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## Fundamentals for remote structural health monitoring of wind turbine blades - a preproject

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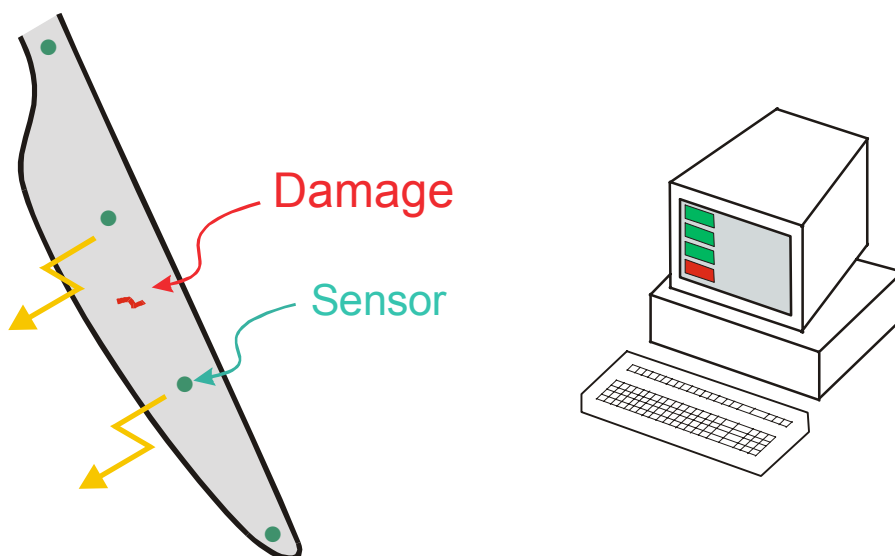
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# Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject

**Bent F. Sørensen, Lars Lading, Peter Sendrup, Malcolm McGugan, Christian P. Debel, Ole J.D. Kristensen, Gunner Larsen, Anders M. Hansen, Jørgen Rheinländer, Jens Rusborg and Jørgen D. Vestergaard**



# **Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades - a Preproject**

**Bent F. Sørensen, Lars Lading\*, Peter Sendrup#, Malcolm McGugan, Christian P. Debel, Ole J.D. Kristensen, Gunner Larsen, Anders M. Hansen, Jørgen Rheinländer★, Jens Rusborg° and Jørgen D. Vestergaard♦**

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**Abstract** This summary-report describes the results of a pre-project that has the aim of establishing the basic technical knowledge to evaluate whether remote surveillance of the rotor blades of large off-shore wind turbines has technical and economical potential. A cost-benefit analysis was developed, showing that it is economically attractive to use sensors embedded in the blade. Specific technical requirements were defined for the sensors capability to detect the most important damage types in wind turbine blades. Three different sensor types were selected for use in laboratory experiments and full-scale tests of a wind turbine blade developing damage: 1) detection of stress wave emission by acoustic emission, 2) measurement of modal shape changes by accelerometers and 3) measurement of crack opening of adhesive joint by a fibre optics micro-bend displacement transducer that was developed in the project. All types of sensor approaches were found to work satisfactory. The techniques were found to complement each other: Acoustic emission has the capability of detecting very small damages and can be used for locating the spatial position and size of evolving damages. The fibre optics displacement transducer was found to work well for detecting adhesive failure. Modelling work shows that damage in a wind turbine blade causes a significant change in the modal shape when the damage is in the order of 0.5-1 m. Rough estimates of the prices of complete sensor systems were made. The system based on acoustic emission was the most expensive and the one based on accelerometers was the cheapest. NDT methods (ultrasound scanning and X-ray inspection) were found to be useful for verification of hidden damage. Details of the work are described in annexes.

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# Preface

This summary report contains the major result of the pre-project "Grundlag for fjernovervågning af vindmøllevingers tilstand (Fase I: Forprojekt)", supported by PSO-funding through Elkraft System, contract no. Bro-91.055, FU nr. 1102. The project was performed within 12 month 2001-2002 in collaboration between Risø National Laboratory (project leader), DELTA, Sensor Technology Center A/S, Force Technology, InnospeXion and LM Glasfiber. Details of the work can be found in the accompanying annexes.

The publications (annexes) of the project are:

Annex A:

"Cost benefit for embedded sensors in wind turbine blades", Lars Gottlieb Hansen and Lars Lading, Risø-R-1340(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex B:

"Sensors and non-destructive testing methods for damage detection in wind turbine blades", Lars Lading, Malcolm McGugan, Peter Sendrup, Jørgen Rheinländer and Jens Rusborg, Risø-R-1341(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex C:

"Fibre transducer for damage detection in adhesive layers of wind turbine blades", Peter Sendrup, Risø-R-1342(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex D: "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex D - Laboratory tests using condition monitoring sensors", Malcolm McGugan, Risø-I-1878(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex E:

"Full-scale testing of wind turbine blade" Ole J. D. Kristensen, Malcolm McGugan, Peter Sendrup, Jørgen Rheinländer, Jens Rusborg, Bent F. Sørensen, Christian P. Debel and Anders M. Hansen, Risø-R-1333(EN), Risø National Laboratory, Roskilde, Denmark, May 2002.

Annex F:

"Identification of damage to wind turbine blades by modal parameter estimation", Gunner Larsen, Anders M. Hansen and Ole J. D. Kristensen, Risø-R-1334(EN) Risø National Laboratory, Roskilde, Denmark, April 2002.

# 1 Overview, Purpose and Main Findings

## 1.1 Purpose of Project

The present work concerns the use of sensors in large off-shore wind turbine blades for monitoring of structural health. A long-term goal is to develop an approach for detection of damage (localisation and type of damage) and estimate the severeness of damage on the residual life of wind turbine blades. The aim of the pre-project is to investigate if there are severe economical or technical obstacles for this.

The major *economical* aspects that will be treated are:

- Development of a cost/benefit analysis for the use of sensors as a structural health monitoring system
- Estimate the price of a structural health monitoring system for large off-shore wind turbines

The following *technical* questions will be answered:

- Which sensors have potential for the detection of damages in wind turbine blades?
- Can the sensors locate the damage site?
- How many sensors must be used for surveillance of a large wind turbine blade (how closely spaced should sensors be?)?

## 1.2 Overview

To answer the questions listed above, a work program with the following points was undertaken:

- Cost/benefit analysis
- Definition of damages; selection of sensor types and NDT techniques
- Laboratory experiments on specimens, using sensors & NDT
- Demonstration of sensors and NDT at full scale tests of a wing turbine blade
- Modelling of wings with damage

This report forms a summary report in which the major results are summarised; full details are given in the annexes. The aim of this format is to make the summary report short and readable, so that the reader can easily get overview over the project and results.

## 1.3 Main findings

Our investigations on wind turbine blades show that:

- The use of sensors for damage detection is economically feasible.
- The investigated sensor systems (acoustic emission, fibre optics displacement transducer for adhesive joints and measurement of changes in global modal shape by accelerometers) are all promising candidates for damage detection.
- The remaining challenge is to establish links between sensor signals, damage state and residual life of a wind turbine blade.

## 2 Cost-Benefit for Embedded Sensors in Large Wind Turbine Blades

Modern wind turbine blades are subject to rigorous quality control before leaving the production facility. However, various types of damages may develop after wind turbines have been set up. Can the cost of a reliable sensor system be justified?

We have compared the total operating costs of a three-bladed 2MW turbine placed offshore either WITHOUT SENSORS (H0) or WITH SENSORS (H1). The cost difference illustrates the cost vs. benefit of using sensors in wind turbine blades. We have applied an operator's point-of-view. However, repair cost is incorporated irrespective of who may be liable for the cost. It is also noted that a rather extensive sensing system is here assumed necessary in order to provide a reliable early warning of emerging damages.

The differential cost analysis aims to present three scenarios, denoted MOST LIKELY, WORSE CASE and BEST CASE, respectively. In all the H1-analyses, the disaster-likelihood is set to a tenth of that of H0 in order to generate a system-independent analysis. It is, however, obvious that different sensor systems have different detection capabilities (type and size of damage) and thus in the real world the disaster likelihood will be different for different sensor systems.

The MOST LIKELY case is based on the estimated sensor price for a sensor system of 120 000DKK per turbine. This price lies in the range of the estimated prices for the sensor systems considered in this project (see Chapter 3). The effect of sensor system price cost is also investigated. Full details about the assumptions of the analysis are given in Annex A.

The differential cost is illustrated for the three cases in Figure 2-1.



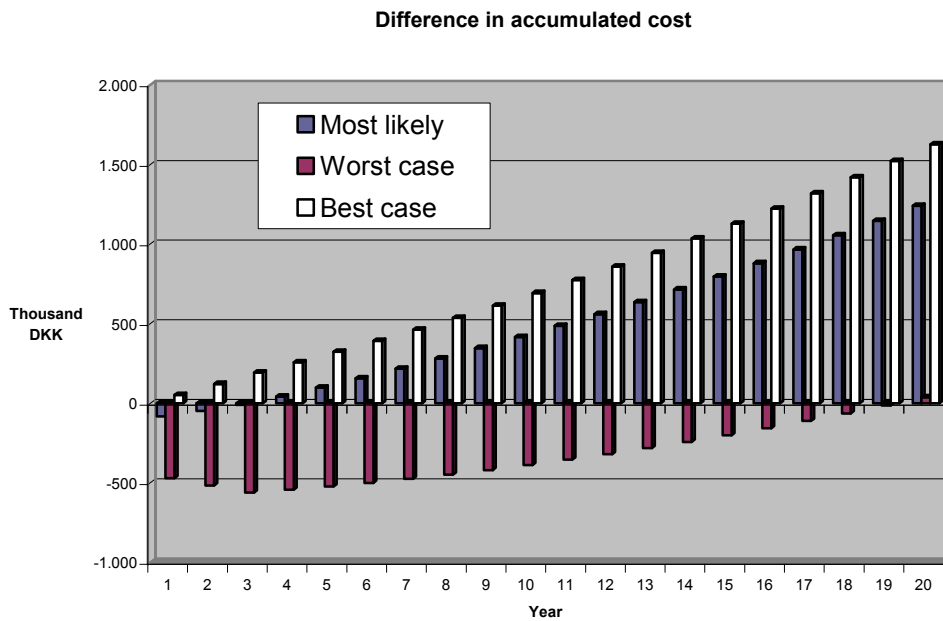


Figure 2-1. Difference in accumulated cost for a 2 MW turbine placed offshore.

In the MOST LIKELY case, the time-to-break-even is slightly more than 3 years when using sensors (H1). The reason is that cost from systematic damages is re-distributed so that more is incurred during the first three years compared to using a wind turbine without sensors (H0), because such damages are now more likely to be discovered early on. In addition to this, it is noted that the use of sensors implies an initial higher cost.

In the BEST CASE this extra cost is assumed to be very low and, consequently, cost savings occur almost from the start. In the WORST CASE the sensor system is very expensive, yet does not reduce the risk of disaster. In addition, lots of unnecessary repair is being undertaken, implying a time-to-break-even in excess of 19 years.

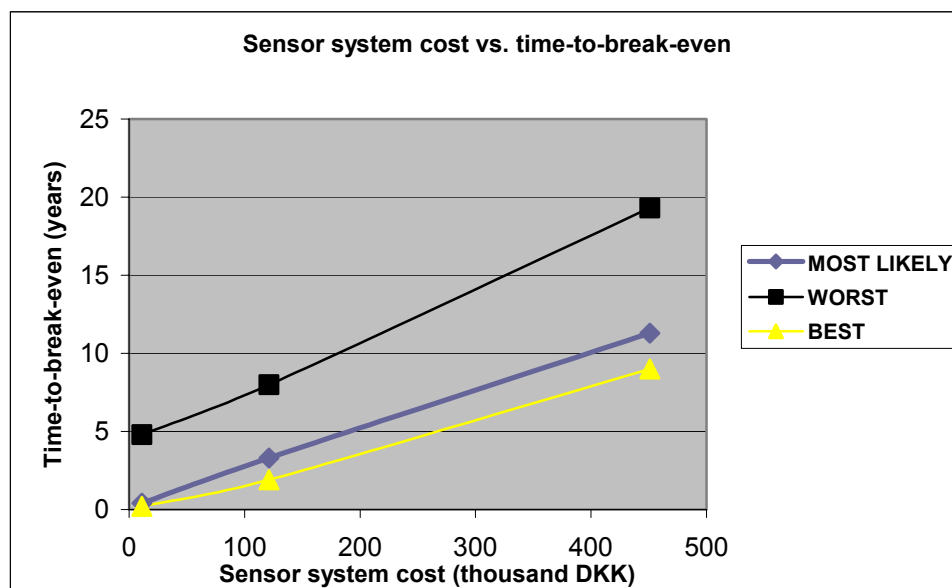


Figure 2-2. Sensor system cost for one wind turbine vs. time-to-break-even

Figure 2-2 illustrates the sensitivity of time-to-break-even to sensor system cost. In the MOST LIKELY case, the time-to-break-even is closely linked to the cost of the sensor system. Furthermore, it is observed that there is quite a gap between MOST LIKELY and WORST CASE, illustrating a considerable downside risk. Time-to-break-even may be nearly as long as the economic lifetime (20 years) under the most pessimistic assumptions.

## 3 Sensors and Non-Destructive Testing Methods

This chapter defines the most relevant damage types in wind turbine blades and sets up criteria for the detection of these damages. An overview of sensors that could be applied to damage detection is given. The sensors investigated in the project are identified. An overview of non-destructive methods (NDT) is also presented. Details about these and other techniques considered for use are given in the Annex B.


### 3.1 Damage Types and Requirements for Damage Detection

A prioritised list of damages to be considered was decided as follows:

1. Cracks in adhesive joints
2. Delaminations (i.e., crack growth between individual layers of laminas)
3. Damage in laminate involving fibre rupture

An important consideration in evaluating NDT methods and sensors is spatial scales (characteristic length of cracks, displacements in the cracks as well as the

minimum length of a crack that is considered relevant for detection) as well as early warning indicators. It was tentatively decided that sensor designs should be based on the following requirements for damage detection:

Cracks in adhesive joints: Cracks length larger than 1 m must be detected. The characteristic displacement that should be detected as a consequence of a crack opening is 100  $\mu\text{m}$  

Delamination: Minimum detected area 100 mm  $\times$  100 mm, minimum crack opening displacement 100  $\mu\text{m}$ .

Laminate damage including fibre rupture: Minimum detected area 50 mm  $\times$  50 mm. The relative smaller area reflects that laminate failure that involves fibre fractures may occur in load carrying areas.

## 3.2 Sensor Types

A number of sensor and NDT methods have been considered (see Annex B). Table 3-1 lists the types of damages considered relevant in this investigation. The table also shows which types of sensors that may be applied to give an early warning of damages as well as the NDT methods that can be applied to investigate the structure of the damages.

Table 3-1. Characteristic types of damages and the sensor types as well as NDT methods that can be applied to detect and/or investigate the damages. A (d) indicates that the method can detect dynamic events (i.e., recording effects of the crack growth process), and an (s) indicates that static structural changes (e.g. changes in local crack opening or global stiffness changes) can be detected. Note, that a fibre sensor is in this table synonymous with a displacement sensor.

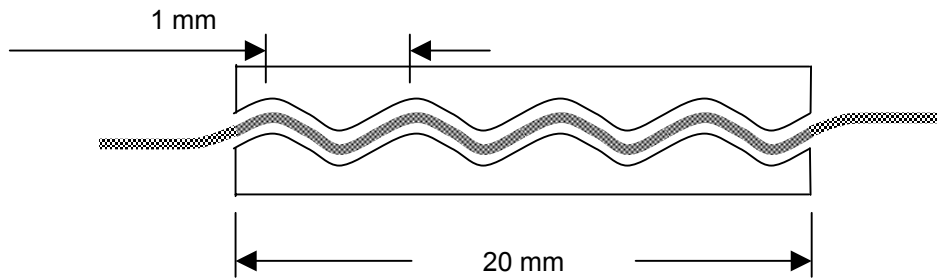
Damage	NDT	Sensor
<i>Fibre breakage (microscale)</i>	Acoustic emission (d) X-ray (s) Ultrasound (s) OCT (d, s)	Fibre (d and/or s) Acoustic emission (d)
<i>Fibre/matrix slip (microscale)</i>	Acoustic emission (d)	Fibre (d) Acoustic emission (d)
<i>Matrix cracks (micro scale)</i>	X-ray (s)	Fibre (d, s) Acoustic emission (s)
<i>Cracks in adhesions (macroscale)</i>	Ultrasound (s) OCT (d, s)	Fibre (d, s) Acoustic emission (d) Ultrasound (s)
<i>Delamination (macroscale)</i>	Ultrasound (s) OCT (d, s)	Fibre (d, s) Acoustic emission (d) Ultrasound (s)
<i>Laminate damage involving fibre fracture (macroscale)</i>	X-ray (s)	Acoustic emission (d, s) Electrical strain gauge (d, s)
<i>Dynamic response of structure (macroscale)</i>	Deflection and acceleration of wing turbine blade	Change in <i>eigen modes</i> detected with accelerometers (s)

### 3.3 Sensor Types and Costs

Sensors are here defined as devices that can be placed directly in or at the construction elements. The sensing is performed under normal operation of the wind turbine. The sensors are tailored to the environment in which they are placed. A more comprehensive description of sensors can be found in the Annex C.

#### 3.3.1 Fibre Optics

Fibre optics is well suited for imbedded detection of mechanical displacements (as well as a number of other physical parameters). Expensive types of sensor systems (e.g. strain gauges based on Bragg grating) have very recently become commercially available. However, they were found to be too expensive and too fragile for the present application. Therefore a sensor based on microbending of fibres was developed for the detection of cracks in adhesive joints. It utilizes the fact that the propagation of light through an optical fibre may be strongly affected by bending the fibre. The basic principle of the detector is illustrated in Figure 3-1. The sensor is described in detail in Annex C.



*Figure 3-1. Fibreoptic sensor for the detection of small displacements. When the two solid corrugated parts are moved to or from each other the curvature of the fibre changes. This affects the transmission of light through the fibre. The sensor developed in this project was designed to be sensitive to displacements perpendicular to the main axis of the fibre. However, the corrugation and support of the two solid parts may be done so that the sensor is sensitive to shear.*

A sensor of this type can be produced at a very low cost (of course depending on the number of elements produced). However, the sensor is only sensitive to displacements at the sensor position. Thus, a number of sensors are needed in order to comply with the required in-plane spatial resolution (which here is specified to be one meter). Also the interface, communication from hub to a central processing unit adds substantially to the cost. To cover the adhesive bond at the trailing edge, we have estimated an initially installation cost of 135.000 DKK for a 40 m blade (using 40 sensors). It is assumed that 1000 wind turbines (three blades each) are produced with sensors annually.

### 3.3.2 Acoustic Emission

Materials subjected to stress or strain may emit sound waves as a result of sudden very small structural changes. The rate and properties of these emissions can be used as indicators of damage growth. Acoustic emission is fundamentally different from strain gauge sensors, which detects displacements.

The primary initial effect of the rupture of a fibre is the emission of a sound wave in a broad frequency range. The bandwidth can be estimated from the ratio of the speed of sound in the material to a characteristic spatial scale of the rupture. We estimate that the bandwidth may be several tens of MHz. The high frequency components of such a stress wave are damped very rapidly in polymer composites, whereas lower frequency components travel much further. At low frequencies however, the signal is dominated by "noise" sources that swamp the damage stress waves. A frequency of 150 kHz is a good compromise between sensoric range of acoustic emission (which is 0.7-1.0 m) and noise rejection.

Acoustic emission sensors are commercially produced. Complete systems are manufactured for both laboratory use and for supervision of large structures such as bridges and large storage containers. The signal processing and initial signal transfer is somewhat more complicated than in the case of fibres. Each sensor needs a dedicated Digital Signal Processor (DSP) with internal analog-to-digital converter. On the other hand, the sensor signal is information rich, all kinds of damages can be detected and a single sensor can detect damage evolution over a relative large area (1-3 m<sup>2</sup>).

It is noted that acoustic emission sensor systems may also be designed with fibre optic transducers. This would eliminate the need for electrical wires in the blades. However, we are not aware of any commercially available transducers, which are directly applicable for the present application.

A scheme is illustrated in Figure 3-2. The installation cost for such a system with 20 acoustic emission sensors, with detection coverage of the entire blade (adhesive joints and laminates), is estimated to 260.000 DKK with the assumption that 1000 wind turbines are produced with sensors annually (same number as assumed for the fibre sensor).

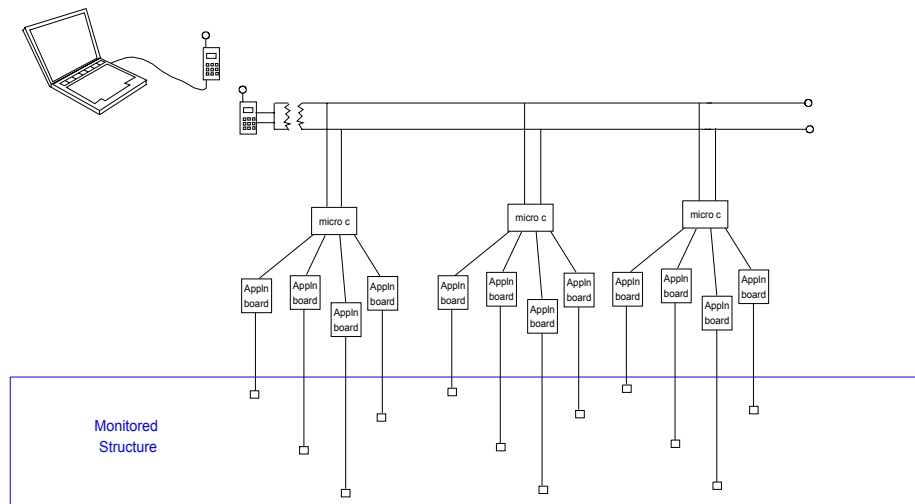


Figure 3-2. A possible architecture for an acoustic emission system. The signals from the piezoelectric transducers are filtered by an DSP. A microcontroller collects data from up to 16 transducers and convert the data to a common bus format (e.g. Can-Bus). A centralized computational reconstruction may be performed in order to estimate the spatial location of acoustic emissions.

### 3.3.3 Inertial sensors

Inertial sensors are devices sensitive to accelerations. Sensors for linear acceleration are very common for laboratory applications. Very low cost acceleration sensors have been developed recently for use in car-protection systems (air bags). They are produced as so-called MEMS devices (Micro Electro Mechanical Systems) with a signal processor in the same small package. In large volumes (> 10.000 units per year) the price per sensor may be below 1 USD.

Angular movements can be detected with gyros. Gyros are used in navigation systems (especially in aeroplanes). Low cost versions are emerging on the market. They are primarily intended for automobiles and also made as MEMS devices. The company *Systron Donner Inertial Systems* have developed a novel miniaturized true gyro, which is suitable for mounting in wind turbine blades. The large volume price is around 10 USD.

Detection of damages by measurement of the change in modal shape is discussed in Section 6 and in Annex F. We have identified commercial low cost devices that appear to comply with the required specifications. A conceptual structure for inertial sensors in a turbine blade is shown in Figure 3-3.

Fibre optic versions of inertial sensors have been demonstrated and are being commercialised. They are attractive for the present application because electrical wires in the blades can be eliminated. However, the cost is still considerably higher than the cost of MEMS devices.

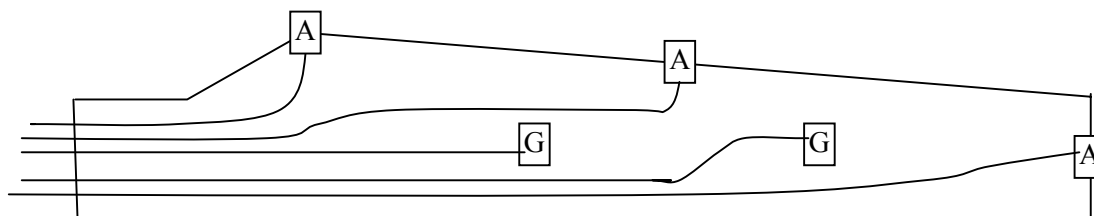


Figure 3-3. A wind turbine blade with estimated positions of acceleration sensors (A) and rotational rate sensors (G) for monitoring the modal dynamics of the blade.

### 3.4 Comments and Conclusion Concerning Sensors

The estimated prices for several different sensor types are presented in Table 3-2. The cost of the transducers themselves is in all cases a relatively small part of the total cost. For the fibre optic sensors we have assumed glass fibres. For the displacement transducer polymer fibres may be an option. This would reduce the cost of the fibre to a negligible value.

Table 3-2. Estimated prices for different sensor types. It is assumed that 1000 wind turbines each with three blades are fitted with sensors annually. The prices given are per turbine (i.e. for three blades) and are only rough estimates and will depend very much on specific developments. The number of transducers listed is per blade.

Cost estimates for damage detection systems x 1000 DKK				
	AE 20 transducers	Inertial MEMS 10 transducers	Inertial fibre 10 transducers	Displacement fibre 40 transducers
Transducers	30	5	5	20
Electronics in blade	100	0	0	0
Electronics in hub	30	30	40	40
Communication	20	20	20	20
Central processor	25	25	25	25
Installation	50	20	10	25
Wiring/cabling	5	2	6	5
<b>Total</b>	<b>260</b>	<b>102</b>	<b>106</b>	<b>135</b>

Some of the main advantages and disadvantages of the different sensor types are listed in Table 3-3. For sensors having a certain spatial range, the number of sensors required for a turbine blade depends on the maximum allowable undetected damage size and the sensoric range, i.e. the radius of the area in which the sensor detects damage.

Table 3-3. Comparison between different sensor schemes. The 'availability' indicates to what extent a system could be devised based on readily available components.

Sensor type	Cost 10 <sup>3</sup> DKK	Sensor detection radius (cm)	Detectable damage types	Smallest detectable damage size (cm)	Determination of damage size	Availability 5=highest/best; 1=lowest	Robustness 5=highest/best; 1=lowest	Electrical wires in the blade
AE (piezoelectric)	260	70-100	all	< 1	yes	4	2	yes
AE fibre	?	?	all	?	?	2	4	no
Inertial MEMS	102	-	all	50-100	yes	transducer: 5 processing: 3	4	yes
Inertial fibre	106	-	all?	?	yes?	2		no
Displacement fibre	135	5	adhesive joint	~5	no	3	4	no
Displacement, semiconductor	?	?	adhesive joint	~5	no	5	2	yes

An acoustic emission system can readily be implemented as shown in Figure 3-2. A system with much less electronics in the turbine blades would be preferable. A fibre optic system can be developed with few uncertainties. For the inertial sensing system the transducers are readily available at low cost. A methodology that can relate accelerations to damages has been outlined, but a concept that can readily be implemented is not available.

We believe that good sensor candidates for a structural health monitoring system have been identified in this project, but no system has yet been developed to a stage compatible with the requirements of commercial wind turbines.

## 3.5 Non Destructive Testing

Non Destructive Testing (NDT) is well established for investigating the structural health of solid mechanical systems. NDT systems are different from sensors in that NDT-measurement cannot be performed during normal operation and may require special precaution. The structural properties of the object being investigated are not affected by the measuring system. A description of the different NDT schemes is given in Annex B.

### 3.5.1 Ultrasound

Ultrasound is a well-established method for investigating the inner structures of solid objects. Ultrasonic scanning is also very useful for investigating composite structures. In relation to X-ray it has the advantage of being *single ended*, that is the transmitter and receiver can be on the same side of the object. Ultrasound probing will typically reveal cracks oriented in a plane perpendicular to the direction of sound wave propagation. A spatial resolution (in the depth direction) is obtained from the time delay of return signals. The in-plane position is given by the position of the scanning head. Cracks of a length down to a few millimetres can be detected.

We note that ultrasound can also be implemented as a sensor. It will then have similarities with acoustic emission systems ("active" mode, see Annex B).



### 3.5.2 X-ray

X-rays can penetrate a large number of materials including composites. However attenuation is generally observed. Typically images are obtained as a kind of shadows revealing variations in the integrated attenuation along the propagation paths. Thus, in contrast to ultrasound X-rays cannot (in the normal mode of operation) reveal cracks in a plane oriented perpendicular to the direction of propagation of the X-rays, but cracks oriented parallel to the rays. An advantage in relation to ultrasound is that images are obtained in parallel - not by scanning. The spatial resolution is somewhat better than for ultrasound. A disadvantage is the fact that special shielding is necessary for safety reasons.

In addition to these systems we have also considered Optical Coherence Tomography (OCT) and non-contact ultrasound based on optical excitation of ultrasound and non-contact optical "microphones". OCT is well established for biological objects (which in general have a composite structure). Very recently the scheme has also been applied to artificial composites. The spatial resolution is excellent, but the penetration range is currently too small for the application to wind turbine blades.

Non-contact ultrasound is currently being investigated. Excitation of ultrasound by pulsed lasers is very efficient in composites. However, sensitive non-contact detection needs further development to be practically feasible in connection with wind turbine blades.

## 3.6 Conclusion Concerning NDT

Ultrasound and X-ray investigations complement each other very nicely. Combined, they can provide better structural information than each of the methods can give alone, although there is some overlap. Both methods are well established and experimentally proven. OCT has a potential for studying small structural changes. However, OCT is not yet an established tool for industrial non-destructive testing.

# 4 Laboratory Experiments on Specimens, using Sensors & NDT

The goal of this work was to trial the sensor systems (acoustic emission and the specially developed fibre optics displacement sensor, see Annex C) prior to their use in the full scale blade testing. In laboratory tests the initiation and growth of specific damage types can be more easily controlled and studied. In addition to gaining practical experience with the sensor systems, this task also addressed specific questions regarding the sensors operation during damage monitoring.

- Can the damage state be determined with the sensors?
- Can the damage location be determined with the sensors?
- How close must the sensors be positioned?
- What is the effect of the laminate?

In this short chapter the three main laboratory tests are described and their findings summarised. Full details of the tests carried out are contained in Annex D.

## 4.1 Determination of Signal Attenuation in Laminates by Leadbreak Tests

An investigation was carried out to establish the stress wave attenuation characteristics of the six polyester polymer matrix materials shown in Table 4-1. It is fundamental, when using surface mounted acoustic emission piezoelectric sensors, to first determine the range at which each sensor can detect a "standard" stress wave emission source, in this case a 0.5 mm pencil leadbreak. This information Table 4-2 informs decisions on sensor placement and locator array formations when monitoring structures.

Table 4-1. Material information.

	Resin	Glass Fibre Reinforcement	Orientation	Lay up	Fabrication technique	Dimensions
<b>A</b>	PO4536 Polyester	Combi 1250	0°/90°	10 layers	Vacuum consolidation	500 x 500 mm
<b>B</b>	PO4536 Polyester	Combi 1250	0°	10 layers	Vacuum consolidation	500 x 500 mm
<b>C</b>	PO4536 Polyester	None	N/A	N/A	Water cooled resin cure	500 x 500 mm
<b>D</b>	410-M912 Polyester	Combi 1250	0°/90°	10 layers	Hand lay up consolidation	500 x 500 mm
<b>E</b>	410-M912 Polyester	Combi 1250	0°	10 layers	Hand lay up consolidation	500 x 500 mm
<b>F</b>	410-M912 Polyester	None	N/A	N/A	Water cooled resin cure	500 x 500 mm

Table 4-2. Leadbreak stress wave detection limit.

	All data	Hand lay up fabrication	Injection fabrication
<b>Pure resin</b>	350 – 375 mm	350 mm	375 mm
<b>stress wave path parallel to reinforcing fibres</b>	425 – 600 mm	425 – 600 mm	475 – 525 mm
<b>stress wave path transverse to reinforcing fibres</b>	275 – 475 mm	350 – 400 mm	275 – 475 mm

The investigation suggested a strong relationship between the material type/reinforcement direction and the attenuation of stress wave energies detected by acoustic emission sensors. A clear difference is visible between the distances a stress wave can travel along the direction of the fibres compared to across the direction of the fibres. This shows the effect of material interfaces in attenuating a stress wave travelling through a structure.

The effect of fabrication method is less clear. The higher material stiffness and greater production quality and consistency resulting from injection fabrication might suggest that this material would be less attenuating than hand lay up material. However the greater density of material interfaces in injection fabricated material may act to increase the attenuating effect. Both material types display the strong effect of reinforcement direction relative to stress wave propagation.

This investigation also suggested several new ways of interpreting waveform characteristics that can lead to improved sensor functionality, for example in order to give a clear correlation between signal rise time and source/sensor distance.

## 4.2 Tensile Fatigue Tests on Laminates

Tensile-tensile fatigue tests to determine differences in recorded acoustic emission were carried out on four glass fibre reinforced polymer matrix materials used in wind turbine blade manufacture. The materials used were those designated A, B, D and E in Table 4-1.

During static loading prior to fatigue cycling it was demonstrated that loading history influences the acoustic emission recorded, with less activity present at previously experienced load levels. It was also observed that compared to metal, glass fibre reinforced plastic (GRP) materials are very "noisy" and emit many acoustic emission stress waves, even during static load and unload periods.

When recording acoustic emissions during high strain rate fatigue testing of polymer composite materials, the high number of "hits" obtained make it impractical to record data continuously. Some heavy form of data sampling or filtering is required, and for these tests the following procedure of sampling was observed. During the fatigue cycling, acoustic emission data was only recorded for 100 of every thousand cycles, no data was recorded by the system for the remaining 900 cycles in each millennium.

Some evidence from the fatigue tests suggested that the level of general activity and in particular the average energy recorded for each acoustic "hit" increases prior to failure. Figure 4-1 shows fatigue curves obtained during the testing of material B (see Table 4-1) at different strain rates. In each case an increase in the average acoustic emission per cycle is observed prior to the failure of the specimen.

However, another conclusion from this set of tests is that the sampling system used here may be unsuitable for general monitoring. It was observed that the level of stress wave emission did not gradually increase during testing but was characterised by periods of activity and periods of relative inactivity. This suggests that a sampling system where so much (potentially vital information) is excluded and therefore not available for analysis is undesirable. A more effective way of handling the amount of data might be to use a continuous recording followed by a segment summarising routine.

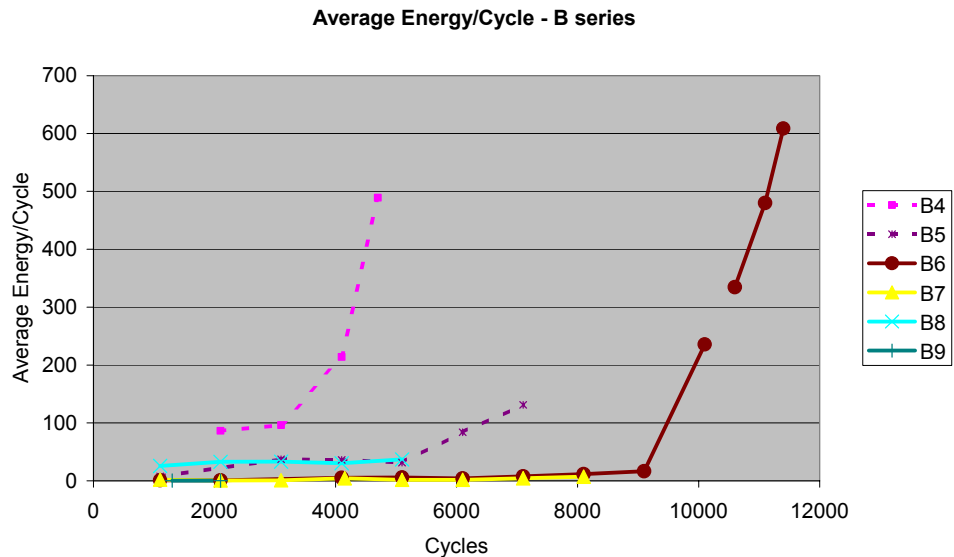


Figure 4-1. Increase in Energy per fatigue cycle prior to specimen failure.

Differences were noted between recorded acoustic emission from the four material types. Unidirectional reinforced specimens showed less general activity than equal bias reinforced specimens and Hand lay up specimens showed less general activity than those consolidated under vacuum. Although in this particular case the differences in activity are also influenced by specimen volumes and strain rates.

X-ray inspection of the test specimens was carried out at various stages of testing; results show the accumulation of damage during tensile fatigue cycling.

### 4.3 Adhesive Layer Crack Opening Tests

A set of Double Cantilever Beam (DCB) experiments were undertaken where crack growth was promoted within the adhesive layer between two bonded polymer composite materials. The crack progression was monitored with two types of sensors, surface mounted piezoelectric acoustic emission sensors and an embedded fibre-optic displacement transducer. The accuracy of the sensors was confirmed with visual observation.

A surface mounted acoustic emission linear location array using time of flight measurements from stress waves successfully tracked the crack progression during the tests. This sensor information is shown in Figure 4-2. The arrows, colour coded to match the AE emission at that time, show the visually determined extent of the crack advance. It should be noted that the crack did not reach sensor A during the first five minutes of the test. It is also clear that a damage "zone" is associated with the crack front, stress wave emission is detected in front of and behind the tip (fibre bridging was observed in the crack wake).



This DCB test simulates a damage type found in wind turbine blade structures, where bonded surfaces develop a crack, which then grows under fatigue loading. Following the test ultrasonic inspection of the specimens established embedded sensor position relative to the visible crack front. This was confirmed by subsequent splitting of the specimens.

## **4.4 Summary of Laboratory Test Findings**

Results from the laboratory experiments have shown that,

- Growth of all damage types in wind turbine blades (cracks in laminates and adhesive joints) will produce effects that can be detected with the monitoring sensors.
- General localisation of damage events was demonstrated for acoustic emission using zonal sensor arrays and more precisely with embedded point sensors and stress wave time-of-flight measurements.
- A field procedure (leadbreak tests) exists for determining optimal sensor spacing with any acoustic emission sensor and material type.
- Stress wave attenuation between source and sensor is dominated by energy dispersing interfaces in the material.
- The fibre-optic microbend displacement transducer is a very effective point sensor for detecting crack opening in adhesive joints.

# **5 Full-Scale Test of Wind Turbine Blade**

## **5.1 Introduction**

To verify the abilities of the different types of sensors and the NDT-methods full scale testing of a LM 19.1 blade was carried out. Two types of artificial damages were chosen for the test, see Figure 5-1. The tests were carried out as static tests. The first damage was a notch in the trailing edge, to promote laminate failure. The second damage was a failure in the adhesive joint in the trailing edge, i.e. the glue in the joint was removed in a part of the trailing edge.

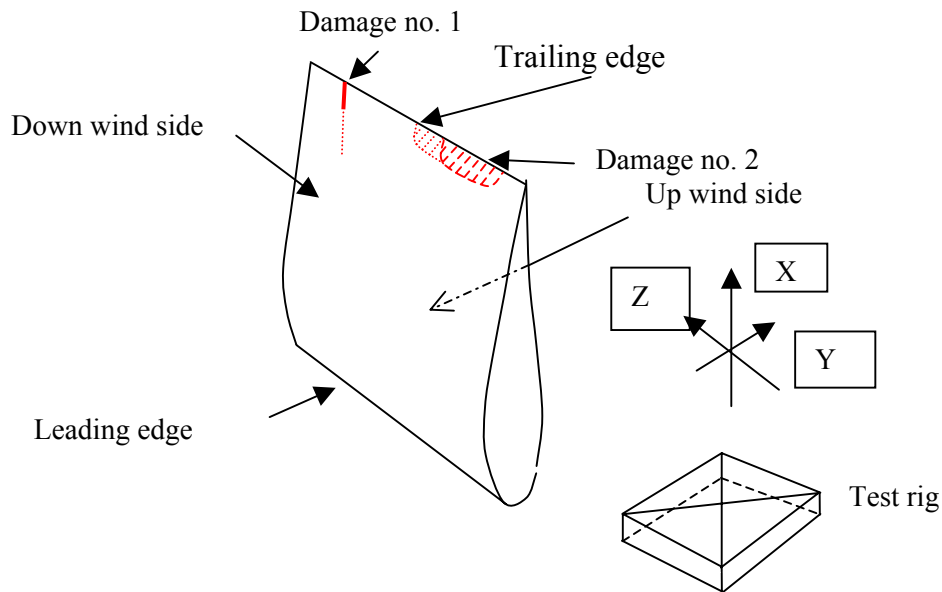


Figure 5-1. Sketch with the definitions that are used during this test.

To monitor the damage during the static tests, sensors were mounted on the blade. These sensors were strain gauges and acoustic emission (AE) sensors for the notch in laminate in the trailing edge and, additionally, a fibre optic micro bending displacement transducer for the adhesive failure in the trailing edge. Two NDT-methods were used during test; ultrasonic scanning and X-ray inspection. Video cameras were used for recording the damage progression.

The tests were carried out in edgewise direction, and were carried out in a numerous steps, these steps are called WING001-008 for the first damage and WING101-118 for the second damage. In general the tests were carried out with an increase in load for each step and all steps starting from no load. Between each step NDT inspections were carried out to determine the propagation of damage within this step. Only a few main results are shown here; full details are given in Annex E.

## 5.2 Damage No. 1, Notch in Trailing Edge

Strain gauges were mounted on the blade in the area of damage no. 1. The strain gauges were mounted in two columns perpendicular to the trailing edge on both up- and down-wind surface. For each of the test steps three different configurations of the AE-set-up was used. The configurations were a near/far, a linear and a zonal location. The blade was loaded such that the damage would grow from the notch due to tensile failure of the laminate. The test was carried out in 8 steps, which caused a total propagation of the damage of 125 mm and 150 mm on up-wind respectively down-wind surface of the blade. The damage was in the form of a damage zone consisting of a fibre-bridged crack. Figure 5-2 shows the downwind surface (the gelcoat) after WING008. The crack appears somewhat zigzag and crack bridging by fibres is clearly seen. Figure 5-3 shows the internal surface of a definite sharp crack, rather a damage zone having a width of 3-12 mm. Crack deflection and branching is seen.

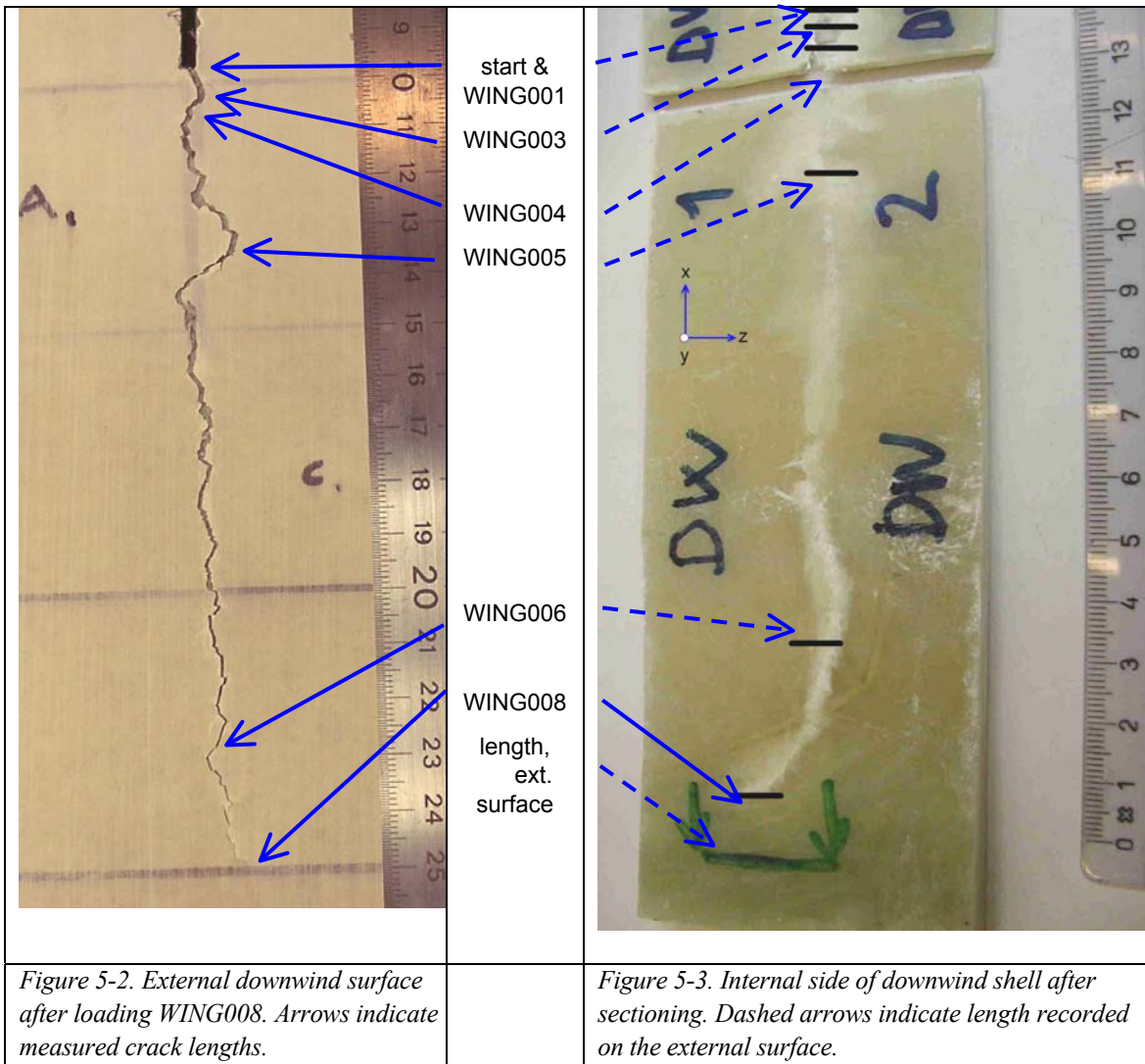


Table 5-1. Showing the propagation of damage during different steps in test, determined from photos of the external surface damage.

test #	UPWIND (pressure side)			DOWNWIND (suction side)		
	crack length at start of test mm	growth during test mm	crack length at stop of test mm	crack length at start of test mm	growth during test mm	crack length at stop of test mm
WING001	0	0	0	0	0	0
WING002	0	0	0	0	0	0
WING003	0	5	5	0	4	4
WING004	5	14	19	4	3	7
WING005	19	81	100	7	25	32
WING006	100	14	114	32	88	120
WING007	114	0	114	120	0	120
WING008	114	11	125	120	30	150



As shown in Table 5-1 the highest growth in damage was seen during step 5 and 6 of the test of the first damage.

It was found that the signal of strain gauges positioned close (~10 cm) to the damage area decreased as the damage front (crack tip) propagated past the strain gauges. For strain gauges positioned further away the strain signals were unaffected by damage growth. This indicates that the strain redistribution associated with damage progression is only significant in a region close to the damage zone.

Figure 5-4 shows an example of damage localisation by acoustic emission; the number of recorded events is shown as a function of position between the sensors (determined by the time-of-flight). The position of the events indicates that the damage progresses in a zone 100-160 mm away from sensor A. Two peaks are seen. This indicates two crack tips.

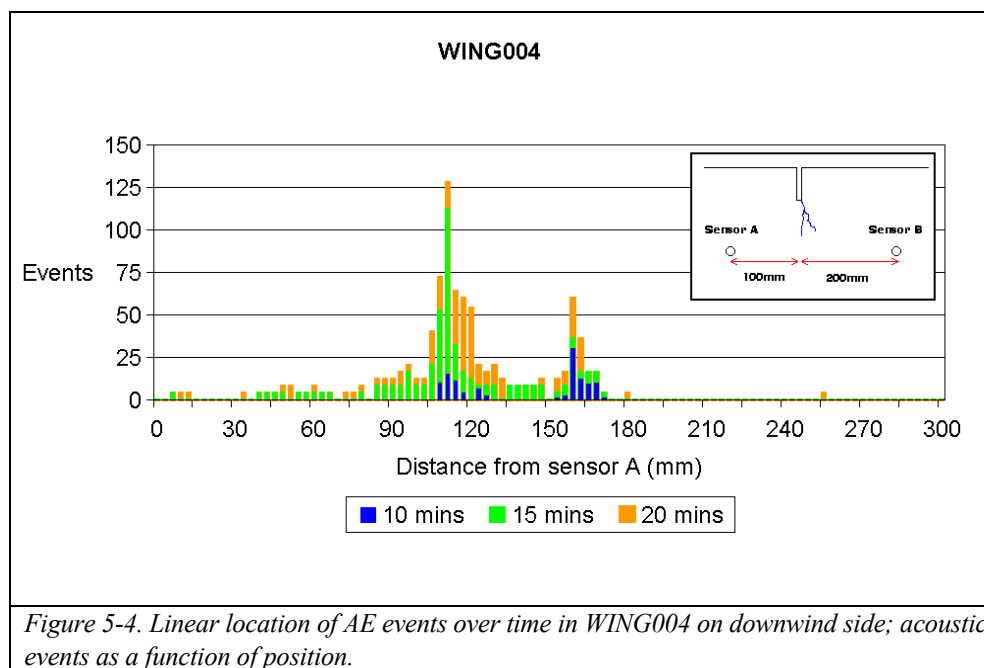


Figure 5-4. Linear location of AE events over time in WING004 on downwind side; acoustic events as a function of position.

Figure 5-5 shows the visual crack in the gel-coat on the down wind side after WING004 along with a photo of the internal side (laminare surface) of the down wind side, taken after the blade has been cut up. It is seen, that the damage on the outside appears as two or three definite (sharp) cracks in the gel coat. However, the internal surface shows a broader (~ 2 cm wide), more diffuse damage zone. The crack branching suggested by the acoustic emission data (Figure 5-4) is clearly seen at the inside surface (Figure 5-5, right).

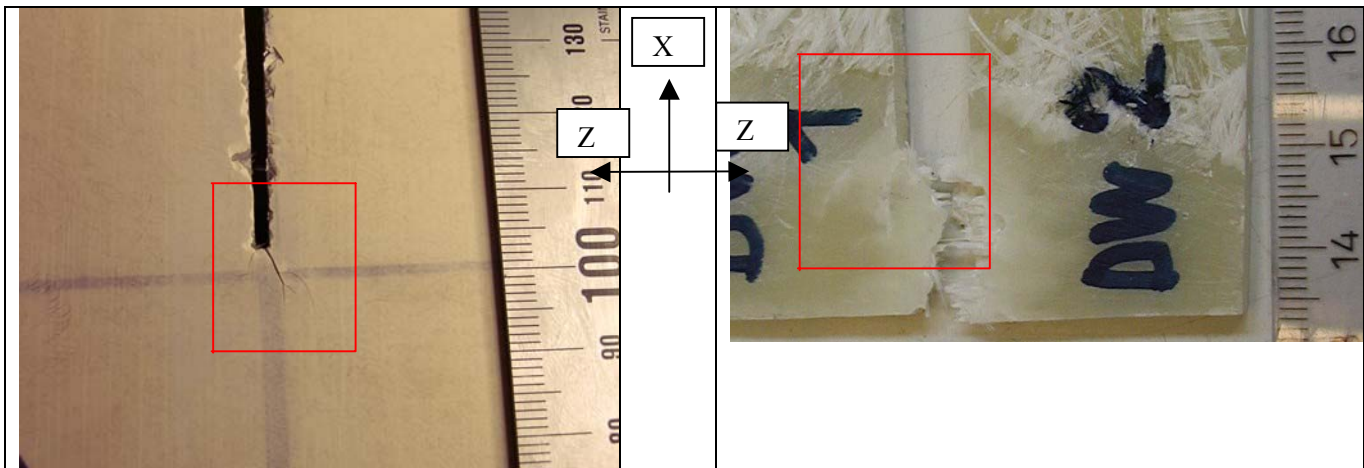


Figure 5-5. Crack after WING004, down-wind surface, and the internal side of the blade after sectioning. In the right hand photo it is visible that the crack propagates in terms of delamination, branching and crack bridging by fibres.

The NDT-inspections by ultrasonic scanning could not detect the damage in the early stages. However, after WING005 a crack extension could be identified by an increase in signal damping. The fact that the ultrasound scanning can detect the damage confirms that the internal damage is rather wide (each measurement point (pixel) represents an area of approximately 15 mm<sup>2</sup>).

Figure 5-6 shows the damage propagation as results of the ultrasonic inspection after WING001, and WING005 – WING008. The length of the damage propagation is found to be in reasonably good agreement with that observed visually from the surface.

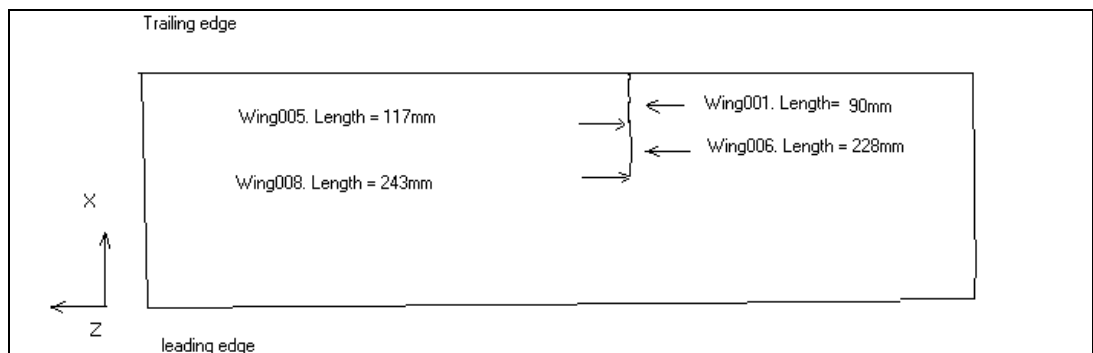
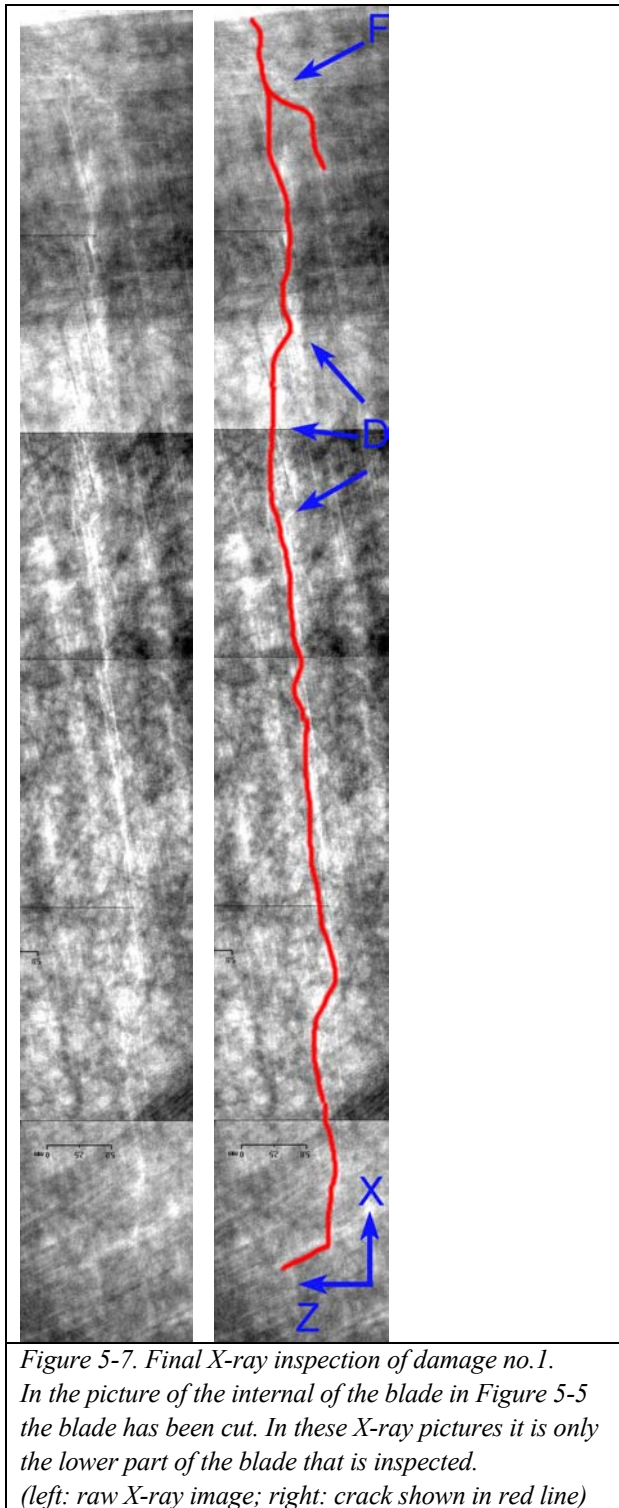


Figure 5-6. Damage propagation determined by ultrasonic inspection of blade after WING008, down-wind surface. The listed lengths represents the total length, i.e., initial notch length plus length of the propagation.



The X-ray inspection was useful for determining the laminate damage evolution after each loading. Figure 5-7 shows the final damage evolution. The zigzag crack path and crack deflection and branching is agreement with the visual damage (Figure 5-2).

In conclusion, for the laminate damage developed in connection with damage no. 1 there is a good agreement between the damage detected by acoustic emis-

sion, by X-ray inspection and the damage observed by visual inspection of the inside of the laminate after the test.

### 5.3 Damage No. 2, Failure in Joint in Trailing Edge

Strain gauges were mounted on the blade in the area of damage no. 2. The strain gauges were mounted in two rows parallel to the trailing edge on down-wind surface. Two optic fibre micro bending transducers were mounted in the trailing edge. The first transducer was lowered into the slot of the artificial damage and glued in. The other transducer was mounted in a plug in a hole drilled through the trailing edge joint Figure 5-8. The hole was drilled from the up-wind surface to the down-wind surface. The X-ray system was used to determine the positions of the transducers prior to the test, see Figure 5-9.

Figure 5-8. SG-position for damage no. 2 Down-wind. The red squared area is a GRP-plate used for mounting sensor no. 2, this plate is visible in the area of transducer no. 2 on the X-ray picture.

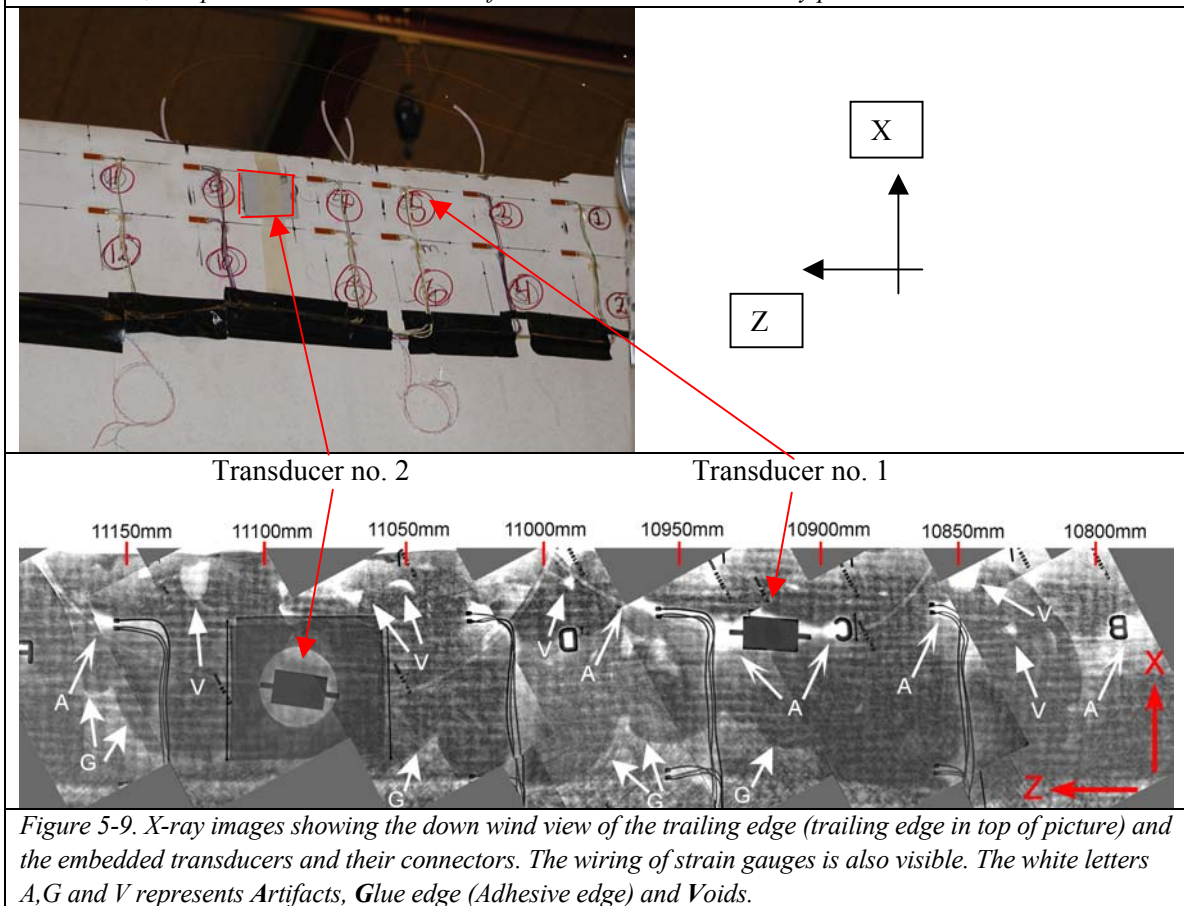


Figure 5-9. X-ray images showing the down wind view of the trailing edge (trailing edge in top of picture) and the embedded transducers and their connectors. The wiring of strain gauges is also visible. The white letters A, G and V represents Artifacts, Glue edge (Adhesive edge) and Voids.

The blade was loaded such that the damaged site was subject to compression. This caused buckling of the adhesive-free laminate, and subsequent failure of the adhesive joint. The test was carried out in 18 steps.

Test no. WING114, WING115 and WING118 were the tests with significant propagation in crack length. Test wing 115 showed an extension in crack length of size 58 mm in visible crack size. During WING115 the micro bending trans-

ducer showed a decrease in transmittance of magnitude 10 %. The decrease is caused by the crack growth.

The correlation between the acoustic emission and the micro bend transducer is showed in Figure 5-10. The fact that the fibre optics microbend displacement transducer shows a transmittance decrease before visible crack growth is detected, suggest that crack growth have started inside the adhesive joint (not at the rear edge).

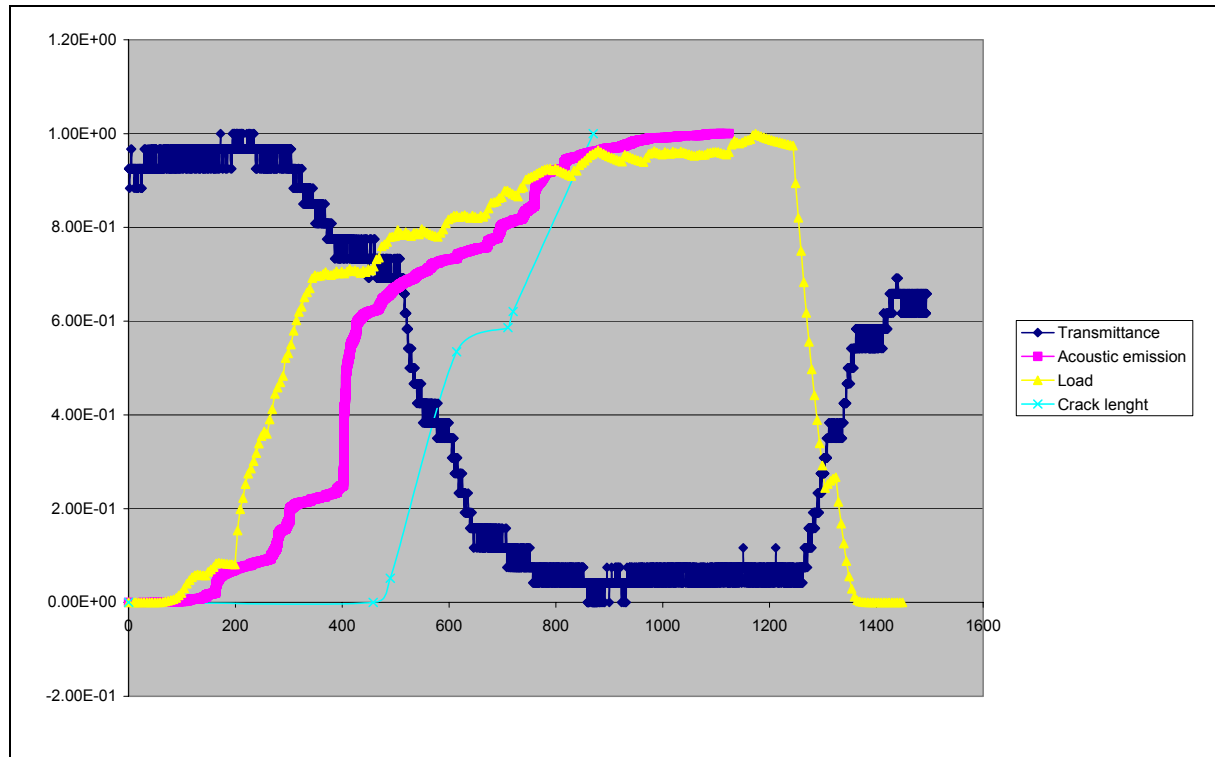
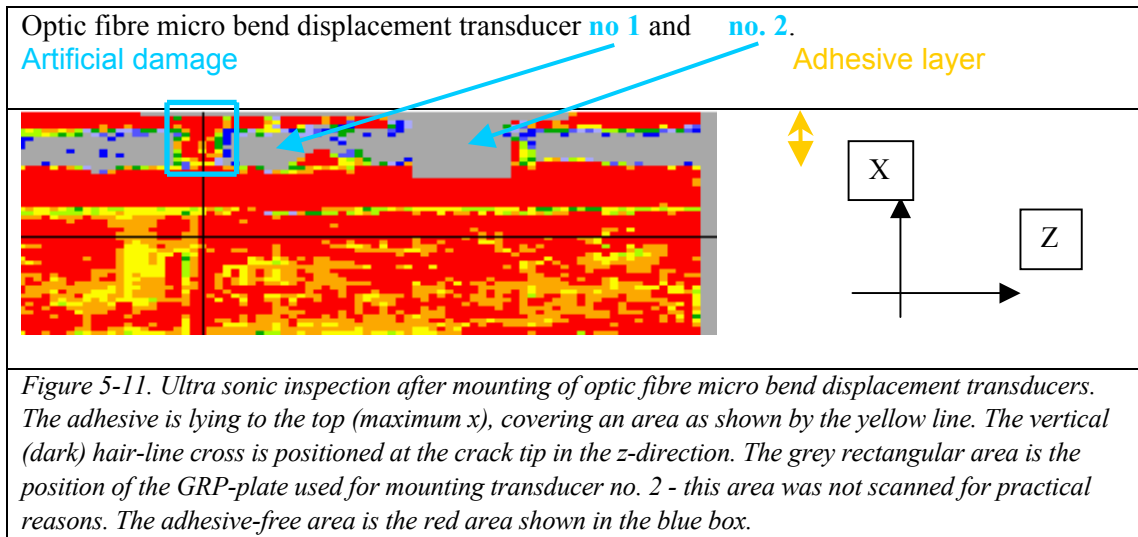


Figure 5-10. Optic fibre micro bend transducer measurements correlated with acoustic emission and applied force in WING 115. The transmittance decreased as the crack front reached the sensor (crack opening). During unloading the transmittance partly recovers, indication that the crack closes again.

The strain gauges measurements cannot be used to determine the crack propagation in the test of this damage, since buckling occurs before crack growth and causes significant non-linearity.

For the NDT-inspections the correlation to the visible crack size is acceptable. The visible size of crack length was app. 68 mm after test WING115 and the ultrasonic inspection determined the crack size to 98 mm. See Figure 5-11 and Figure 5-12 for typical NDT results. The rainbow colour code represents signal reflection - the red colour shows high reflection indicating a small thickness (e.g. thin laminate or adhesive failure), while the blue and grey colours represents low and no reflection, respectively, indicating a thick laminate or an adhesive joint without delamination.



Crack growth can be identified by changes in the reflection. When the crack at adhesive joint propagates, the delaminated area changes from a low reflection (blue/grey colours) to a high reflection (red), since the signal only has to go through a single laminate. During the test the artificial damage was elongated by use of a saw. Therefore, the crack appears to have propagated both towards left (the root end of the blade) and towards the two transducers; the latter is the true crack growth.

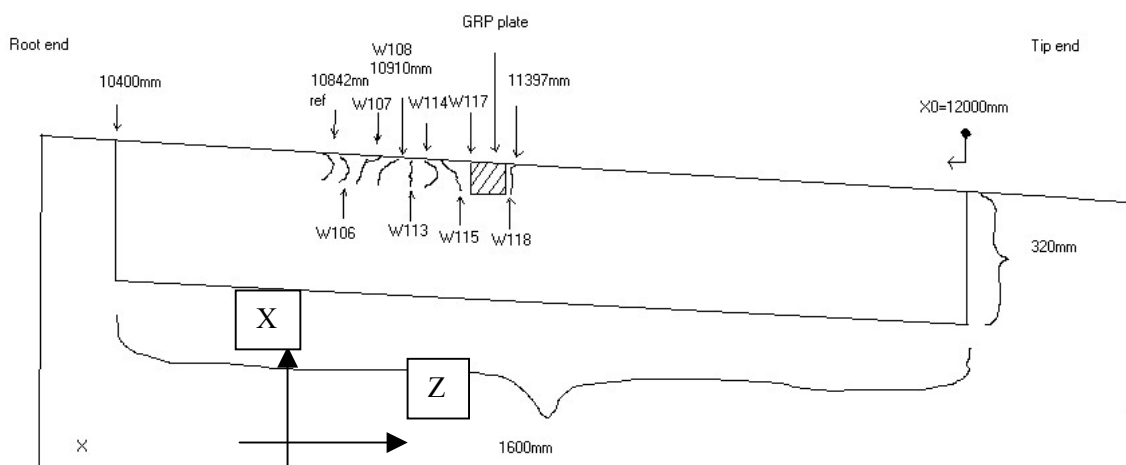
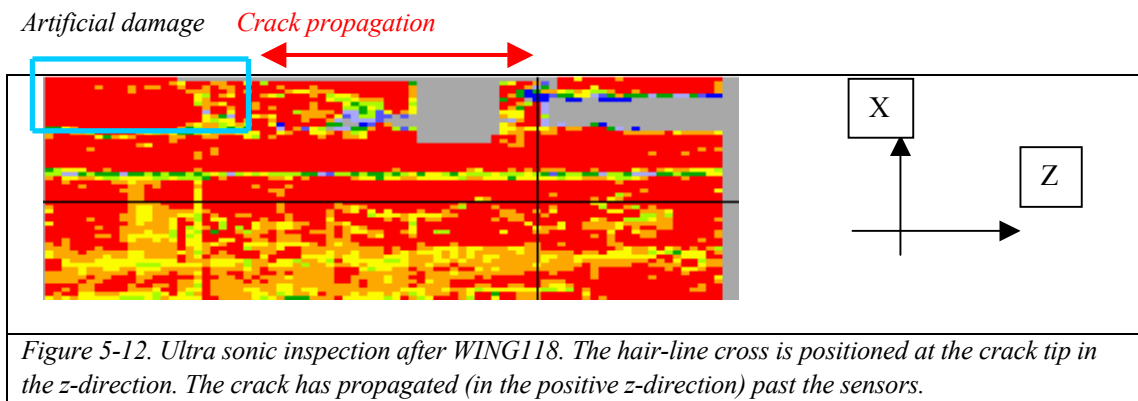


Figure 5-13. Crack propagation determined by the use of ultrasonic inspection of the blade between the tests.

## 5.4 Conclusive Remarks (Full Scale Test)

Strain gauges: By use of strain gauges it is possible to measure changes in strain distribution caused by propagating damages. The necessary number of gauges depends on the size of damage the system is monitoring.

Acoustic emission: The acoustic emission system is very capable of detecting even minor crack propagation. The position and severity of damage source events has been successfully determined using both zonal and linear time-of-flight localisation arrays.

The optic fibre micro-bend displacement transducer is capable of determining cracks in adhesive joints (and possible also delaminations). It is at least useable for determining crack sizes corresponding to the distance between each transducer. The transducer signal transmittance is gradually decreasing when the transducer is passed by the crack front and the crack advances. Potentially, the value of the crack opening may be used for estimation of a minimum crack extension, with a resolution better than the distance between the transducers. It is very important that the transducer remains attached to the separating surfaces because the crack is detected by the relative displacement.

Both the X-ray and the ultrasonic equipment are capable of locating the damage and determining the size of the damage. The ultrasonic system is well suited for determining the size and location of failure in the adhesive joint and most likely also delaminating failures. For the laminate damage (the notch in the trailing edge) the resolution of the ultrasonic system is too low to give an accurate position of the crack tip. For this damage type the X-ray technique proved to be very versatile. Used in combination, ultrasonic scanning and X-ray inspection are strong NDT-tool for damage detection and localisation in wind turbine blades.

In general, very satisfying agreement were found between the information on damage size and location by sensors, NDT-techniques and post-testing analysis.

## 6 Damage Detection by Modal Parameter Estimation

The goal of this work is to perform an investigation of the potential of *modal analysis* used for *detection* and *localisation* of damages in wind turbine blades. Such an investigation has successfully been conducted with the perspective of establishing a cheap, reliable and efficient remote sensing system. A detailed description of the investigation is reported in Annex F (Larsen et al., 2002).

The principle is based on the fact that damage growth will affect the structural stiffness and thus, in turn, appear as changes in the structural modal properties. The investigation has comprised analysis of possible *damage detection measures* as well as *estimation of modal shapes* - the latter with emphasis on output-only modal analysis being the method of commercial relevance.

## 6.1 Damage Detection Measures

The basic idea behind damage detection measures in the present context is to compare a reference mode shape (referring to the undamaged wind turbine blade) with the (analogous) mode shape reflecting the blade with some kind of damage imposed. The investigation of selected damage detection measures has comprised analysis of numerically determined mode shapes as well as mode shapes resulting from full-scale experimental tests.

Initially, various damage detection measures were investigated based on mode shapes obtained from a numerical study of a blade similar to the LM 19m blade. Reference mode shapes corresponding to an undamaged blade, as well as mode shapes associated with blades with a realistic structural damage imposed, were computed and subsequently analysed in the framework of the selected damage detection measures. The investigation has shown that it is indeed possible both to detect and locate even relative “small” damages with this technique.

Secondly, the damage detection measures were applied on mode shapes obtained from a laboratory full-scale modal analysis of a (shortened) LM 19m blade. The blade was exposed to cyclic loading until extensive failure of the blade occurred. The reference mode shapes were established (by means of conventional modal analysis) before the loading of the blade was initiated. Subsequently, a number of mode shape sets were determined at different stages in the structural degradation process. Also for the full-scale test, the investigation has shown that it is possible to detect and locate structural damages even with the relatively coarse spatial resolution of the mode shapes applied.

## 6.2 Output-only Modal Analysis

Conventional modal analysis is based on simultaneous recording of forces and structural response. This strategy is well suited for laboratory investigation of structural dynamic characteristics. However, for large engineering structures, exposed to natural loading in terms of e.g. wind loading or wave loading, it is usually not possible to record the excitation forces. Therefore, as the last step, the potential of output-only modal analysis (i.e., without knowledge of the load history) in the estimation of mode shapes has been investigated.

The investigation is based on aero-elastic simulations of the response of a blade exposed to stochastic loading caused by atmospheric turbulence. The result of the simulations, i.e. time-series of the accelerations at different locations on the blade, was subjected to output-only modal analysis, and this method proved to be an efficient tool in identifying the requested mode shapes - even mode shapes related to modal directions perpendicular to the dominating modal direction are satisfactorily resolved. The mode shapes referring to the undamaged as well as to the damaged blade have been identified. Localisation of the damages has subsequently been performed by a graphical comparison between the mode shapes related to the damaged and undamaged blade, respectively. This comparison is shown in Figure 6-1.



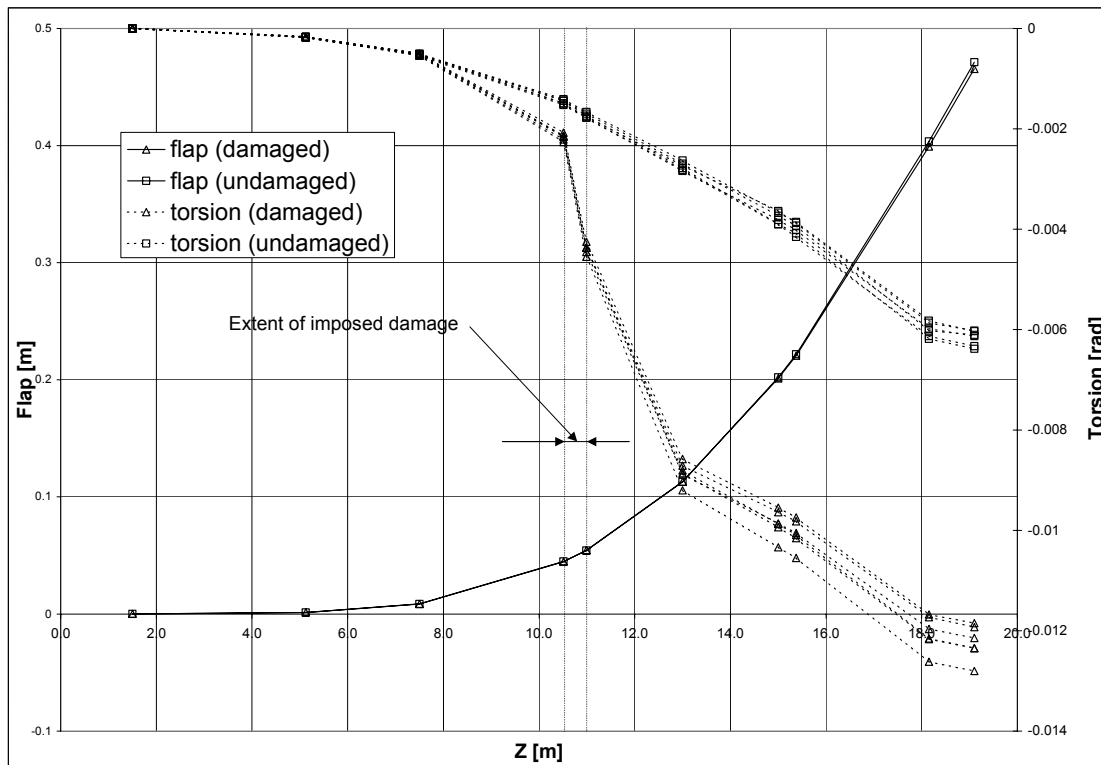


Figure 6-1. Flap and torsion component for the 1<sup>st</sup> flap mode for un-damaged and damaged blade.

Figure 6-1 shows the flap content (solid lines) and the torsion content (dashed lines) for the 1st flap mode identified by the output-only modal analysis method. The damage imposed to the (damaged) blade is a span-wise crack in the middle of the beam closest to the trailing edge between  $Z=10.5$  m and  $Z=11.0$  m. The results from 12 time series, each having a length of 10 minutes, are included in the figure (6 for the undamaged and 6 for the damaged blade). The flap content is almost identical for the damaged and the undamaged blade, but the torsion content clearly indicates the location of the imposed damage close to the middle section of the blade.

### 6.3 Summary of Findings

Basic requirements of a remote monitoring system to be of practical relevance is that it is robust, reliable, relatively cheap, and provide information that can be used for damage detection and localisation. The present method has that potential. It has been demonstrated that mode shapes can be resolved based on only stochastic structural response recordings, and that these mode shapes subsequently can be used to detect and locate possible structural damages. An example of the methodology has shown that even a structural damage, which is considered to be small, can be detected. Although, the principle is illustrated for wind turbine blades only, it is equally well applicable for detection of damage in other structural components of the wind turbine.

## 7 Conclusions

The major results of the present pre-project are summarised in this chapter.

- The most severe damage modes on modern wind turbine blades are failure of adhesive joints, delamination and failure of the load carrying laminates.
- Acoustic emission (general damage detection), embedded fibre optics displacement sensors (failure of adhesive joints) and inertial sensors (general damage detection) are all promising systems for structural health monitoring of wind turbine blades.

The *major economical* results are:

- The price of a structural health monitoring system of a price of 100 000 DKK (per turbine) results in a break-even time of about 3 years. For a price of 300 000 DKK the break-even time is about 8 years. The cost/benefit analysis has large uncertainties; for instance, the success of the sensor system depends strongly on its capability to distinguish between damage that requires repair and damage that does not.
- For acoustic emission sensors resonant at 150 kHz in a zonal source location array, a spacing of 2.0 m is anticipated. Thus, for a 40 m long wind turbine blade, the number of acoustic emission sensors required is about 20, giving an estimated system price (turbine with three blades) of 260 000 DKK.
- For the fibre optics displacement sensor, the estimated spacing required is 1 m, and the number of sensors to cover the adhesive joint at the trailing edge of a 40 m long blade is about 40, giving a system price of 135 000 DKK per turbine.
- For a system based on damage detection by inertial sensors the number of sensors required is about 5 per blade, giving an estimated cost of about 102 000 DKK per turbine.

The estimated sensor system prices, given above, are subjected to large uncertainties; such as trying to predict what the prices are of computers and sensor hardware in five years. In contrast, the technical results (given below) are subjected to much less uncertainty.

The *main technical results* of tests of laboratory specimens and full-scale wing turbine blade test with artificial damages are:

- Growth of damage in wind turbine blades produces effects that can be detected with the monitoring sensors used in this project. Therefore, the use of a structural health monitoring sensors greatly improves the value of full-scale testing of wind turbine blades.
- Acoustic emission sensors have a very high sensitivity; all relevant damage types can be detected before they become visible (< 1 cm); the damage size can be determined and they can be located very precisely. The method has the potential for distinguishing between the damage types. The broad-band sensors used have a detection range (lead break) of 0.3-0.6 m; a resonant sensor has a detection range of about 0.7-1.0 m.
- The fibre optics displacement transducer, developed in the project for detecting adhesive failure, has a high sensitivity; crack openings ~0.01 mm are easily detected. A sensor can detect cracking in the range of ~ 1 cm to the sensor; the crack size can be determined by the number of sensors it activates; i.e. the spatial resolution is equal to the distance between the sensors.
- The approach for detecting damage by inertia sensors (i.e., based on analysis of modal shapes) is conceptually born with a build-in filter excluding dam-

ages not giving rise to significant modifications of the stiffness properties (and thus in turn in the mode shapes). At least damages with an extend of 0.5 m, most likely smaller, can be detected, and it is expected that relevant damage types can be detected and localised;

Concerning NDT-techniques, the main results are:

- Real-time X-ray inspection is a viable, accurate and effective technique for detection of laminate damage.
- Ultrasound is a powerful tool for the detection of internal damages that create new, flat surfaces such as adhesive failure and delamination.

In conclusion, results of this pre-project suggest that the concept of using sensors for structural health monitoring systems on wing turbine blades is both economically attractive and technologically possible. However, a future challenge is to develop the approaches. The establishment of relationships between damage types, sensor signals and residual life of a wind turbine blade seems to be possible. The use of NDT-techniques greatly improves the verification of the technical capability of the sensors.

## 8 Perspective

### 8.1 The Vision

Since access to off shore wind turbines is costly, there is a desire to limit the need for manual inspection of the wind turbine. This concerns all important components of the turbine (for instance, oil temperature, wind speed, structural loads on tower and blades as well as vibrations of bearings and gearbox). Therefore, general surveillance systems are being developed outside this project. These *general systems* (e.g. Cleverfarm) take care of information handling, and transmittance of warnings and data to remote supervisor, see Figure 8-1.

As a consequence, within the problem area of this project, the focus of future research projects should be on the key parts that are necessary to master structural health monitoring of wind turbine blades. That is to create knowledge that enables the determination of the seriousness of the detected damage, i.e. the knowledge needed for the determination of the residual life of a wind turbine blade with an identified damage type, size and location.

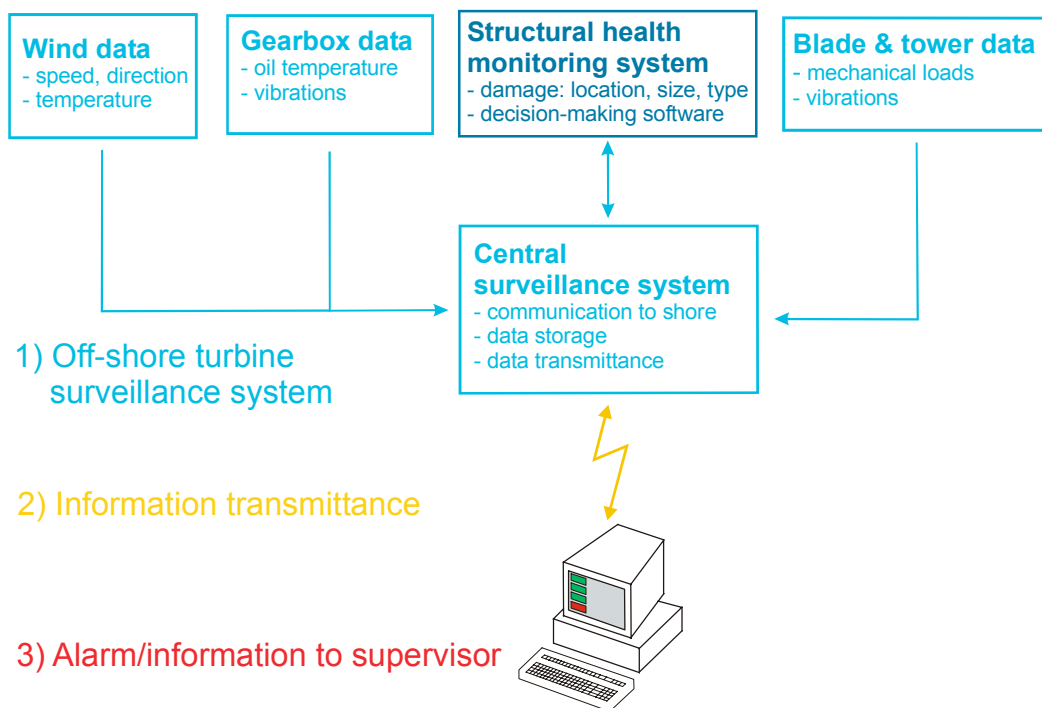


Figure 8-1. The concept of remote surveillance. Illustration of how a structural health monitoring system for damage detection in wind turbine blades may be part of a general purpose turbine surveillance system, that transmits information to and from a supervisor at land.

## 8.2 Research Needs

The results obtained in this project prove the potential for use of acoustic emission, inertia-sensors and fibre optics as sensors in future structural health monitoring systems for wind turbine blades. We think that it is best to proceed with the following points:

- 1) Establishment of better criteria for the *minimum damage size* that sensors must detect (for each damage type)
- 2) Establishment of knowledge relating damage *types* and sensor signals
- 3) To *verify the methods* on a full scale wind turbine blade during normal operation
- 4) Regular use of sensors during full scale testing

Concerning the first point, we have in this project defined some criteria for the damage sizes that the sensors must be able to detect. These criteria are chosen from the best of our knowledge, but are subjected to great uncertainties. At the present time there is simply too little knowledge about the progression of damage to define reliable criteria for the maximum allowable damage sizes. Until such knowledge has been established it is far too premature to make any conclusions regarding which sensor types are preferable (the number of sensors required depends strongly on the spatial range of the sensors and the maximum allowable un-detected damage size). The criteria regarding maximum allowable damage size should be based upon rigorous models of damage propagation (e.g. FE models of blades with different damages) or experimental investigations, with the premise that no significant damage growth takes place under extreme

loads and the growth rate under cyclic loading is very low. Such criteria may be different for different blade constructions, and will most likely be different for different positions in the blade. For some damage types (e.g. laminate failure involving fibre failure) the maximum allowable damage size is expected to be rather small; for other damage types (e.g. failure of adhesive joints) much larger sizes may be allowed. Practical considerations are also important. Smaller damages are easier to repair than larger ones. If repair can be done on the blade without dismounting the blade from the turbine, costs are significantly reduced. Also, from a point of view of planning repairs on off-shore wind turbines, it is preferable to receive early warnings.

The second point, relating sensor signals and damage types are only of relevance for the approaches that can detect multiple damage types (acoustic emission and modal analysis) - the fibre optics displacements transducer is designed for use only in adhesive joints. For acoustic emission, studies in the laboratory tests should cover the evolution of damage, from undamaged state to specimen failure, will be detected by sensor and by NDT-methods. Damage type and evolution will be related to the characteristics of sensor signals and NDT-data. Sensor signal "fingerprints" of different failure modes and types can be identified in this manner, i.e. for all relevant failure modes. For modal analysis further work is required to fine tune the output-only modal analysis to stochastic processes of the type experienced by a rotating wind turbine in an atmospheric turbulence field, including simultaneous periodic deterministic excitation originating from mean wind shear and tower shadow. It may also be investigated if it is possible to extract supplementing relevant information from modal damping characteristics.

The third point concerns the use of sensors in a wind turbine to investigate the stability over time of the sensors. It must be investigated whether sensors can operate satisfactory for a long time under real working conditions. Surface mounted sensors must not peel off during cyclic loading; fibre optics transducers that are embedded in adhesive joints should not act as crack starters themselves. Some of these potential problems may be investigated by laboratory experiments on smaller specimens subjected to cyclic loading.

The fourth point concerns the use of sensors during full scale testing. First, some blade should be subjected to very high loads (cyclic or extreme loads) to ensure that damage develops. The progression of damage can be promoted by built-in artificial damage. The purpose would be that the sensors should be able to detect the damage location and damage type. The use of NDT-techniques and post-testing investigations should be used for verification.

The next logical step is to use the sensors as a standard tool in the full scale testing and approval of new wind turbine blades. Identification of possible damage evolution in the blade during prototype testing is very useful for the blade manufacturer - possible weak point in the design or manufacture may be determined and corrected before the blade is put into mass-production.

### **8.3 Further Development and System Application**

The final points to address before sensors can be used in blades on off-shore wind turbines parks are:

- 5) Software development for automatic determination of damage states (data analysis)
- 6) Development of systems for transmittance of information to land (remote surveillance)

The last two points are regarded as specific system developments (rather than general research) and should be done by companies, and as such is not part of the research programme outlined here. Also, it should be noted that the transmittance of signals from the wind turbine to land could be done by the use of general purpose systems, such as the ones that are already being developed. Therefore, this point also falls outside the scope of the proposed research programme.

## **References**

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Title and authors

Fundamentals for Remote Structural Health Monitoring of Wind Turbines Blades – a Preproject

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Abstract (max. 2000 characters)

This summary-report describes the results of a pre-project that has the aim of establishing the basic technical knowledge to evaluate whether remote surveillance of the rotor blades of large off-shore wind turbines has technical and economical potential. A cost-benefit analysis was developed, showing that it is economically attractive to use sensors embedded in the blade. Specific technical requirements were defined for the sensors capability to detect the most important damage types in wind turbine blades. Three different sensor types were selected for use in laboratory experiments and full-scale tests of a wind turbine blade developing damage: 1) detection of stress wave emission by acoustic emission, 2) measurement of modal shape changes by accelerometers and 3) measurement of crack opening of adhesive joint by a fibre optics micro-bend displacement transducer that was developed in the project. All types of sensor approaches were found to work satisfactory. The techniques were found to complement each other: Acoustic emission has the capability of detecting very small damages and can be used for locating the spatial position and size of evolving damages. The fibre optics displacement transducer was found to work well for detecting adhesive failure. Modelling work shows that damage in a wind turbine blade causes a significant change in the modal shape when the damage is in the order of 0.5-1 m. Rough estimates of the prices of complete sensor systems were made. The system based on acoustic emission was the most expensive and the one based on accelerometers was the cheapest. NDT methods (ultrasound scanning and X-ray inspection) were found to be useful for verification of hidden damage. Details of the work are described in annexes.

Descriptors INIS/EDB

ACCELEROMETERS; ACOUSTIC EMISSION TESTING; COST BENEFIT ANALYSIS; DAMAGE; FIBER OPTICS; INDUSTRIAL RADIOGRAPHY; REMOTE SENSING; TRANSDUCERS; TURBINE BLADES; ULTRASONIC TESTING; WIND TURBINES





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