UNIVERSITY OF TWENTE.
PONTIS ENGINEERING
LM WIND POWER a GE Renewable Energy business
TNO innovation for life

SLOWIND PROJECT
TEWZ115012

STRUCTURAL HEALTH AND LOAD MONITORING OF WIND TURBINE BLADES

Date	30 January 2019
Author(s)	T.H. (Rob) Jansen & H.L.M. (Haico) van der Heijden (TNO)

Number of pages	14
Project name	SLOWIND
Project reference nr.	TEWZ115012

Contents

1 Introduction

The main drivers of the maintenance costs in off-shore wind turbines are the drive train and the rotor blades. The blades are periodically inspected manually, which implies roping access of inspectors. This requires the wind turbine to be stopped (no revenues), takes a lot of time (costs) and brings along serious risks for the people involved in the inspections. Monitoring and predictive maintenance will thus reduce the operational costs during lifetime.

This project (reference number TEWZ115012) has been funded by the RVO and is entitled SLOWIND, which stands for 'Structural health and Load monitoring of WIND turbine blades'. The project has been started on October 2015 and should have finished by 1st of May 2018. This deadline has not been met since WMC had to postpone the final testing to June and July 2018. Considering reporting and internal reviewing the final close out meeting was held at 12th of October 2018.

The project has been coordinated by TNO, together with three partners, shown in the table below:

Table 1: SLOWIND project partners

Partner	Contact person	Role
TNO	Rob Jansen	Projectcoördinator
Universiteit Twente	Richard Loendersloot	Project partner
WMC*	Francisco Lahuerta	Project partner
Pontis Engineering	Darren Ellam	Project partner

** **Note**: At the end of the SLOWIND project WMC has been taken over by LM Wind Power R&D. This has been communicated to TKI using the form 'aanmelding deelnemer + machtiging penvoerder', signed by the 'new' partner LM Wind Power on the 1st of October 2018.*

The main objective of the SLOWIND project is the reduction of maintenance costs by developing a load and structural health monitoring system that can replace the time-consuming, dangerous and costly manual inspections of composite turbine blades. In addition to only detecting imminent failures or damage (i.e. diagnosis), insight in the dynamic loads on the blade and the present health status, as provided by the developed monitoring system, also enables to calculate the remaining useful life of the blades (i.e. prognosis). The latter aids to optimize the maintenance and operations process in the long term.

The project resulted in a proof of concept for an advanced blade monitoring system based on a combination of optical fibres and distributed piezo sensor network and has been tested in the laboratory, on small scale using coupons and on a real turbine blade during the 'full scale section test' at WMC. The concept can be used as starting point for full scale testing and demonstration in a more realistic setting on real operational turbines (in future projects).

2 Progress of the project

2.1 Plan of work

The structural health of the wind turbine blades is directly related to a combination of fatigue and impacts. The regular dynamic loads on the blades may lead to fatigue damage (delamination or cracks), whereas impact by large objects also lead to delamination of the composite structure. Moreover, high speed impact of rain or hail on the blade leading edges leads to erosion of the blade surface, resulting in a decreased aerodynamic performance and eventually a decrease in structural integrity. Finally, the loading of the blade in combination with harsh environmental conditions may lead to the degradation or even failure of adhesive joints between the various parts of the blade structure.

To improve the detection and localization of these types of blade damage, the present project is divided in 5 work packages (and one project management WP) which are described in detail below.

- WP 1 Identification of typical failures in composite rotor blades;
- WP 2 Load monitoring by embedded optical fibres;
- WP 3 Structural health monitoring by a distributed network of piezo sensors;
- WP 4 Demonstration and validation of monitoring concepts;
- WP 5 Integration of sensor networks and prognostics.

2.2 Progress realised

2.2.1 WP 1 Identification of typical failures in composite rotor blades

Task owner WMC, supported by Pontis, TNO & UT

To be able to develop relevant sensor networks, it is very important to thoroughly understand the dynamic behaviour of the blades and to characterise the typical failures. A comprehensive overview of failure and damage mechanisms has been made which has been used in the project as a reference for the development of the SLOWIND monitoring system [Ref 1].

Another aspect that has been considered is the thickness of laminates which are increasingly present in large composites structures such as wind turbine blades. Designs are based on static and fatigue coupon tests performed on thin laminates. However, a thickness effect has been observed in limited available experimental data.

For this reason, standard experimental data cannot automatically be transferred to thicker laminates. Several factors are suspected to be involved in the decrease of static and dynamic performance of thick laminates which have been reported in WMC report 'THICKNESS EFFECT IN COMPOSITE LAMINATES IN STATIC AND FATIGUE LOADING' which was also considered.

2.2.2 *WP 2 Load monitoring by embedded optical fibres*

Task owner TNO, supported by Pontis & WMC

The use of optical fibres with Fibre Bragg Gratings (FBG's) is known in the wind industry but very rare. If FBG's are applied they are mounted inside the turbine blades, attached onto the surface of the composite to monitor the deformation (strain) of the blades during operation. In this way, the load history of the blade is known, and fatigue models can be used to estimate the remaining life of the blades.

In WP2, FBG sensors will be mounted in the turbine blade, embedded in the composite structure. This is currently not available, leading to additional benefits:

- Better contact between sensor and structure, resulting in more reliable data;
- No need of mounting sensors after manufacturing the wind turbine blade;
- Potentially closer to the failure location;
- Damage/strain evolution detection in specific layers (e.g. most sensitive to a damage);
- Detection of through-thickness strain/humidity/temperature profiles in thick laminates and complex details.

The following has been done within the scope of WP2:

- The "thick laminate experiment" was performed at WMC as preparation for the large-scale section test (WP 5);
- In total 9 fibres were installed at three different layers;
- At each layer two normal and one special Fibre Bragg Grating (FBG) was embedded to quantify the inhomogeneous lateral stress distribution, inherent to the composite materials;
- All fibres survived the experiment, but no significant difference was observed between the normal and special fibres;
- This, together with the relative shallow depth of the fibres in the large-scale experiment resulted in applying standard fibres in the fatigue experiment of WP5;
- However, if the unidirectional forces will increase the special fibre might be required.

In Figure 1 the thick laminate experiment is shown (left) and a picture of the demonstrator model of the special FBG. A special FBG has open holes inside while a regular FBG doesn't. The shape of the special FBG is designed to transfer radial compression of the fibre to a rotation, instead of compression of the fibre core. In that way, the FBG will keep a constant grating period under both lateral and axial load, and the shape of the FBG reflection spectrum is maintained, resulting in reliable data output.

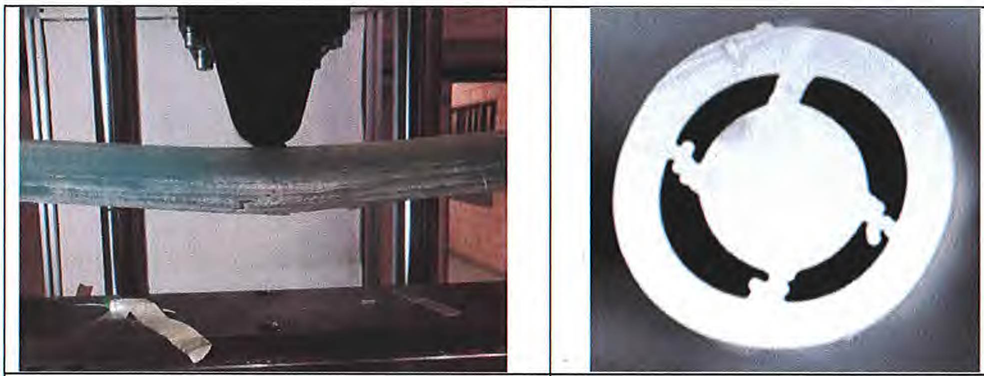

Figure 1a: Thick laminate experiment, performed at WMC.

Figure 1b: Demonstrator model of the Special Fibre Bragg Grating (FBG) patented by TNO.

Figure 1. Embedded optical Fibres

Using FBG sensors also other parameters besides strain can be measured. Therefore, an experiment has been performed to investigate whether impact of droplets could be detected with FBGs, sampled at high frequency. The source of impact was a small ball bearing, dropped from a known height.

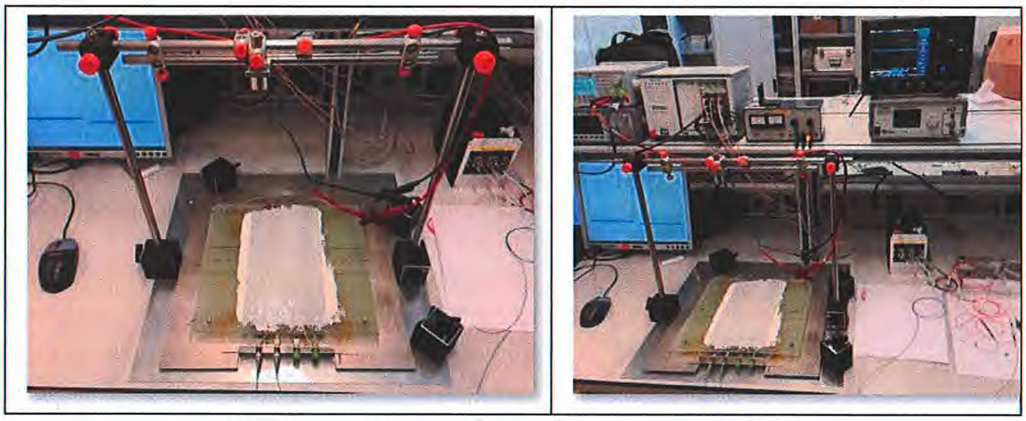

Figure 2. Experimental set-up at TNO to measure the impact with a small bearing before and after the erosion test at WMC

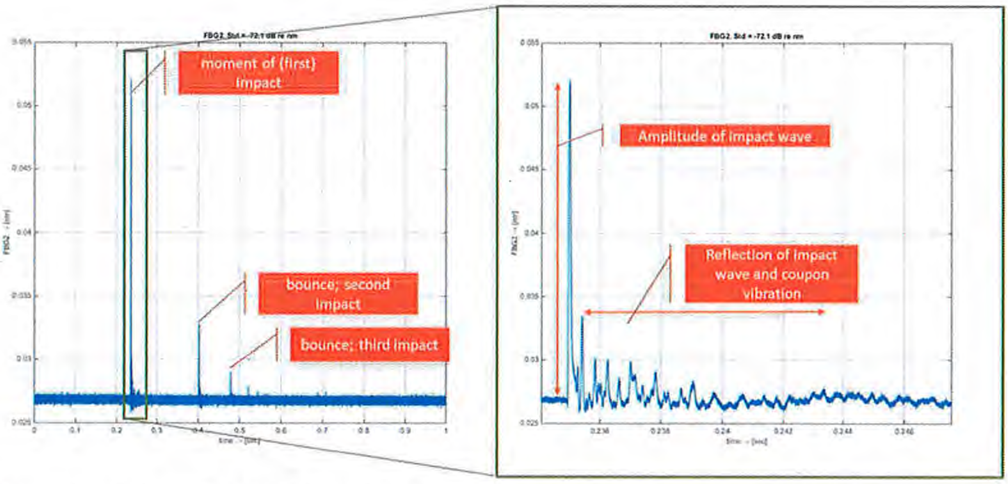

Figure 3. Test result - droplet impact measurement with ball bearing at TNO

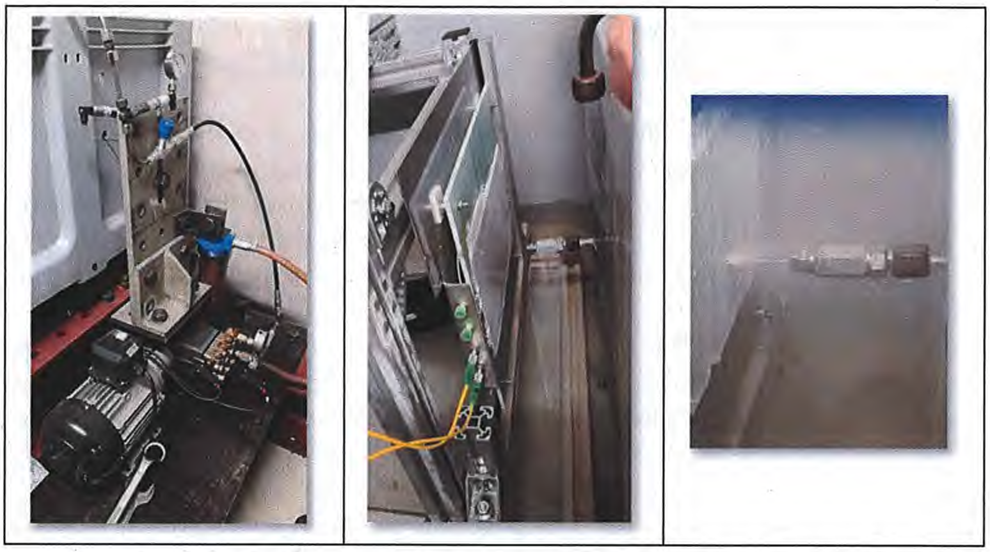

Figure 4. Experimental droplet erosion set-up at WMC (on the left the pump, in the middle the composite with the coating to prevent rain droplet erosion and on the right a zoom-in of the spray nozzle.

Based on the droplet erosion test the following can be concluded:

- Erosion areas created @ WMC is different compared to erosion of a turbine blade in practice;
- Two different Fibre Bragg Gratings have been applied, coated and non-coated. The Uncoated FBG showed more consistent FBG signal;
- The amplitude depends on the following parameters (height and weight → impact energy) and the distance to the FBG (x position). This has been demonstrated with a steeper slope for higher impact energy shown in Figure 5;
- It can be concluded that it is possible to measure rain droplet erosion with an FBG embedded in the composite, combined with a TNO read-out unit able to sample at high frequencies.

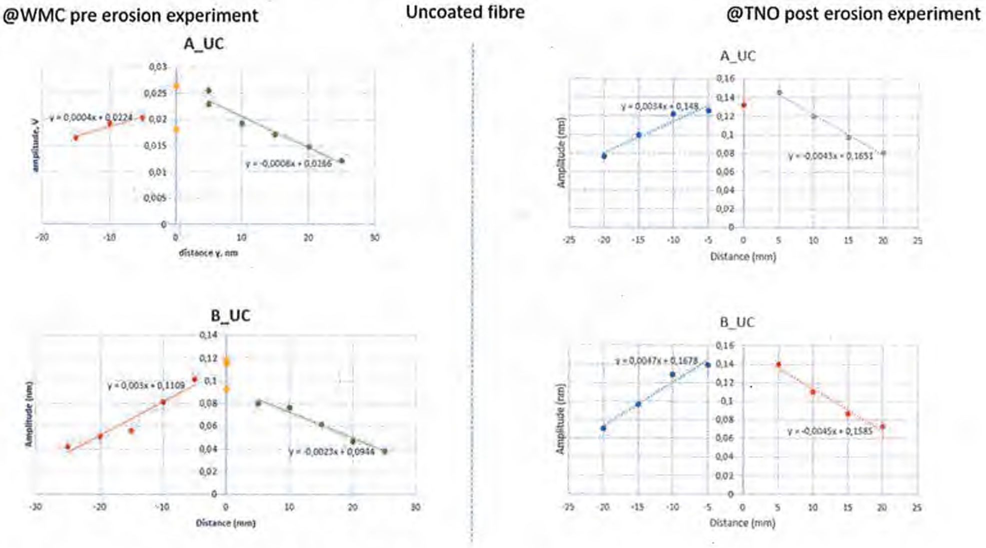

Figure 5. Test result – droplet erosion measurement

2.2.3 *WP 3 Structural health monitoring by a wireless network of piezo sensors*

Task owner UT, supported by Pontis & WMC

The dynamics based maintenance group at the University of Twente has been working on the development of structural health monitoring and damage algorithms for composite structures, the development of wireless senor networks, the development of local interrogation sensors networks and power harvesting and will use this knowledge to develop the proposed system for wind turbine blades.

Within the scope of WP3 a distributed sensor network of piezo-electric transducers is considered that can actively interrogate a thick composite beam and a thin coated laminate. The focus lies on active measurements with ultrasonic bursts using the Non-Destructive Testing (NDT) technique, Acousto Ultrasonics (AU). This technique is widely used for thin, plate-like composite structures and will be used to actively interrogate a structure for its structural integrity. The application of the AU technique to thick composite structures, such as the spar cap of rotor blades of wind turbines, is also considered promising by the authors, yet not addressed by any other research, and is the focus within the SLOWIND project for UT. A problem for the spar caps is fatigue damage.

The objective is to detect the fatigue damage before the damage is noticeable by a bending stiffness degradation derived from force and displacement signals. The bending stiffness is already determined for multiple identical specimens by The Knowledge Centre Wind turbine Materials and Constructions (WMC). A global assessment of the structural damage state is therefore needed that can be compared with the bending stiffness degradation over time.

Two laboratory specimens with a thickness of 56 mm, width of 60 mm and length of 900 mm are equipped with piezo-electric transducers on the top and bottom surface. Short ultrasonic burst waves with varying actuation frequencies are sent by one transducer and measured with the other transducers. Preliminary tests are executed to assess the damage detection capability. The damage on the first beam is simulated by drilling a hole at one location with a stepwise increasing depth of 10 to 56 mm. The number of actuator-sensor paths crossing the simulated damage increases for increasing hole depth.

Damage Indicator (DI-)algorithms and the Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) are used for damage assessment and visualization. A correlation between the DI values and the severity and location of the damage is found. This result is a positive indication for the applicability of AU for damage detection in thick composite structures. The results of the first beam are presented on the first international conference on health monitoring of civil and maritime structures (HeaMES conference) in London and on the European Workshop on Structural Health Monitoring in Manchester (EWSHM conference).

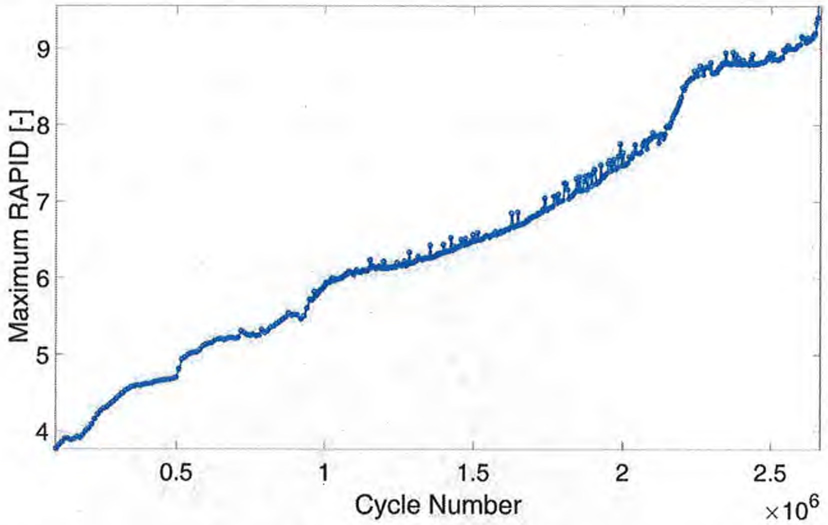

Figure 6. Damage accumulation versus the cycle number of the fatigue test. Only the cycles 100k up to 2.6 million are shown. The actuation frequency is 200 kHz.

2.2.4 *WP 4 Integration of sensor networks and prognostics*

Task owner UT, supported by Pontis, TNO & WMC

In this WP, the methods and techniques developed in WP 2 & 3 have been combined and integrated to yield an advanced structural health assessment and prognostics system. The actual integration has been done in WP5 where an optical load monitoring and piezo element health monitoring have been combined. Prior to this (full scale section) test, assessment of the blade condition, as well as a good prediction of the time until expected failures were made based on the coupon tests described in WP 2 & 3.

2.2.5 *WP 5 Demonstration and validation of monitoring concepts*

Task owner: all partners

The sensing and monitoring concepts developed in the previous two WPs will be demonstrated and validated on laboratory scale test set-ups and in full scale set-ups. An example of a section of the turbine blade that has been tested is shown below.

Figure 7. The section of the wind turbine blade.

Figure 8. A photo of the section of the wind turbine blade at WMC, with all the installed sensors of TNO, UT and WMC.

The embedded fibre optic Fibre Bragg Grating (FBG) sensors survived the fatigue & extreme static load experiment up to 170 kN, shown in Figure 9.

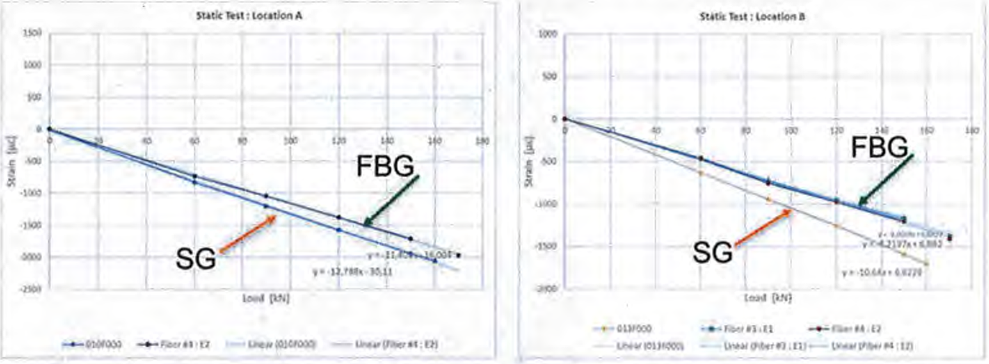

Figure 9. Strain signals of embedded fibre optic Fibre Bragg Grating (FBG) sensors at two locations.

The same holds for the Acousto-Ultrasonic damage monitoring system designed and build by the UT. The system makes use of a distributed sensor network of piezo-electric transducers, connected with the black cables in Figure 8. A fully automated test program, based on LabVIEW and an NI CompactRio data acquisition system was integrated into the test set-up of WMC. During the fatigue test it was stopped at predefined intervals and then triggers the AU-measurement to start. The fatigue test restarts automatically after completion of the AU-measurement. In addition, the program is designed to execute AU-measurements while the fatigue test is running. These parallel measurements showed however some difficulties due to the large strains in the thick beam and could not be executed during the fatigue testing. The actual cause will be a topic of further research.

No actual fatigue was detected, as was the case for the thick composite beam. This is attributed to the relative low amount of stress in the structure. However, it was shown that a consistent, long term measurement can be executed in an operational environment, employing Piezo-electric Transducers.

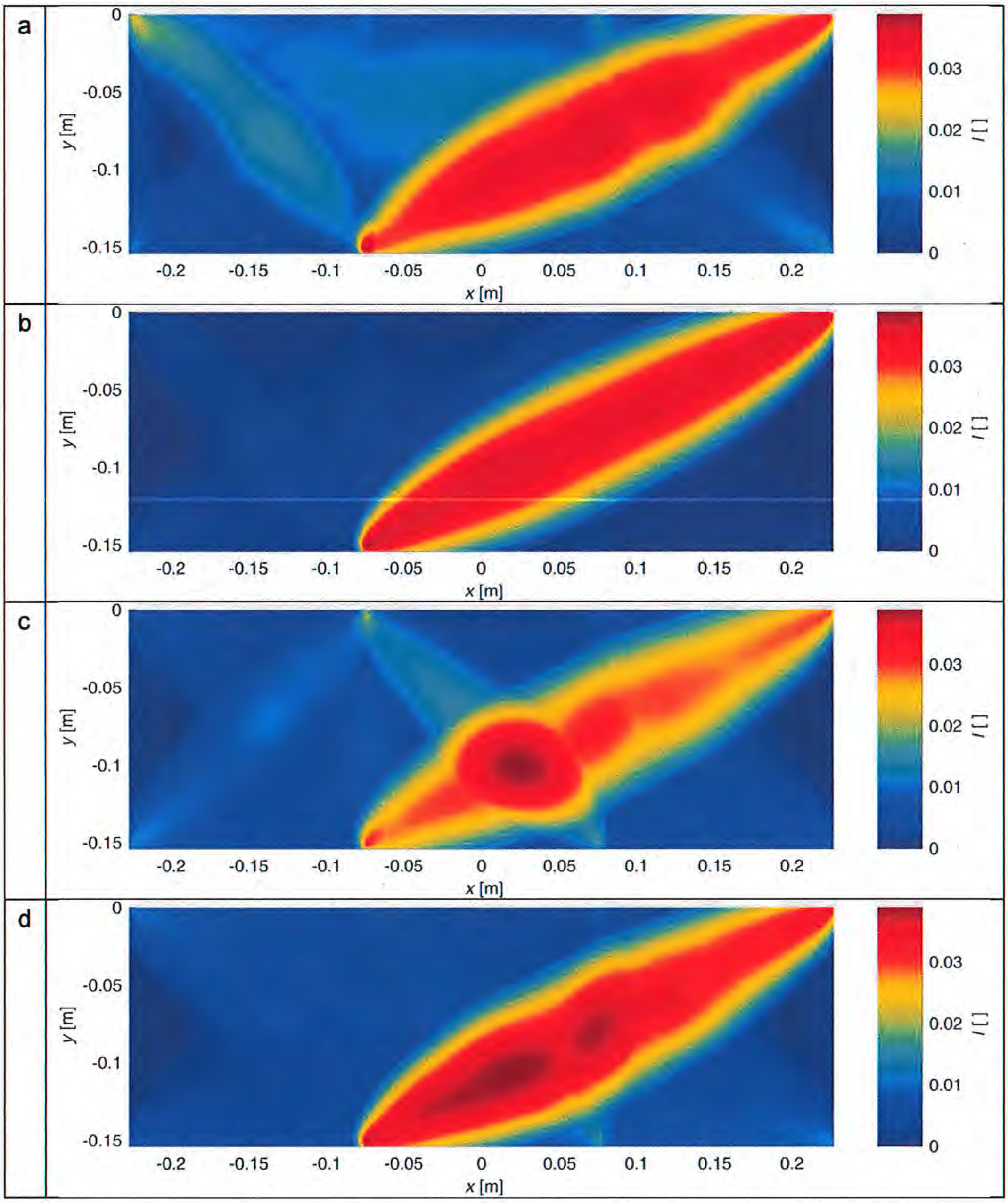

Figure 10. The RAPID plot, showing the damage accumulation probability in the area enclosed by the transducers, using the signal amplitude peak squared percentage difference algorithm and an actuation frequency of 200 kHz after a: 554 cycles; b: 759 cycle; c: 4777 cycles; and d: 8782 cycles.

3 Realised contribution

3.1 Knowledge and technology

The SLOWIND project developed novel load and damage monitoring system to reduce maintenance costs. It gave important insight in the critical aspects to further mature novel Structural Health Monitoring (SHM) concepts. The concepts introduced by TNO and UT have been developed within this project from proof of principle (Technology Readiness Level TRL1) to proof of concept (TRL 4):

- TNO; special FBG for load monitoring using an embedded fibre optic sensor;
- TNO; high speed measurement of FBG for droplet impact measurement to evaluate the thickness of the Leading Edge Protection (LEP) coating;
- UT; Acousto-Ultrasonic fatigue damage accumulation monitoring of a thick composite beam, using a distributed sensor network of Piezo-electric Transducers.

3.2 Market position

The SLOWIND project contributed in introducing and maturing novel Structural Health Monitoring (SHM) concepts that could be used for turbine blade monitoring of load and damage in the different blade stages:

- Blade transport (damage monitoring);
- Wind turbine operation (Structural Health Monitoring);
- Wind turbine optimization (pitch control).

In this project, delamination and blade erosion have been quantified which are damages encountered in (offshore) turbine blades. Furthermore, the fibre optic based FBG sensor system could cover the entire blade. It is also a robust sensor system since the optical fibres can be embedded in the composite structure. In most cases standard FBG's can be applied but if the unidirectional forces will increase the special fibre of TNO might become required.

3.3 Future project

A future project might focus on:

- Embedding of sensors to minimize the occurrence of flaws during production and for Structural Health Monitoring (SHM) when in operation;
- Development required on making the sensor more robust and a feedthrough for the connection to the read-out unit located in the hub;
- Applying SHM in sub article testing.

4 Publicity

4.1 Presentations

1. O. van der Togt. Structural Health and Load Monitoring of Offshore wind turbine blades SLOWIND - Conferentie Winddagen 2016 in Rotterdam, June 2016.
2. T.H. Jansen. Sensors and sensor networks for smart structures – ISN 2019 Ahoy Rotterdam, January 2019.

4.2 Conference papers

1. R. Loendersloot. "Acousto-Ultrasonic Damage Monitoring in a Thick Composite Beam for Wind Turbine Applications", EWSHM 2018 https://www.ndt.net/article/ewshm2018/papers/0138-Loendersloot.pdf.
2. R. Loendersloot. "The detection of fatigue damage accumulation in a thick composite beam using acousto ultrasonics", HEAMES 2018.
3. L. Cheng. "Test results of lateral load insensitive FBGs embedded in composites to suppress spectral distortion", Smart Structures Conference USA 2019.
4. L. Cheng. "1 MHz high-sensitivity FBG sensor system to measure low energy impact in droplet experiment", Smart Structures Conference USA 2019.

4.3 Technical reports

Ref. 1 F. Lahuerta. Identification of typical failures in composite rotor blades and structural health monitoring. Technical report TKI SLOWIND, Knowledge centre WMC, Wieringerwerf, The Netherlands, 2016.

Ref. 2 F. Lahuerta. SloWind; large scale experiment preliminary results (strains). Technical report TKI SLOWIND WMC-2018-089-01, Knowledge centre WMC Wieringerwerf, The Netherlands, 2018.

Ref. 3 L. Cheng, Large scale experiment results, Technical report TKI SLOWIND, TNO, The Netherlands 30 Augustus 2018.

Ref. 4 R. Loendersloot. Damage detection using acousto-ultrasonics. Technical report TKI SLOWIND, University of Twente, The Netherlands 29 September 2018.