Requirements Workshop

Report from the Workshop on NDT and SHM Requirements for Wind Turbines

13-14 February 2019

**Offshore Renewable Energy Catapult,
National Renewable Energy Centre, Blyth, UK**

BINDT
THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

...engineering safety, integrity & reliability

Workshop on NDT and SHM Requirements for Wind Turbines

Chair: Robert Smith, Professor of NDT and High Value Manufacturing, University of Bristol, Director of the UK Research Centre in NDE (RCNDE) and Past President of the British Institute of NDT (BINDT)

While a significant amount of non-destructive testing (NDT) is already performed on wind turbines, the sector needs further support in a number of areas. The manufacturers, owners and operators of renewable energy systems seek cost-effective and reliable operation of their installed facilities. Inspection and health monitoring technologies are struggling to adapt to the increasing size and hazardous environment of offshore wind turbines in particular. In order to develop and apply improved solutions, it is essential to identify and define the requirements for the inspection and monitoring of structural components and drive systems. This workshop was designed to facilitate the targeted application of appropriate inspection and monitoring technologies to realise the necessary long-term economic operational performance.

The workshop was designed to bring together stakeholders (regulators, insurers, manufacturers, owners and operators) and the NDT community to:

- Understand the inspection problems faced by the manufacturers and operators of wind turbines;
- Establish the requirements for improved NDT solutions for large thick-section composite structures, metallic components and systems; and
- Consider the application of emerging inspection tools and technologies.

This report forms the main outcome of the workshop and details the presentations and discussions, summarising the requirements identified and what success will look like so that it will be clear when or whether the requirements have been met in the future.

A technical panel from academia and industry convened the workshop, comprising:

- Professor Robert Smith, University of Bristol
- Peter Thayer, UK Research Centre in NDE (RCNDE)
- Dr Richard Freemantle, Wavelength NDT
- Tony Fong, Offshore Renewable Energy (ORE) Catapult
- Tim Camp, LOC Group
- Michael Stephenson, Carbon Trust
- Professor Ian Cooper, TWI
- Robert Ernst, Vestas.

This technical panel was acknowledged and thanked by Professor Smith, Past President of the British Institute of Non-Destructive Testing (BINDT), in his opening remarks, as were the RCNDE and BINDT for making the workshop possible through their support.

Key participants in the workshop represented designers (LOC Group), constructors (Vestas), asset managers (Natural Power, Uniper, etc) and owners/operators (EDF Energy and Uniper). Also represented were academia, High Value Manufacturing (HVM) Catapult centres (National Composites Centre (NCC)) and Catapult centres from the Offshore Renewable Energy Catapult, as well as several NDT equipment suppliers and service providers. A list of the 38 delegates who attended the workshop is given in Appendix A.

In addition to short invited presentations, a key feature of the programme was focused discussion time, facilitated through breakout sessions and panel-led discussions that were carefully recorded and documented. This report provides a summary of these presentations and discussions, with an emphasis on documenting the NDT and structural health monitoring (SHM) requirements identified during the workshop.

Introduction

Professor Robert Smith, University of Bristol

Professor Robert Smith welcomed the attendees, explained the aims of the workshop and presented the programme for the day, which comprised six sessions:

- Session 1 – Understanding the industry
- Session 2 – Design, failure modes and the effect of defects
- Session 3 – NDT, SHM and condition monitoring (CM) experiences from the field
- Session 4 – Potential future NDT and SHM improvements
- Session 5 – Breakout session (four groups of ten, 15-minute rotation)
- Session 6 – Panel session.

Professor Smith informed the delegates that the UK Composites Leadership Forum (CLF) had produced a ‘UK Composites Strategy’ document in 2016 forecasting a potential rise in UK turnover in renewable composites from £601 million in 2015 to between £646 million and £685 million by 2020 and a further opportunity to grow to between £878 million and £1100 million by 2030. The workshop was not solely focused on composites; it was convened to explore the opportunities for composite blade technologies but also to understand the needs of wind turbine structures and drivetrains with a view to determining NDT requirements for this growing sector.

Session 1: Understanding the industry

Wind turbine design drivers

Tim Camp, LOC Group

Tim Camp is from London Offshore Consultants (LOC), which provides technical support to marine renewable energy projects, including marine warranty services for offshore activities. LOC Renewables focuses on offshore wind farm projects. The company's skillsets include naval architects, master mariners, marine and mechanical engineers, civil and structural engineers, etc, and it designs support structures as well as providing wind resource assessment and wind turbine performance assessment.

Recent growth in the wind turbine sector has occurred due to the move offshore. The high cost of positioning a wind turbine offshore means that it makes economical sense to install as big a turbine as possible to offset the balance of plant costs, hence the growth in scale. The GE Haliade-X (12 MW) is nearly as tall as the Eiffel Tower, with a blade length of 107 m (*cf* Airbus A380 wingspan of 80 m). These blades break the mould for aerodynamics and composite construction; 370 tons of air passes through the diameter of such a turbine every second (equivalent to the mass of 50 London buses per second!).

This presentation addressed design drivers for wind turbines. External conditions combine with a given design situation to give a 'design load case'. In the load case of normal conditions and normal operation, wind turbines are basically 'fatigue machines': their performance is limited by cyclic fatigue loads rather than static loads. They are flexible, dynamically active structures with multiple modes of vibration, stimulated by stochastic aerodynamic and hydrodynamic loads. This drives the design of much of the structure. It is important to avoid exciting resonance frequencies in the structure, which would significantly increase the strains. Modelling is used to simulate time histories of fatigue loading according to realistic fatigue spectra. Fatigue drives the design of the hub, mainframe, tower welds, grouted joints, support structure joints and rolling elements (bearings/gears).

In extreme conditions (sea or wind) but with normal operation, the design standards combine the 50-year return of environmental conditions with a normally operating or idling turbine. Such extreme loads drive the design of blade-tower clearance, tower buckling and foundation design, etc. Extreme waves drive the air-gap requirements (distance from wave to the platform at the base) and (possibly) foundation strength.

Finally, annual return external conditions combine with fault states of the turbine (such as sensor/actuator faults). Other possible design drivers, which are not covered by formal design load cases, include corrosion, scour of the seabed around the structure, lightning strike (although there are conductors and studs for protection) and leading-edge erosion (80-90 m/s velocity), which constrains blade-tip speed and makes drivetrains more expensive.

Relevant design standards are numerous and were listed, but there is an increasing trend for harmonisation of these standards:

- IEC 61400-1 'Wind energy generation systems – Part 1: Design requirements'
- IEC 61400-3-1 'Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines'
- DNVGL-ST-0437 'Loads and site conditions for wind turbines'
- DNVGL-ST-0126 'Support structures for wind turbines'
- DNVGL-ST-0361 'Machinery for wind turbines'
- Deutsche Institut für Bautechnik (DIBt) 'Guidelines for loads on wind turbine towers and foundations'
- DS4 72 'Load and safety for wind turbine structures'
- NEN 6096 'Safety requirements for wind generators'
- ABS 195 'Guide for building and classing floating offshore wind turbine installations'
- And others…

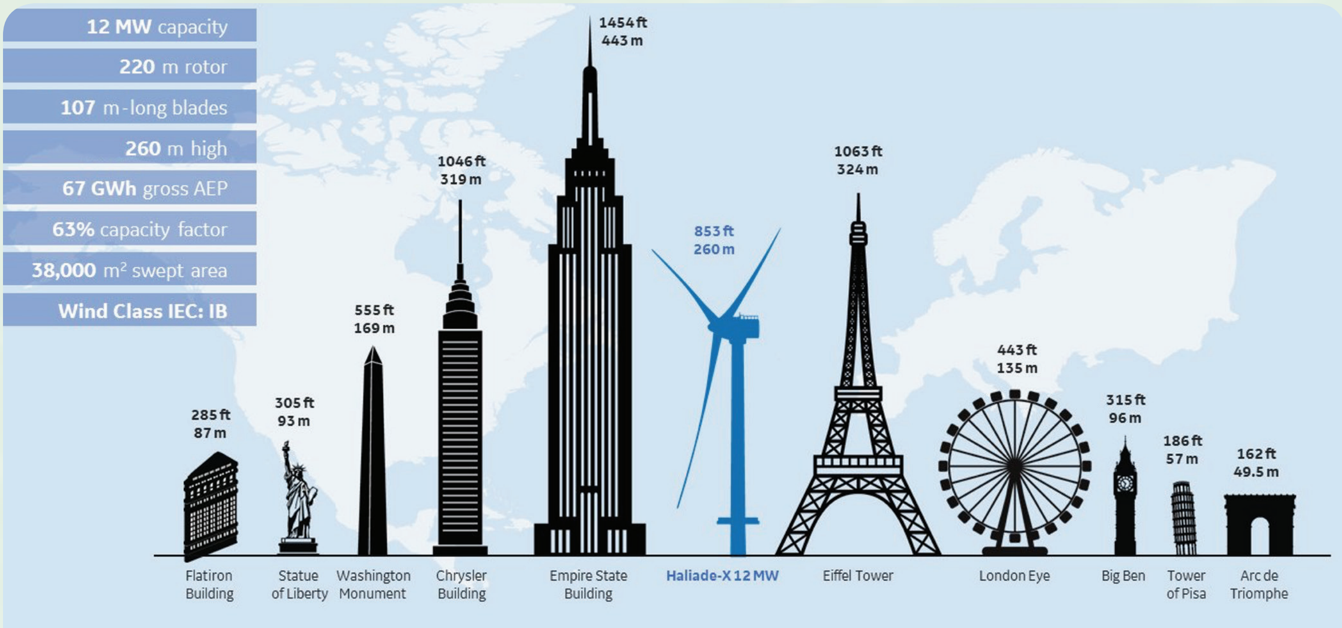


Figure 1. Comparison of the GE Haliade-X 12 MW wind turbine with other well-known structures

In terms of drivers for NDT and SHM, there is a rising number of first-generation onshore wind turbines reaching 20 years of age (usual safe life) and owners are showing greater interest in understanding the residual life and value of their assets and what their options are for continued operation in terms of life extension, adaptations or decommissioning/repowering. The best approach to take is not well understood in the wind sector. There are a number of options, such as: (1) a numerical approach with a digital twin model for simulation with on-site wind speeds to estimate a value for fatigue life; or (2) no modelling but basing life estimates on inspections with NDT to estimate the health; or, more likely, (3) some combination of the two, though such a combination is a challenge that has not yet been addressed.

SHM should be installed well before the end of the safe life but best practice is not well defined in the wind industry, so there is room for developments in this space.

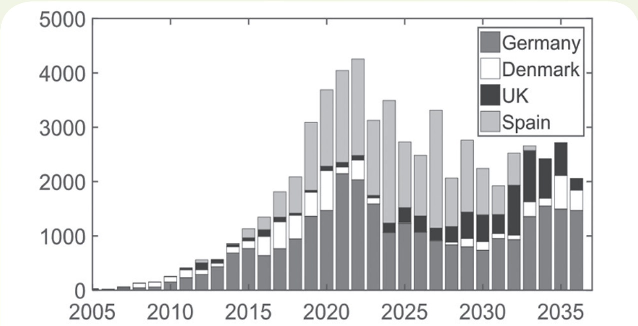


Figure 2. Number of onshore wind turbines reaching 20 years of age

Within the questions at the end of this presentation, Tim was asked whether there are any legal constraints on the continued use of a wind turbine beyond the safe life. He said that there could be constraints on the land lease but not on structural condition (in the UK), other than normal health & safety requirements. However, in other countries there are legal checks required on the structure, which are performed by a third party.

There was a question on the validation of the modelling through, for example, instrumentation of a tower. There have been a number of heavily instrumented prototype wind turbines but there is a shortage of shared databases, so accessing the data is difficult unless as part of a collaborative research programme.

Tim was asked how improved information about the health of a structure, or conformance to design, would provide benefit and what would be the result for designs. There are a number of conservative elements in the design process and if there was better NDT information about defects in a structure then the safety factors would decrease while maintaining the same safety levels, which would result in lighter structures. So, there is a constraint on weight due to having insufficient information from NDT. Being able to reduce the mass of the rotor nacelle assembly would be especially beneficial as this would allow for the design of a less stiff support structure; tower-top mass is expensive.

When asked about the digital twin idea, Tim said that DNV GL has developed a digital twin model but it is important to recognise its limitations because it only includes the information that has been input. The most important part, the turbine model, including the aerodynamics, blade and control systems, would only be accessible by agreement with the turbine manufacturer. For owners, important datasets include the on-site wind speed measurements and the turbine supervisory control and data acquisition (SCADA) system data.

Drivers for manufacture

Robert Ernst, Vestas

Robert Ernst works in the blade department for Vestas, a wind turbine manufacturer, and was representing the manufacturing community. In late 2018, Vestas reached a milestone of 100 GW of installed wind turbine power-generation capacity – 10% of the world's total 1 TW of installed wind and solar energy capacity[1]. Since 1979, the basic wind turbine generator design has grown in size by a factor of 8 (see Figure 3).

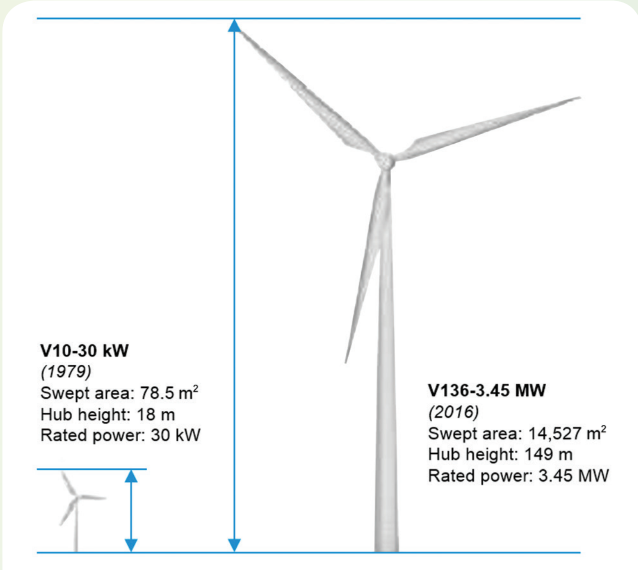


Figure 3. Evolution of wind turbine generators. One Vestas V136 is generating the same amount of power as 115 Vestas V10s

The market is still growing, with a high demand for both onshore and offshore wind turbines. What has changed is the way they are being sold: eAuctions and early selling are the new defaults. This means that manufacturers have to commit to customer requirements before the product is fully developed. This challenges engineering and means design margins are becoming tighter. Positively speaking, this has improved the competitiveness of the wind energy sector over other power-generating industries but it also means that the tolerance for manufacturing deficiencies has decreased.

Typical manufacturing flaws include: irregularities in bonded joints, air inclusions, snow-flaking (dry laminate), wrinkles/ply waviness and delaminations, etc. This presentation looked into the processes of monitoring bond and laminate quality.

Bond integrity is currently ensured by semi-automated ultrasound testing. A system developed by FORCE Technology, consisting of a mobile array of single-element low-frequency ultrasonic probes, is scanning every blade. Even though this technique is semi-automated, it takes a significant amount of time, making it an expensive process. Consistent coupling to the non-plane curvature is a fundamental challenge in this process. Data analysis is computer assisted and sourced centrally in a data centre away from production.

From an NDT point of view, the obvious challenge is to find a compromise in ultrasound frequency. The most important information from the scan is the backwall echo, which is behind several centimetres of glass fibre-reinforced polymer (GFRP). Here, attenuation and signal-to-noise ratio (SNR) becomes an issue. On the other hand, information from the plies between the back wall and the transducer is impaired by the low frequencies. A way of improving the temporal resolution in thick composites is a key requirement. Additionally, consistent coupling of the transducers to the blade is crucial. Due to the size of blades and high volume of blade production, transducers are swiped over impressive distances and wear becomes an issue.

Another important area of NDT in blade production is wrinkle detection. This is currently carried out through visual inspection only. Surface irregularities are compared with zonal charts showing allowables for different zones in the blade. This comes at the risk of overlooking wrinkles that do not cause a surface bump. Typically, these wrinkles are of steep curvature and imply a high reduction in strength.

Different techniques are suggested for the detection and qualification of wrinkles. Most of these techniques are sensitive to typical wrinkle 'side effects'. While these side effects are detectable with traditional NDT techniques, they are not the driving parameter for the reduction in strength. Wrinkles may come along with surface bumps, varying ply spacing, resin pools and changes in local stiffness. These characteristics can be detected through visual inspection, ultrasound due to the sound speed variations, ultrasound due to reflections on resin pools and guided waves, respectively. Strength-wise, however, the important parameter is the curvature of the fibres. Very few methods are sensitive to this parameter. One exception is a technique currently developed by Professor Smith's group at the University of Bristol. The technique involves 'tuning' ultrasound frequency into the periodic structure of the laminate and can recover the curvature of the fibres from the phase information of the received signal. While this technique has shown good results in aerospace, Vestas is collaborating with the University of Bristol in adapting the method to the peculiarities of wind-grade GFRP.

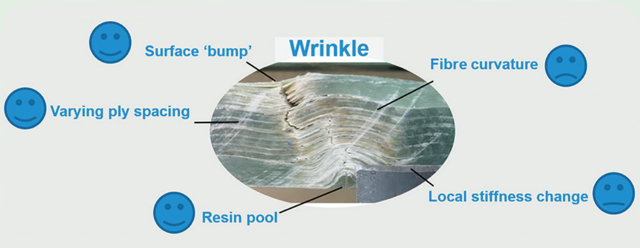


Figure 4. Wrinkle features. A critical parameter is fibre curvature, which is typically difficult to determine non-destructively

Drivers for operators and owners of onshore/offshore wind turbines

Andy Morris, EDF Energy

Andy Morris presented a view on behalf of EDF Energy Renewables on the challenges faced by the operator, with some recent examples of in-service failures. Andy initially explained EDF's journey to accelerate the development of renewables generation, which most recently has led to the construction of five large (8.3 MW) gravity base foundation wind turbines off the coast at Blyth. Further large-scale offshore projects are currently under development off the coast at Fife and three wind farms off the French coast. Andy emphasised the importance of ensuring that adequate design assurance is in place at all stages, from the design phase and into service; this was emphasised by way of examples.

The first example illustrated the importance of ensuring that sufficient diligence on original design is carried out. The space frame structure installed inside the tower on offshore wind turbines to support the transformer, switchgear and other equipment suffered from extensive cracking after only a few months of generation. The subsequent remediation took a considerable amount of time to resolve, requiring technical support and close collaboration with the original designer. This required the use of traditional non-destructive evaluation (NDE) ultrasonic inspection techniques on key structural members, coupled with the installation of additional accelerometers on the structure, with significant analysis and ultimately a redesign of the internal space frame. The root cause of the problem was attributed to insufficient scrutiny of the original fatigue assessment of the structure in the design phase, coupled with poor installation practice.

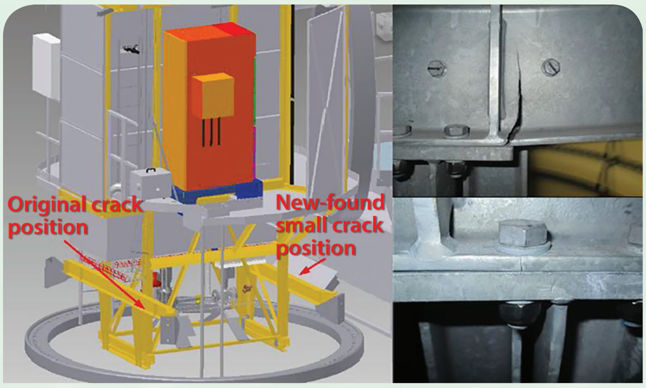


Figure 5. Internal space frame cracking

Other examples included wind turbine blade failures for both vintage and more modern blade designs, which emphasised the difficulty in arriving at a conclusive root cause assessment in every case. One of the failures discussed on a vintage blade was conclusive and attributed to defects initiating from previous repair locations. Blade inspection and assessment continues to present a challenge in striking the right balance between inspection technique, inspection periodicity and criticality with respect to recommendations for repairs.

Examples of the use of inspection methods and procedures, along with the development and implementation of structural health monitoring transfer functions through to life assessment models on thermal plant, were provided. This concept was used to explain the benefits of adopting practices from other industry sectors that could be considered as well established and transferable to the renewables sector. Andy concluded by summarising current challenges and misconceptions regarding NDT and SHM and again emphasised the importance of applying appropriate NDT/SHM methods throughout the complete lifecycle, from the initial design concept and testing stage through to cost-effective and informative in-service condition monitoring.

Figure 6. Example of a recent blade failure

Drivers for innovation

Andrew Tipping, ORE Catapult

Andrew Tipping gave an introduction to the ORE Catapult and some background on the industry and the aims of the Catapult, which is one of ten in the UK and has seven centres, including the one at Blyth where the workshop was held.

Drivers for non-destructive testing

The main driver for innovation in offshore wind is cost reduction, as developers compete to secure projects in competitive auctions. Due to this there has been a trend over the past decade towards larger turbines, increasing the power generated per offshore turbine from 8 GW now to 30 GW by 2030. It is expected that there will be 4000 offshore turbines by 2030 (there are currently 2000), while onshore turbine numbers are unlikely to grow further. There has also been a trend towards 'smarter' farms, *ie* wind farms that make decisions based on data and analytics. Larger, smarter turbines drive down the levelised cost of energy (LCOE), in £/MW, but increase the risk and cost of failure. Unplanned maintenance can cost upwards of £16,000 a day in vessel operation, £50,000-£100,000 in replacement parts and repairs and then £9,000 a day in loss of revenue from power production. This is exacerbated by delays due to weather and lead time on replacement parts and can cost many hundreds of thousands of pounds per failure.

Figure 7. Cost reduction is the main driver for innovation in offshore wind

Operators are therefore moving towards improved reliability testing of components, using an increased number of sensors, condition monitoring, data analytics and remote inspection tools to predict the condition of turbines and optimise and maintain them. This allows for increased reliability and potentially results in the life extension of assets.

Health & safety offshore is also a big driver for NDT. Increased reliability reduces the need for maintenance in often harsh conditions offshore. Also, increased autonomy and remote monitoring reduces the need for technicians to be working at height/with roped access to monitor and maintain the structures. NDT technology enables safer working practices while broadening the weather conditions under which inspections can be carried out.

Requirements and innovations in NDT

Some of the key innovations in NDT are in sensors and condition monitoring. The data available through condition monitoring, sensors and remote inspection are increasing year on year. This, along with reliability testing and commissioning, allows original equipment manufacturers (OEMs) and operators to analyse failure modes and increase revenue through optimised maintenance.

Another key innovation is in robotics and remote sensing. For example, key components such as blades can be inspected using X-ray backscatter, ultrasound or electromagnetic waves, such as infrared or light systems. These sensors, deployed on drones or robotics, can provide insights concerning the level of degradation on components without accessing the turbine. Some operators are moving to systems where remote inspection can be carried out without needing to turn the turbine off, thus increasing revenue further.

The last key innovation is in algorithms and data-based decision-making to improve the optimisation and maintenance of wind turbines. These algorithms improve with the data provided from sensors, inspections, reliability testing and computer models. Data-based decision-making can drive down running costs and failures and improve the lifetime of existing assets.

The Catapult can provide valuable insight to innovators in offshore wind. Their extensive knowledge on testing methodologies and standards helps developers to test their new devices. The Catapult also provides industry requirements and needs for sensing and monitoring systems, driving the user needs to the service providers and spurring innovation in the sector.

Figure 8. One of the key innovations is in robotics and remote sensing

Session 2: Design, failure modes and the effect of defects

Design drivers for long-term management

David Thompson and Tony Fong, ORE Catapult

Long-term management for an offshore wind turbine can be described as the evaluation of real-life conditions against original design assumptions and the managing of discernible variations. Such comparisons can include environmental and weather conditions, operating regime, structural static and dynamic response, material degradation, manufacturing defects, commissioning non-conformances, etc.

The long-term management of assets may be either a requirement or optional. Mandatory requirements such as legislation and commercial or financial agreements may impose the need for management on asset owners. An example of such is under which the consent conditions for the wind turbine have been granted or the certification criteria for the asset provided. In Germany, there are requirements for a minimum number of turbine structures to be monitored and data provided to the consenting authority. Other reasons for long-term management may be non-mandatory, such as to support operational strategic decision-making on the running of the asset to maximise its performance, to justify the integrity of the asset for life extension or perhaps to enable future design optimisation.

Despite the numerous reasons for undertaking through-life management, a key number of factors can be identified when considering the integrity of the offshore structure. The industry design standard for offshore wind turbine structures is DNVGL-ST-0126 'Support structures for wind turbines'. The typical design approach applied is the load resistance methodology, whereby a structure is designed and evaluated in its ability to safely resist foreseeable load cases across its operational life. In the early stages of design, assumptions and estimations are made as to the loads experienced by the structure, as well as its ability in resisting these loads. Once the design is operational, an evaluation of the early assumptions, as well as the actual response of the structure, can be undertaken. The categories of load and resistance assumptions from the standard highlight several key areas for consideration in long-term management.

A prime example of long-term management is the evaluation of foundation integrity of an offshore wind turbine. Monopile foundations are among the most common foundation structures within the industry and consist of a steel pile embedded into the seabed, supporting a transition piece that interfaces with the turbine above. These structures are predominantly fatigue driven due to the cyclic loading experienced. As such, the determination of remaining useful life is becoming a prevailing topic of interest for the industry due to an increasing number of ageing assets. Monopiles (and foundation structures) are usually a safe-life design, in that they are designed to operate for the life of the asset without the need for planned maintenance. However, a number of incidents across the sector, including manufacturing defects, unexpected internal corrosion, excessive scouring of the seabed and turbine up-rating, have led to the need for reassessment of fatigue life using measured data and hence through-life management.

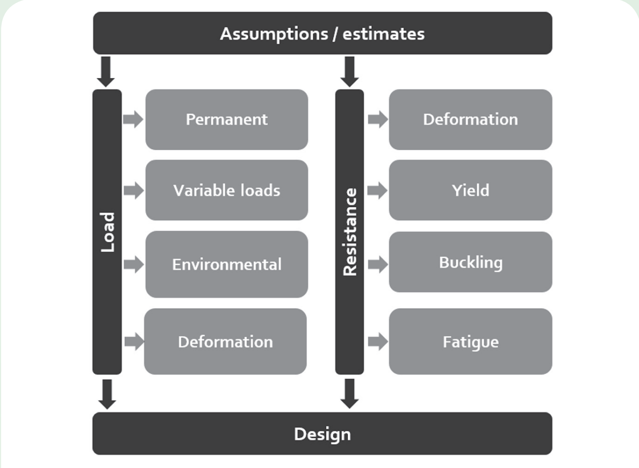


Figure 9. In the early stages of design, assumptions and estimations are made as to the loads experienced by the structure

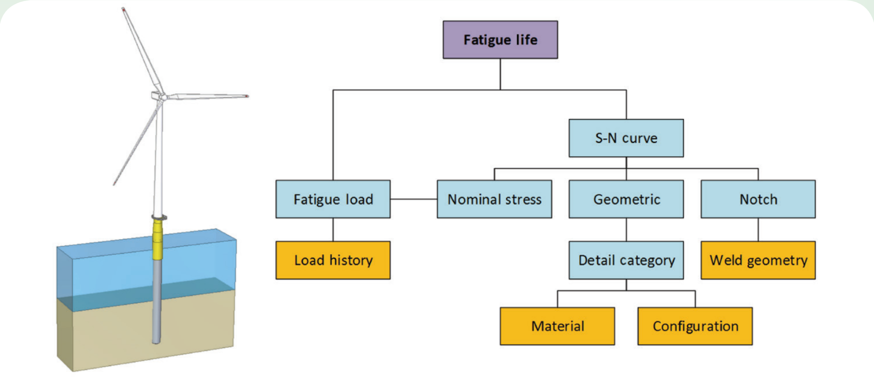


Figure 10. Various parameters affect the fatigue life of the asset

A typical fatigue design for a monopile structure utilises fatigue (S-N) curves, which correlate a given stress with an acceptable number of cycles. Through the life of an asset, an update on the fatigue load can be obtained through structural monitoring (*ie* strain gauging and accelerometers) and the fatigue life re-evaluated. Other factors are the material used, the configuration of joints and details of specific welds. These parameters are specific to each asset as the material and weld parameters should be inclusive of any corrosion detail and the weld geometry and joint categories should account for as-manufactured conditions.

If a design assumption in one of these areas is discovered to be non-conservative, there is often a task of validation of structural integrity, which involves assessing the other driving factors to counterbalance the negative impact in one area by using the conservative margins from another. Therefore, there is a requirement to understand the real conditions of any structure concerned in order to justify its safe continued operation.

This example highlights the importance of SHM and NDE of offshore structures for the purpose of integrity management. As this is a new area of offshore engineering and design standards are still evolving with experience, the ability to quantify and measure the real characteristics of an offshore structure is necessary for the validation of structural integrity and the through-life management of modern wind turbine structures.

Failure analysis of offshore wind turbine monopile foundations

Dr Ali Mehmanparast, Cranfield University

Dr Ali Mehmanparast is a Senior Lecturer in Structural Integrity at Cranfield University and Manager of the REMS Centre for Doctoral Training. His presentation focused on the types of failure experienced by the monopile foundations of offshore wind turbines.

The majority of offshore wind turbine (OWT) foundations are made of monopiles (Figure 11). These structures are fabricated by welding thick plates in the longitudinal direction to make individual cans and then welding the cans circumferentially to produce a full-length monopile structure (Figure 12). Operating in a very harsh offshore environment, OWT foundations are subjected to corrosion damage and cyclic loading conditions. Therefore, corrosion fatigue is known as the dominant failure mechanism for these structures. Due to the lack of sufficient experimental data on OWT monopiles, the Structural Lifecycle Industry Collaboration (SLIC) Joint Industry Project (JIP) was formed to investigate the structural design and integrity enhancement of monopile structures and eventually reduce the levelised cost of offshore wind energy. The corrosion fatigue crack growth behaviour of monopile weldments was extensively investigated in this project by performing fracture mechanics tests on compact-tension specimen geometry with the notch tip located in the base metal (BM) and the heat-affected zone (HAZ).

Figure 11. A typical monopile foundation

Comparison of the experimental results with the recommended trends in the BS 7910 standard has shown that the simplified and two-stage fatigue crack growth trends recommended in BS 7910 can provide conservative estimates of the fatigue crack growth rates in monopile structures. Moreover, the experimental results have revealed that the environmental reduction factor (ERF) can on average be around 2, which is 50% lower than the ERF value recommended in BS 7910. Preliminary studies have been performed on residual stress measurements in monopile weldments using destructive (for example contour method) and non-destructive (for example neutron diffraction) techniques. The results show that residual stress values can be quite significant around the weld toes in monopile structures. This implies that the welding residual stresses must be measured and accounted for in the structural integrity assessment of these structures. Further studies need to be performed in future work to account for welding residual stresses in the structural integrity assessment of monopiles, as well as developing effective inspection plans for life estimation/extension of these gigantic structures.

Figure 12. Monopile foundations can be up to 10 m in diameter

Risk and asset management

Daryl Hickey, Natural Power

Daryl Hickey is a Senior Inspections and Reliability Engineer with Natural Power (NP), a leading independent renewable energy consultancy and service provider. NP offers proactive consultancy, on-site management and due diligence services, backed by an innovative product range, across the onshore wind, offshore wind, solar and energy storage sectors. Daryl takes a leading part in the technical and innovation side of the NP inspections team. He has conducted more than a thousand drivetrain inspections and has been involved in more than twenty end-of-warranty inspection campaigns. He is also heavily involved in troubleshooting and analysis exercises on turbine main components, mechanical and hydraulic systems, SCADA and energy management control systems.

Predictive maintenance

A predictive maintenance approach to inspections means that damage and defects on a wind turbine generator (WTG) can be detected, categorised and quantified and damage progression can be tracked so that operators can plan scheduled maintenance ahead of catastrophic failure and during periods of low power production. This minimises downtime and reduces the number of major component replacements. By adopting this approach to monitoring, a good reliability engineer will add value to a client by uncovering minor, stand-alone or serial defect issues affecting the efficiency of a WTG. The flowchart in Figure 13 demonstrates a good approach to inspecting the turbine through all available data and attempting to isolate maintenance to up-tower, as much as is reasonably practical.

It is important to note that failure is a process and not a single event. The optimum window for fault detection is right after the beginning of fault propagation and before serious wear and secondary damage occur. For example, as a bearing fault starts to grow, more and more wear debris is shed, which is carried by the lubrication system. Debris particles travelling through the gearbox, where they can find their way into other gear and bearing designations, usually cause further damage, escalating the repair costs. For an owner/contractor, avoiding this secondary damage is key to saving money.

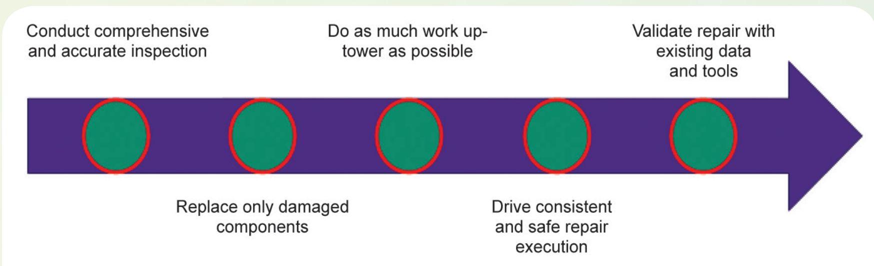


Figure 13. Flowchart demonstrating a good approach to predictive maintenance

The ultimate goal is to be able to utilise a good maintenance and inspection programme coupled with excellent data analysis and combine the results to predict damage, schedule repair accordingly in times of minimum production and availability and avoid high maintenance costs and secondary damage. This would be the ideal solution to the headache of crane costs and unplanned downtime.

Tools for fault prediction and inspection

SCADA systems on modern wind turbines usually incorporate computing power and storage of the output from numerous sensors, including capacity factors and wind speed, tower oscillation, particle counting in gearbox oil and temperature analysis on the rotor bearing, gearbox bearing, generator bearing, gearbox oil sump and control cabinet. Analysis of all of this data, as well as yaw and pitch analysis and power analysis, provides a considerable amount of information that is useful in fault detection and predictive maintenance.

In terms of vibration analysis, limits specified in VDI 3834 state that an RMS vibration velocity of 3.5 mm/s (10-1000 Hz) is the warning alarm level for the gearbox of an onshore wind turbine up to 3 MW and requires the turbine to be inspected. A higher level of 5.6 mm/s RMS requires the turbine to be shut down. Similar limits are set for the nacelle and tower, the rotor and bearing and the generator and roller bearing.

Inspections are carried out up the tower as much as possible to minimise the costs of a crane and these include endoscopic gear and bearing inspections, with bearing features classified to ISO 10825, visual inspections and thermographic inspections, preferably when the turbine is running. At present, NP does not really use NDT; however, it is keen to learn what can be offered to help with asset management.

Managing blade integrity – guidance on allowable defects

Peter Greaves, ORE Catapult

Peter Greaves, from the ORE Catapult, presented on a methodology for ensuring blade integrity. He started by explaining that the primary function of a wind turbine blade is to capture the wind and transfer the load to the shaft. This creates a bending moment on the root bearing and a torque on the main shaft. A blade is a large cantilever beam, which is primarily loaded in two ways. Flapwise, or out-of-plane, bending loads arise from aerodynamic forces and edgewise, or in-plane, bending arises from the blade's own weight.

The blade structure is designed to resist these loads while having a shape that is as close as possible to the optimal aerodynamic shape. The suction-side and pressure-side shells are large aerodynamic panels designed to 'catch the wind' and transfer the loads to the spar caps. They are typically moulded in two 'blade shell' tools and adhesively bonded to each other along their leading and trailing edges and to the spar caps in the middle (see Figure 14). Shell skins are thin, lightweight glass fibre and need to be stabilised by the use of a lightweight core to prevent buckling. The shells are bonded together at the leading and trailing edges. The spar caps are generally made of uniaxial material placed at the thickest part of the section to maximise their contribution to the bending stiffness. The shear webs transfer the forces between the spar caps and are typically made of biaxial fabric with a core material.

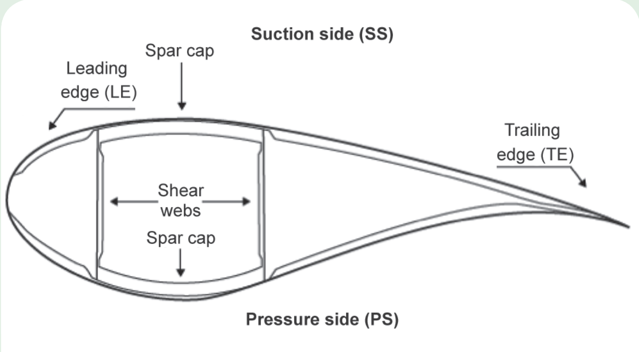


Figure 14. Cross-section of a wind turbine blade showing components referred to in the text

There are five main failure modes that occur on wind turbine blades: buckling, bondline failure, skin debonding, interlaminar failure and strain-based failure (see Figure 15). Buckling is a non-linear in-plane stability phenomenon. It can be predicted by non-linear finite element modelling (FEM) using a combined loading case for both numerical simulations and testing will capture the phenomenon.

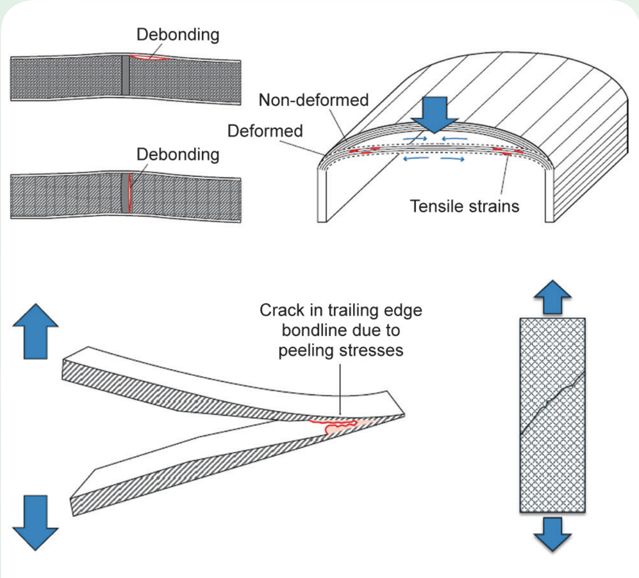


Figure 15. Failure modes: skin debonding and interlaminar failure (top), trailing-edge bondline failure (bottom left) and in-plane strain-based failure (bottom right)

Bondline failure often occurs at the trailing-edge joint, which will be forced to open and close as the gravity and aerodynamic loads interact, causing the hollow blade structure to 'breathe'. This creates a peeling stress at the trailing-edge adhesive joint.

Skin debonding and interlaminar failure refers to the detachment of the skin from the core material or through-thickness failure of the laminate. Full-scale or subcomponent testing can be used to capture this; it occurs because the panels are being bent by transverse stresses.

Strain-based failure is rare if a blade has been properly designed, because in-plane failure of the laminate is considered right from the start of the design and validation process.

Apart from in-plane strain, these failures are all driven by deformation of the blade cross-section. When the blade is loaded in combined bending and torsion it causes the panels of the blade to bend, which drives interlaminar failure and stresses the bondlines.

Without detailed knowledge of the blade structure and the materials used, it is not possible to decide whether a given defect will grow using simulation. For this reason, experience can be used to decide if a defect of a given size needs to be repaired immediately or if it can be left for longer. The Next Generation Inspection Report (compiled as part of the EUDP Project LEX and EUDP Project RATZ) gives detailed information on how to assess the severity of damage for different blade architectures. It also gives an industry-standard photocard for documenting damage (see Figure 16).

A question was asked about whether these failure modes are seen in static testing. Peter said, in response, that some of this is seen in testing and some is not, depending on the test type.

Inspection approaches and machine learning for wind turbine integrity

Daryl Hickey, Natural Power

Research and development within wind turbine inspections is largely driven by the necessity for speed and cost. It may seem obvious, but unplanned turbine downtime is not acceptable within any business model. The large costs incurred in any inspection campaign lie in the deployment of personnel, production losses during downtime, the equipment required for inspections and the time taken to analyse data and produce reports.

The Natural Power inspections department has attempted to address some of these cost issues for their clients by introducing its drone programme to the market. The innovative method that Natural Power has adopted uses state-of-the-art on-board technology that allows the drone to fly a blade inspection campaign

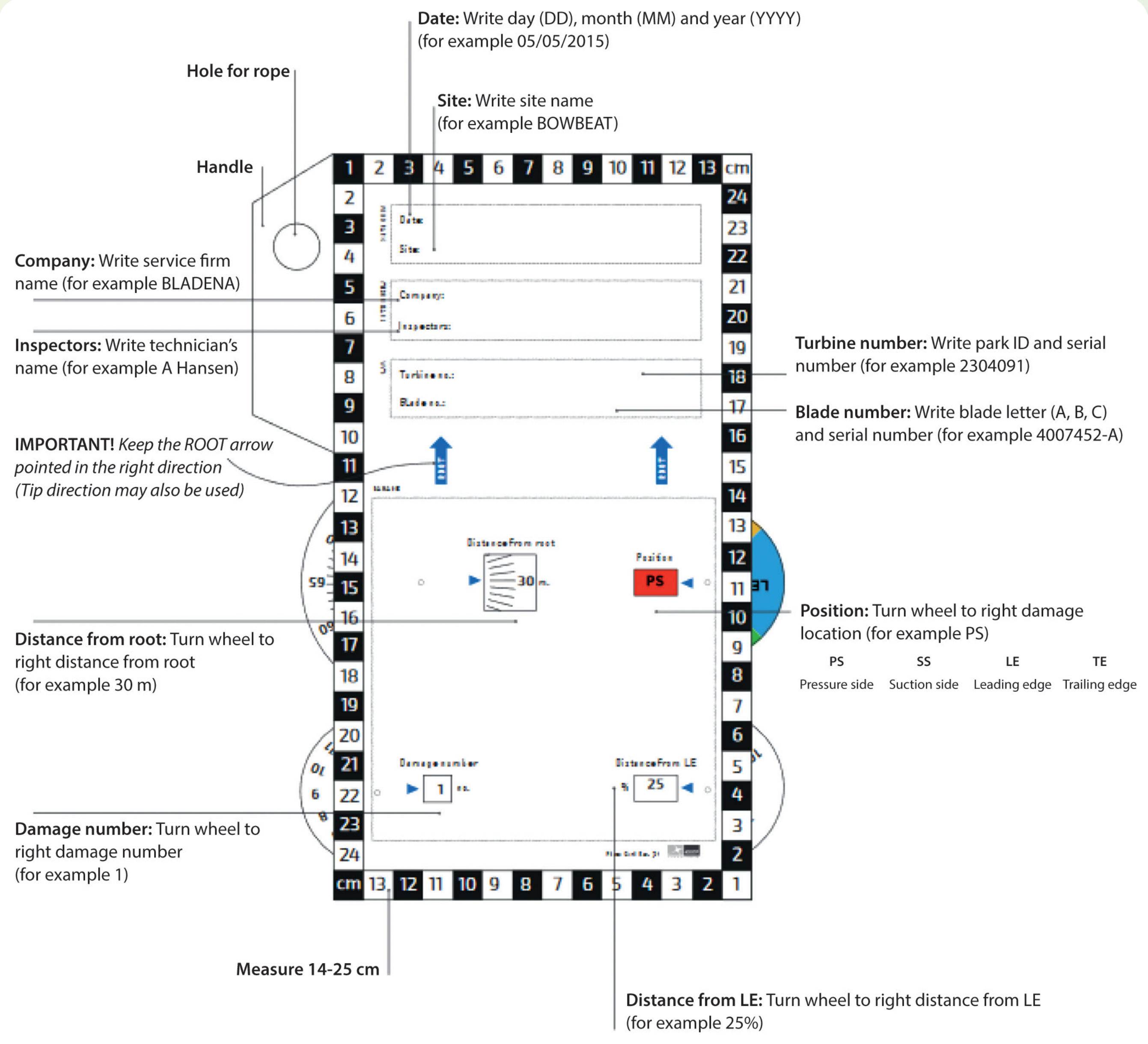


Figure 16. Industry-standard photocard for documenting damage

autonomously (see Figure 17). The software technology ensures that the drone flight sensors can interface with the on-board camera to make sure that the correct distance from the blade is always maintained to achieve good focus and capture good images of potential defects. This autonomous approach provides an enhanced inspection speed and thus reduces the turbine downtime issue. Regarding the offshore blade inspection market, time benefits are further gained by the removal of personnel transfer from the vessel to the turbine transition piece. All inspections can be conducted from the vessel. It is vital to point out that legislation permits the process to be completely automated with an auto-pilot, provided a suitably qualified pilot can take back control of the drone to take evasive action to avoid any form of accident.

Figure 17. Drone visual inspection

The data that is captured by the sensors is processed using machine learning tools to assist the inspector in making decisions on damaged areas of the blades. Machine learning in the form of a convoluted neural network algorithm has been trained to decide between a defect-free and defective portion of an image and the team of blade analysts can then make categorisation decisions. This further benefits the client by driving down the cost of reporting and allowing technological advances in computer programming to assist the Natural Power team.

Session 3: NDT/SHM/CM experiences from the field

NDT standards and best practice guides

Dr Richard Freemantle, Wavelength NDT

Dr Richard Freemantle from Wavelength NDT focused on the inspection of composite wind turbine blades. There is already a significant body of high-level guidance documentation, including from DNV-GL (www.dnvgl.com), which Richard presented.

Concluding that the level of detail in NDT standards and methods needs some development, Dr Freemantle noted that the words 'inspection' and 'surveillance' are used interchangeably, with NDT usually mentioned for welding but rarely for composites. There is an implied use of NDT to support life extension in one document. There is a comprehensive guideline covering CM but not a similar one for NDT. The IEC 61400:22 standard has been withdrawn and split up into numerous documents (see Table 2) and opportunities exist for an NDT guidance document to be inserted. Another standard, IEC 61400-23, deals with full-scale structural testing of rotor blades and contains a list of useful NDT methods.

Table 1. List of relevant guidance documents and standards

DNVGL-SE-0073	Project certification of wind farms according to IEC 61400-22
DNVGL-SE-0074	Type and component certification of wind turbines according to IEC 61400-22
DNVGL-SE-0190	Project certification of wind power plants
DNVGL-SE-0263	Certification of lifetime extension of wind turbines
DNVGL-SE-0436	Shop approval in renewable energy
DNVGL-SE-0439	Certification of condition monitoring
DNGVL-SE-0441	Type and component certification of wind turbines
DNVGL-ST-0262	Lifetime extension of wind turbines
DNVGL-ST-0376	Rotor blades for wind turbines

Table 2. List of IEC-RE documents into which IEC 61400-22 has been split

OD-551-14 ed.1.0	Blades testing assessment – 2016 type certification
OD-502 ed.1.0	Project certification scheme
OD-501-1 ed.1.0	Conformity assessment and certification of blade by RECB

Dr Freemantle then presented some examples in which comprehensive guidance would help; they were all ultrasonic techniques but he emphasised that SHM and CMS methods are required to target these methods because applying them alone is expensive and time consuming, particularly for in-service inspections.

Case study 1 – wrinkles

This is based on Dr Freemantle's own experience of inspecting for wrinkles, which is usually performed at the request of the blade manufacturer. Often a specification on wrinkle evaluation (usually based on micrograph work) is available, but there is limited modelling and test data to guide the establishment of the acceptance criteria for each parameter and for each design of blade. Dr Freemantle had full access to the manufacturer's NDT Level 3 and their production NDT procedures, but there were no existing methods for wrinkle detection or evaluation. Previously verified aerospace methods were successful on test coupons used for qualification for the evaluation of low to moderate waviness severity (see Figure 18). However, they were not successful on high-severity wrinkles. This was due to the limitation in amplitude sizing of high-angle wrinkles, which led to the underestimation of ply angle. Ideally, actual blade parts should be used for validation and qualification work as there is a risk associated with coupons, which are often of a higher quality than the actual blade material and do not replicate the actual wrinkle geometry.

The key challenge is finding methodologies for deriving stress- and design-calculated acceptance criteria for wrinkles using mechanical testing and/or finite element modelling. Access to this information helps to ensure that the NDT method (ultrasound or otherwise) is able to measure the required parameters over the full measurement range.

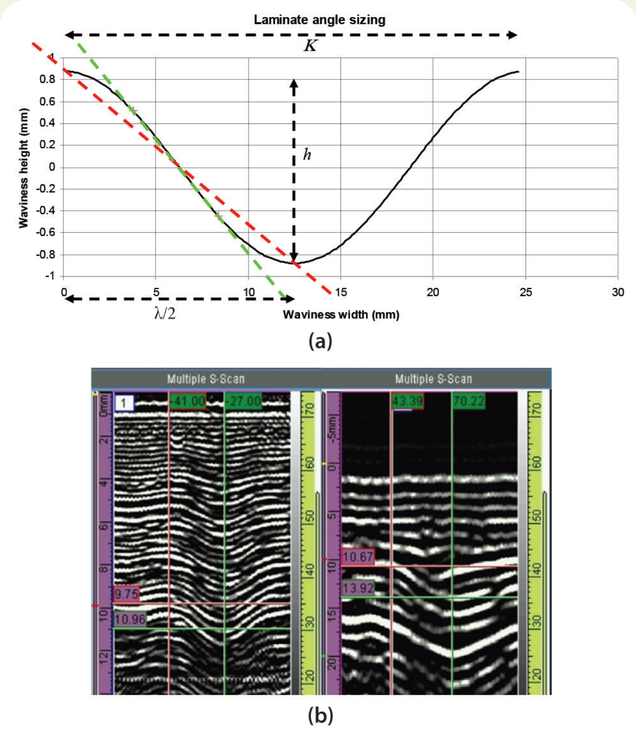


Figure 18. (a) Diagram showing waviness parameters; and (b) waviness imaging of CFRP aerospace laminate at 5 MHz (left) and GFRP wind turbine laminate at 1 MHz (right)

Case study 2 – bonding

In this case, the NDT was requested by the wind farm operator, who was interested in blade life extension. Communication with the blade manufacturer was limited and there was no access to the blade drawings, production NDT reports or test samples. While this was not ideal, the wind farm operator had performed some engineering analysis to establish the level of disbonding that would be acceptable. There was enthusiasm to conduct destructive trials on previously failed blades and these were inspected to assess and validate the NDT method. This gave confidence to conduct some inspections aloft to further evaluate the benefits of the NDT and to understand the timescales and access issues. It is likely that more of this type of work will be required in the future to support life extension programmes. The challenge here is that manual NDT inspections, such as ultrasound, can be very difficult to perform aloft and the area that can be covered in a typical shift pattern is relatively small, if the intention is to inspect whole sections of the blade. Strategies such as visual inspection, risk-based approaches and targeted NDT based on detailed design and production information from the blade manufacturers would help to reduce the inspection time.

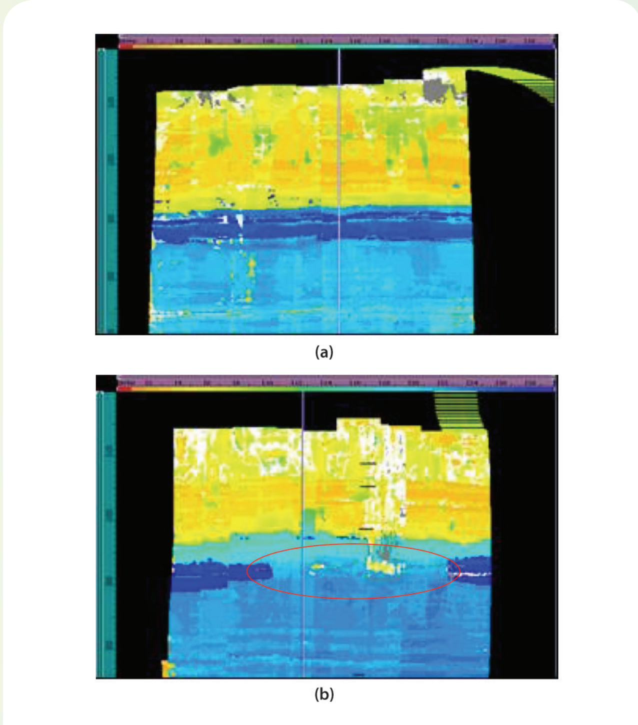


Figure 19. C-scan of internal web-to-blade-skin bonding: (a) well-bonded web (dark blue strip); and (b) disbonded web (circled)

Conclusions

Dr Freemantle then summarised what he thought the key challenges were for NDT by considering the requirements of the various stakeholders, such as the blade manufacturer, the blade designer, the wind farm operator, structural certification, regulatory bodies, underwriters and the inspection companies themselves. Communication is key and establishing constructive dialogue between the various stakeholders on how to develop and direct NDT inspections is difficult in this industry. Further commercial research projects are required to study how new and existing SHM and CM techniques could be utilised to direct and target NDT. Specific guidance for NDT of composite wind turbine blades is needed, covering: technique development, 'effect of defect' studies (to aid acceptance criteria derivation) and qualification and validation of inspections. In some areas of the industry (for example generator infrastructure), data exchange and linking of data between the stakeholders is improving and this approach is required for blades, particularly where life extension is a requirement or there are safety concerns.

NDT case studies and quick wins

Dr Colin Brett, Head of NDT, Uniper Technologies

Over the past fifteen years, Uniper Technologies (formerly E.ON Technology), has extended its NDT, CM and structural assessment services from conventional power generation plants into the renewable energy arena, including onshore and offshore wind turbines. Services have been provided to clients throughout the construction, operation and decommissioning phases of the asset lifecycle and a growing market is to adapt traditional methods for life extension into the provision of informed options for owners of ageing wind assets.

This presentation consisted of a variety of case studies taken from Uniper Technologies' experience of supporting owners of operating wind turbines. In general, they have all arisen from component failures that have had significant consequences for other turbines of the same design. Published figures suggest that 38.9% of operations and maintenance (O&M) costs are due to unplanned maintenance and these costs account for 25% of the overall cost of offshore wind[2]. Clearly, NDT has a role to play in detecting problems before they progress and become failures, thereby helping to reduce the overall O&M costs.

In most of these case studies, laboratory investigations have established the root cause of a failure and then identified solutions to mitigate further events. This has translated into the development and deployment of NDT inspections into the field at operational wind turbine sites. None of the case studies presented concern the blades themselves; experiences have shown that the majority of failures that prevent turbines from operating originate from other components.

Nacelle bedplate cracking

One design of turbine that is used both onshore and offshore has experienced metre-long cracks in the bedplate structure that supports the nacelle and its equipment. A repair protocol has been established that takes into account the length of the cracks and their positions. This builds on advice provided by the OEM to reinforce the structure to prevent cracks reinitiating. Unfortunately, weld repairs are made difficult by the fact that the bedplates are galvanised, parts of the cracks are not easily accessible for an NDT operator and the excavated crack opening is often changing as the nacelle is buffeted by wind, making weld repair problematic. The NDT is simple: magnetic particle inspection (MPI), ultrasonic and alternating current potential drop (ACPD), but it is vital to implement it carefully to ensure that the full lengths of any cracks are excavated and that the weld repair is as sound as possible.

Figure 20. Cracking in a nacelle bedplate. The full length of this crack is over a metre

Blade cans

Cracking between the bolt holes in the blade cans that connect the blades to the hub has caused blades to be shed at a small number of wind farms (Figure 21). The presence of any cracks can be detected and sized using ultrasonic phased arrays. When the blades are removed, a specially designed machine tool can be used to reprofile the bolt hole and remove any stress raisers and defects can be verified as being removed using eddy current inspection.

Figure 21. Field inspection using eddy currents of the blade can bolt holes

Bearing case corners

Another problem caused by stress raisers is cracking in certain generator bearing cases. Again, simple NDT can be deployed to detect and size such cracking. This then informs the process needed to reprofile the affected corners.

Blade pitch rams

Cracking has also been found in the pitch rams that articulate a blade on its main axis. If the ram fails then the turbine can no longer be operated as the blade cannot be feathered into and out of the wind. Unfortunately, up to a third of the rams on one wind farm have cracks, so a programme of replacements has been instigated. Ultrasonic testing in the very cramped nose cone section of a turbine can establish a priority order, but it has been found that newly installed rams can crack in a short period of time.

Bolts

There are a very large number of bolts in a wind turbine and many of these have been found to crack across the diameters due to overload and/or fatigue while in service. A small number of axial cracks have also been found that must have been present during manufacture, as protective paint has been found on the crack faces. There is a growing interest in using ultrasound to measure the loads in bolts that are already installed, as lost loads have been found at some wind farms.

Summary

There are other examples of component failures that have led to some form of remedial action, including NDT, being necessary in the field. In some cases the problem is due to a poor design, for example stress raisers in components experiencing cyclic loads, and in others it is due to inadequate NDT performed at the manufacturing or installation phases. What is clear is that the same quality control of NDT is required in renewables as for other industries. The remoteness of many wind turbines and the difficulty of access to many components means that there is an equally high need for reliable, robust and carefully documented inspections to ensure the availability of assets. Much of the NDT that is needed can be considered to be fairly basic, but it is still important to implement it methodically and correctly.

Ultrasound equipment and data acquisition on blades

Leif Jeppesen, Force Technology

Leif Jeppesen is known for his development of the P-scan system at Force Technology in Denmark. Force Technology is a self-owned not-for-profit institution founded by the Danish government in 1940 to assist industry by introducing NDT for production. For the wind industry it inspects blades, towers and foundations, both in production and on site, providing equipment and services. This started with the testing of prototype blades for the pioneering Danish wind turbine industry based on Force Technology's experience testing composite boats.

The P-scan stack system is an ultrasonic scanner for the inspection of blades in production and is capable of inspecting large blades in two to five hours with one-man operation at Level 1 UT for data acquisition. Full digital documentation is possible along with later comparison to in-service inspection data. In addition, data can be sent around the world to be checked by NDT specialists and to ensure that consistent evaluations are performed globally.

Figure 22. The P-scan system scanning in a manufacturing facility

The main challenge is the prioritising of NDT by the manufacturers. Blade designers should be able to give the critical defect size and the required detectable defect size as well as the thicknesses and required defect-sizing tolerances so that NDT engineers have an opportunity to state whether this is inspectable. At the design stage, sometimes the critical locations are known about but are covered in such a way that they can no longer be inspected or monitored. The difficulty of production of some critical components introduces further defects that were unforeseen at the design stage. Inspection time is critical for production because the production process has to wait for the inspection.

Defect types include dry areas, delaminations and wrinkles. Wrinkles can be detected and a severity assigned but a method for quantifying the size of wrinkles is needed.

One of the issues now is the analysis of large datasets. For example, the AMS-71 0.5 MHz probe array is sprung to the surface and can inspect 5 m of blade per minute. This generates 10 GB of data in four hours, but the analysis may take ten hours. So, automated evaluation of the data is an important requirement (see the presentation on page 15 by Niels Jeppesen). The new AMS-71 PA uses a phased array ultrasonic testing (PAUT) method with a special array that is flexible to follow the blade curvature. With limited space between probes, the whole array can act together with data density that is maybe 100 times more than the previous probes. Full ultrasonic waveforms are stored so that there is no limit to the kind of evaluation that can be performed.

For on-site inspection, a vacuum crawler is used that can still pass over non-contact areas without falling off. It can carry any kinds of probes or NDT systems that are required. The data can be uploaded to cloud storage from the scanner ready for manual or automated analysis.

Research projects include several with the Technical University of Denmark (MADE SPIR, MADE Digital, etc) and the RELIABLADE joint project between Denmark and Germany, looking specifically at the digital twin concept and establishing the required capabilities. Siemens, Vestas, IBM and LM Windpower are also all included as partners in the project.

Finally, there is a concern that some companies do not take inspection seriously and there is evidence of inadequate inspection procedures. For some, the paperwork is more important than the inspection and the inspections may never find defects.

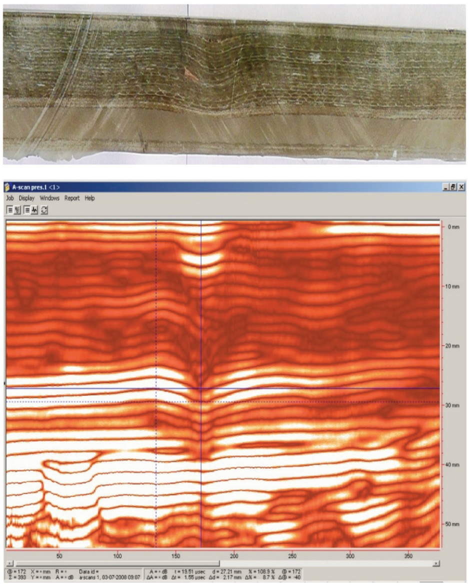


Figure 23. Example of a wrinkle in a blade structure and an ultrasonic B-scan cross-section

Tour of the Offshore Renewable Energy Catapult Centre at Blyth

The delegates of the workshop were taken on a tour of the Blyth Catapult Centre and saw the test facilities for blades of lengths up to 100 m and powertrains up to 15 MW.

Figure 24. The tour group setting off to visit the blade, generator and gearbox testing facilities

Session 4: Potential future NDT and SHM improvements

Examples of research and state-of-the-art NDT

Professor Robert Smith, University of Bristol

Professor Smith, Director of the UK Research Centre in Non-Destructive Evaluation (RCNDE), began by describing RCNDE for the benefit of the wind turbine sector delegates. It is a collaboration between six universities (currently Imperial College London and the universities of Bristol, Warwick, Nottingham, Manchester and Strathclyde) and 15 industrial companies. RCNDE has existed since 2003 and is in the final year of the third phase of funding NDE. It also has over 35 associate members from the NDE supply chain. The result is a pipeline of more than 50 exploitable products across a range of technology readiness levels (TRLs) from TRL2-9 (see Figure 25).

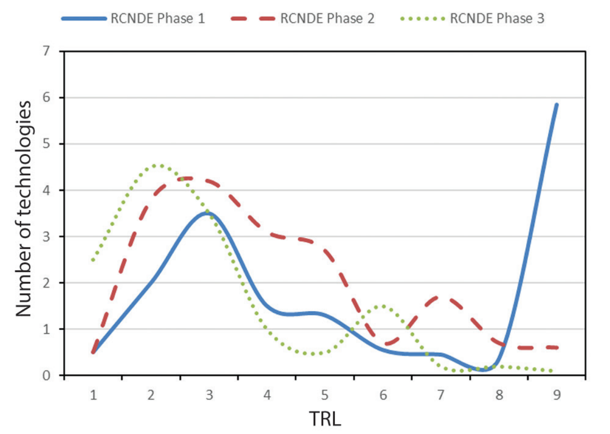
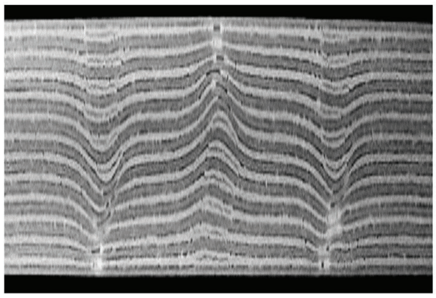


Figure 25. Fitted curves through the 2018 TRL levels of the technologies from projects in the three phases of RCNDE

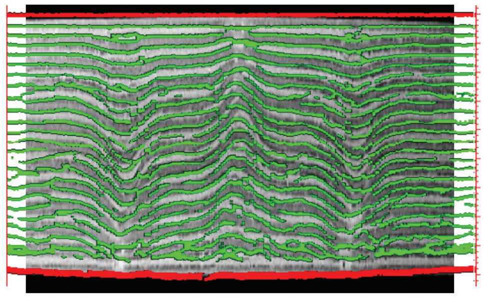
A Centre for Doctoral Training (CDT) is linked to RCNDE, for which the next phase of funding has just been awarded by the Engineering and Physical Sciences Research Council (EPSRC) until 2024. As a result, over 80 NDE specialists at doctoral level and above have been trained and recruited into the industry, with the additional benefit of research transitioned into industrial use.

Professor Smith then moved on to describe the work on 3D characterisation of composites carried out by his NDT of Composites team at the University of Bristol, where he is Professor of NDT and High Value Manufacturing. Novel inversion methods are used to unravel the ultrasonic response of multi-layered composite structures, allowing the tracking of plies through ply drops and out-of-plane wrinkling to be performed in order to increase the confidence in conformance to design of the manufactured structure[2-5] (see Figure 26). The output of the methods can also be used to build 3D finite element models to predict the mechanical performance of the as-built structure and this work has shown that the maximum ply-wrinkle angle is the dominant factor in determining strength knock-down[6]. While these methods have primarily been focused on the aerospace sector, interest has been shown by the automotive and marine sectors as well as an application to wind turbine structures containing wrinkles[7,8].

Finally, new metrics of 'mean ply spacing' and 'spacing difference' were presented as potential scalar parameters for the rapid detection of wrinkles and other defects as they can be calculated in real time from each ultrasonic waveform, independently of surrounding data, which could be ideal for scans of large wind turbine blades.



(a)



(a)

Figure 26. Ultrasonic analytic signal imaging for a specimen containing numerous aligned tape gaps and overlaps, causing out-of-plane wrinkling: the X-ray CT image (a) has an overlay inverted from the analytic signal response (b), where red lines are the front and back surfaces, while the green lines are the resin layers between plies, all determined automatically from the ultrasonic full-waveform data[2]

Automatic evaluation of ultrasound data from blades

Niels Jeppesen, Force Technology and the Technical University of Denmark

Niels Jeppesen is a PhD student at the Technical University of Denmark and is researching the use of machine learning (ML) tools to analyse ultrasonic data obtained from wind turbine blades. He began by explaining that ML tools have become widely available in data science libraries and applications, making their use and comparison of different models significantly easier. For instance, it is possible to train and predict a vast number of different ML models using just a few lines of Python or MATLAB code. If there is access to high-quality and homogeneous data, this makes training and using ML models an easy task. The NDT community should leverage the possibilities of ML to improve the quality of services and reduce costs.

The biggest challenge of using ML is that even though data is often abundant, it is not properly labelled. In the worst case scenario, data is not labelled at all and, even when it is labelled, the quality of the labels is often too low or the type of label does not match what we want to predict.

```
from sklearn.neighbors import KNeighborsClassifier

model = KNeighborsClassifier()
model.fit(x_train, y_train)
y = model.predict(x)
```

Figure 27. Code needed for creating, training and using an ML model. For this example the KNeighborsClassifier model was used, but many other models could be used in the same way

When performing quality control on wind turbine blades, large amounts of ultrasonic data is often collected and evaluated manually. Manual evaluation usually results in a report, which includes information about defects, such as type, position and other properties. However, it turns out that the recorded position and properties are often inaccurate and limited.

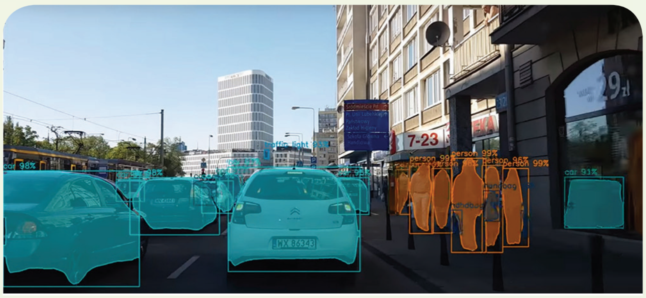


Figure 28. Instance segmentation

www.youtube.com/watch?v=OOT3UIXZztE

For image-like data, classification and segmentation are the two most common tasks for ML. Given an ultrasound image, classification could be used to detect whether the image contains one or more defects. However, the prediction provides no further information, which is a problem, as the position and size of the defects usually needs to be recorded. Segmentation, on the other hand, classifies each data point, which allows the sizes and positions any segmented defects to be measured. The downside of ML-based segmentation is that it requires segmented labelled data to train.

Segmentation provides much more detailed information than classification. The two biggest advantages of this are: (1) defects can be located and measured; and (2) it provides explicit visual feedback to users and data scientists, which helps in understanding the predictions. This is especially important if the model predicts incorrectly, as it helps us to understand why. For classification, understanding incorrect predictions can be very difficult.

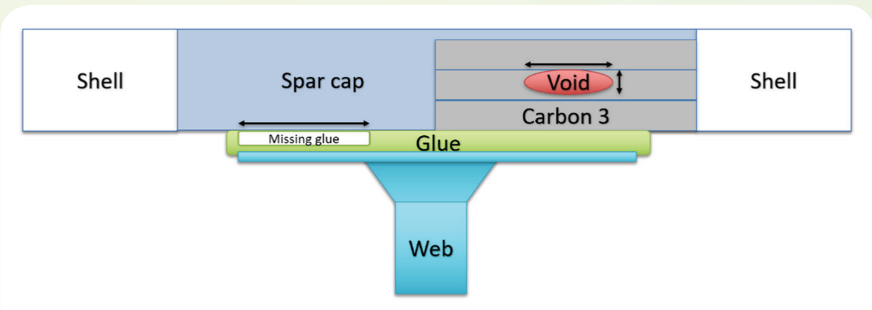


Figure 29. Detecting and measuring defects in the spar cap of a wind turbine blade

Manufacturers usually have specifications for permissible defects, which depend on type, size and location. These specifications often change over time. This means that the artificial intelligence (AI) models used for evaluation need to adjust accordingly. Using segmentation-based evaluation to detect defects, followed by rule-based logic to determine severity, a flexible system can be made, which allows the specifications to be easily changed without requiring the segmentation model to change. At the same time, the process is made much more transparent, as the segmentation provides clear information about which parts of the structure the defect was detected in.

Session 5: Breakout debrief

In the breakout session, four groups each spent 15 minutes on the following four discussion topics, giving everyone an opportunity to contribute to each topic:

- Requirements for manufacturers;
- In-service requirements for composite blades;
- In-service requirements for non-blade structures; and
- Potential for new NDT, CM and SHM approaches.

The contributions from all groups are summarised over the next few pages for each of these four topic areas.

Requirements for manufacturers

Leader: Peter Thayer, RCNDE

It was felt that the wind turbine manufacturing sector is still highly competitive between manufacturers and is missing out on the advantages of improved collaboration to share knowledge and experiences for the collective benefit of the industry as a whole. Other sectors should be studied to gain from their experience in non-competitive collaborations. Examples of benefits are: sharing of best practice, standardised guidelines, common criteria, common requirements, enforcement of standards and ensuring compliance by suppliers.

There is also a sense that the NDE supply chain is not offering the required capabilities for wind turbines, such as test and calibration blocks of suitable composite materials, and this is an obstacle to NDE development. For blade inspection, this could be because composites are still relatively unusual for the NDE supply chain to deal with. In fact, the whole concept of NDE of composites is still poorly understood and there is a shortage of skilled composites NDT inspectors. There needs to be an agreement on the wind sector needs, like that produced by HOIS on NDE equipment for the oil & gas sector.

Better quality assurance is required both for NDE procurement of service provision and for component parts. Better informed clients and operators are required with awareness of NDT capability in other sectors. It is important to buy in the most appropriate NDT products and services. There needs to be a better understanding of critical defects and how to characterise them. The designers need to pass on information about potential degradation locations and then design structures so that these can be inspected and repaired. For example, more carefully positioned access ports would assist inspection.

The wind sector is a rapidly changing industry, with moving goalposts for targeting research and development and a question over whether all parts of the system are capable of being scaled up in size. The codes and standards are scarce and incoherent; where they exist, they are being out-grown by proprietary components. There are many non-standard components and there is a poor awareness of the requirements by the NDE industry.

More open dialogue is required in the industry in the areas of design, materials, quality, inspection standards and requirements, limits on defect sizes, design assumptions, legacy information on failure experiences, likely defect locations, repair strategies and history, life extension experiences, etc. OEMs should advise on repair schemes in service as in the aerospace industry, where a maintenance and repair manual is provided and added to throughout the life of a fleet of aircraft. Operators should receive bulletins on known issues.

There was a question about whether production NDE is used in process control as much as it could be to improve the production rate and the quality of the product. Maybe faster higher-resolution NDE at manufacture would identify more potential defect sites. Also, it would be beneficial if manufacturing data could be made available to operators. There are instances of selling a new product before the design, proof testing and validation have been finished.

Operator user groups should be formed to share information on products. These operators may pay more up front for better experience through life in terms of the cost of operation. They would benefit from a better understanding of the costs of repair, inspection, etc, to help to judge the economic options, including in investing in product development by the NDE supply chain.

In-service requirements for composite blades

Leader: Tony Fong, ORE Catapult

This breakout session focused on the in-service requirements for the inspection of composite blades. Participants were asked to discuss their views on the challenges and opportunities surrounding this topic. A number of themes appeared and are summarised below:

- ***Access and turbine downtime*** are two of the largest challenges in the inspection of offshore wind turbine composite blades. Traditional rope access is time consuming and costly, with technicians needing to transit from shore, transfer to the turbine, access the nacelle and then perform rope access inspection in order to undertake a conventional inspection of the blades. Rope access in an offshore environment makes this process high risk in terms of health & safety and, additionally, the long periods of associated downtime coupled with the offshore labour requirements makes this expensive.
- ***Robotics, autonomous systems and condition monitoring systems*** offer the potential to inspect turbine blades while reducing costs and health & safety risk through the reduction of rope access inspections and by decreasing the time required for inspection. The industry ideal would involve an inspection that requires no stopping of a turbine, no people and is available regardless of wind speed. A suite of integrated sensor technologies within the blade/turbine could be utilised to provide detailed information on the health of the blades, monitored over the life of the asset. Utilisation of SHM data could be applied to optimise the need for inspection; however, correlation of SHM measurements and failures will need to be developed and understood.
- ***Remote NDE*** does not currently provide reliable inspection of subsurface damage in offshore wind turbine blades. The majority of NDE carried out on blades is remote visual inspection, assessing the blade surfaces for potential signs of damage. Subsurface damage inspection using remote vehicles (*ie* unmanned aerial vehicles (UAVs)) could identify potential costly failures before they become severe, potentially allowing for them to be remediated at a lower cost. Subsurface NDE techniques exist; however, the wind sector requires techniques that can measure large areas of thick laminate at a high speed, which is not currently feasible for remote NDE technologies.
- ***OEMs and industry data sharing:*** Data sharing is an important requirement as the sector matures. There is a need for more information and guidance on NDT requirements and how OEMs and designers can provide relevant information to assist the production of that guidance and the performance of the NDT. Inspection and maintenance plans with schedules for pre- and post-warranty periods should be produced. There are potential NDT technologies that are not being applied because the NDT industry does not understand the business model for the OEMs or for owners/operators. Information is required to build business cases for NDT.

  This is perceived as a common challenge across the offshore wind sector due to commercial (and other) constraints. Data sharing between OEMs, turbine owners/operators, the supply chain and innovators is limited. This adds a number of challenges, which include: visibility of inspection requirements for innovators and supply chain to develop potential solutions, lack of through-life service records (manufacturing through to operation) for improved O&M decision-making; and an unclear understanding of the holistic cost to industry of blade O&M.
- ***Non-standard inspection and maintenance plans:*** A lack of standardisation across the industry on inspection and maintenance is seen as a key challenge for the sector. Unlike other sectors, such as oil & gas, rail and traditional power generation, offshore wind does not have clear standards for inspection and maintenance. Standards across the industry would improve overall quality and the cost of blade inspection and maintenance. Examples were provided from the rail sector (and others), where scheduled and preventative maintenance standards help to reduce failures and decrease operating expenses (OPEX). Standards would also enable better NDT and SHM solutions to be developed. Technology transfer from other sectors should be considered.

In-service requirements for non-blade structures

Leader: Dr Colin Brett, Uniper Technologies

A common theme with this breakout discussion was the need for better communication. Forums for operators, manufacturers and inspection companies would be a good outcome of this very valuable workshop. We could then share knowledge and experiences and all will benefit, including all levels of staff, filtering down to the actual NDT operators where, for example, guides for interpreting standards could be produced as 'apps'. A lot of data is retained by OEMs, which are aware of more data than the operators, but it is difficult to access. The sector should work more closely together; for example, OEMs could have open days (annual or biennial) for operators. Databases of information could be set up to foster greater openness and collaboration, ultimately reducing cost and creating better designs.

As the generating power of wind turbines increases, so does the financial pressure, but this works against sharing and collaboration between manufacturers and operators.

More involvement from insurance companies would be beneficial, as they could apply pressure to act more responsibly. Premiums could be reduced if information on NDT is understood by insurers: spending on NDT in return for cheaper premiums. Cost is always the driver for both operators and manufacturers. All cost is being driven down. Root cause analysis can significantly reduce costs of ownership. By sharing information on unscheduled maintenance, this could be converted to a cost saving by benefiting from better inspections. We should learn from the HOIS model for offshore oil & gas and GENSIP in the power industry. Sharing information on failures is beneficial, for example HOIS has a database system available for members. GENSIP undertakes research on failures but still openly shares; all will benefit and health & safety issues will be reduced.

It was felt that both the Health & Safety Executive (HSE) and insurance companies should be involved in mandating inspection requirements from OEMs and the following of maintenance and repair procedures, training of staff and service providers. Communication between NDT staff and management within the company is crucial and the aerospace industry mandates that the responsible Level 3 is a very high-ranking post. Full-life costing should include not only the cost of NDT, but also the financial consequences of not performing adequate NDT.

Potential for new NDT, CM and SHM approaches

Leader: Dr Richard Freemantle, Wavelength NDT

For the inspection of structures any method needs to have large-area coverage. If it does not use installed sensors (SHM/CM) then the method would preferably be non-contact for in-service testing. The same technology should be considered by the OEM at the manufacturing stage to give baseline data. The OEM could feed the inspection technology out or specify methods to be used and even equipment approved for use. Potential large-area non-contact methods are: thermal imaging, visual imaging and digital image correlation (DIC). Once a methodology or sensor design has been selected, it will probably need to be enhanced and optimised for in-service use and then validated/qualified.

Condition monitoring systems generate large amounts of data, which can contain false calls or just bad data. Machine learning could be used to filter out anomalous data and focus on the information that is relevant to indications of defects, which can then be fed to an expert with a good overview.

Suppliers of inspection and monitoring equipment should be aware of the importance of training their clients in the wind sector. Just leaving technology with people without adequate understanding causes a large overhead for the equipment supplier and lowering of confidence in the technology itself and can result in indications or problems being missed. Whoever performs the CM/SHM, or provides the systems, should have to prove competency and experience in the same way an NDT professional has to. An option is for SHM/CM information to be used as a low-level filter to indicate if something is wrong but without knowing what or where it is. This level can be used by the client. Advanced analysis can then be deployed by the OEM of the CM technology to help track what and where the issue is.

To improve the take-up of new technologies by wind OEMs and operators, they need to be proven in the field. Government-funded projects will help to demonstrate the potential return on investment in terms of savings on unplanned maintenance if a customer subsequently utilises the new CM/SHM technology. Developments in CM/SHM may be within the gift of the OEMs; if one manufacturer starts using it, competing companies will have to adopt it as well, particularly if an improved warranty is offered as a result.

The drivers for blade manufacturers and operators are better designs, better quality assurance, reduced monitoring with increased reliability and better life extension opportunities. CM and SHM systems can assist, but only if their suppliers and designers are given adequate information on what their systems need to cope with and where to deploy sensors, etc. Then, an improvement in the reliability will be seen in the technologies and this will cut the costs of unplanned maintenance and aid life extension programmes.

Efficient and effective deployment of sensors is important for SHM. Sparse sensors on some blades for hotspots could be considered, but another option is to have a higher density of sensors but on fewer blades to obtain a detailed view on a small population, which can then be extended to the wider population. Once the metrics are understood, the sensor density can be adjusted accordingly. The stability of installed sensors and designing for this stability is important.

Camera-based vision systems could be in-built within the structure or can be deployed from the ground or a ship, but robotics, drones and crawlers are still small with low payloads. However, there is the possibility of tethered drones, where greater payloads and better motion control and stability are possible with the additional power capability.

As no single NDT, CM or SHM system will be able to provide all of the required inspection and monitoring capability, there needs to be a toolbox approach. To arrive at the right toolkit, the technologies should be used as much as possible in the development stage (pilot programme, new blade design testing, etc). At present, there is a feeling that CM/SHM sensors are not sufficiently reliable, so there is insufficient confidence in using them to prompt the extra work required from the OEMs.

There is a reluctance to adopt these inspection and monitoring technologies by the OEMs, so we now have a huge firefighting effort. The question was raised about who should be funding, adopting and utilising CM/SHM technologies and how we will ensure they are used (certification, regulation and health & safety). This is about issues of making a business case to use CM/SHM technologies in production (with a view to then migrating them out as an in-service tool). OEMs could build SHM into the price of supply with benefits of reduced operating and overhead costs. A service agreement that offers the use of CM/SHM (with reduced servicing costs) may be a way to encourage adoption. There is an analogy here with using NDT in the marine (yacht) sector, where underwriters offered to pay for 50% of the NDT costs incurred for inspecting a yacht before accepting it for insurance. This cost share between underwriter and owner meant that lower premiums could be offered on the basis that the insured asset would be a lower risk. Another example is bridge monitoring, with a cost share between the owner and the operator and benefits of the technology gained by both. This is easy for static structures, whereas there are lots of different dynamic loads and spurious signals on a wind turbine.

We may be missing the input from the operators managing the assets and we need to take a fleet view rather than one installation at a time. The point was made that certification paperwork is not sufficient on its own; the example being in the rail industry, where not enough oversight was undertaken of quality and safety procedures. Another issue concerns who should be responsible for analysing a fault. There is a similar problem in the marine (yacht) sector, where the manufacturer blames the owner and *vice versa*; insurers on both sides seek to lay blame. The designer (and the inspector) are often stuck in the middle.

At present, the specification for a wind turbine is certified but not the design in terms of whether it meets that specification, so certification of designs could be introduced and used to allow a cheaper but more damage-tolerant design to be used to achieve the same specification of requirements. This, in turn, could lead to better NDT in terms of the provision of supporting structural integrity information to track a structure through its life. Use of such data as part of the damage-tolerant design philosophy is key. This is not just about retaining data for warranty purposes (certificate) but also recording enough data so that, if a problem occurs in service, enough production data exists to see if the problem is production/design related or more closely related to how the structure has been operated in the field. The wider point is that if full data is retained (and collected) then the number of warranty and in-service issues will reduce. The exception to this is rain erosion, which is apparently a big issue and highly variable, so it is hard to predict how a blade will fare in the field.

There are potential benefits in using SHM/CM to help target NDT. This point is about having a better understanding of potential issues from CM/SHM technologies to aid in the deployment of targeted NDT. Instrumenting towers is key and then we should ensure that the knowledge and data is exchanged widely, not just on a specific project, between 'competing' operators and the manufacturer for the common good of the industry. This raises the general conditions in the industry, which is immature in the sense of adopting technologies or having a measured, strategic approach to asset management. The industry is procurement-led (price) and the point that Colin Brett made was picked up by many people on the day: 'Cheap NDT is the most expensive NDT'. Rapid growth means that the industry is outpacing the standards and maintenance technologies.

The offshore industry drives quality because offshore wind turbines are difficult to access on a regular basis. If something goes wrong (as it did for one OEM when it first entered the offshore market and suffered gearbox failures) then this results in a massive quality correction, which, while damaging for the OEM, ultimately results in a better design with fewer maintenance issues. Unlike in the oil & gas industry, there has yet to be a major accident to drive up standards and increase the use of technology. Safety is key. Accidents tend to drive improvements, unfortunately. The oil & gas sector has been more proactive in adopting CM/SHM technologies with an emphasis on remote sensing technologies because of major incidents. This is about who audits and regulates the certification process. As in the rail industry, in-depth oversight of the processes only occurs after loss of life, disaster, etc.

The rapid growth of the industry has seen standards lagging. In order to implement standards effectively it is necessary to check with the supply chain regarding experience, competency and performance. Do not wait for serious accidents to occur.

Session 6: Panel session

The panel was chaired by Professor Smith and comprised the following presenters from the workshop: Daryl Hickey, Tony Fong, Andy Morris, Colin Brett, Robert Ernst and Richard Freemantle. Professor Smith began by asking each panel member to state what they felt was their top priority for NDT to provide to the wind turbine industry.

Colin Brett noted that more communication is needed among the different key players in the industry: manufacturers, constructors and owners. Everybody should share experiences and learn together how to improve things.

Richard Freemantle added to the previous comment that this increased communication also needs to involve data exchange between those parties. All parts of the industry generate data and the benefits come from sharing and combining it. This, in turn, ultimately benefits the final consumer and the general public. The tools for this data sharing already exist, so no new technology is necessarily needed. What is needed is a desire for the different players to share the information.

Andy Morris felt that the most important requirement for the renewables industry was learning to do simple things right at both the construction and monitoring stages. Sometimes the simplest monitoring solutions may be best and simplifying the reporting of data will also help to share the data among parties and benefit the end-user.

Tony Fong observed that understanding the bigger picture is essential. Most of the time, different parties only get involved with a specific area and it is important to understand questions such as: 'Why do it?'; 'What for?'; and 'Will this technique get the job done?' It is about understanding why the customer wants us to do something and not just complying with specifications and requirements.

Daryl Hickey also stressed the importance of better communication and the need for instruments that put all the relevant parties in touch. There is a requirement for different parties to be exposed to the type of data, not only NDT, that others generate.

Robert Ernst observed that, unlike other industries, the wind turbines sector lacks standard guidelines, which is holding the sector back. There is also not enough training or certification for those carrying out NDT of composites in this industry.

Daryl Hickey suggested that an ideal solution could be to create a matrix of inspection technologies for each type of defect, including the cost/benefits of each particular technique. Robert Smith noted that this idea had also been suggested as beneficial in other sector workshops. An interactive knowledge database (IKB) for NDT of composites already exists but probably needs updating, for which some funding would be required. Richard Freemantle suggested that there could be a subscription-based industry database that could be used by OEMs and operators to share NDT and other types of data.

A question arose about whether the renewables sector would benefit from having a HOIS-type organisation. HOIS (originally the Harwell Offshore Inspection Service) is a joint industry project (JIP) in the oil & gas sector. It involves oil & gas producers (operators), NDT service companies, NDT equipment vendors and the regulatory authority (UK HSE).

Tony Fong mentioned that the ORE Catapult is preparing a database with anonymised information on production figures, shutdown incidents and causes, etc, but it is only available to wind turbine owners that have bought into the scheme. The database is used by asset owners as a benchmarking tool to compare their performance against others. The information from this tool is sometimes analysed and used in reports from the ORE Catapult. Robert Smith asked whether the ORE Catapult could be interested in leading a HOIS-type organisation for the renewables sector. Tony Fong replied that the Catapult is well-placed to ask the potentially interested partners whether they would want to proceed with an initiative like this. They could also look at whether there is some government funding available to help set up the organisation and afterwards it could continue via industry subscriptions.

Tony Fong also noted that another current initiative at the ORE Catapult is a monthly owner/operator forum exclusive for owners. A suggestion was made that NDT providers and operators could be involved in these meetings as a way to start improving the communication between all of the different key parties in the sector. Tony Fong said that this idea could be explored but it would be necessary to make it clear to NDT providers that the objective of the forum would be to share experiences and not to act as a sales pitch for their NDT solutions.

Andy Morris suggested bringing in other sector experience of similar initiatives, for example the Network Rail 2011 forum to improve efficiencies and availability. The rail sector was in a similar position to the renewables sector in 2011 and, by creating a forum that involved all the key players, it managed to turn the situation around.

Robert Smith suggested that it would be a good idea to designate a person from the ORE Catapult who could act as a champion for all of these initiatives, as well as a point of contact to the workshop attendees, so that the different requirements identified are addressed.

Summary of requirements

The requirements raised at the workshop were prioritised into the following four themes:

- Wind sector organisation
- Linking inspection to structural integrity and cost
- Informing the sector about NDT, SHM and CM
- Inspection capability.

Wind sector organisation

- More open dialogue is required in the industry in the areas of design, materials, quality, inspections standards and requirements, limits on defect sizes, design assumptions, legacy information on failure experiences, likely defect locations, repair strategies, history and life extension experiences, etc.
- Increased understanding is required of the big picture related to the drivers behind and the needs for inspection and monitoring.
- Improved communication is needed between key players in the industry: manufacturers, constructors and owners. Everybody should share experiences and learn together how to improve things. This needs to include data exchange between those parties, for which the tools already exist. Forums for operators, manufacturers and inspection companies would be a good outcome of this very valuable workshop. There is potential for NDT providers to be involved in the ORE Catapult's owner/operator forum.
- The industry needs to learn to do the simple things right at the construction, monitoring and reporting stages. Benefits could result from learning about other sectors that have been in similar positions, such as the rail sector.
- OEMs should advise on repair schemes in service as in the aerospace industry, where a maintenance and repair manual is provided and added to throughout the life of a fleet of aircraft. Operators should receive bulletins on known issues.
- The sector would benefit from an industry-funded user group organisation linking operators, NDT service companies, NDT equipment vendors and the regulatory authority (UK HSE). The ORE Catapult could initiate this, seeking government funding to set it up and ongoing funding through industry subscriptions. These operators may pay more up front for better experience through life in terms of the cost of operation. They would benefit from understanding better the costs of repair, inspection, etc, to help judge the economic options, including investing in product development by the NDE supply chain.

Linking inspection to structural integrity and cost

- There needs to be a better understanding of critical defects and how to characterise them.
- The designers need to pass on information about potential degradation locations and then design structures so that these can be inspected and repaired.
- Standards and guidelines are required of the same type used in other industries to guide the use of NDT, training and certification of NDT practitioners in the wind turbine industry.
- Insurance companies should be more involved and they could apply pressure to act more responsibly. Premiums could be reduced if information on NDT is understood by insurers.
- Certification of the turbine specification is insufficient on its own; the design should also be certified as meeting the specification and oversight should be undertaken of quality and safety procedures.
- Responsibility should be assigned for analysing a fault.
- Certification of designs could allow a cheaper but more damage-tolerant design to be used to achieve the same specification of requirements. This, in turn, could lead to better NDT in terms of the provision of supporting structural integrity information to track a structure through its life.
- Both HSE and insurance companies should be involved in mandating inspection requirements from OEMs and the following of maintenance and repair procedures and training of staff and service providers.
- Suppliers and designers of CM and SHM systems need adequate information on what their systems need to cope with and where to deploy sensors. A reliability improvement will cut the costs of unplanned maintenance and allow for life extension.
- A business model is required for using SHM/CM. OEMs could build SHM into the price of supply, with the benefit of reduced operating and overhead costs. A service agreement that offers the use of CM/SHM (with reduced servicing costs) may be a way to encourage adoption. A cost share between underwriter and owner of the cost of NDT would lower risk and result in lower premiums.

Informing the sector about NDT, SHM and CM

- Better quality assurance is required both for NDE procurement of service provision and for component parts.
- Better informed clients and operators are required with awareness of NDT capability in other sectors.

- The industry is procurement-led (price), but 'cheap NDT is the most expensive NDT'. Rapid growth means that the industry is outpacing the standards and maintenance technologies.
- Information is required to build business cases for NDT. There are potential NDT technologies that are not applied because the NDT industry does not understand the business model for the OEMs or for operators.
- A knowledge database is required covering capabilities and limitations of NDT, SHM and CM techniques to help match techniques to specific inspection requirements, defect types, materials and structures, etc, similar to those created in the past for offshore inspections and for composites. Funding would be required but maybe a subscription-based system would fund the maintenance of such a database.

Inspection capability

- There are two main in-service inspection requirements: large-area global inspection for the identification of areas of concern and local detailed inspection to detect and characterise defects. Thus, the detailed survey is targeted by the large-area sweep.
- The large-area methods should either use installed sensors or be non-contact, preferably remote from the structure.
- SHM/CM information can be used as a low-level filter to indicate if something is wrong but without knowing what or where it is. This level can be used by the client. Advanced analysis can then be deployed by the OEM of the CM technology to help track what and where the issue is.
- A major requirement is inspection during turbine operation, preferably regardless of wind speed or with minimum downtime, either by CM and SHM sensors or by remote or autonomous robotic NDT.
- As no single NDT, CM or SHM system will be able to provide all of the inspection and monitoring capability required, there needs to be a toolbox approach.
- The NDT industry needs to start providing a range of items required by the wind turbine industry, such as test and calibration blocks in relevant materials and thicknesses.
- Whoever performs the CM/SHM or provides the systems should have to prove competency and experience in the same way an NDT professional has to.
- Machine learning could be used to filter out anomalous SHM/CM data and focus on the information that is relevant to indications of defects, which can then be fed to an expert with a good overview.

References

1. Bloomber New Energy Finance, https://about.bnef.com/blog/world-reaches-1000gw-wind-solar-keeps-going
2. D Milborrow, Windpower Monthly, 5 June 2017.
3. R A Smith, L J Nelson, M J Mienczakowski and P D Wilcox, 'Ultrasonic analytic-signal responses from polymer-matrix composite laminates', IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol 65, No 2, pp 231-243, 2018. DOI: 10.1109/TUFFC.2017.2774776
4. L J Nelson, R A Smith and M J Mienczakowski, 'Ply-orientation measurements in composites using structure-tensor analysis of volumetric ultrasonic data', Composites Part A: Applied Science and Manufacturing, Vol 104, pp 108-119, 2018. DOI: 10.1016/j.compositesa.2017.10.027
5. L J Nelson and R A Smith, 'Fibre direction and stacking sequence measurement in carbon fibre composites using Radon transforms of ultrasonic data', Composites Part A: Applied Science and Manufacturing, Vol 118, pp 1-8, 2019. DOI: 10.1016/j.compositesa.2018.12.009
6. N Xie, R A Smith, S Mukhopadhyay and S R Hallett, 'A numerical study on the effect of out-of-plane wrinkle severity, shape and extent on the compressive strength of composites', Materials and Design, Vol 140, pp 7-20, 2018. DOI: 10.1016/j.matdes.2017.11.034
7. B Larrañaga-Valsero, R A Smith, R B Tayong, A Fernández-López and A Güemes, 'Wrinkle characterisation from ultrasonic scans of composites', Proceedings of the 55th Annual British Conference on Non-Destructive Testing (NDT 2016), Nottingham, UK, 12-14 September 2016.
8. B Larrañaga-Valsero, R A Smith, R B Tayong, A Fernández-López and A Güemes, 'Wrinkle measurement in glass-carbon hybrid laminates comparing ultrasonic techniques: a case study', Composites Part A: Applied Science and Manufacturing, Vol 114, pp 225-240, 2018. DOI: 10.1016/j.compositesa.2018.08.014

Appendix A: Delegate list

Tim Bradshaw	Mistras Group Ltd
Guido Bramante	Dow Italia SRL
Colin Brett	Uniper Technologies
Paul Cairns	Mistras Group Ltd
Tim Camp	LOC Group
Joe Corcoran	Imperial College
David Dakers	Tees Valley Inspection
Dave Deeney	Sonatest
Mike Dempsey	Sonatest
Steve Drake	Ashtead Technology
Kirsten Dyer	ORE Catapult
Robert Ernst	Vestas
Tony Fong	ORE Catapult
Richard Freemantle	Wavelength NDT
Peter Greaves	ORE Catapult
Mark Griffiths	BHGE
John Hansen	ETher NDE
Daryl Hickey	Natural Power
Dave Hughes	Novosound Ltd
Leif Jeppesen	Force Technology
Niels Jeppesen	Technical University of Denmark/ Force Technology
Jordi Jimenez	IENDE SL
Neil Kewin	Baker Hughes
Richard McAllister	Baker Hughes
Ali Mehmanparast	Cranfield University
John Moody	BINDT
Andrew Morris	EDF Energy
Benjamin Read	HTSL
Rob Rose	National Composites Centre
Steve Shanahan	VINCI Technology Centre UK Ltd
Robert Smith	University of Bristol/RCNDE
Peter Thayer	RCNDE
David Thompson	ORE Catapult
Andrew Tipping	ORE Catapult
Graeme Urquhart	Novosound Ltd
Elizabeth Watson	Tees Valley Inspection
Ian Winstanley	Euroteck Systems UK Limited
Behzad Yari	Shahroud Technology University

Published by:
The British Institute of Non-Destructive Testing
Midsummer House, Riverside Way
Bedford Road
Northampton
NN1 5NX, UK
Tel: +44 (0)1604 438300
Email: info@bindt.org
www.bindt.org

ISBN: 978 0 903132 75 3
DOI: 10.1784/report.2019.001

...engineering safety, integrity & reliability