Bladena

BLADE ENABLER

Regain of operational life time of installed WTG blades with structural defects

EUDP project 64012-0128 – End of project report

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1 Introduction

This report is the end of project reporting for the project titled “Regain of operational life time of installed WTG blades with structural defects”, the project was supported by the Danish Energy Agency EUDP program “Development and Demonstration” EUDP project file number 64012-0128 also called “Bondline Project”. The project was a two-year project which started the 1st of July 2012 and finished on scheduled the 30th of June 2014. The total budget of the project was 9,5 mio. Dkr and 50% were supported by the EUDP program. The project was carried in collaboration with a strong group of industrial and university partners. The partners of the project are:

- Bladena APS
- DTU - Technical University of Denmark
- AAU - Aalborg University
- Vattenfall
- DONG Energy
- Total Wind Blades

The overall scope of this project was to develop, prepare for market and demonstrate an applicable method for regaining operational life of installed wind turbine blades with structural defects based on Bladena’s patented technology D-String® for limiting deformations in panels. The D-String® retrofit solution was developed to a product ready for implementation and its effectiveness was demonstrated on an operating wind turbine. It was demonstrated that the solution was able to remove the root cause for bond line defects in the maximum chord area of blades, which are one of the dominating defects on blades.

1.1 Motivation

Wind energy is developing rapidly towards being a major contributor to the overall power supplies, and is simultaneously evolving into a significant political/financial tool in the effort to ensure much needed sustainable and job rich economic growth. The business is being professionalised with requirements of profitability and bankability. To ensure the continued success of wind energy as an efficient energy supplier and an effective tool to meet political objectives, the cost-effectiveness and competitiveness towards other power producing technologies must be improved. A number of reliability issues continues to be unsolved and hence still negatively and significantly impact the cost of energy produced on wind turbines. A particular issue is the fatigue life of bond lines on blades. Due to deformation in the trailing edge panels of the blade, the peel stresses on the bond lines holding the two aerodynamic shells of the traditional blade together outweigh the peel strength of the bond lines, illustrated in Figure 1. The issue of deformations in the trailing edge panels has been investigated and documented by several experiments test performed at DTU Risø wind turbine blade test facility [1].

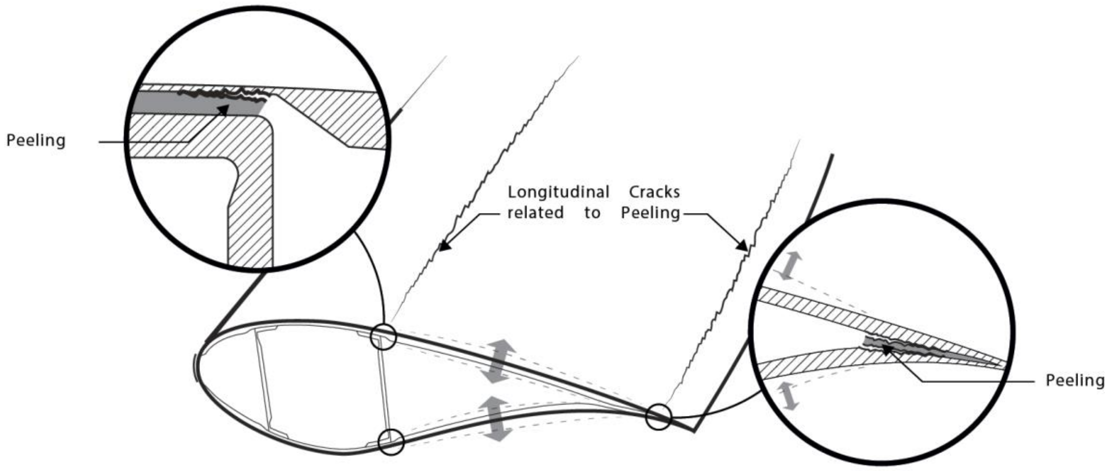


Figure 1. Sketch showing the peeling in TE area of blades

Typical damage found on blades in operation due to peeling is trailing edge cracks, shown in Figure 2. This issue requires continuously and costly repairs and often pre-mature replacement of the blades. As the size of the turbines grows, this issue grows with it. Regardless of blade size, the peel strength of bond line remains the same, while the peel stress increases significantly when the blade length increase. Today, this is a major problem on many turbines with blades length on approx. 30- 40 meters and above, it will be a significant cost driver on the current turbines and the future very large and highly loaded offshore turbines.

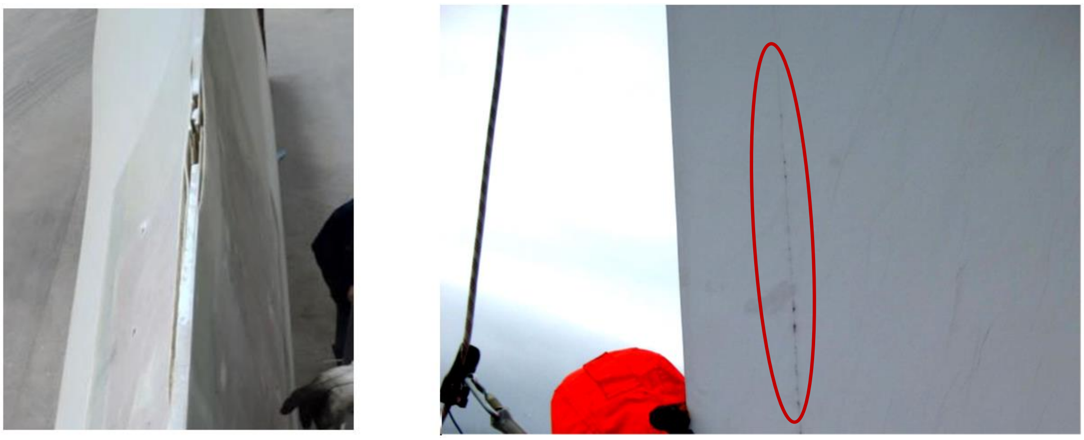


Figure 2. : a. Trailing edge bondline crack. b. Longitudinal crack near the trailing edge discovered by periodical inspection

The issue must thus be solved. A relevant and innovative technology for permanently addressing this bond line issue is Bladena's patented "wire between TE panels", which will be mounted at the back end panels on the blade, and as such limit the outgoing deformation of the panels. The outgoing deformation is the deformation which induces the peeling stress in the bond lines. Unlike the current repair solutions, the wire address the root cause by minimising the peeling stresses, and by that prolongs the fatigue life of the bond lines significantly. The effect of this will be increased blade reliability and significantly reduced operational cost of the turbine.

1.2 Description of project

The project was organized in 5 different work packages; the scope of each of the work packages is briefly described in the following. Each of the sections in the report presents an extensive summary of the work performed in each of the work packages.

WP1 – Risk and cost analysis: In this task, a generic model will be developed for modelling life cycle costs, i.e. initial costs as well as costs related to inspections, repairs and possible failures. A procedure will be developed for reliability analysis where physical, statistical, measurement and model uncertainties are integrated. Especially integration of statistical information from full-scale tests, sub-component tests and numerical simulations will be integrated based on a Bayesian statistical approach.

WP2 – Damage assessment and measurement techniques: This work package co-ordinates the application of various inspection and monitoring technologies to provide adequate detail regarding the structural response and damage condition around the trailing edge panels during operation, and when undergoing dynamic fatigue sub-component test loading. This work package will also deliver a structural assessment of the wind turbine blades taken out of service and made available to the consortium.

WP3 – Field testing: This work package covers tests of a Vestas 2.0 MW wind turbine owned by Vattenfall. The full-scale tests performed in this project will include comprehensive monitoring technology to measure the effect of the D-String® reinforcement solution.

WP4 – Sub-component fatigue testing and analysis: The purpose of this work package is to perform advanced instrumented fatigue testing on blade components in the DTU Structural Lab facilities, extracted from damaged as well as intact blades, in order to be able to both evaluate the residual lifetime of the bond lines in trailing edge blade components without retrofit reinforcements as well as for trailing edge components retrofitted with the new retrofit concept. The fatigue component testing entails a development and manufacturing of a suitable test rig with multi-axial loading capabilities, as well as analysis and measurements (from WP 3) of the load configurations to be applied in the component tests. The test rig will be used to measure residual lifetime in terms of trailing edge opening vs. applied cycles at pre-defined positions along the turbine blade. Additionally, similar measurements will be carried out for retrofitted trailing edge component specimens to verify the effect on the residual lifetime.

WP5 – Product development of retrofit reinforcement: The purpose of this work package is to develop a practical approach on how to implement the D-String® reinforcement into a blade on an operating wind turbine. The work packages also includes an extensive testing program in order to verify that the D-String® product do not negatively affect the blade structure.

2 WP 1 – Risk and cost analysis

WP responsible: John D. Sørensen - Aalborg University

2.1 Objective and scope

The main objective of this work package is development of a generic life cycle cost model, with special focus on costs related to inspections, maintenance, repairs and possible failures of wind tur-bine blades incl. bondline failures / defects. The cost model is developed to be able to estimate the expected total costs in the remaining design working life.

Further, the objective is to develop / describe methods and techniques to be used to estimate the re-liability and the probability of failure, incl. models for uncertainties using information from full-scale tests, sub-component tests and numerical simulations, and failure modes based on generic damage models for bondline failures. This is to be included in a generic reliability- and risk-based procedure for cost-optimal planning of inspections and maintenance of wind turbine blades.

2.2 Theoretical basis

This section briefly describes the theoretical basis for the reliability- and risk-based procedures for cost-optimal planning of inspections and maintenance. In the following section applications of the theoretical basis are described. More details can be found in:

- Sørensen, J.D. & H.S. Toft (2013) Modeling of uncertainties for wind turbine blade design. Proc. ICOSSAR2013, New York.
- Florian, M. & J.D. Sørensen (2014) Wind turbine blade life-time assessment model for preven-tive planning of operation and maintenance. Proc. ASRANET 2014.
- Sørensen, J.D. (2014) Bondline: Cost, Inspection & Maintenance planning for wind turbine blades. Report, AAU, June 2014.

To obtain high availability and efficiency, wind turbine blades must be inspected, cleaned or repaired if needed. This requires knowledge, expertise and special equipment together with highly trained technicians. Access to the blades needs special tools and technicians using e.g. cranes or access by ropes, and can be quite costly. Further, repair of polyester and prepreg / epoxy wind turbine blades require highly experienced technicians. For offshore wind turbines access by boats and/or helicopter require god weather conditions which for some locations complicates the operation & maintenance and can imply high additional costs.

Blade maintenance / service include among others:

- Cleaning the leading edge of the blade.
- Repair structural and surface damages that are on the blade
- Apply a leading edge protective coating, e.g. tape

Maintenance strategies can generally be characterized as:

- Corrective maintenance where a failure / defect is repaired as soon as possible after the failure is detected.
- Preventive maintenance where maintenance is performed before a failure has occurred. Preventive maintenance can be performed following different schemes:
    - Time-tabled where inspections, maintenance and possible repairs follows a prede-fined time schedule, e.g. following service visits each 3, 6 or 12 months.
    - Condition-based where maintenance and possible repairs is decided on the basis of predefined limits.
    - Risk-based where the cost-optimal inspection and maintenance plan for the remain-ing lifetime is determined using principles from risk analysis and Bayesian decision theory.

These strategies can be applied to wind turbine blades and has to be combined with planning of in-spections / monitoring in order to obtain information / knowledge on the condition of the blades. This information can be related to both direct measures and indirect measures (indicators) of de-fects, cracks etc. in the blades.

Planning of operation and maintenance in general for wind turbines is a research area with many ongoing research projects e.g.: NORCOWE (2009), NOWITECH (2009), LEANWIND (2013) and FLOW, Asgarpour (2014). Research results and recommendations for practical applications can be found in e.g. Besnard (2013), Nielsen (2013), Nilsson (2009) and Shafiee et al. (2013).

The preventive maintenance strategies are often used in combination with information from Condi-tion Based Maintenance (CBM) techniques where continuous monitoring and / or inspection tech-niques are used to detect possible faults early, and to decide on necessary maintenance tasks before failure. This involves collecting, analysis and interpretation of data and decisions on optimal maintenance actions and can be achieved using condition monitoring systems. CBM aims at mini-mizing the costs of maintenance.

In Risk-based Maintenance Planning (RMP) probability of failures and failure rates are combined with the consequences (in Euros, DKK,…) to obtain a risk based measure to be used for decision making. In a risk-based approach future inspection and monitoring can be accounted for if a deci-sion rule dependent on the observations (future and unknown) is established for future inspections, maintenance and repairs.

For cost modelling blade damages can generally be categorized into two types:

- Minor damage, which only causes a loss in wind capture without resulting in stop of the tur-bine
- Major (catastrophic) damage, which stops the wind turbine and can only be corrected by re-placement / major repair

An optimization model to derive an optimal (preventive) maintenance strategy should be formulated such that the expected total life cycle costs are minimized taking into account unknown future (sto-chastic) weather conditions and (partly) random occurrence of defects, damages, etc.

The blades usually have an expected lifetime of 20-25 years. However, in offshore wind farms, the lifetime of a blade is often significantly shorter than the expected lifetime. The reason is that the blades are “stressed” in a harsh maritime environment and extreme weather conditions and are ex-posed to different types of damages, such as wear, fatigue, deterioration, crack, corrosion, and ero-sion; as mentioned above. In the following more detailed descriptions on maintenance strategies are presented, based on Nielsen (2013).

Unplanned (corrective) maintenance is usually performed when failure occurs, even in small com-ponents. The direct corrective maintenance costs are related to spare parts, technicians, and vessels. For failures of larger components, larger vessels such as crane ships or jack-up vessels can be nec-essary, and these are typically expensive. Failures generally imply turbines to be shut down until they are repaired, resulting in additional costs due to lost production. This cost is increased for wind farms located far from the shore in harsh environment. The maintenance costs can be reduced by increased maintainability, accessibility and reliability. However, e.g. increased reliability may imply more expensive blades implying that a cost optimal decision has to be made on the optimal reliability level. Figure 3 shows typical failure rates for wind turbine components. For blades the annual failure rates are seen to be 0.02 and 0.09 for major and minor failures, respectively.

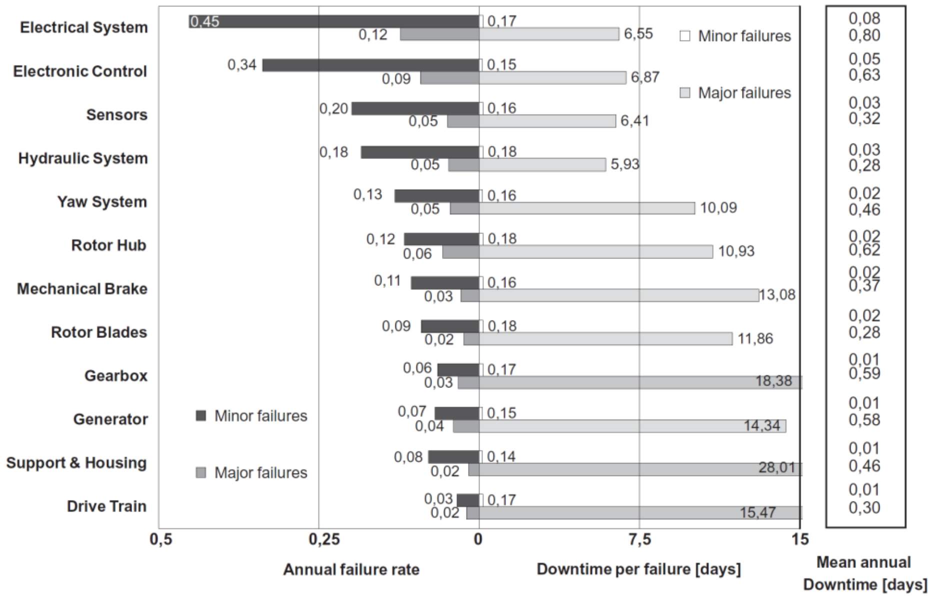


Figure 3. Failure statistics Faulstich et.al (2011).

Preventive maintenance can be used for deteriorating components such as blades with damage in-creasing with time. Figure 4 illustrates how to obtain the optimal level of maintenance minimizing the total lifetime costs to maintenance and possible failure.

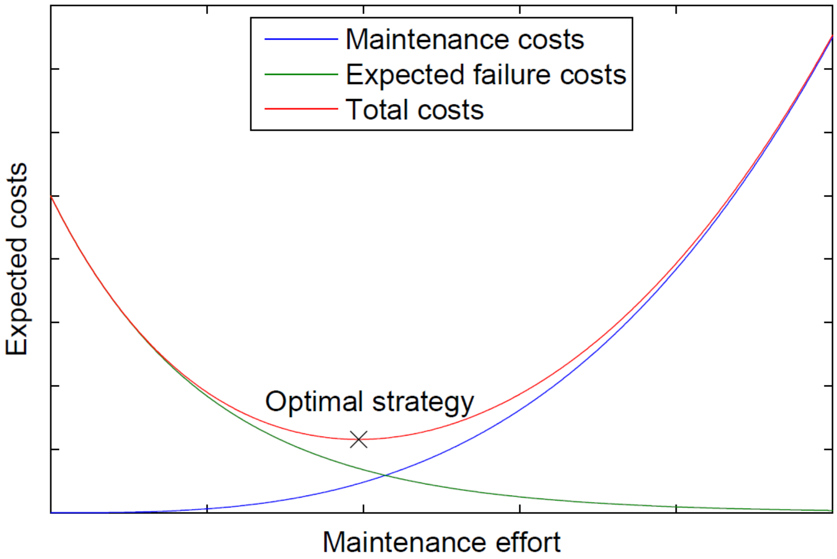


Figure 4. Optimal maintenance effort – from Nielsen (2013).

To estimate costs for **corrective maintenance** it is necessary to have information about the failure rate and the expected costs can be estimated, typically using Monte Carlo simulation.

An Excel based O&M tool has been developed by the ECN, see Rademakers et al. (2003). The ex-pected costs to corrective maintenance are estimated based on failure rates and expected failure costs for each failure type. To estimate the costs, the expected waiting times for weather windows of given lengths are needed for each vessel type. These are found based on the processing of time series of significant wave heights and mean wind speeds. The mean waiting time is found for a number of weather window lengths. As input, the program needs the overall failure rate for each component, division into failure types with matching maintenance classes with specified duration, weather limits and costs.

Other simulation based tools for assessing the costs of corrective maintenance for offshore wind farms are:

- CONTOFAX from Delft University of Technology, van Bussel & Bierbooms (2003)
- O2M from Garrad Hassan, Philips et al. (2006)
- MWCOST based on SLOOP from BMT, Stratford (2007)
- OMCE from ECN, Rademakers et al. (2008)
- NOWIcob, Hofmann et al. (2011)

In **preventive maintenance** decisions are made using information from inspections or condition monitoring, see more detailed descriptions in Sørensen (2014). A general framework for formulation of the life-cycle approach for planning preventive maintenance of wind turbine blades can e.g. be found in (JCSS 2008) with procedures based on pre-posterior Bayesian decision theory, see e.g. Raiffa and Schlaifer (1968) and Benjamin and Cornell (1970), see also Sørensen (2014). The risk-based approach can be used for operation and maintenance planning related to different failure & error types incl. rotor blades. Both a component and a system approach can be applied.

Decisions related to operation and maintenance can be related to different time scales:

- short (minutes) for decision related to e.g. parking the wind turbine,
- medium (days) for e.g. decisions on when to start offshore maintenance / repair actions depend-ing on e.g. weather forecasts, or
- long (months / years) for e.g. preventive maintenance and service / inspection / monitoring planning for blades.

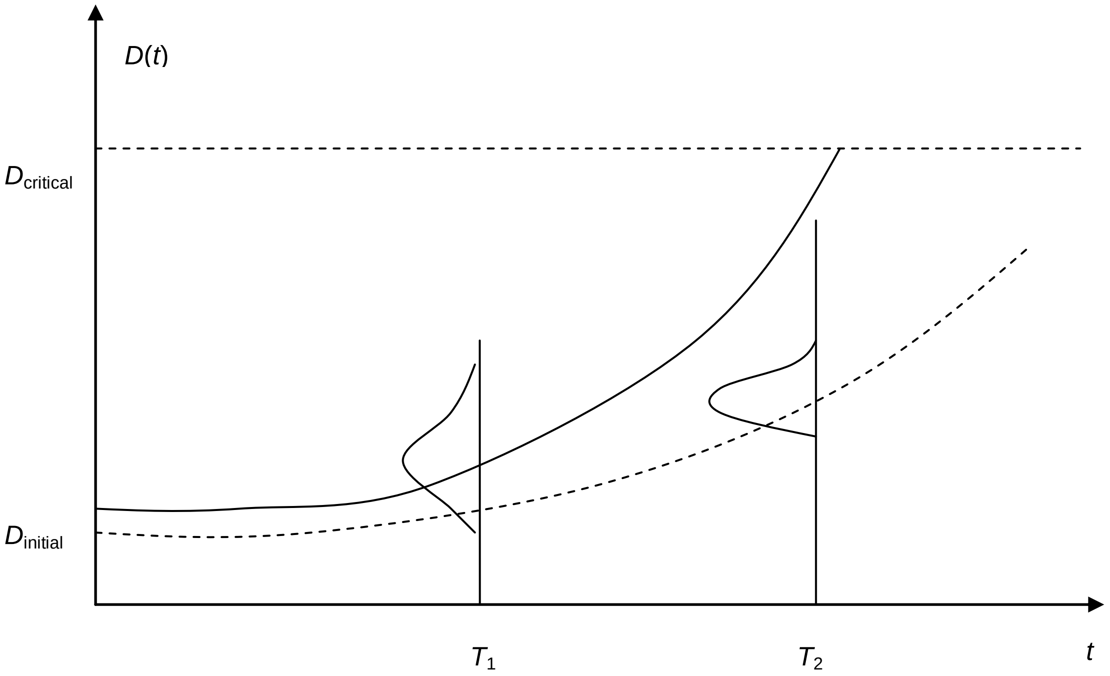


Figure 5. Damage model and updating by inspection at time T_1.

Deterioration mechanisms such as fatigue, corrosion, wear and erosion of blades are associated with significant uncertainty. Observations of the degree of damage D(t) can increase the reliability of predictions using Bayesian statistical techniques as illustrated in Figure 5. The observations could be from direct inspection results, but also indirectly from e.g. from Structural Health Monitoring. Gen-erally an inspection at time T_1 and associated maintenance / repair will decrease the uncertainty and both the standard deviation and the expected mean damage level at time T_2 will be smaller since most realizations with large damage level at time T_1 can be expected to be maintained / repaired.

It is important to note that preventive maintenance incl. risk-based methods require that a damage model is available.

When inspection planning for wind turbine blades is considered, it is important to take uncertainties into consideration. It is also important to realize that the decisions of maintenance / repair is strongly influenced by the reliability of the inspections, i.e. their ability to detect and size degradation / damage. The reliability of inspections themselves may be subject to significant uncertainty and this must also be taken into account in the planning of inspections, e.g. by using Probability Of Detection (POD) curves.

The decision problem of identifying the cost optimal inspection & maintenance plan may be solved within the framework of pre-posterior analysis from the classical Bayesian decision theory see e.g. Raiffa and Schlaifer (1968) and Benjamin and Cornell (1970), see Sørensen (2014). In the general case the parameters defining a monitoring / inspection & maintenance plan are the number of in-spections / services *N* in the service life T_L , the times of the inspections / services and possible re-pair/maintenance $\boldsymbol{T} = (T_1, T_2, \dots T_N)$, the monitoring / inspection methods (qualities) $\boldsymbol{q} = (q_1, q_2, \dots q_N)$ and the possible repair / maintenance actions which are modeled by the decision rule *d*. These inspection parameters are written as $\boldsymbol{e} = (N, \boldsymbol{T}, \boldsymbol{q})$.

The outcome of inspections (typically a damage level, e.g. a crack size, the extent of corrosion, wear, …) is modeled by a random variable since it is unknown at the time of decision making. A decision rule d(S) is then applied to the outcome of the inspection to decide which repair / maintenance should be performed. The different uncertain parameters (stochastic variables) modeling the state of nature such as load variables and material characteristics are collected in **X**.

If the total expected costs are divided into fabrication, inspection, repair, maintenance, strengthen-ing and failure costs the optimal decision is obtained as the solution (**e,**d) that maximize the total expected benefits:

$$\max_{\mathbf{e},d} \quad \mathrm{W}(\mathbf{e},d) = B(\mathbf{e},d) - C_I(\mathbf{e},d) - C_{OM}(\mathbf{e},d) - C_F(\mathbf{e},d)$$

where

W	total expected capitalized benefits minus costs in the service life time
B	expected benefits
C_I	initial costs
C_{OM}	expected costs to operation and maintenance, incl. inspection / service costs (labour, transport, … costs)
C_F	expected costs of possible collapse (major failures)

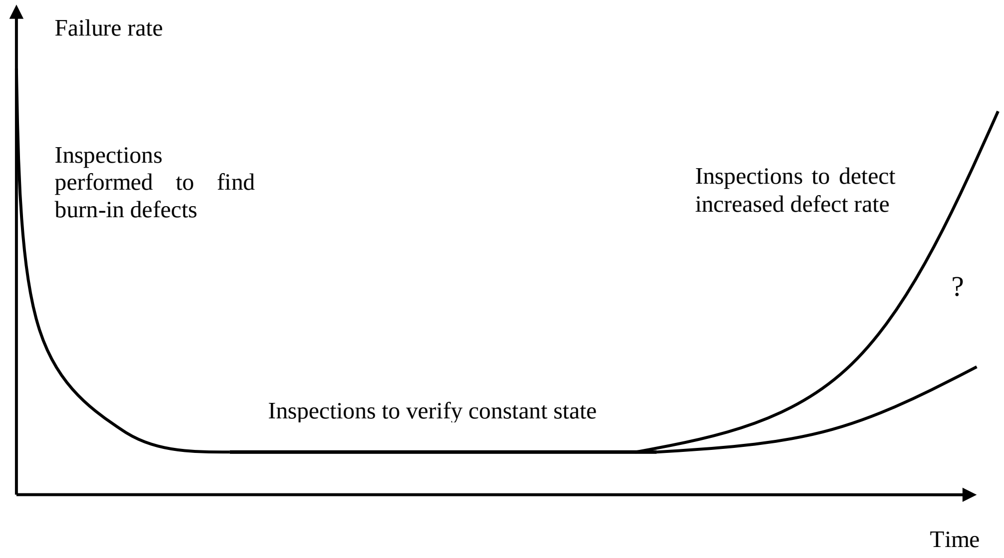


Figure 6. Bath-tub model for lifetime failure rate.

For many wind turbine components incl. blades subject to degradation / damage accumulation the bath-tub model in Figure 6 can be used to illustrate the development of the failure rate during the lifetime. Initially a high failure rate can in some cases be expected due to fabrication / burn-in defects. Next, a period with a 'normal' constant failure / defect rate will take place. Corrective maintenance can be performed in this period. At the end of the lifetime of the component the failure / defect rate can be expected to increase. If the failure rate increases strongly then preventive maintenance should be performed. If the failure rate is moderately increasing deterioration / damage can be observed before failure, and condition-based control & risk based maintenance should be performed and planned using the principles described above for risk-based inspection & maintenance/repair planning.

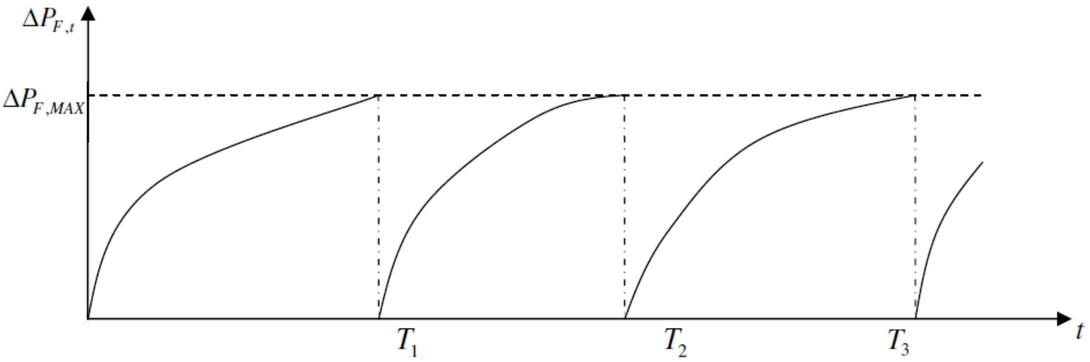


Figure 7. Illustration of inspection plan where inspections are performed when the annual probability of failure exceeds the maximum acceptable annual probability of failure.

The above methods for planning of inspections and maintenance require cost models to be formu-lated. A simplified planning can be performed by requiring inspections (and possible maintenance / repair) to be made when the probability of failure exceeds a critical value, see Figure 7. Such a sim-plified methods is applied e.g. when planning inspections for fatigue cracks for oil & gas offshore platforms, see Sørensen (2014).

2.3 Application for wind turbine blades

In this section the theoretical models described above are illustrated by examples.

2.3.1 'Simple' illustrative example of decision making for a wind turbine blade

This example describes the principles in optimal decision making on when to perform inspections and which type of maintenance/repair to perform. A defect detected by visual inspection in a wind turbine blade is considered. The defect could e.g. be characterized using the tool Guide2Defect as:

- A defect in a bondline
- A surface crack
- Etc…

For illustration the defect (e.g. in the trailing edge) is quantified as follows:

- The length of the detected defect / crack is 10cm
- If the defect grows to a length >100cm this is expected to result in serious damages implying stop of the wind turbine and a replacement of the blade

Three levels lengths of the defect size and related consequences / maintenance is considered:

- $D = D_1 = 10$ cm
- $D = D_2 = 20$ cm
- $D > D_F = 100$ cm

The development of the defect is uncertain and could be modelled by the following probabilities of the defect size after year 0 (now), year 1 and year 2:

Time	$D = D_1 = 10$ cm	$D = D_2 = 20$ cm	$D > D_F = 100$ cm
Year 0	100%		
Year 1	$P_{D1,1} = 90\%$	$P_{D2,1} = 9.0\%$	$P_{F,1} = 1.0\%$
Year 2	$P_{D1,2} = 63\%$	$P_{D2,2} = 25.2\%$	$P_{F,2} = 10.8\%$

Or using a more detailed (but equivalent) model:

Time	10 cm	20 cm	100 cm
y0=Year 0	100%		
y1=Year 1	P(10cm at y1 given 10cm at y0) = 90%	P(20cm at y1 given 10cm at y0) = 9%	P(>100cm at y1 given 10cm at y0) = 1%

y2=Year 2	P(10cm at y2 given 10cm at y1) = 70% 0.9x0.7=0.63	P(20cm at y2 given 10cm at y1) = 20% P(20cm at y2 given 20cm at y1) = 80% 0.9x0.2+0.09*0.8=0.252	P(>100cm at y2 given 10cm at y1) = 10% P(>100cm at y2 given 20cm at y1) = 20% 0.9x0.1+0.09x0.2=0.108

For illustration the following decision alternatives could be considered:

1. Do noting
2. Minor repair (implying that wind turbine is stopped for very little extra time) at y0 and do nothing y1 and y2
3. Major repair (implying that wind turbine is stopped for some time) at y0 and do nothing y1 and y2
4. Do nothing y0 but inspection in y1 and minor repair at y1 if D = 10cm or major repair if D = 20cm. If repair then probability of failure at y2 is assumed equal to 0.

The reliability of the inspection, POD (Probability Of Inspection):

- POD(10cm) = 50% probability that a defect = 10cm is detected
- POD(20cm) = 80% probability that a defect = 20cm is detected
- POD(>100cm) = 100% probability that a failure is detected

The major repair is assumed to be ‘perfect’ i.e. no damages occur at y2.

The minor repair is assumed not to be ‘perfect’ such that there is a small probability of failure at y2 = $P'_{F,2}$ = 5%.

Cost models (normalized values):

- Cost of inspection: Cinsp = 10
  - (marginal) costs of mobilization, transport, labour, equipment
- Cost of minor repair: CR,minor = 100
  - (marginal) costs of mobilization, transport, labour, equipment, material
- Cost of major repair: CR,major = 500
  - (marginal) costs of mobilization, transport, labour, equipment, material, lost produc-tion of electricity
- Cost of failure: CF = 10 000
  - costs of corrective replacement incl. mobilization, transport (incl. possible waiting time due to bad weather), labour, equipment, material, lost production of electricity

Decision making: the alternative with the smallest expected costs are selected.

The effect of the real rate of interest is not taken into account (but can easily be included).

Total expected costs of alternative 1 (do nothing):
$E[C] = P_{F,1}\, C_F + P_{F,2}\, C_F \qquad = 1180$

Total expected costs of alternative 2 (minor repair):
$E[C] = C_{R,minor} + P_{F,1}\, C_F + P'_{F,2}\, C_F \qquad = 700$

Total expected costs of alternative 3 (major repair):
$E[C] = C_{R,major} + P_{F,1}\, C_F \qquad = 600$

Total expected costs of alternative 4 (inspection at y1):

$E[C] = C_{insp} + P_{F,1}\, C_F \quad +$
$+P_{D1,1}$ P(no detection at y1 if D=10cm) P(>100cm at y2 given 10cm at y1) C_F
$+P_{D1,1}$ P(detection at y1 if D=10cm) $C_{R,minor}$
$+P_{D2,1}$ P(no detection at y1 if D=20cm) P(>100cm at y2 given 20cm at y1) C_F
$+P_{D2,1}$ P(detection at y1 if D=20cm) $C_{R,major}$

$= 577$

The conclusion is thus that in this example alternative 4 should be chosen, i.e. wait with an inspec-tion until year y1.

2.3.2 Inspection and maintenance planning for offshore wind turbine blades

This example presents a life-time cost analysis of an offshore wind turbine using a physical degra-dation model planning of preventive maintenance and focuses on analysing the effect of different decision parameters on the total expected maintenance cost. Details can be found in Florian & Sørensen (2014).

For illustration a single blade of an offshore wind turbine is considered. It is subjected to uncertain loading over a duration of 20 years. The model considers both preventive maintenance, thus ac-counting for online and offline condition monitoring, as well as corrective maintenance in the event of a collapse (failure before preventive maintenance). The NREL 5MW turbine with a rated wind speed of 11.4 [m/s] is chosen as a reference turbine for the model, see Florian & Sørensen (2014).

Wind and wave data from measurements at a typical North Sea location situated approximately 80 km off the coast of Denmark are applied. The lost energy production is estimated for the downtime periods, when O&M activities are performed or where a failure occurs.

Transport to the turbine site is assumed to be done ship for both inspection and repair activities. The weather conditions allowable for transportation and the time needed to reach the turbine are chosen for illustration as shown in Table 1. In order for an activity to take place, the weather conditions need to be below the limits outlined in the table for the entire duration of the mission, considering both transport and the activity. If this is not satisfied at the scheduled time of the activity, the action is postponed to the nearest acceptable weather window.

Description	Value	Unit
Wind limit	12	[m/s]
Wave limit	1.5	[m]
Transport	8	[h]

The inspection model considers the scheduled inspection time, the duration for an inspection and the probability that an inspection is successful, i.e. a defect is detected if there is a defect. This is modelled using the probability of detection (PoD) curve in Figure 8 which is a function of the dam-age size D [m], see Florian & Sørensen (2014).

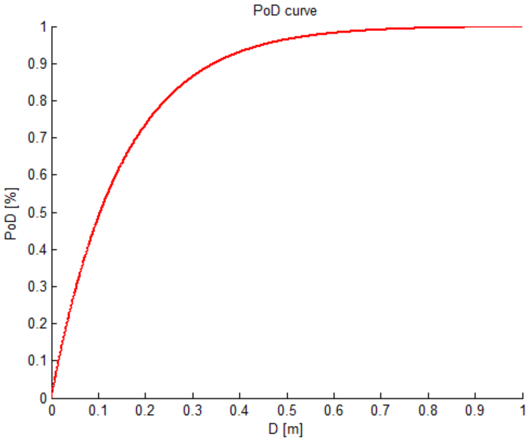


Figure 8. Inspection probability of detection.

In order to build a reliable damage model, a failure mechanism is modelled, see Florian & Sørensen (2014). The size and positions of the defects / cracks at the beginning of the blade life-time is un-known / random. Therefore random initial damage sizes are generated as illustrated in Figure 9 where the distances l1, l2 …. ln are generated from a Poisson process and the size a of each crack is randomly generated using a Lognormal distribution.

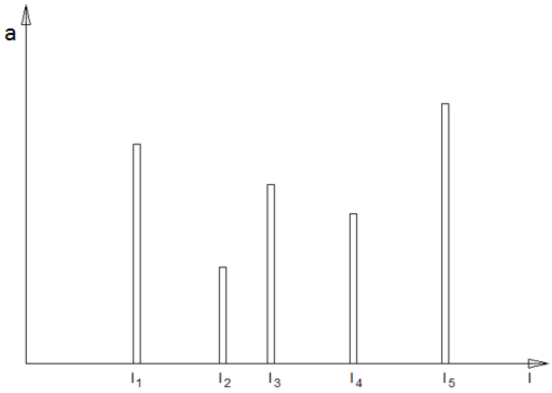


Figure 9. Initial damage / defect sizes along the blade.

The average number of defects is chosen as 0.3 per meter length of the blade. It is noted that this model assumes defects to be evenly distributed along the length of the whole blade. This may not be realistic, but other models within defects concentrated in certain areas of the blade can easily be implemented. The model used to estimate the growth of the defects depends on the blade load cycles as described in Florian & Sørensen (2014). To determine the distribution of the load cycles as function of the environment, a series of 10 minute simulations is made using the aero-elastic simu-lator FAST Jonkman et al. (2005) covering all operational wind bins of the NREL 5MW turbine.

Failure is assumed to occur when the defects / cracks reach a certain critical value a_{fail}. Figure 10 shows an example run of the damage model, illustrating all stages, for a_{fail} equal to 1 [m].

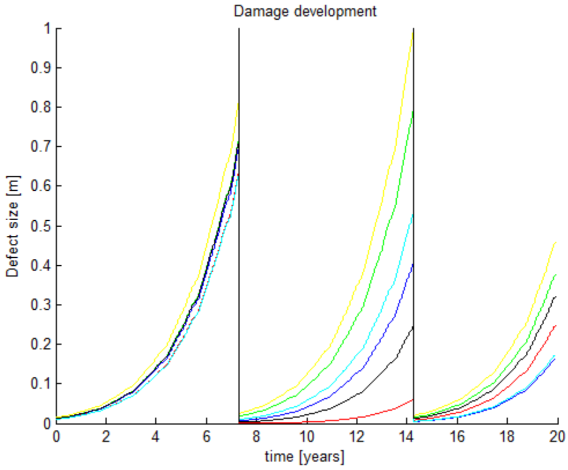


Figure 10. realizations of damage development as function of time.

Both preventive/condition based and corrective type maintenance are considered. A preventive re-pair is scheduled when a crack with a length greater than a certain value a_{rep} is successfully detected. The value of the repair limit is an important decision parameter. In the event of a collapse (where the defect / crack is not detected before failure), a corrective repair is performed. Both types of in-tervention are dependent on the transport vessels and if the weather conditions do not permit for an immediate intervention, the activity is postponed until an appropriate weather window appears. The power loss is also estimated during the downtime of the turbine, considering both the duration of the repair itself and the downtime caused by inappropriate weather.

A cost model is formulated covering costs of inspections, maintenance interventions and revenue losses as a result of downtime from each activity and eventual failure. Further, a stochastic model is formulated for the uncertain parameters, see Florian & Sørensen (2014).

The inspection activities are the main tool in determining whether or not a blade needs to undergo a repair, potentially saving considerable expenses by avoiding future corrective repair. However, if the interval between two consecutive inspections is too small, it can lead to unnecessary high maintenance cost. The optimum time between inspections is found as the time interval where the total expected preventive and corrective maintenance cost is minimised. The optimum interval is dependent also on the reliability of the inspection, as described above.

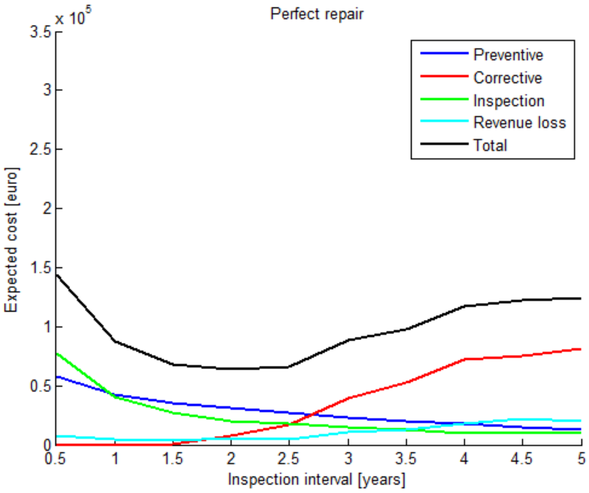


Figure 11. Expected total costs as function of inspection interval – assuming perfect repairs.

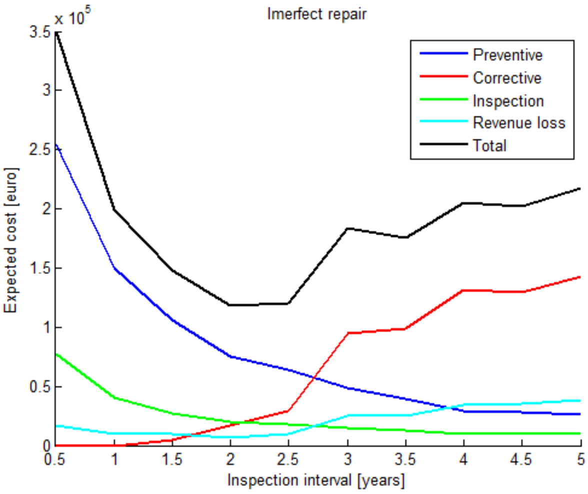


Figure 12. Expected total costs as function of inspection interval – assuming imperfect repairs.

Figure 11 and 10 show examples of results obtained using both perfect and imperfect repairs. A min-imum is seen at a time interval of 2 years for both assumptions. Below this point, the amount of preventive maintenance and the associated cost is unnecessary high, due to the low risk of failure, as illustrated by the corrective cost function. On the other hand, choosing a larger time interval in-creases the chances of collapse, greatly raising the expected corrective cost as well as the revenue loss.

Figure 13 shows an example where the influence of the repair limit is considered. The decision on the repair limit has a strong influence on both the amount of preventive maintenance and the risk of corrective repair. By choosing a high limit, the degradation state is allowed to approach the failure limit, raising the risk of a collapse event. On the other hand, repairing damage on sight (i.e. low repair limit) raises the amount and cost of preventive maintenance by wasting significant portions of the blades remaining life. The cost functions in figure 10 are for an inspection time interval of 2 [years]. It should be noted that the importance of the repair limit is highly dependent on the damage model used. For fatigue cracks as used here the model will be quite sensitive to the repair limit.

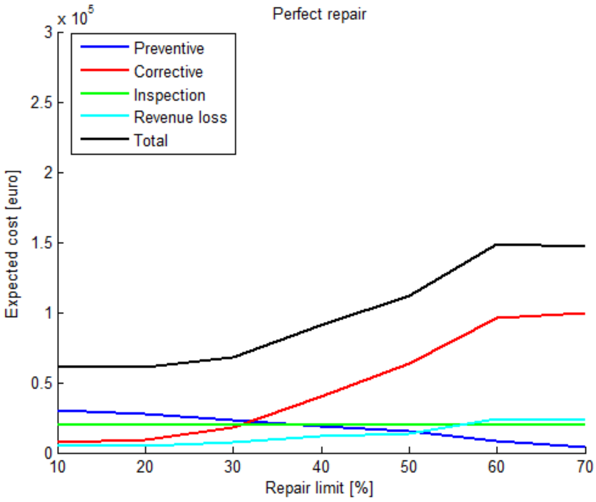


Figure 13. Expected total costs as function of the repair limit – perfect repairs.

2.4 Summary

In this work package a cost model is formulated with the objective to be used in cost optimal plan-ning of inspection and maintenance. For offshore wind farms this includes consideration of lost rev-enue due to bad weather conditions. Cost models for initial design incl. upscaling of blades can be found in e.g. UpWind reports, see Sieros et al. (2012).

The generic life cycle cost model has special focus on costs related to inspections, maintenance, re-pairs and possible failures of wind turbine blades incl. bondline failures / defects such that the ex-pected total costs in the remaining design working life can be estimated.

Next, it is described how to estimate the reliability and the probability of failure including models for uncertainties using information from full-scale tests, sub-component tests and numerical simula-tions, and failure modes based on generic damage models for bondline failures.

Examples are presented to illustrate how the theoretical models can be applied for planning of in-spection and maintenance. The models used in the examples can for practical applications be im-proved and adapted to various types of blades used in the industry by coupling it with information from destructive / non-destructive tests. Knowledge of initial imperfections in the bonding material, crack propagation and limit of failure can be used to update and reduce the uncertainties in the models. Damage models for the development of defects can either be formulated based on a theoretical basis or be calibrated based on laboratory tests and field measurements. The complex naval logistics for offshore wind turbines and a detailed cost model were not the scope of the examples.

It is also described how a simplified planning of inspection and maintenance can be performed without requiring a detailed cost model. This planning requires the reliability to be estimated and inspections / maintenance is performed when the reliability becomes too low.

3 WP 2 - Damage assessment and measurement techniques

WP responsible: Malcolm McGugan - Technical University of Denmark Wind Energy Department

WP2 of the Bondlines project dealt with relevant damage assessment and measurement techniques for blade structures (and sub-structures) and was led by the Technical University of Denmark Wind Energy Department (DTU Wind).

The following major tasks were completed within WP2

Task 1 Structure acquisition, transport, assessment and section (deliverable to WP4)

Task 2 Measurement of operational response (deliverable together with WP3)

Task 3 Sub-component instrumentation (replaced by measurement system assessment)

Each task is reported briefly here, with reference to the project documentation.

3.1 Damage assessment

This task involved acquiring representative blade structure(s) for assessment and sectioning into relevant sub-components and a larger substructure component suitable for mechanical testing. All blade material was made available to the consortium by the Bondlines partner Total Wind Blades (TWB).

It was agreed that a series of Trailing Edge sub-sections could be cut directly from one of the stored blades at TWB Brande, and delivered to DTU MEK in Lyngby for mechanical testing. This series of tests is reported in Work Package 4 and 5.

In addition material characterisation (microscopic analysis) was conducted by DTU Wind and is available on the LEX-EUDP project website (WP2).

Figure 14. SSP34 blade with leading and trailing edge sections removed prior to and following spar sectioning at R15m - ready for transport to DTU MEK for substructure testing

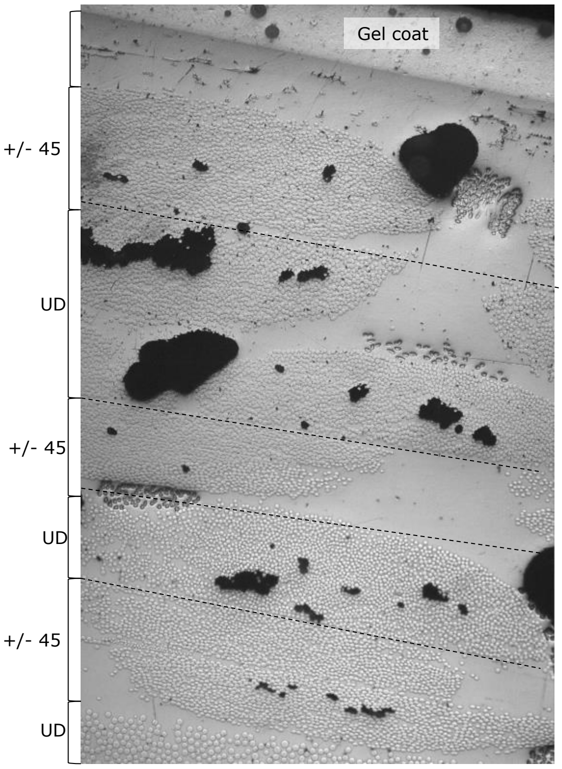
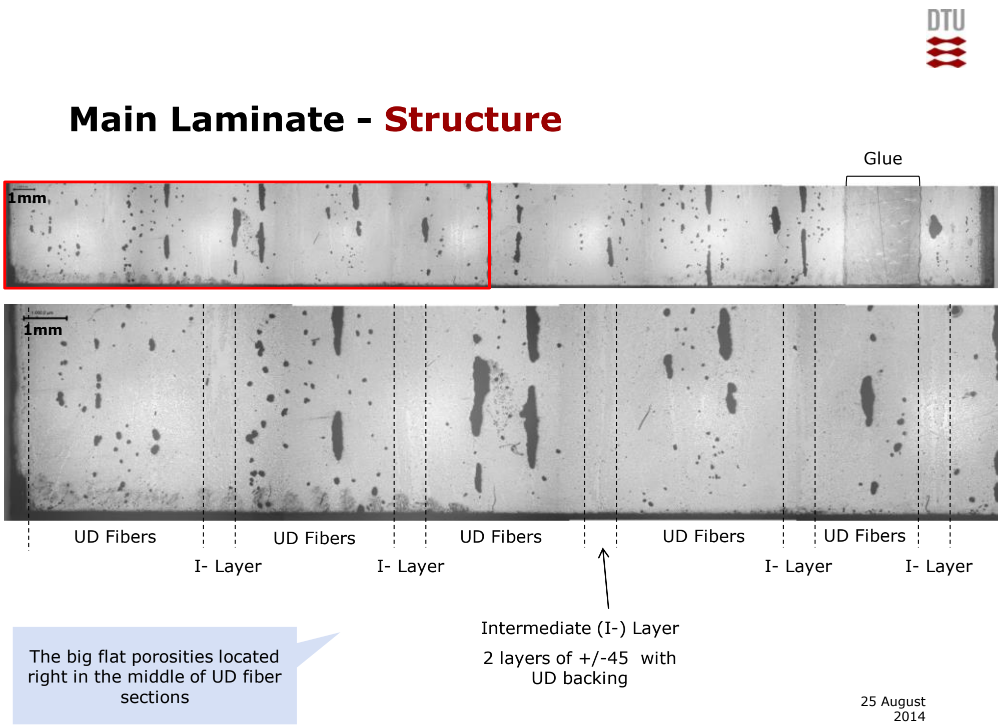


Figure 15. Micrograph showing the complex structure in the Trailing Edge of the SSP34 blade; analysis showed a high level of porosity (around 5%) in the trailing edge laminate.



Main Laminate - Structure

The big flat porosities located right in the middle of UD fiber sections

25 August 2014

Figure 16. This micrograph shows the structure within the thick upper cap of the SSP34 spar; note the porosities associated with the pre-preg layup of stiff unidirectional (UD) laminate

3.2 Instrumentation for measurement of operational response

This task involved close collaboration with WP3 to agree on and implement an instrumentation plan suitable for the structural blade sections of interest in an operating wind turbine (V80). All relevant measurement hardware and attachment consumables were assembled and tested within this task, including establishing an appropriate data acquisition system, prior to application in-situ. This instrumentation was then installed by Total Wind Blades (TWB) as agreed between the measurements (WP2) and operational test (WP3) partners; first for the non-reinforced and then for the reinforced trailing edge panels. All data analysis and presentation of results was then done by DTU Wind within this WP task.

Date		**Action**
2012	23 Jul	Initial discussions
	16 Aug	Project Kickoff meeting followed by sourcing and pricing of hardware
	04 Sep	Initial meeting with Total Wind (Brande) “Fittings” manufacture by DTU Wind
	18 Sep	System check (Ground Check) at Brande
	03 Oct	Instrumentation check (Ground Check) at Brande
	19 Oct	Power supply check (Turbine check) with Vattenfall (Tjæreborg)
	23 Oct	On-site measurements (Unreinforced blade) - rope access and instrumentation of the blade - initial force transducer measurements
	24 Oct	On-site measurements (Unreinforced blade)

		- morning: more force transducer measurements - afternoon: trailing edge displacement measurements - evening: instrumentation for the internal box beam shear measurements
	25 Oct	On-site measurements (Unreinforced blade) - internal box beam shear measurements
2013	08 Jan	On-site measurements (Reinforced blade) - Mark and drill blade positions for D-string reinforcements
	09 Jan	On-site measurements (Reinforced blade) - Finish drilling, thread strings, bond fittings, attach and tension D-strings
	10 Jan	On-site measurements (Reinforced blade) - Install DAQ in the hub - Measure residual deformation in the trailing edge panels

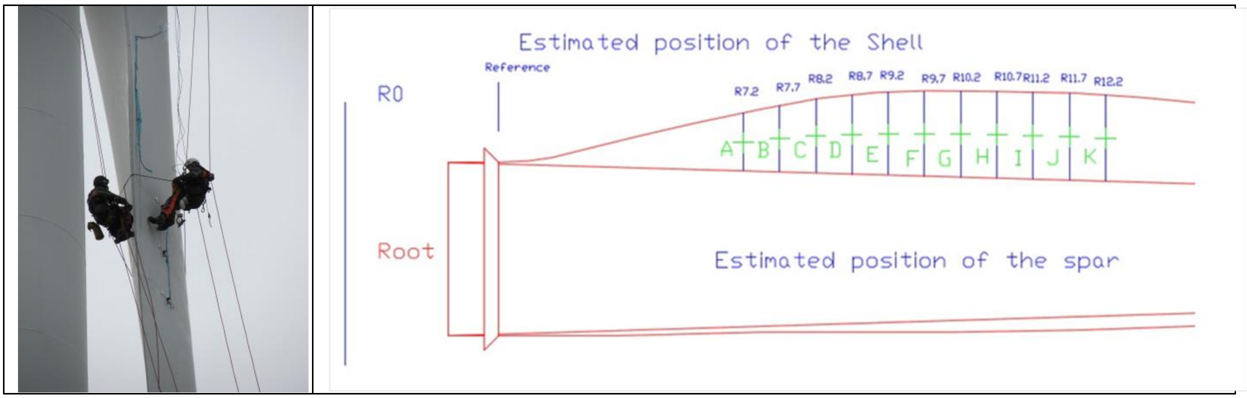


Figure 17. Schematic showing the area of interest on the blade; Trailing edge between R7m and R12.5m

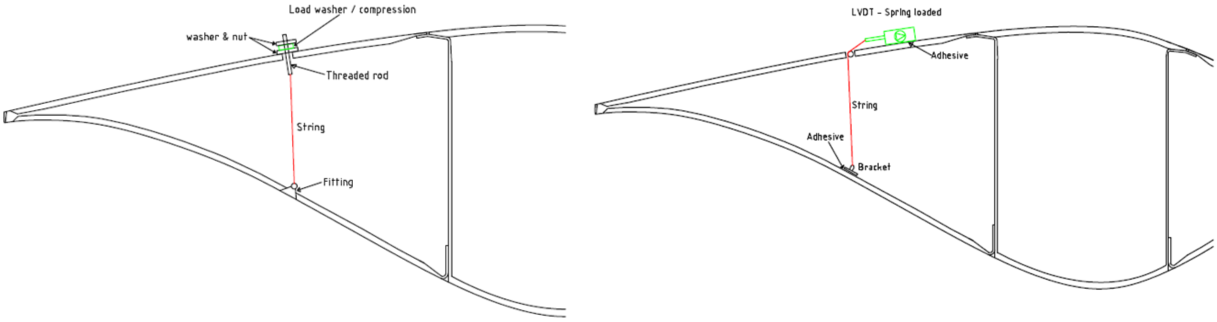


Figure 18. Schematics showing the sensor configurations for trailing edge panel force transducer (left) and displacement (right) measurements

During the initial discussions and the Project kick-off meeting over the summer of 2012, the general approach was discussed; this involved threading a string between the pressure and suction faces of the trailing edge panels in order to measure the force generated between the two once connected in this way, and later the relative displacement generated under normal operation conditions when the panels are again free to deform.

Following these initial meetings DTU Wind began assembling the necessary hardware during autumn 2012, with input from the other partners (Bladena, Vattenfall, and TWB) to confirm the system hardware set-up (18 Sep 2012), an instrumentation check (03 Oct 2012) where the practical problems of “threading” and mounting the sensors and cabling was addressed, and finally a power check (19 Oct 2012) on the V80 turbine at Tjæreborg to confirm that the auxiliary lighting system power could run the measurement acquisition system.

Figure 19. Hardware used in the WP2/WP3 trials

Shown in the image above:-

- Laptop with DASYLab on (SSD) hard drive
- DAQ Box (with power supply)
- Strain gauge amplifier
- 3 Compression Ring Load Washer (15m cables)
- 1 Inclinometer (2m cable)
- 3 ”Posiwire” String potentiometers (15m cables)

The results from instrumentation on the unreinforced blade during October 2012 showed a generated force of between 100 and 200 N across the trailing edge panels when constrained, and a displacement of between 6.5 and 10 mm when free to deform. These measurements were obtained during blade pitch, auto-run, and “slam” stop conditions at wind speeds of between 5 and 10 m/s. Once the blade was reinforced with the D-String stiffeners in January 2013 the displacement measurements between the trailing edge panels reduced to less than 1mm under similar conditions and operation. The effect of the D-String reinforcement is confirmed by these results, which showed that out-of-plane deformations were reduced with 97%.

All the details of the Bondlines blade instrumentation and measurement results are contained in the measurement report [26].

3.3 Measurement system assessment

In the project description, task 2.3 involved supporting the sub-component and sub-structure mechanical testing in WP4 with non-destructive inspection (ultrasonic) and test measurement systems (fibre-optic Bragg grating, resistance strain gauge, acoustic emission, etc.).

However, as the details of the structural test program in bondline project were developed it became clear that only a limited support from DTU Wind could be justified here. Instead, various optical systems of interest to the Bondlines consortium were investigated and assessed for their applicability; both in the current and subsequent operational monitoring tasks (Structural Health Monitoring applications), the full-scale certification testing of blades, and the experimental, destructive testing of sub-structural components.

The 1st International Workshop on Embedded optical sensors for composite materials was held on the 7th and 8th of October 2013 at Gent University in Belgium. Malcolm McGugan (DTU Wind) attended and presented various work, including the measurement aspects of the EUDP Bondlines project. Following the conference contacts with Industry (HBM) and research groups (Cranfield and Gent) have been maintained in order to assess the current available systems and the development potential.

HBM

Following the contact made at the Conference, two meetings were held on DTU Risø between DTU Wind and HBM to discuss the Bondlines project and other common areas of interest regarding fibre optic measurement systems; Bladena (Mikkel Lagerbon) was also present at these meetings. The first was held on 07/Oct-2013, the second on 17/Jan-2014 - the following main items were discussed:-

- Strain correction factors for compliant substrates
- Hardware available for assessment by DTU (structural and sub-component testing)
- HBM as a future partner in research projects
- Technical discussions on fibre optic sensing
- Commercial considerations for structurally embedded fibre optic systems

Current activities between DTU Wind and HBM include the loan of an HBM fibre optic system (OPTIMET-OMF) for investigation of the strain effects around “damaged” Wind Turbine Blade root bolts within the MARE_WINT network (www.marewint.eu); and a Non-Disclosure Agreement signed to allow collaborative experimentation on more accurate strain measurements for compliant substrates.

A final comment regarding the assessment of HBM and their systems for fibre optic measurement is that despite the extensive activity and excellent reputation of the HBM group in measurement technology, their optic systems are not especially further ahead in development terms compared to others in the market, and as HBM rely on external suppliers for many components in their fibre optic systems, it is considered that Fibersensing (see below) might be a preferred project partner.

Baumer

As part of the 2013 shared activity in WP2 (measurement hardware) and WP3 (On-site installation) it was proposed to demonstrate the Baumer system on an operating turbine (V80 at Tjæreborg). However, this was not completed due to unsolved installation issues with the hardware available.

At the Bondlines planning meeting (held in Aalborg 28.Jan.2013), it was agreed that Baumer would supply a measurement system direct to Total Wind (TWB) that would be ready to install at Tjæreborg.

When the system arrived at Brande in early March it was clear that the system was not ready for installation as there were issues with both data transfer and power cabling. The installation was planned for 18/19 march, but no representatives from Baumer were available to assist TWB on these days and the opportunity was lost. As the system was not installed, it was transported to DTU Wind (Roskilde) to investigate if the issues identified by TWB could be resolved as an extra part of task 2.3. The power cabling issues were straightforward to address, but the lack of an available wireless network on the Vattenfall demonstration turbine was more challenging.

The preferred (non-wireless) solution for all sensor data acquisition and handling on the turbine had already been agreed between the WP2 and 3 partners following recommendations from the Test and Measurement experts at DTU. This data acquisition and storage hardware formed the “backbone” of all the measurement actions installed on the Tjæreborg demonstration turbine (both in Bondlines, and the subsequent LEX project) and was the only approach approved by the WP2 project group. Modifying the Baumer system was not achievable within the WP2 and 3 budget and personnel availability.

The Baumer system has previously been successfully demonstrated at Risø for static blade structure tests [27]. Note that this report also describes a demonstration of an optical backscatter reflectometry instrumentation of the blade test structure.Preferred instrumentation approach for the Baumer optical blade monitoring system is described in [28].

FiberSensing

DTU Wind is a partner of Fibersensing within the MARE_WINT network (www.marewint.eu) and are supplied with various fibre optic measurement systems for laboratory and structural testing.

In the course of 2014, the WINDMETER system for root strain measurements in operating wind turbine blades (http://public.fibersensing.com/Interships/NicolasMorisset/UserManualUnitWindMETER.pdf) will be demonstrated within the EBRII EUDP project at DTU Wind Risø Campus Blade test facility, and also within the LEX EUDP project at Blæst test centre in Aalborg.

4 WP 3 – Field Testing

WP responsible: Johnny Plauborg – Total Wind Blades

Two field tests were performed within the project; one in October 2012 and another in January 2013. First test in October was performed on the turbine, in order to verify the occurrence of out-of-plane deformation of the trailing edge panels. The scope of second test in January was to install the D-Sting® reinforcement and to confirm the effect of the solution. The installation of measurement equipment and D-String® reinforcement was performed by technicians from Total Wind Blades. All installations on the blade were performed by rope access.

Figure 20. The wind turbine in Tjæreborg

Figure 21. Technicians working on the blade.

Figure 20 show the Vestas V80 turbine in Tjæreborg on which the field testing was performed. In Figure 21 are two technicians working on the installation and instrumentation of the measurement equipment on the blade. The blade was successfully instrumented with measurement equipment and in the second test also with the D-String® reinforcement. In both tests the blade had to undergo a series of operations, involving pitching, normal operation and emergency stops, while performing measurement of the response. A full detail of the field testing is found in the measurement report [26].

5 WP 4 – Subcomponent testing

WP responsible: Christian Berggreen – Technical University of Denmark MEK

The objectives of the tests were to develop a test machine able to perform static and fatigue test on wind turbine blade trailing edge specimens in order to evaluate the benefits obtainable using the D-String® reinforcement.

5.1 Test setups

Two different testing concepts have been developed within the scope of the project; both test setups are described in detail in the following section.

5.1.1 Gorilla test

The static and the fatigue tests have been done using an innovative and custom made test machine. The test rig is an axial torsional rig composed of two axial actuators mounted on two rails which permits free movement of the actuator on a plane. This set-up permits to make static and fatigue test, performing Mode 1 and Mode 2 in any mode mixity. The test rig consists of two independent torsional actuators with the possibility of free motion in two perpendicular directions which would make it possible to eliminate any force on the specimen and make sure only moment was applied to it.

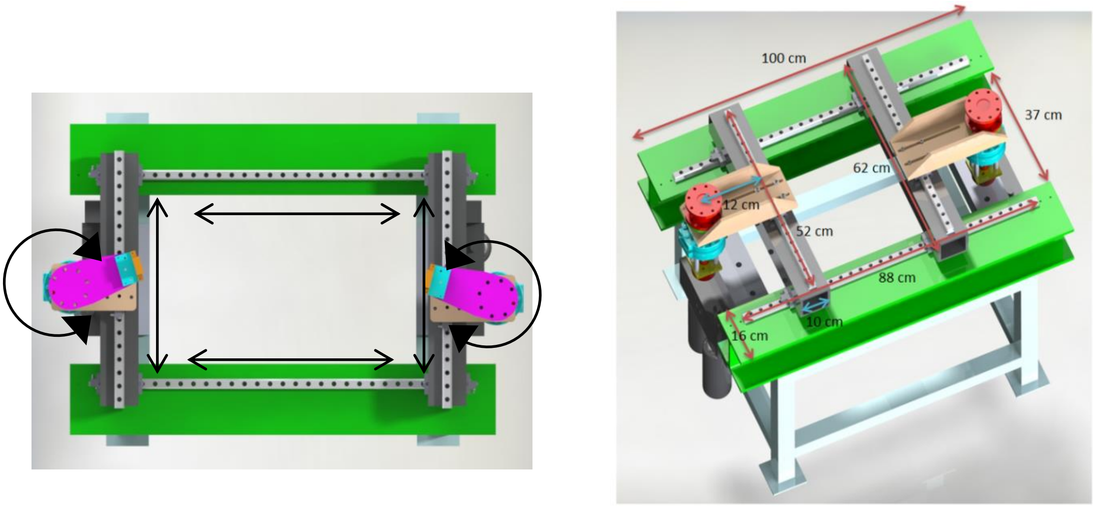


Figure 22. Test rig.

The actuators can impose a moment of 773 Nm rotating 360°, both of them where equipped with two axial torsional load cell with a capacity of 565 Nm each. The load cells have been calibrated in DTU Structural Lab.

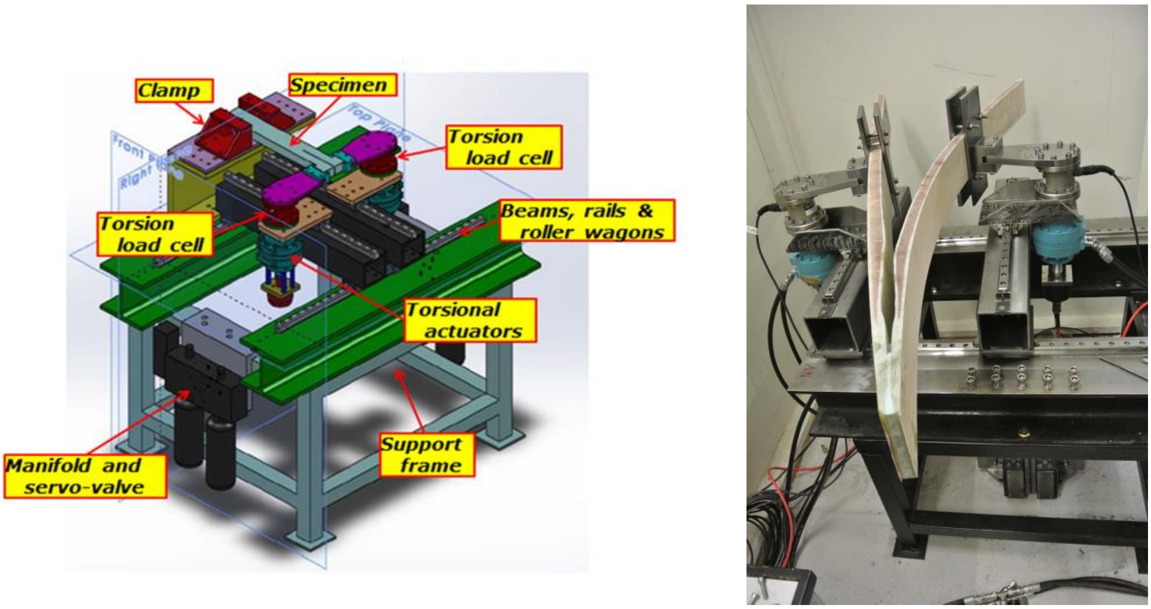


Figure 23. Left; Schematic illustration of test rig. Right; Blade specimen installed in test rig.

The machine and controller can perform tests in angle-, strain- and torsion control. In strain control is the torsional load applied to the specimen and the strain at fixed locations is evaluated by using strain gauges. Strain control is used in cyclic fatigue test where the applied torsion is dissipated by the inertia of the actuator frames. Strain control ensures that the correct forces are applied to the specimen.

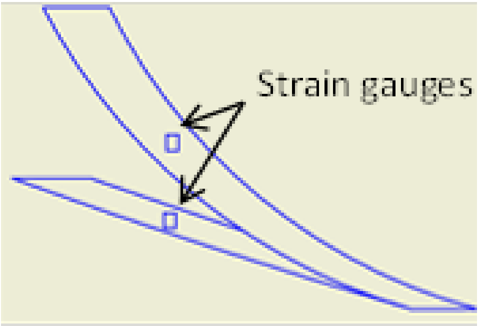


Figure 24. Specimen with strain gauges.

5.1.2 Breathing test

The breathing test is a more simple method for simulating the Mode 1 peeling stresses in the trailing edge bondline. The breathing behavior of the trailing edge, illustrated in Figure 25, is simulated by using this test setup. The out-of-plane deformation of the panels is causing pealing stresses in the trailing edge bondline as well as in the bondline between shear web and trailing panel. The scope of the test is to introduce out-of-plane deformation equivalent to what is observed on operating turbines. The test is performed for reinforced specimens and without reinforcement. The test specimens are cutouts form blades which consist of the trailing edge panel and the aft shear web.

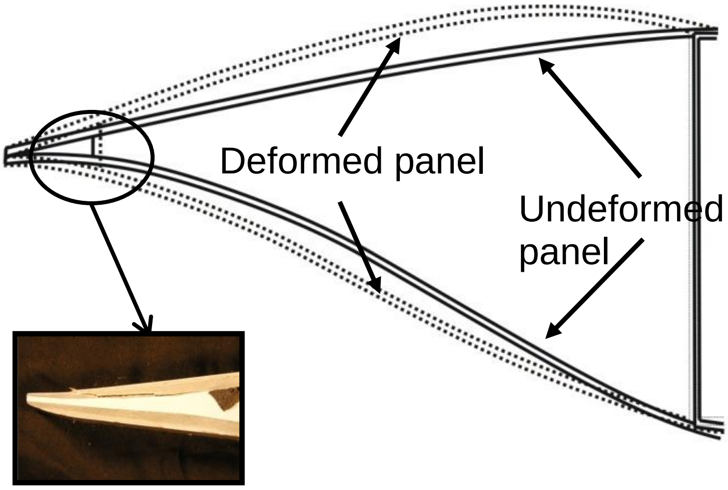


Figure 25. Breathing behavior of the trailing edge panels.

The test setup configuration is illustrated in Figure 26. Two load application clamps are attached to each of the panels at the mid-points. The load is applied through hinge joints which allow rotation of the specimen as panels is deformed out-of-plane. Applying this method of constraining the specimen ensues that it is only peeling forces from the out-of-plane deformations that are introduced in the bondline. The position of the load clamps is same as where the D-String® reinforcement is installed, because of this are holes introduced in the load clamps to facilitate the D-String®.

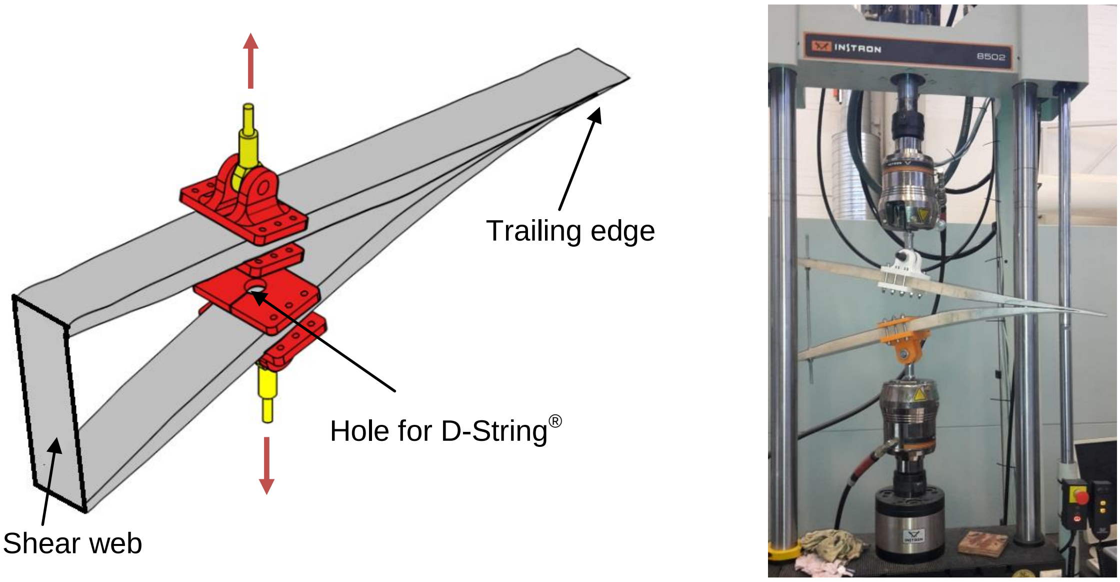


Figure 26. Breathing test setup.

The simpler breathing test setup makes to possible to perform fatigue tests with a higher excitation frequency. The actuators force are applied directly at the area of interest on the specimen, thus reducing the actuator movement which implies that tests are performed faster than compared to the gorilla test.

6 WP 5 – Product development

WP responsible: Mikkel Lagerbon - Bladena

The purpose of this work package was to develop Bladena’s patented retrofit reinforcement solution from concept to a commercially available product ready for installation on operating wind turbine blades. The product specifications of the D-String® solution is define by the collected information on loads and deformation of the trailing edge panel on an operating wind turbine in WP2/WP3. The requirements to the installation procedure of the D-String® solution is developed together with Total Wind Blades, who have a great deal of expertise and know-how about accessibly and constraints related to doing maintenance- and repair-work from rope access on wind turbines. Product testing have been performed at the structural laboratory at DTU in order to verify that installation of the D-String® solution will not cause any potential risks to the wind turbine blade structure.

In the following sections are the components of the D-String® product presented together with experimental product testing results.

6.1 D-String® product

Figure 27. The D-String® solution

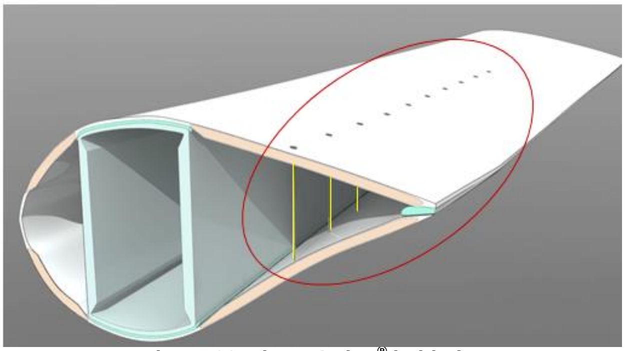


Figure 28. The D-String® in blade.

The full D-String® product consists of the following components:

- Cones for anchoring the reinforcement in the blade panels
- Reinforcement string
- Overload protection safety device
- Special tools for installation

Figure 29 is showing the D-String® solution installed in a wind turbine blade sample. Two anchoring cones are installed in both of the trailing panels opposite one another on both pressure and suction side respectively. The reinforcement string is installed between the panels and attached to both the anchoring cones. The overload protection safety device is integrated in the reinforcement string. After installation is the anchoring cone covered with adhesive and finally sealed off in order to prevent water ingress and to ensure that the reinforcement do not affect the aerodynamic performance of the wind turbine blade.

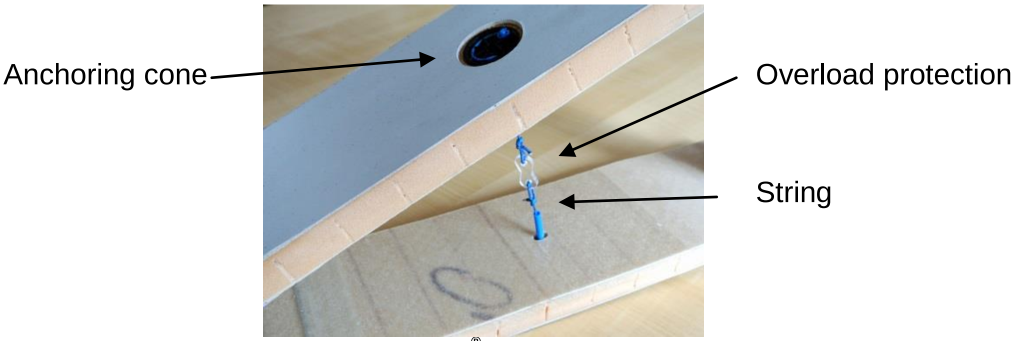


Figure 29. Demonstration of D-String® installed in wind turbine trailing edge.

6.1.1 D-String® anchoring cone

The anchoring cone is cone-shaped which allows easy installation and alignment in the panel. A conical hole is drilled in to the sandwich core material with a special tool which the anchoring cone easily fits into. During the project DTU has performed an extensive numerical and experimental study addressing the effects on the panel core material from this anchoring concept [25]. The study concluded that by applying an optimized shape of the cone a significant reduction of the stress concentrations in the core material could be obtained, thus preventing that the D-String® solution is introducing damages in panels. The string is attached to the anchoring cone by an easy-to-use clam method which provides a simple and efficient installation procedure.

Figure 30. D-String® anchoring cone.

The cone is designed without any mechanical or moving parts and requires no assembly prior to installation and can be manufactured by an injection molding process.

6.1.2 String

The string has to constraint the out-of-plane panel deformation, a high strength braided string with high stiffness and low elongation is used for the D-String® solution. An overload protection device is integrated with the reinforcement string. The overload device is activated if the load in the reinforcement string exceeds a critical design level. Tension is released before the load reaches a level which could cause damage to the panels. The overload protection device is shown in Figure 31.

Figure 31. Reinforcement string with integrated overload protection device

6.2 Product testing

A testing program for the D-String® solution has been performed at DTU structural laboratory. The purpose of the testing was to document that installation of the D-string® reinforcement in a wind turbine blade does not affect the existing structural integrity of the blade, and that the blade panels are able to withstand the forces introduced from the D-String®. Furthermore, testing of the individual components of the D-String® was performed, ensuring the functionality of the product.

6.2.1 String and cone assembly

The strength of the assembly between the reinforcement string and the anchoring cone was tested in static load. Two different aspects of the connections was tested; first a locking mechanism between the cone and string which is used only to apply pre-tension in the reinforcement during installation procedure, shown in Figure 32 and Figure 33. The other aspect tested was the final locking according to the installation process, when the locking mechanism is sealed off with adhesive, as shown in Figure 34.

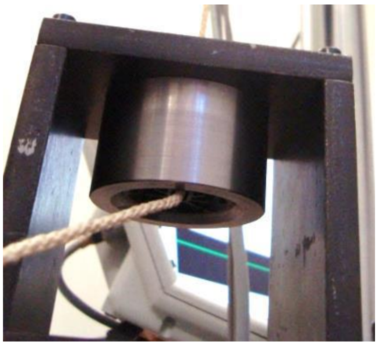


Figure 32 – Setup 1: No glue

Figure 33 – Setup 1: No glue

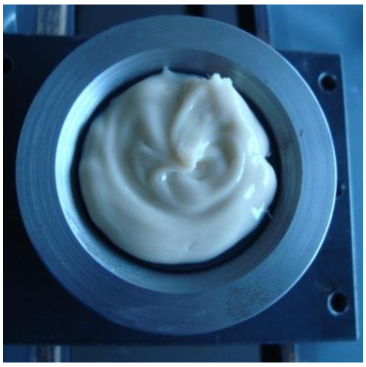


Figure 34 – Setup 2: Glue

The tests were performed on a tensile testing machine using a fixing tool to clamp the cone. The actuator rate of movement during the test was 0.166 mm/sec. The load curve for test setup 1 is shown in Figure 35. This test is focused on the ability of the cleat to hold the string in position during the installation in the blade panel process. On average the cleat mechanism was able to hold a force of 0.3 kN, which is sufficient for the applied pre-tension during the installation.

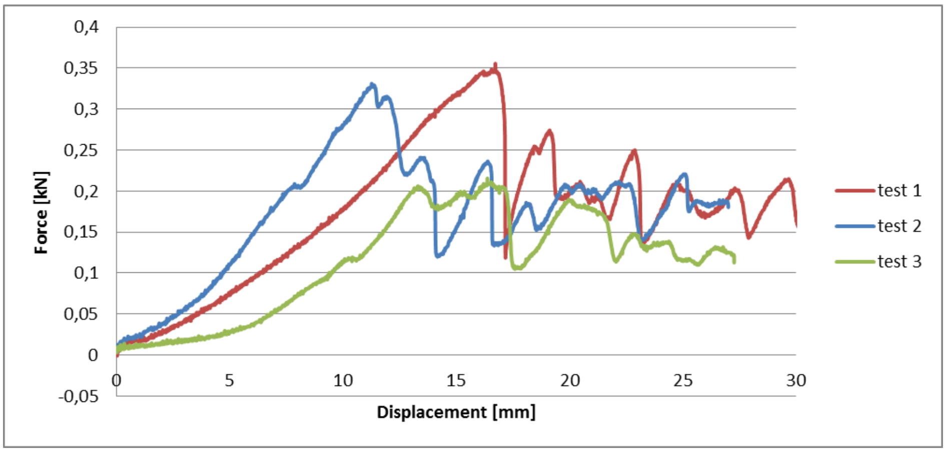


Figure 35. Force-displacement curve for test setup 1.

Test setup takes into consideration all aspects of the connection between the cone and reinforcement string. The test specimens were prepared according the procedure for installation of the D-String®. The adhesive had a curing time of 20 hours before testing. In Figure 36 the force – displacement curve for the test is shown. An average maximum load of 2.3 kN was obtained for the test specimens, which is well above the measured loads on the operating turbine.

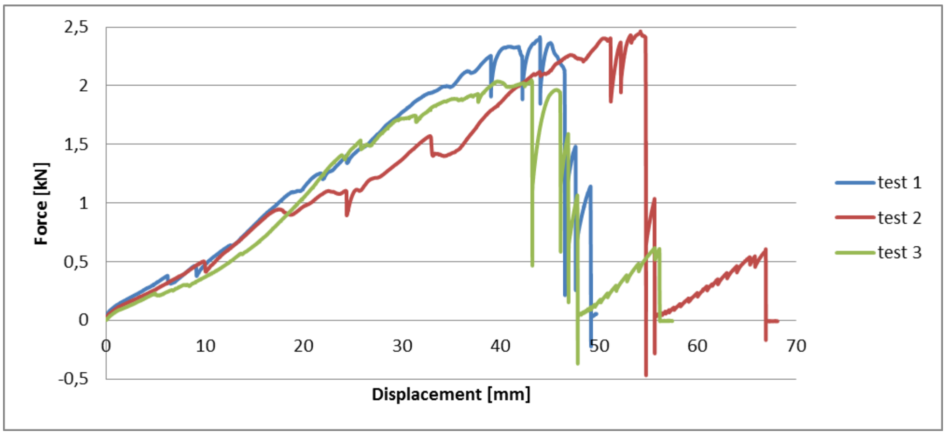


Figure 36. Force-displacement for test setup 2.

6.2.2 Static panel testing

Testing was performed with the D-String® anchoring cone installed in specimens of trailing edge panels from a wind turbine blade. The purpose was to determine the maximum load carrying capacity of the panel for the specific cone design. The anchoring cone was installed in the panels following the same procedure as used for field installation of the D-String® solution, shown in Figure 37. A load was applied directly to the cone similar to the way forces are acting on the D-String® reinforcement. The load was continuously increased until the breaking point of the blade panel. Figure 38 shows the tensile testing machine and the full testing setup.

Figure 37. Anchoring cone in specimen.

Figure 38. Test rig

The direction of the load is shown in Figure 39. The load is a applied to the cone by a perfection loop knot together with a steel pin and a washer have been inserted in the cone, this ensuring an even distribution of the pulling force on the whole cone; Figure 40.

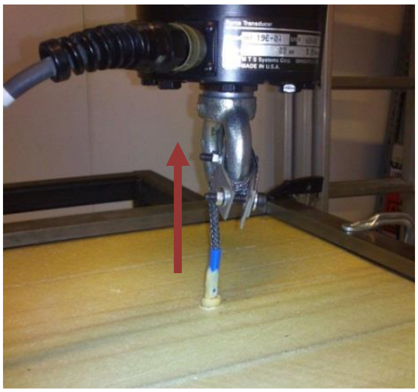
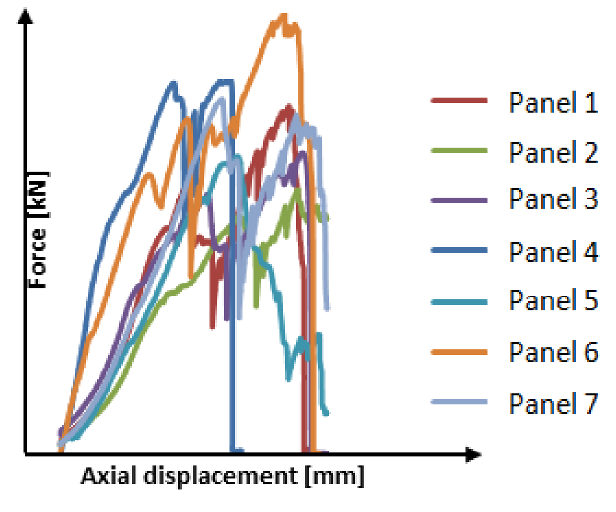


Figure 39. Testing panel detail

Figure 40. Load application

The results from the static tensile tests are shown in Figure 41. The force-displacement curve for the 7 tests is shown in the plot. In the table the load for failure of the panels is shown, the max load is the load as failure occurs. The mean load is the average of max load for all tests and the standard deviation is calculated for all tests.

The static panel test showed that in order to damage occur in a test panel by installing the cone, a force of over 3.5kN is necessary to be applied. It was observed that the core of the panel is breaking in shear not in compression, 90 degrees from the cone exterior surface.



Test	Max load [kN]
Panel 1	3,64
Panel 2	3,17
Panel 3	3,48
Panel 4	5,00
Panel 5	3,98
Panel 6	4,72
Panel 7	4,75
Mean load	4,11
Std. deviation	0,72

Figure 41. Test result from static panel test.

6.2.3 Fatigue panel testing

Fatigue test of the D-String® solution installed in panel specimens from wind turbine blades has been performed. The D-String® is installed in the according to general installations process and the test setup is similar to the static test, except that the load is applied to the actual reinforcement string. The fatigue tests were performed with an excitation frequency of 4 Hz at different loads. The maximum peak load in the load cycle is called F_{max} and the minimum load in the cycle is called F_{min}. The relation between F_{max} and F_{min} is the ratio R=0.1. In Figure 42 is the obtained S-N curve from the fatigue test shown. It is observed that the fatigue limit approximately is at F_{max} = 0.5kN, which is where trend line has a horizontal asymptote, this limit is well above the load measured on the blade in operation in WP2/WP3. Several of the tests specimens experienced 2 million cycles with without any failure of blade panel or D-String® reinforcement. After reaching 2 million cycles the tests where stopped because this is equivalent to unlimited fatigue life.

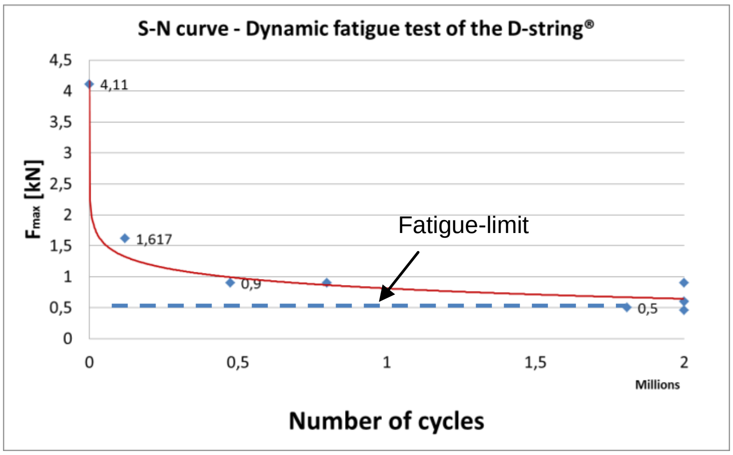


Figure 42. S-N curve for fatigue test.

7 Summary

In the following a short summary from each work package is presented together with a more general summary of the future perspectives related to the outcome of the project.

7.1 WP1

Generic models for life cycle costs of wind turbines, i.e. costs related to inspections, repairs and possible future failures of blades have been developed. Examples were presented to illustrate how the theoretical model can be applied for planning of inspection and maintenance. The owners have provided valuable knowledge and inputs regarding the assumptions and estimation of the different cost parameters used in the modelling. The theoretical models have been well received by the wind turbine owners within the project, who have showed interest in risk- and reliability-based procedures for cost-optimal planning of operation as tool for reduced cost of energy.

7.2 WP2 / WP3

Monitoring techniques have been developed for measuring the effect of the D-String® solution on an operating wind turbine. The methods were demonstrated in field test on a Vestas V80 turbine in Tjæreborg owned by Vattenfall. The measurement confirmed that the D-String® reinforcement is constraining the damaging out-of-plane deformations of the trailing edge panels. The field measurements showed that deformations were reduced by 97 %. Various new measurement systems and techniques i.e. fiber optics were investigate and assessed for their applicability; both for operational monitoring tasks and full-scale certification testing of blades and experimental, destructive testing of sub-structural components. The recommendation and conclusion of this investigation will be used in an ongoing EUDP project 64013-0115 "*Torsional stiffening of wind turbine blades – mitigating leading edge damages*" also lead by Bladena. In that project a recommended fiber optic system is demonstrated on an operating turbine and in full-scale testing.

7.3 WP4

Two new methods for sub-component testing of the trailing edge bondline have been developed at DTU structural laboratory. The new testing methods are developed specifically to simulate the actual loads in the trailing edge bondline on operating wind turbine blades. The methods are used to investigate failure modes as well as evaluating the strength of the trailing edge bondline. Fatigue tests were performed in order to determine the extended life-time of a blade with the D-String reinforcement installed compared to a blade without reinforcement.

7.4 WP5

The patented concept for reduction of the trailing edge panel has within the project been developed to the retrofit D-String® reinforcement solution, which is now commercially available. The functionality of the D-String® has been through an extensive testing program at DTU structural laboratory. The effect of the D-String® has been demonstrated and documented by field testing on an operating turbine. Furthermore the D-String® is now installed on turbines in Europe and United States.

7.5 General summary

The D-String® reinforcement product is now available and ready to enter the market commercially. Although the commercial breakthrough is still waiting, it is expected to happen soon. A strong network has been build-up with service partners (Total Wind Blades, Ropepartner and Broadwind) both in Europe and United States.

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