavner at SUPERGEN WIND in 2011, the annual failure rate for the rotors based on WMEP database was presented to 0.11 with an average downtime per failure of 3.2 days. This corresponds to an average downtime of 9 hours per year per turbine, which corresponds to probability of 0.10% for each turbine [1]. On the other hand the annual failure rate for the rotors based on LWK in the same presentation is mentioned to be 0.23 with an average downtime per failure of 11.4 days. This corresponds to an average downtime of 62 hours per year per turbine, which corresponds to a probability of 0.71% for each turbine [1].

The downtime of a wind turbine because of blade failure is presented as 7% of the total technical downtime in the VTT database in a failure analysis performed by Stenberg & Holttinen [2]. This corresponds to 18 hours per year per turbine, which again is corresponding to 0.21% probability for each turbine. The annual failure rate for the rotors is calculated to be 0.04 with an average downtime per failure of 17.3 days.

In case of the Vindstat database, 8% of the downtime is assigned to rotors in general in a report for wind turbine reliability analysis performed by Lange et al [3], even though the total downtime was not available in the literature. In the same report the failure rate for the rotor is mentioned to be 21% and 8% of the total failure rate based on WindStats database for Germany and Denmark respectively. Also according to [3] the total failure rates are 1.44 and 0.73 according to WindStats Germany and WindStats Denmark respectively. Combining the percentage for rotor failure with the total failure rates leads to the annual failure rate for the rotors of 0.29 and 0.06 respectively.
While the downtime for each failure is considered to be 125 hours in average, the downtime probability of wind turbine blades will be 36 hours per year per turbine in WindStats German database and 7.5 hours per year per turbine in the Danish database. This corresponds to 0.41% and 0.09% respectively [3].

Many of the references and reports have been using data provided by ReliaWind (i.e. [4], [5], [6] and [3]). The ReliaWind database includes data from about 350 wind turbines which are all between 1 to 6 years old and pitch regulated [7]. In the mentioned data the failure contribution of wind turbine blades failure to the total downtime is suggested to be 1.5% per turbine per year.

In the CREW database it is presented that there are 34 unavailable events in average per year caused by the rotor/blades [8]. Each has a downtime of 0.9 hour in average [8] giving 31 hours per year per turbine corresponding to 0.35% probability for each turbine. In the data provided by DNV KEMA used in a NREL study presented in [9], it is stated that annually 1% - 3% of turbines require blade replacements with the highest occurrence in years 1 and 5. Blade replacements in years 1 and 2 are typically the result of manufacturing defects or damage that occurs during transport and construction. On average, about 2% of turbines per year (through 10 years of operations) require blade replacements. It was found that lightning strikes are the most commonly noted cause of failure [9].

Table 2 Probability of blade failure based on different databases

Resource	Downtime		Annual failure rate
	Hours per year	Probability	Rotor
WMEP	9	0.10%	0.11
LWK	62	0.71%	0.23
VTT	18	0.21%	0.04
WindStats Germany	36	0.41%	0.29
WindStats Denmark	8	0.09%	0.06
CREW	31	0.35%	

J.D. Sørensen in a presentation about probabilistic design of wind turbine blades [10] proposes a probability of failure of blade from 0.01% to 0.1% per year. Sørensen himself in another presentation claims that the failure probability of blades for a turbine in one year is can be about 0.2% [11]. In Table 2 the probability of blade failure per turbine is presented for different databases.

3. Wind turbine blade failure modes

Wind turbine blades can fail by a number of different failure and damage modes. The details of damage evolution will differ from one blade design to another. However, experience shows that, irrespective of specific blade design, several types of material-related and structural-related damage modes can develop in a blade. In some instances, these damage modes can lead to blade failure or require blade repair or replacement.

There can be many causes that a composite structure fails ultimately.

- Geometrical factors associated with buckling, large deflection, crushing or folding.
- Material factors associated with plasticity, ductile/brittle fracture, rupture or cracking damage.
- Fabrication related initial imperfections such as initial distortion, residual stresses or production defects.
- Temperature factors such as low temperature associated with operation in cold weather, and high temperature due to fire and explosions.
- Dynamic factors (strain rate sensitivity, inertia effect, damage) associated with impact pressure arising from explosion, dropped objects or similar.
- Age-related deterioration such as fatigue cracking.

A considerable amount of knowledge is required to assess how damage develops in a wind turbine blade and to design a blade against failure using analytical or numerical methods. Therefore, in order to validate the design, and to provide insight into possible damage modes and their severity, blades are sometimes tested to failure by full-scale testing. Fig. 1 shows sketches of the failure modes found in a wind turbine blade tested to failure [15].

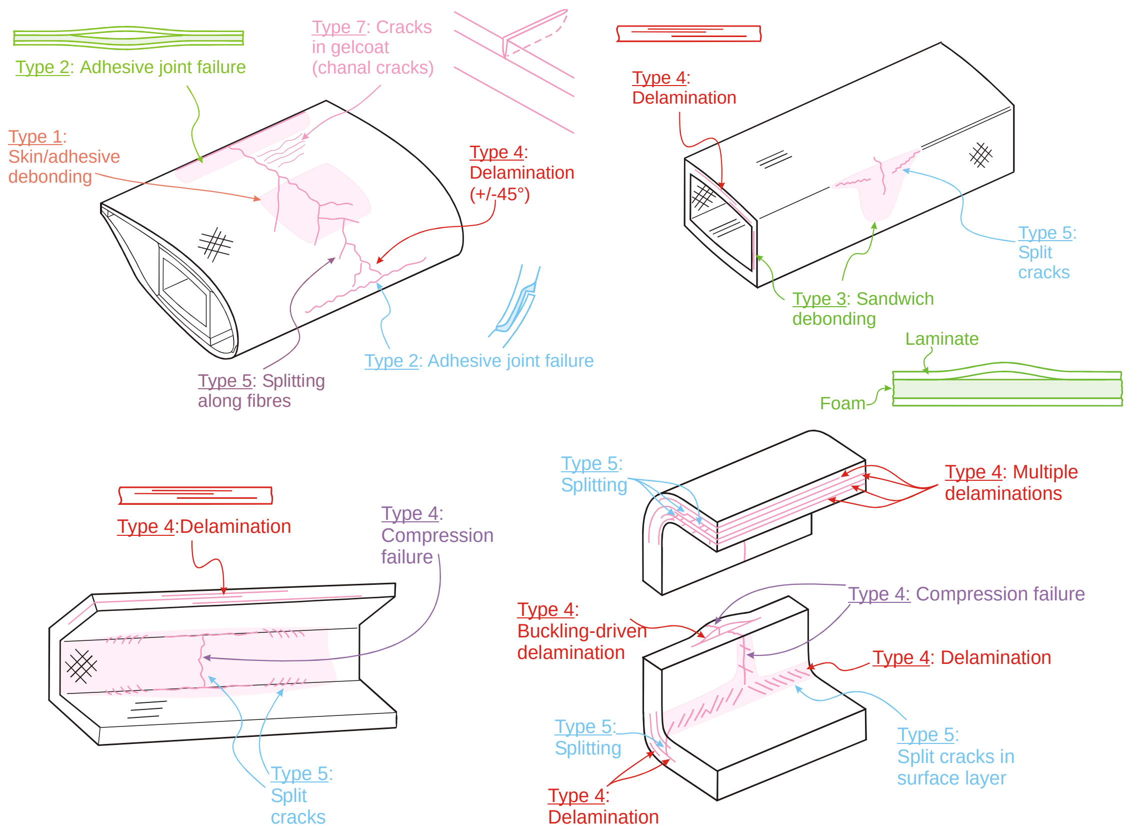

Figure 1 Sketches of observed failure modes in a wind turbine blade purposely tested to failure [15]; damages in the aeroshell and box girder.

In the presentation prepared by Find M. Jensen, Bladena [12] several different kind of failures and defects in wind turbine blades are categorized. The failure modes are presented in Table 3 while an extra column for categories of failure have been added base on the failure categories presented by Strange Skriver from Danmarks Vindmølleforening. [13]

Table 3 Wind turbine blade failure modes

Failure mode	Category	Reason
Interlaminar failure	V2-V3	Brazier effect, Bending moment
Delamination - faulty injection	V1	
peeling / wear	V1	wear
Erosion of the sealing of the root	V2	
flaking of the top coat	V1	air bubbles from the manufacturing /poor quality
missing external parts	V2-V3	Flaking and external objects impact
fine cracks in topcoat	V1	Low quality of material
transverse cracks from trailing edge	V2-V3	Poor design
transverse cracks on blade surface	V2-V3	Poor design
Front edge cracks (transverse and longitudinal)		
Web failure	V3	Brazier effect, Bending moment, poor design

Fatigue failure in root connection	V3	Poor design
Fatigue failure in root transition area	V1-V2	
Fatigue failure in bond lines, longitudinal cracks in the trailing edge	V1-V2	Transversal shear distortion, Deformation of trailing edge panels, Trailing edge buckling
UV effect on the fibers	V1	wear, flaking,
lightning damage	V3	Lightning
Tower hit by blade	V3	High Tip deflection
balsa / composite cracking (transverse and longitudinal)		
Transport damage	V0-V3	
Complete separation	V3	

Where V0: Observation, No harm, V1: Damage to be repaired at an opportunity, V2: Damage must be repaired as soon as possible & V3: Serious damage. The turbine is stopped.

In the following pages a few pictures of different blade damages are presented.

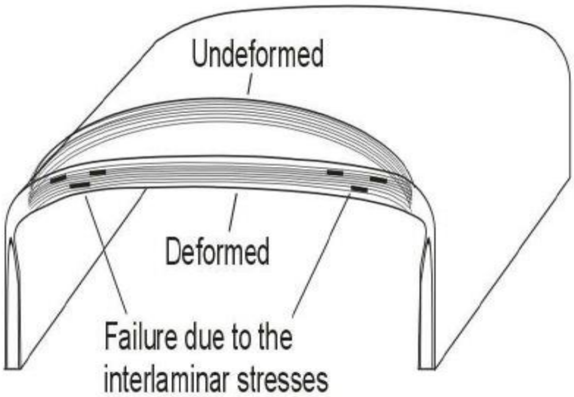

Figure 2 Interlaminar failure

Figure 3 Front edge cracks (transverse and longitudinal)

Figure 4 Delamination - faulty injection

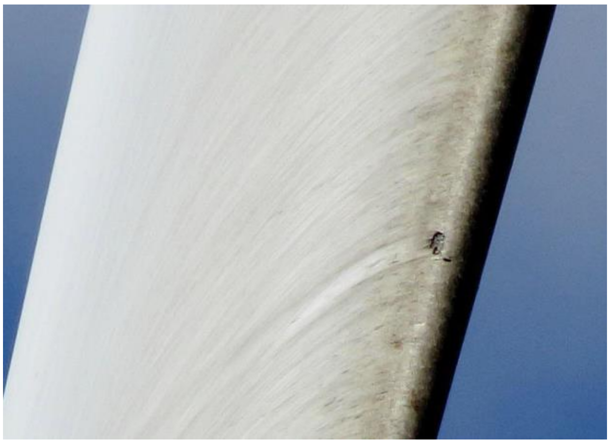

Figure 5 Peeling / Wear

Figure 6 flaking of the top coat

Figure 7 Fatigue failure in bondlines, longitudinal cracks in the trailing edge

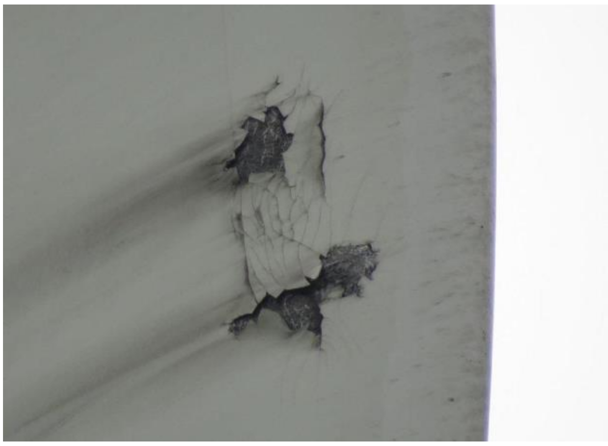

Figure 8 Missing external parts

Figure 9 lightning damage

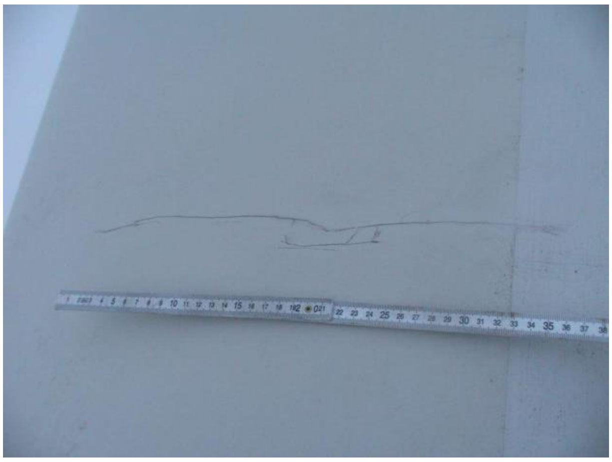

Figure 10 Transverse cracks on blade surface

Figure 11 Transport damage

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Acknowledgements

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DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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