Chapter 9

Testing and Condition Monitoring of Composite Wind Turbine Blades

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I. INTRODUCTION

In a wind turbine system, blades are one of the most critical components. They capture energy from wind and convert it to a mechanical energy for electricity power generation. However, once the blades are defective, the power generation efficiency of the turbine will be significantly affected. In worse case when the blade is seriously damaged, the turbine will have to be shut down completely for the sake of safety. Furthermore, they are exposed in direct harsh environment, suffering constantly varying wind loads, experiencing temperature and humidity changes, erosion and corrosion, as well as the cyclic fatigue loads arising from their self-weights in operation. As a consequence, blades are also the most vulnerable component in the entire wind turbine system. The long-term onshore wind farm practice has shown that blade failures account for about 10% of all wind turbine failures reported [1, 2], and result in over 15% of total downtime of the turbines [3, 4], which means a significant revenue loss to operators. Therefore, blade failures have a profound impact on the cost of energy from wind. To improve the reliability of wind turbine blade is of great significance to increase the availability of the wind turbines and economic return from them.

At present, two tendencies are being exhibited in the wind industry; these are: (i) more and more wind turbines are being deployed offshore and in remote lands, where expensive operation and maintenance costs (e.g., blade inspection and repair) are always associated with due to the limited accessibility of site; (ii) wind turbine, more precisely wind turbine blade, is continually growing in size, which requests the blades to be more reliable and stronger than ever before to sustain higher static and cyclic loads that are randomly applied to the turbines. Both tendencies request researchers and designers to further improve the long-term reliability of wind turbine blades, so that to reduce their failure rate and downtime. Today, many measures can be taken to reach such a purpose; for example adopting a more conservative design of the blade by using a larger factor of safety, enhancing the quality control in the manufacturing process, taking an innovative manufacturing method to reducing the potential failure risks emerging in conventional ‘sandwich’ blade structures, using more reliable light-weight materials to replace the glass fibre that is being popularly used in turbine blades, etc. However, every improvement needs to be fully validated in advance before extensive application. Therefore, various subcomponent and full scale blade testings are often conducted in laboratory. In contrast to testing in field, laboratory testing is regarded as one of the most feasible and cost-effective approach to obtaining a comprehensive understanding of the quality and reliability issues of a new blade design within constrain of time and expenses. However, it is aware that laboratory testing of a wind turbine blade, especially the fatigue testing of the blade, is still time consuming and costly.

Laboratory testing can help to quickly prove the new design and/or improvement, and predict the long-term reliability of blade in its 20 to 30 years life time. But laboratory testing cannot fully guarantee the actual energy capture efficiency of a wind turbine blade in operation. In practice, the blades will operate in harsh environments and experience various severe loading conditions that can be distinctly different from those simulated in laboratory testing. In order to ensure the reliability of wind turbine blades and their high energy capture efficiency over a long service period, it is essential to have an instant understanding of the actual health condition of the blades and their energy capture efficiency, particularly under extreme weather and loading conditions (e.g. raining and snowing storms, lightning strike, typhoon, etc.). Thereby, remote online condition monitoring is strongly recommended to the operator. Today, condition monitoring has been widely recognised as a key measure to protect blades and the entire wind turbine system from being damaged under extreme conditions and guarantee their high energy capture efficiency under normal conditions [5].

In view of the great significance of laboratory testing and condition monitoring in achieving the long-term reliability of wind turbine blades and ensuring their high energy capture efficiency in practical operation, an overview of the knowledge, practices and relevant lessons learnt in laboratory testing and condition monitoring of full scale wind turbine blades are introduced in the following sections.

II. FAILURE MODES OF WIND TURBINE BLADES

The typical structure of a blade used for large Megawatt-scale wind turbines is shown in Fig. 1. The spar structure of the blade varies considerably with manufacturers, but it is typically in the form of a box beam or one or more webs, which may be adhesively bonded to form an integral part of the aero-shell structure. In most structural designs, adhesive joints are present along the leading and trailing edges for sustaining the core bonding on sandwich panels.

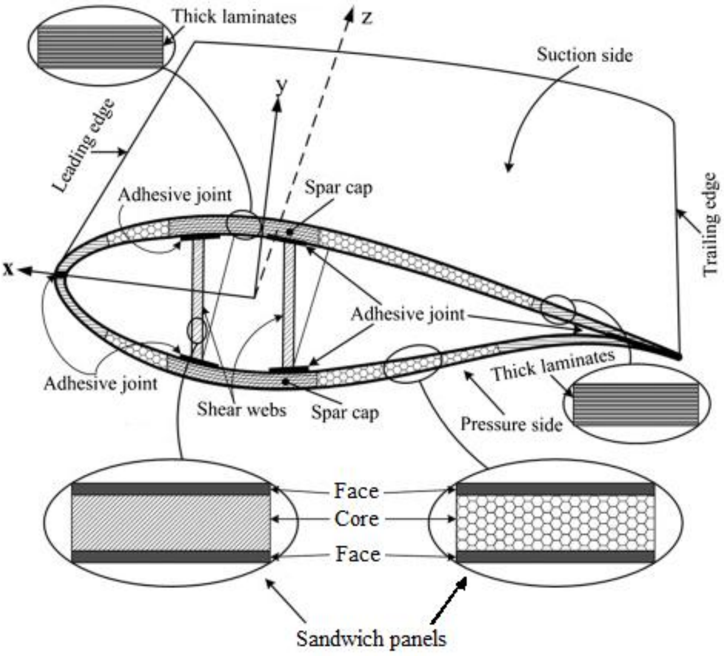


Fig. 1 Typical structure of a blade for large Megawatt-scale wind turbine

The spar beam is made of unidirectional fibres aligned with the blade axis. As the primary load-bearing component, it will provide both bending stiffness and torsional rigidity to the blade. The aero-shell defines the blade profile. It is typically constructed using fibre-reinforced polymeric composites and sandwich structures with lightweight PVC (polyvinyl chloride) foam or balsa wood cores bonded to the spar beam through high-toughness adhesives. These high-toughness adhesives are also used to bond the laminates at leading and trailing edges of the blade. In the design of long blades for Megawatt-scale wind turbines, carbon fibres and fiberglass/carbon hybrids are often adopted by taking advantage of their higher stiffness to reduce the static and cyclic blade deflections and also to improve the blade buckling resistance. Similar to the manufacturing process of aircraft wings and composite boat hulls, wind turbine blades are manufactured also using the popular hand lay-up technique, pre-preg technology and vacuum assisted resin transfer moulding [6].

Fig. 2 shows the schematic of the flapwise and edgewise loads that would be suffered by wind turbine blades in operation. Herein, it should be aware that in reality, the actual loading condition experienced by the blade is much severer than this due to wind turbulences.

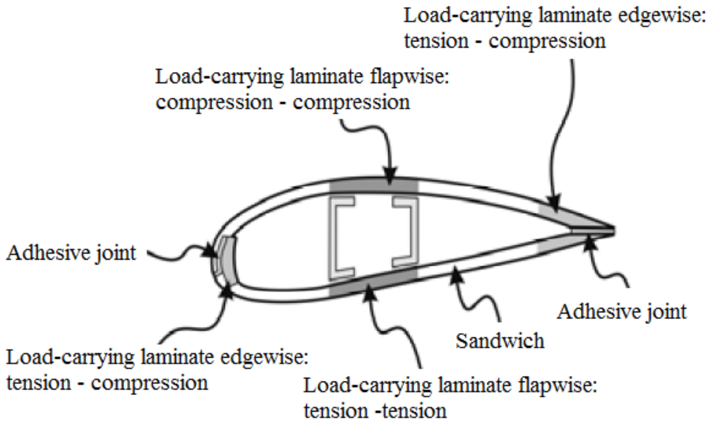


Fig. 2 Schematic of the flapwise and edgewise loads suffered by wind turbine blade

Owing to the aforementioned specialities of wind turbine blade in design, material, structure, and complex loads being subjected, the blade is often damaged by various means, as shown in Fig. 3.

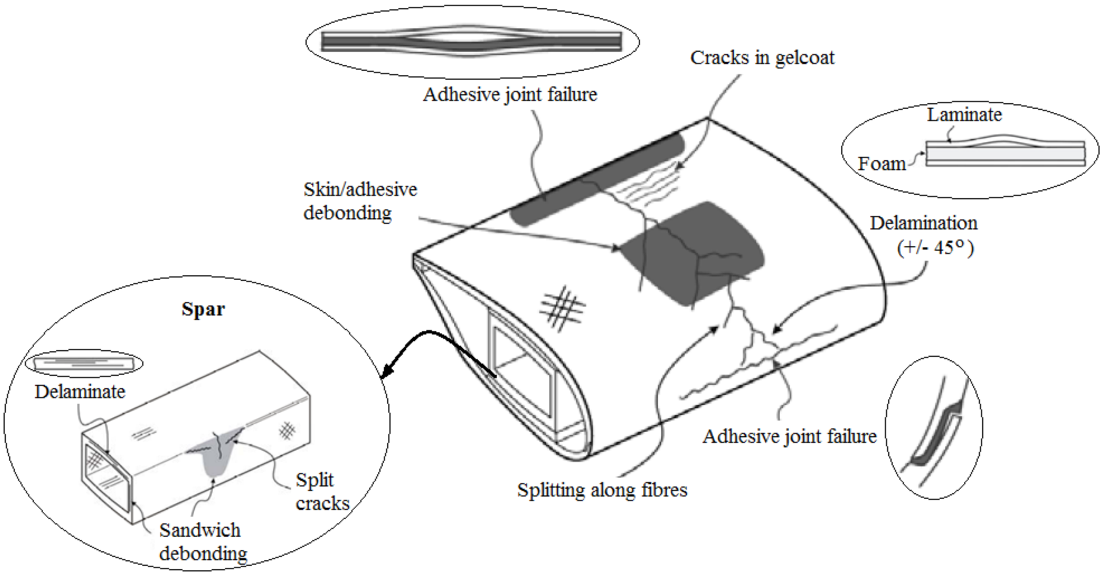


Fig. 3 Failure modes of wind turbine blades

During rotation, the wind turbine blade is subjected to large edgewise and flapwise bending moments, which, together with the self-weight of blade, introduce cyclic stresses in the aeroshell, in adhesive joints and in spar beam. Over a long period, splitting cracks (along fibres), delamination (between composite plies), and debonding (along adhesive joints) will initiate inevitably. But if these micro-defects cannot be detected and repaired instantly, a catastrophic failure of the blade could be resulted in the end, even the entire machine could be lost in storm.

In addition to the random fatigue loads, the thermal expansion induces dimensional mismatches between blade aeroshell and spar beam, and blade sandwich structures can cause blade damage as well, although a well-designed composite joint allows for a certain amount of elastic modulus mismatch. But in any case, defects or cracking between composite plies and the vicinities of geometry changes are inevitable even through in normal operating conditions of the blade.

Since wind turbine blades are made of composite materials, the most common failure mechanisms related to composite materials are listed in Table 1 for information.

TABLE 1 FAILURE MODES OF COMPOSITE MATERIALS [7]

Failure mechanism	Comments
Global buckling	○ Global buckling of laminate
Fibre failure	○ Fibre failure with dominant strain parallel to the fibre direction exceeding the tensile or compressive strength capacity of the individual fibres. ○ Fibres can buckle at a micro and macro levels. Buckling will reduce the compression strength drastically, with imperfections further increasing the effect of buckling. ○ Fibres generally do not yield experiencing brittle fracture.
Matrix failure	○ Matrix failure can occur due to longitudinal/transverse tensile and compressive or in-plane shear stresses. ○ Matrix failure results in degraded strength and stiffness of the laminate, and can lead to further delamination. ○ Can be critical for transverse loaded UD laminates, and in 0°/90° laminate loaded in in-plane shear, as well as at joint details. ○ Yielding of the matrix material is also to be evaluated. ○ Matrix failure analyses shall consider both the matrix and the interface to the fibre. Seizing of the fibre may have a significant impact on the interface strength.
Inter-laminar failure	○ Inter-laminar shear failure occurs in the matrix between adjacent plies/laminate due to shear stresses. ○ Inter-laminar tension failure occurs in the matrix between adjacent plies/laminate due to tensile stresses. ○ These failure modes can lead to delamination and sub-laminate buckling.
Sandwich failure	○ Ultimate failure of the sandwich core material due to tensile, compressive and shear loading. ○ Local yielding of the sandwich core due to tensile, compressive and shear loading. ○ The sandwich interface with the laminate. ○ Additional potential buckling failure modes for the sandwich structure of wrinkling, shear crimpling and face dimpling.
Fatigue failure	○ Cyclic loading leads to the accumulation of fatigue damage, with the fatigue damage phases characterised by matrix cracking, delamination, progressive fibre breaking, and final fracture. ○ If it can be demonstrated that the structure can withstand the degradations inherent in the fatigue damage phases, then the fatigue failure mode can be selected as final fracture.

Herein, it is worth noting that fracture resistance of blade adhesive joints varies with different types of load modes. For instance, the adhesive joints of a rotating blade are usually subjected to mixed mode loads (i.e., Mode I and Mode II). An interface flaw along an adhesive joint in one region could be harmless, but the same size of adhesive joint flaw located in other region could propagate quickly due to different mode mixities or higher stresses. In view of this, the technique used for evaluating blade cracking behaviour should be applicable to a wide range of mode mixities. This point of view, to certain extent, highlights the necessity and importance of both static and fatigue blade tests, in which the blade can suffer from different types of loadings.

To capture more energy from wind, wind turbines are preferred to be deployed in remote open locations, where wind has high speed and less turbulence. However, the open field makes the turbine easy to be the tallest structure in the vicinity. As a consequence, the turbine has high probability of being struck by lightning in harsh weather environment. Statistics have shown that more than 90% of lightning strikes to a wind turbine connect with the blades. As lightning can produce very brief but extraordinary high temperatures (often more than 30 000^{o}C), the blade composites could catch fire once the built-in lightning current conductor of the blade are not perfect in either design or performance.

III. BLADE TESTING METHODS AND ASSOCIATED FACILITIES

An increase in blade length indicates a corresponding increase in load levels. As being subjected to higher level of loads, the blades for large Megawatt-scale wind turbines require more extensively laboratory testing to ensure that the new design is able to continually provide long-term reliability. In other words, the blade should not fail before the end of its expected service life. Survey shows that 90% of the uncertainty concerning fatigue life predictions for wind turbine blades can be attributed to uncertainties related to material properties [8]. Thus, the aim of testing the blade is to demonstrate whether the structural parts and materials of the blade are able to withstand the ultimate loads probably occurring in extreme climates, and whether they can show high reliability when suffering long-term fatigue loads experienced in normal service conditions. To reach such objective, the testing of full scale blades generally consists of static testing and fatigue testing.

A. Static Testing Methods and Systems

The purpose of the static testing is to predict the blade capability of withstanding ultimate loads as those caused by storm, hurricane, typhoon or others happening in extreme weather. The objective of this type of testing is to determine and/or verify the ultimate strength of the blade through analysis of the testing results, which could be the distribution of strains along blade length under different static loading conditions or other related information.

In static testing, distributed loads are applied to the blade statically in one direction to establish the required ultimate strength. Such a test can be performed in a number of ways. In the very early days of the wind industry, static testing of wind turbine blade was conducted by placing sandbags along the blade length to mimic the bending moment distribution, as shown in Fig. 4.

Fig. 4 The early experience of static blade testing using sandbags

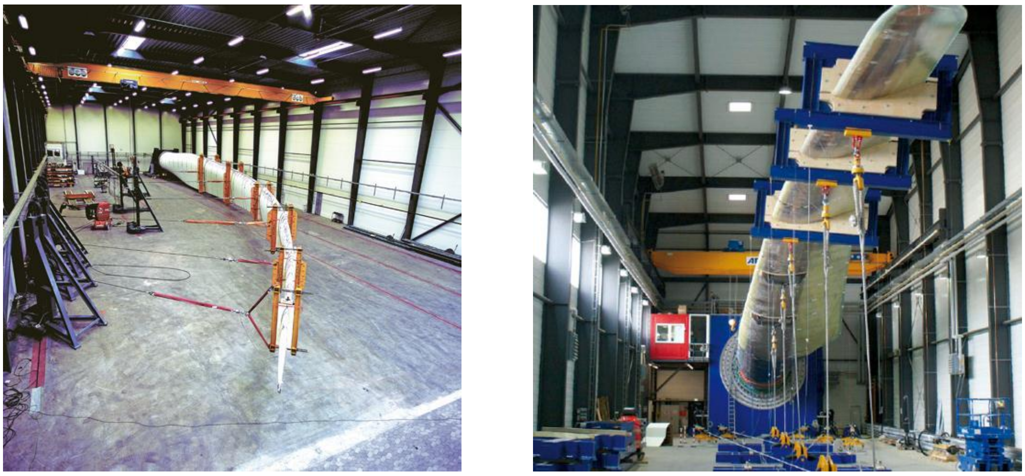
Later on, ballast weights were hung at specific locations of the blade to create the expected static loads. In the case of testing long blade, the blade under investigation will usually be attached to the test stand at a specific angle in order to prevent the tip of the blade from touching the ground, as shown in Fig. 5.

Fig. 5 Static testing of a long blade using ballast weights

In the past, hydraulic actuators were also experienced for creating the expected bending moment loads along the blade length. But the large deflections resulting from long wind turbine blades under static testing make them an expensive option. For this reason, today hydraulic actuators are rarely used in the static testing of large wind turbine blades. However, they are often adopted in the static testing of marine turbine blades attributed to their short length, as seen in Fig. 6.

Fig. 6 Static testing of a marine turbine blade using hydraulic actuators

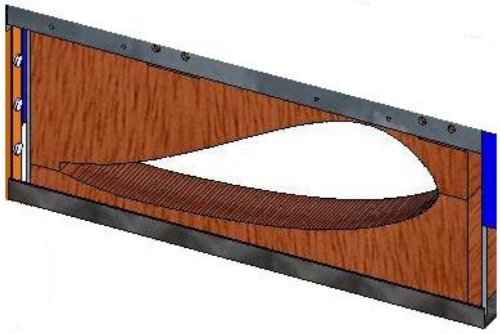
Nowadays, the most popular force application method used in static testing of full scale wind turbine blade is resorting electric winches attributed to their ease of control, as shown in Fig. 7.



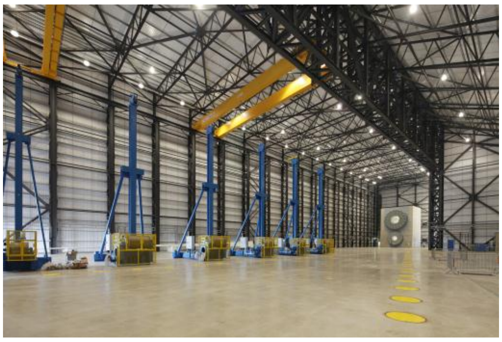
(a) Horizontal arrangement (b) Vertical arrangement

Fig. 7 Static testing of a long blade using electric winches

As shown in Fig. 7, the static testing is generally performed by attaching wooden saddles to the blade at the prescribed locations along blade length. These saddles are carefully shaped (see Fig. 8a), so that they can fit snugly around the blade profile in order to minimize the risk of damaging the local blade skin due to stress concentration at load application locations. Winches (see Fig. 8b) attached to the saddles are then used to load the blade such that the bending moment distribution along blade length can match as closely as possible the ultimate loads that the blade exercises in service.



(a) Wooden saddle



(b) Winches

Fig. 8 Saddle and winches used in static testing of blade

B. Single-axis Fatigue Testing Method and Systems

Fatigue testing of a wind turbine blade is performed mainly in order to identify structural defects inherent in either the design or manufacturing process and verify durability of the blade withstanding long-term fatigue loads during the course of its design life of 20 years or more. A modern multi-Megawatt wind turbine can undergo more than 100 million revolutions, which indicates that its blades will undergo at least 100 million cycles of fatigue loads. In each cycle, the loads applied to the blade will oscillate and regularly cause the maximum deflections in both flapwise and edgewise directions, as illustrated in Fig. 9. However, it is impractical to take the blade through so many cycles in laboratory testing because that would take several years to complete. Hence, in laboratory testing an increased load is usually adopted to achieve an equivalent amount of damage [9] accumulated after approximate 1 million cycles, allowing the testing to be completed in just a few weeks.

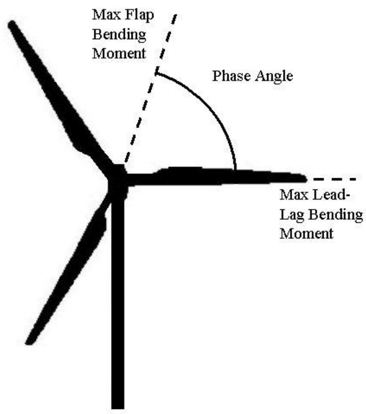


Fig. 9 Positions where the maximum flapwise and edgewise deflections occur

Fatigue testing of wind turbine blades provides extremely valuable data for blade manufacturers and turbine end-users, in terms of design validation and certification for in-service requirements [10]. Fatigue testing at present tends to use only one loading direction at a time, with flapwise and edgewise testing done separately. Such a testing procedure is called single-axis fatigue testing. It is a gross simplification of the fatigue loads experienced by the blade in service, but is seen as the best that can be reasonably achieved within time and cost constrains.

Fatigue testing of blade is conducted using either forced displacement or resonant methods. Both methods will be introduced below. Moreover, various practical means for introducing the loads into blade have been devised, including the use of hydraulic actuators for forced actuation and the use of rotating eccentric masses or oscillating masses to induce resonant loading. All these load application devices will be graphically illustrated as well.

1) Forced Displacement Testing:

Forced displacement testing is a method of performing fatigue testing by displacing the blade using mechanical means. The forcing mechanism can be a hydraulic cylinder, or some other mechanical mechanisms such as a rotating cam and rod or lever. An example of a forced displacement system using a hydraulic cylinder actuator is shown in Fig. 10. In this example, the fatigue load is applied to a single load application point. However, multiple load application points are possible. In a similar way as mentioned in static testing, in principle the simultaneous use of multiple load application systems in fatigue testing will enable the distribution of bending moments along the blade length to be as close as possible to the designed distribution curve, therefore a more reliable prediction to the durability of the blade is obtained. However, this will increase the complexity of the control. To certain extent, it can be said that using an advanced control method or algorithm to ensure all load application systems be able to move in synchronisation and work correctly is always a challenging issue in practical testing.

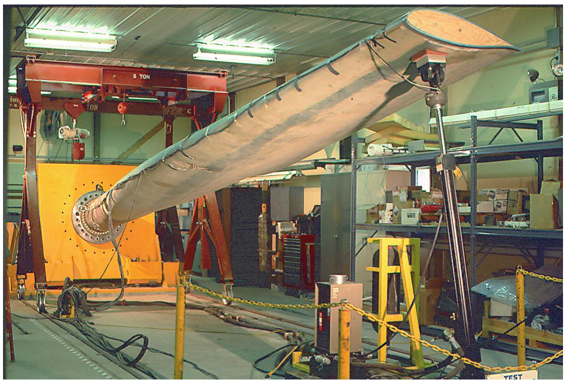


Fig. 10 Example of a forced displacement testing using a hydraulic actuator

In such a test, a known force is applied at each specific location on the blade, delivering the required root bending moment for the fatigue testing. The forcing mechanism needs to be able to displace the blade at a sufficient distance to generate the required tension and compression forces to the blade. Attributed to the controllable nature of forced displacement testing, the generated loading can be either constant or variable, depending on the concrete requirement of testing. To control the testing accurately, feedback information of loads and displacements is essential in the testing procedure. Sometimes, the measurements of strains and accelerations are also required.

2) Resonant Testing:

The resonant testing exploits the resonant natural frequency of the blade. By exciting the blade at its first natural frequency the blade can be displaced and loaded in a cyclic manner. Excitation of the blade can be achieved in several ways, but whichever method is used, the function of the exciter is to maintain energy input into the oscillation and to balance out the losses that occur through material and aerodynamic damping, which would otherwise cause the blade resonance to decay with time. At present, two main methods are being popularly adopted in achieving resonant excitation for fatigue testing. They are accomplished through either a rotating eccentric mass (see Fig. 11a) or oscillating masses (see Fig. 11b).

(a) Rotating eccentric mass

(b) Oscillating mass

Fig. 11 Resonant excitation for fatigue testing

Rotating eccentric masses, powered by an electric motor, can provide fixed-amplitude fatigue testing. Once the location and size of mass have been chosen, the frequency of rotation becomes the only variable that could be controlled when the test is underway. However, since the frequency is actually fixed by the natural frequency of the blade and the test equipment, it is in effect not actually a controllable variable and the testing must be performed at this frequency. In actual testing, minor changes in natural frequency of the blade do arise due to changes in stiffness of the blade (for example resulted by the changes in temperature and thus material modulus). But these changes can be accommodated by adjusting the rotational speed of the mass. If variable-amplitude fatigue testing is required, it is necessary to stop the testing and change the mass, which then requires the test frequency to be re-determined.

Oscillating masses, powered by hydraulics, move linearly and are able to perform both constant- and variable-amplitude fatigue testing more easily than rotating eccentric masses. This is because the amplitude of mass movement can be altered without changing the test set-up and this allows for changes in the strain levels to be introduced if variable-amplitude fatigue testing is required. But they are also constrained to operate at the natural frequency of the blade and test system.

Other methods for inducing resonant fatigue loads could be used, dependent on the ingenuity of the test designer. But any resonant fatigue system needs to provide a means of introducing energy into the blade, whilst not retaining a fixed connection between the blade and the floor, or other similar sturdy reaction point.

In the long-term practice of fatigue testing, the blade testing technology and operating system are also improved gradually in order to achieve more accurate control of loads, higher reliability of testing systems and a more efficient and cost-effective testing. Take the blade testing technology evolution at National Renewable Energy Centre (Narec, UK) as an example. Narec's first fatigue testing method was developed through a Cooperative Research & Development Agreement (CRADA) with National Renewable Energy Laboratory (NREL, USA). This technology used a moving mass, powered by hydraulics, resonating at the natural frequency of the blade, as illustrated in Fig. 12.

Fig. 12 Narec's first fatigue testing equipment – a resonant mass system powered by hydraulics

This first system required two support saddles to be mounted on the blade, with the moving mass system mounted at the top of these two saddles. As can be seen in Fig. 12, the moving mass is mounted well above the blade. The entire testing set-up is simple. However, the testing on blades of around 40m length revealed that there were limitations to using this test set-up. This is due to the "toppling" effects of the mass mounted above the blade. The forces generated by the oscillating movement of the resonant mass system create an over-turning moment on the saddles, which leads to high point stresses at the edges of the saddles acting on the skins of the blades. The option of reinforcing the saddles to make them more rigid was considered, but the added mass required made the solution impractical. Moreover, the testing equipment was originally set up in order to perform a flapwise fatigue testing. It did not lend itself to easily perform an edgewise fatigue testing, which would require a large resonant mass system to be balanced on the edge of the blade at some height above the blade edge that would be very unstable position.

To overcome the difficulties of applying the first generation of resonant mass system to performing the fatigue testing in edge direction and the limitations in performing flapwise testing, the second generation of resonant mass system, called as 'saddlebag', was developed, as shown in Fig. 13. In essence, it is a resonant mass driven by a through-rod hydraulic cylinder. Herein, it is worth noting that in Fig. 13 only one 'saddlebag' resonant mass system is illustrated. But in practical prototype test, a pair of hydraulic systems was used in order to reduce torsion loads and generate larger excitation force with smaller individual resonant mass. The second system was mounted on the opposite of the blade. The results obtained from trial tests with the saddlebag system were positive and fully demonstrated the advantage of positioning the moving masses close to the blade neutral axis. The through-rod hydraulic cylinders were suitable for proving the concept, but were not optimum, since the seals on the hydraulic cylinders were subjected to loads from the moving masses and wear rates on the seals were too high to be used in commercial tests.

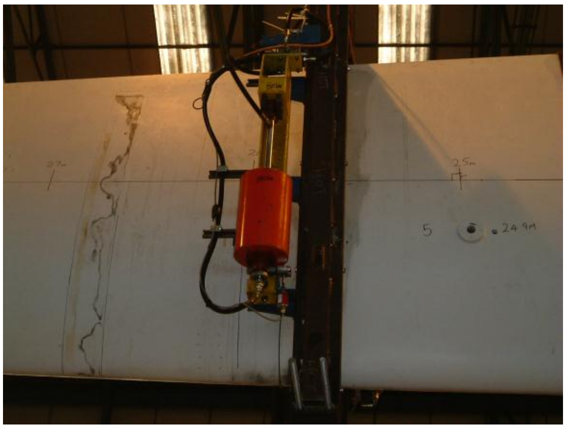


Fig. 13 Narec's 'saddlebag' resonant mass system

The third generation and also the final development of Narec's fatigue testing system was to keep the same concept of moving masses located near to the blade neutral axis, but the moving masses are mounted on rails to prevent loading onto the hydraulic seals. This third generation of system is Narec's Compact Resonant Mass (CRM) system, as illustrated in Fig. 14.

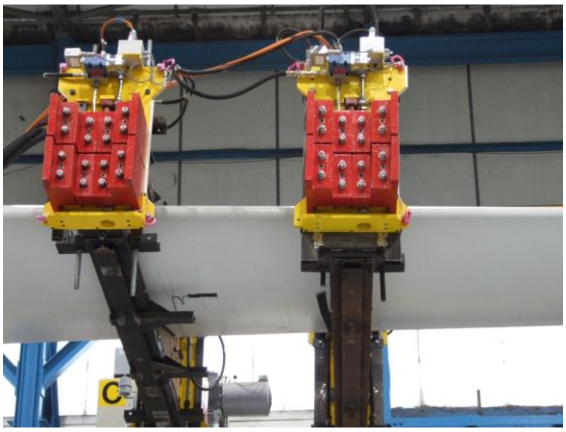


Fig. 14 Narec's compact resonant mass (CRM) system

Within Narec's CRM system the variables are:

- position of CRM along the blade length;
- size of moving mass;
- frequency of moving mass;
- amplitude of mass movement.

Some of these variables are linked together, for instance altering the mass of CRM will change the natural frequency as well. So, although frequency is a variable, the natural frequency is in fact fixed for a particular blade and mass combination. Hence for maximizing efficiency of energy transfer, the CRM system needs to be controlled so that its frequency of movement matches the natural frequency of the blade-mass system.

The control of a fatigue testing usually resorts strain gauge signals that provide feed-back to ensure that the blade is being tested at the correct strain level. If the strain level alters outside of pre-set limits then the CRM control system can change either the natural frequency and/or amplitude of mass movement to bring the strain back to the correct level. Several other signals are also monitored to provide emergent shut-down capability, e.g. accelerations, overall blade deflection and strain levels.

The latest progress of Narec on developing the advanced blade fatigue testing technology is that Narec has mastered the technique of utilizing multiple sets of CRM units to accomplish the resonant testing of a long wind turbine blade. The CRM units move in synchronisation at the resonant frequency of the blade-mass system. It can be said that this is a major move forward in technology, since it allows the energy input system to be distributed over the length of the blade. Undoubtedly, this significantly improves the bending moment distribution of the blade being tested in comparison with a single load introduction point method and also reduces the loads into the blade at any given point.

C. Dual-axis Fatigue Testing Method and Systems

The single-axis flapwise and edgewise fatigue testings of a full scale wind turbine blade are usually performed sequentially, e.g. first testing in edgewise followed by testing in flapwise direction. To shorten the testing duration, dual-axis fatigue testing of blade is now discussed with great interest in both industrial and academic communities. In dual-axis fatigue testing, both flapwise and edgewise loads are applied simultaneously to the blade, not only allowing to accomplish the fatigue testings in both directions in parallel in a shorter overall duration but better simulating the loads that are actually experienced by a blade in service. In addition, it is found that the phase angle between the flapwise and edgewise loads also have a significant effect on the amount of damage that accumulates around the blade [11]. This finding further highlights the significance of dual-axis fatigue testing. But at present, dual-axis testing is still an area of research under investigation in several countries [10, 12]. It is not an industry standard, nor are there many requests from blade manufactures for this type of testing.

A dual-axis fatigue testing could be delivered potentially by using several methods. The conceptually simplest method is to use forced actuation as illustrated in Fig. 15, which is used in the Stevin lab at Delft University of Technology in Netherlands. In the forced actuation test set-up, the hydraulic actuators react from frames to load the blade in flap- and edge-directions, and any combination of flapwise and edgewise loads can be applied to the blade.

A second possible technique was developed by NREL in USA, as illustrated in Fig. 16. It is a test set-up using hydraulic actuator and side-mounted push-rod. In the testing operation, forced actuation is used for the flap-direction and a second cam mounted push-rod provides edge loading. The edge loading is applied in synchronisation with the flap loading so that the phase angle between flapwise and edgewise loadings is maintained within the required limits.

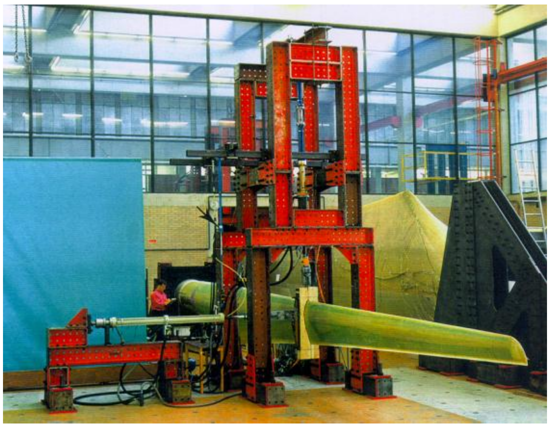


Fig. 15 Dual-axis test set-up using hydraulic actuators

Fig. 16 Dual-axis test set-up using hydraulic actuator and side-mounted push-rod

The main limitation with the aforementioned two test set-ups respectively developed by Delft University of Technology and NREL is that for long blades it becomes extremely difficult to apply the large deflections required. Long-stroke actuators will be needed to create the large deflection of the blade. These require heavy reaction frames and large hydraulic flow capacities, which will significantly increase the testing cost. In view of this, a third dual-axis fatigue testing method was recently developed by Narec in the UK, as illustrated in Fig. 17 [13]. This method uses resonant excitation simultaneously in both flap- and edge-directions.

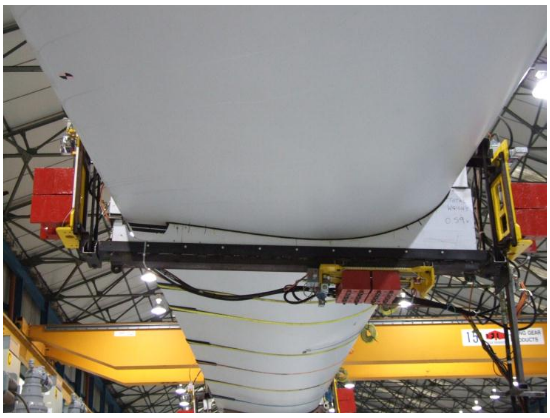


Fig. 17 Narec's CRM set-up for dual-axis testing

Prototype testing of this new method has been conducted by Narec. In the testing, a full-size blade of around 40 m length was excited in flap- and edge-directions simultaneously [13], and the testing results were promising. In this new achievement, Narec used its CRM system mounted in two orthogonal directions. The CRM system consists of a few sliding masses mounted on rails. The sliding masses moved by hydraulic rams as seen in Fig. 17. Since the flap- and edge-direction first natural frequencies are not the same, two separate CRM systems are respectively controlled to oscillate at the required flapwise or edgewise frequencies.

Experimental investigations have shown that in dual-axis testing, the resultant motion of the blade and the induced strain levels follow a complex pattern, which appears to be chaotic, but is in fact not, it being a pre-determined if sensitive combination of flapwise and edgewise loadings. The normalised path of the tip of a blade undergoing a dual-axis testing is shown in Fig. 18. It indicates how the blade experiences a full range of loadings, rather than the constant amplitude loading undergone in single-axis testing.

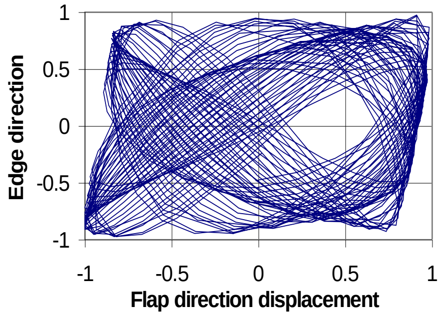


Fig. 18 The normalised movement orbit of a blade tip during dual-axis testing

D. Lightning Strike Testing

Blade represents a special lightning protection challenge unique to wind turbines. The wind turbine blades are complex in geometry and construction, and up to more than 60 m long, made from fibre reinforced composite materials, placed on more than 100 m high tower, and rotate in a vertical plane (for horizontal-axis wind turbines), while exposed to direct lightning attachment. Moreover, wind turbines are usually deployed in open field, making their blades be the most exposed structural elements in vicinities. In lightning strike, the blade will experience the full electromagnetic and mechanical (pressure wave) impact and energy content from the lightning current, the electric field, and the magnetic field associated with the lightning strike. For these reasons, the wind turbine blades have to be safely protected once they are struck by lightning strikes. In fact, this risk is always inevitable in wind turbine operation. To date, the lightning protection of blades fabricated from composite materials has been addressed in different ways by blade manufacturers, firstly on a trial and error basis, and over the last decade on the use of more dedicated research and development programs including field and laboratory testings. The lightning protection concepts that are popularly used in large modern composite material wind turbine blades are shown in Fig. 19, which shows the basic structure and composition of the blade lightning protection systems.

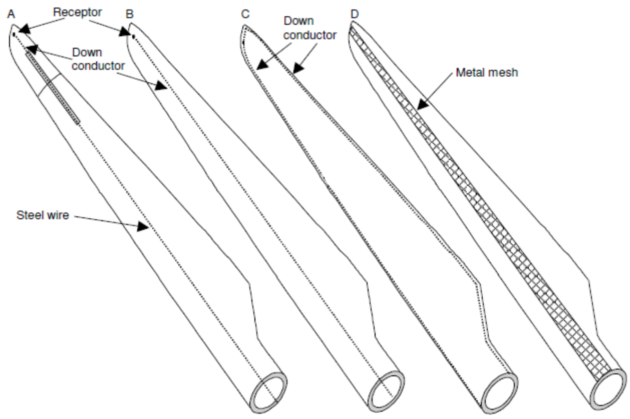


Fig. 19 Lightning protection concepts for large modern composite wind turbine blades

The Part 24 of IEC 61400 standard has explained how to apply the existing technologies to the lightning protection of wind turbine and its critical substructures, especially the blades. In this standard, an effort has also been made to describe a range of high voltage and high current tests, which were originally developed and used successfully for qualification of aircraft structure. In recent years, the similar tests have been adapted to the lightning strike testing of wind turbine blades.

The criteria for adequacy of protection for blades are to show that the design and positioning of the lightning air termination system on the blade ensure efficient lightning interception, and that the down conductor system can sustain the effects of lightning current corresponding to the lightning protection level I (unless shown by risk analysis that LPL-II or LPL-III is sufficient) as shown in Table 2.

TABLE 2 LIGHTNING PROTECTION LEVELS

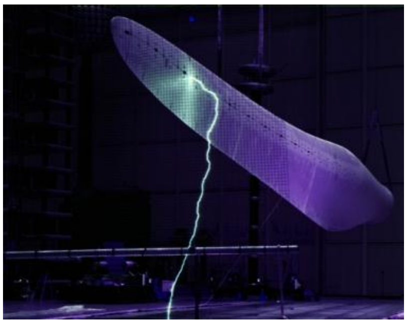
Protection level	Peak current (kA)	Specific energy content (kJ/Ohm)	Average rate of current rise (kA/μs)	Total charge transfer (C)
I	200	10 000	200	300
II	150	5 600	150	225
III/IV	100	2 500	100	150

Although lightning may attach anywhere on most of the blade surfaces, the long-term field experience shows that the majority of lightning attachments are located at blade tip, and that only a minority attaches elsewhere on the blade. It is therefore concluded that the air termination system positioning tools in IEC 62305-3 [14] do not apply to wind turbine blades. In view of this, in wind turbine blade lightning strike testing it requires to verify the ability of the air termination system and down conductor system to intercept lightning strikes and conduct lightning currents by either of the following methods:

- High voltage and high current tests;
- Demonstration of similarity of the newly designed blade type with a previously certified blade type, or a blade type with documented successful lightning protection in service for a long period under lightning strike conditions;
- By using analysis tools previously verified by comparison with test results or with blade protection designs that have had successful service experience.

At the moment, the laboratory testing of the lightning protection system of wind turbine blades has not been widely performed due to the high costs of professional equipment and facilities. But some testing organizations have either partially or completely possessed this capability. For example, the lightning impulse generator at Narec can generate both lightning (1.2/50μs) and switching impulse (250/2500μs) voltage waveforms with positive and negative magnitudes up to 3.2MV and 2MV, respectively. This enables Narec to conduct both swept-channel and leader-attachment tests on wind turbine blades. The overview of equipment for lightning strike testing and an illustrative lightning strike testing example are shown in Fig. 20.

(a) Equipment



(b) Illustrative example

Fig. 20 Overview of equipment for blade lightning strike testing and an illustrative example

The items to be tested would usually be specimens of the blade, including the tip and sufficient portions of the blade inboard of the tip to represent the complete lightning protection design including down conductor systems, connecting components and other components of the lightning protection design.

The tests include both high voltage strike attachment tests and high current physical damage tests:

- The high voltage strike attachment tests are intended for wind turbine blades. The tests can be used to assess location of possible leader attachment points and flashover or puncture paths on blades, optimization of the location of protection devices (e.g. air terminals, receptors, etc.), flashover or puncture paths along or through dielectric surfaces, and performance of protection devices.
- The high current physical damage tests are used to assess actual damage from lightning currents, for example arc attachment damage, hot spot formation, metal erosion at receptors, adequacy of protection materials and devices, magnetic force effects, blast and shock wave effects, behaviour of joints and hardware assemblies, and voltages and currents at points of interest throughout a lightning protection system. The testing methods depicted in the standard are applicable to both complete tip designs and to smaller sections of the down conductor.

The test specifications will include discussion of purpose of test, detailed instructions of each test set-up, test specimen selection, test impulse waveforms, measurements and data recordings, data interpretation and step-by-step test procedures.

IV. STANDARDS FOR WIND TURBINE BLADE TESTING

Today, blade testing has been required as part of turbine certification to meet international design standards, such as IEC and DNV, benefiting developers in mitigating the technical and financial risk of deploying mass-produced wind turbines. To perform the static and fatigue testing of full-scale wind turbine blades, there are already a number of blade testing facilities that have been established across the world, for example Risø National Laboratories in Denmark, National Renewable Energy Laboratory (NREL) in USA, National Renewable Energy Centre (Narec) in the UK, the Centre for Renewable Energy and Sources (CRES) in Greece, the wind turbine Materials and Constructions Knowledge Centre (WMC) in Netherlands, National Renewable Energy Centre (CENER) in Spain, LM glass fibre in-house testing facility in Denmark, the Blade Test Centre Gujarat (BTCG) in India, SGS's blade testing facilities around the world and so on. All these testing organizations are required to run the testing laboratory in accordance with the standard ISO 17025, which provides general requirements for the competence of calibration and testing laboratories.

The requirements to the structural safety and design loads of wind turbine blade have been specified in the Part 1 of IEC 61400 standard. Static and fatigue testing is an essential element of wind turbine certification. In order to provide valid static and fatigue type testing, there are three key areas that need to be addressed, i.e. right loads, right test specimen, and right documentation. The right loads are addressed through the correct development of extreme and fatigue loads, the selection of the correct safety factors, and the correct set-up and execution of test program. Although there will always be one particularly fatigue area on the blade, it is still desirable to obtain the correct bending moment distribution over as much of the length of the blade as possible; the right test specimen is addressed through the selection of a representative test blade, and the inclusion of critical structural elements during the test; and finally the testing program must be thoroughly documented, capturing the key information required to provide confidence in the test results, the design, and ultimately to achieve certification. The detailed requirements for full scale blade testing are already specified in the standard IEC 61400 Part 23. The major manufacturers, laboratories, research institutions and certificating bodies have participated in developing these standards. However, the detailed qualification of blade materials, design, and manufacturing procedures are yet to be included. For this reason, DNV issued a new standard DNV-DS-J102: Design and manufacture of wind turbine blades, offshore and onshore wind turbines in October 2010, replacing its previous version DNV-OS-J101 issued in 2004 and providing a more comprehensive and detailed guideline to the development of new wind turbine blades. The contents widely cover the blade material qualification, design analysis, blade manufacturing, blade testing, and documentation requirements. At present, DNV-DS-J102 standard serves as detailed guidance to achieve IEC WT-01 certification for wind turbine blades.

As mentioned above, the lightening protection of wind turbines, particularly the lightning protection of wind turbine blade, as well as the known lightning protection technologies have been specified in the standard IEC 61400 Part 24, which is however limited to horizontal axis wind turbines. The standard uses the lightning current parameters defined in the standard IEC 62305-1 for wind turbine lightning protection system design, and for lightning protection component dimensioning, selection and testing. The lightning current parameter values defined in IEC 62305-1 standard are generally considered adequate for lightning protection of wind turbines.

In wind turbine blade engineering, the qualification of materials, design and manufacturing procedures is dependent on the individual blade manufacturers. They utilise unique and individual materials, design approaches, and manufacturing processes, the details of which are often confidential. This is one of the major differences when compared to other industries, such as civil engineering and ship building, where the materials, design solutions and manufacturing methods are more or less common for all manufacturers.

In addition to the IEC and DNV standards mentioned above, some other industry standards are in connection with the qualification, design analysis and testing of composite materials. Some of them are listed in Table 3 [7].

TABLE 3 GUIDELINES AND STANDARDS IN CONNECTION WITH COMPOSITE DESIGN AND TESTING

Reference	Title
ASTM C297	Determination of the core flat wise tension strength of sandwich structures
ASTM C613	Standard test method for constituent content of composite prepreg by soxhlet Extraction
ASTM D 5379	Standard test method for shear properties of composite materials by the V-notched beam method
ASTM D1781	Standard test method for climbing drum peel for adhesives
ASTM D2344	Standard test method for short-beam strength of polymer matrix composite materials and their laminates
ASTM D2584	Standard test method for ignition loss of cured reinforced resins
ASTM D3167	Standard test method for floating roller peel resistance of adhesives
ASTM D3171	Standard test methods for constituent content of composite materials
ASTM D3479	Standard test method for tension-tension fatigue of polymer matrix composite materials
ASTM D3529	Standard test method for matrix solids content and matrix content of composite prepreg
ASTM D3530	Standard test method for volatiles content of composite material prepreg
ASTM D3531	Standard test method for resin flow of carbon fibre-epoxy prepreg
ASTM D3532	Standard test method for gel time of carbon fibre-epoxy prepreg
ASTM D5528	Standard test method for mode I inter-laminar fracture toughness of unidirectional fibre-reinforced polymer matrix composites
ASTM D5868	Standard test method for lap shear adhesion for fibre reinforced plastic (FRP) bonding
ASTM D695	Standard test method for compressive properties of rigid plastics
Danish Energy Agency	Recommendation for design, documentation and test of wind turbine blades
ISO 14129	Fibre-reinforced plastic composites – determination of the in-plane shear stress/strain response, including the in-plane shear modulus and strength, by the ±45 °tension test method.
MIL-HDBK-17-1F	Volume 1. Polymer matrix composites guidelines for characterization of structural materials
MIL-HDBK-17-3F	Volume 3. Polymer matrix composites materials usage, design, and analysis

V. STRUCTURAL HEALTH AND PERFORMANCE MONITORING OF WIND TURBINE BLADES

Blades are crucial and expensive components of a wind turbine. However, they are one of the components that are most likely to fail [4] due to their exposure to high loads even in normal operation. Moreover, failure of a blade can cause significant downtime or even machine loss, as well as negative publicity. Particularly with present large megawatt wind turbines and the highly competitive electricity generation market, the loss of revenue from one machine due to component failure can cause considerable financial stress to operators. So, to understand the actual health condition of the blades and detect their structural failure as early as possible is of significance not only to the revenue of an individual wind farm operator but to the competitiveness of the whole wind industry. For this reason, condition monitoring is regarded as one of the most efficient and cost-effective approaches to minimizing the risk of blade failure and the downtime.

In the standard IEC 61400 Part 23, the failures of a wind turbine blade are categorized into three levels according to their severity, effects and consequences, as listed in Table 4 [10].

TABLE 4 FAILURES OF A WIND TURBINE BLADE

Damage levels	Presentation of the failures
Catastrophic failure	○ Breaking of primary blade structure ○ Complete failure of structural elements, internal and external bond lines, skins, shear webs, root fasteners ○ Major parts become separated from the main structure
Functional failure	○ Reduction in stiffness by 5-10% ○ Permanent deformation ○ Substantial permanent change of cross-sectional shape ○ After unloading the blade, a mechanism is no longer capable of performing its designed objective
Superficial failure	○ Small cracks not causing significant strength degradation or bond line weakening ○ Gel coat cracking ○ Paint flaking ○ Surface bubbles ○ Minor elastic panel buckling ○ Small delamination

However, the failures mentioned in the standard are all characterized by the physical damages of material and structure of the blade. In condition monitoring practice, some blade-related rotor failures are also need to monitor. They could be not harmful to the structural health of the blade, but could result in significant degeneration in energy capture efficiency. This kind of failures could be characterized by [15]:

- increase in the blade surface roughness due to pollution, icing, blowholes, exfoliation, remains of insects, etc.
- mass imbalance due to icing, water penetrating through cracks, loose material (e.g. remaining material from production processes) moving inside the blades, etc.
- aerodynamic asymmetry due to blade pitch angle failures, aerodynamic profile production tolerances, profile deformation during operation, etc.

Accordingly, the existing blade condition monitoring techniques can be roughly classified into two categories, i.e. (1) structural health condition monitoring, and (2) energy capture efficiency monitoring. The former is for detecting the structural failures occurring in blade, and the latter is for detecting the change in performance due to failures or defects of the blades or associated systems (e.g. pitch control system).

As depicted in [15], up to now condition monitoring of wind turbine blade is accomplished mainly by visual inspections onsite at regular intervals (usually once every 2 years) to provide ‘snapshots’ of the actual rotor condition, as shown in Fig. 21. Obviously, it is unlikely to perform such kind of work in unfavourable weather conditions. For this reason, the suitable time for carrying out onsite inspection of wind turbine blades is limited, as wind turbines are intended to be deployed in remote windy and cold areas. Moreover, onsite inspection of blade requires specialized equipment (cranes, working platforms, etc.) and expert personnel, consuming a lot of time and money. For offshore wind turbines, onsite blade inspections will become even more problematic and cost intensive due to the limited access to rough sea site and additional costs on vessels, cranes and other tools specially required in the work on sea. For these reasons, online condition monitoring is strongly recommended, especially for those wind turbines deployed offshore and in remote lands. The benefits of having a blade condition monitoring system can be summarized as:

- avoidance of premature breakdown: prevent catastrophic blade failures and secondary damages;
- reduction in time for blade inspection and maintenance cost: inspection interval can be increased with online inspection, prolong the service life of a blade, and schedule the replacement of defective blades at right time;
- supervision at remote sides and remote diagnosis: reduce the times of visual inspection at remote sites;
- improvement of capacity factor: with early warning of impending failures of blades, maintenance action can be taken during low wind season and hence will not lower the capacity factor very much;
- support for the improvement of blade design: the condition monitoring data obtained can be used to improve designs for the next generation of turbine blades with higher reliability.

(a) Before inspection (b) In inspection

Fig. 21 Visual inspection of wind turbine blades

In the past decades, lots of efforts have been expended to develop the condition monitoring techniques for wind turbine blades [5, 16, 17, 18]. A brief overview of existing techniques is given below, although a truly effective and reliable online monitoring technique has not been fully achieved today.

A. Structural Health Monitoring

Although structural damage can happen to any structural component of a highly loaded wind turbine, the most common type of structural damages stem from blade or tower failures [19]. Accordingly, extensive attention has been given to detecting the structural failures of blade by using various non-destructive testing techniques. The major of them include [16, 20]:

1) Vibration Analysis:

Vibration analysis is the most known technology applied for condition monitoring. The types of sensors used depend on the frequency range, i.e. displacement transducers are used for low-frequency range, velocity transducers for middle-frequency range, and accelerometers for high frequency range. In the current condition monitoring practice, research people rarely use vibration sensors to measure the vibration response directly from the blade. But the cases of successful application of vibration analysis in blade condition monitoring are often reported. For example, it was reported in [15] that a rotor mass imbalance fault was successfully detected with the aid of two accelerometers. Both accelerometers were installed in the nacelle of a constant speed 600 kW wind turbine. One was in front of the tower vertical axis (i.e. close to the rotor when looking from the hub), and the other was located at the rear of the vertical tower axis. The rotor mass imbalance fault was resulted from an asymmetric icing condition of the blades. An illustrative example of this situation is shown in Fig. 22.

Fig. 22 Ice on wind turbine blade

2) Acoustic Emission:

Acoustic emission is now a popular idea used for monitoring the structural health condition of wind turbine blades, although this technique has not been fully validated in wind industry. Acoustic emission monitoring is realized through a piezoelectric acoustic sensor, which is attached to the blade by flexible glue with low attenuation, as shown in Fig. 23.

The sensor is able to detect the high frequency component of the elastic waves (or stress release waves) generated by the energy loss processes due to cracking, deformation, debonding, and delamination failures occurring in the blades. It has been reported that acoustic emission event will cluster around a certain point where damage occurs [21]. So, acoustic emission monitoring is potentially an effective method for locating the blade failure or damage locations. In addition, acoustic emission signals are characterized in terms of amplitude and energy, and inferences can be made about the kinds of damage processes taking place in the blade. However, acoustic emission is less capable in damage characterization and further damage evaluation if a suitable algorithm is not available. The varying wind loads applied to the blade makes such kind of testings further challenging.

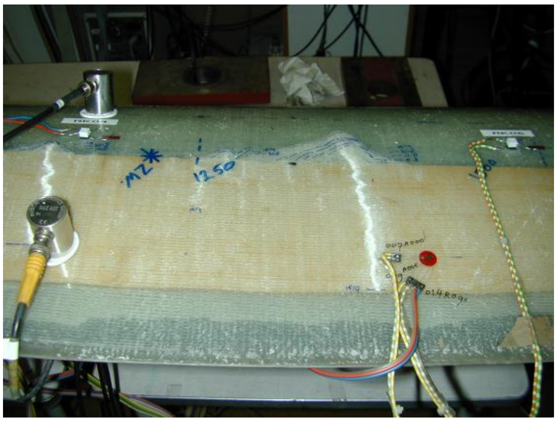


Fig. 23 Acoustic sensors attached to blade

3) Thermography:

Thermography is often applied to monitoring and failure detection of electronic and electric components. For example, hot spots, due to degeneration of electric or electronic components or bad contact, can be readily identified by the approach of thermography. In recent years, thermography has been further applied to wind industry. The successful detection of blade failures by thermography in the lab has been reported [20], as shown in Fig. 24. It is especially effective in detecting subsurface defects or anomalies that can cause temperature differences on surface of the blade. The advantage of thermography is that it is able to produce a full-field measurement in image form, which allows a fast evaluation even for a non-professional user. The main problem of thermography monitoring technique lies in the thermal excitation method. Passive excitation can be used but is limited to those composite materials that produce excessive heat during operation of the blade. In addition, environmental temperature is also a factor that cannot be ignored in thermography testing.

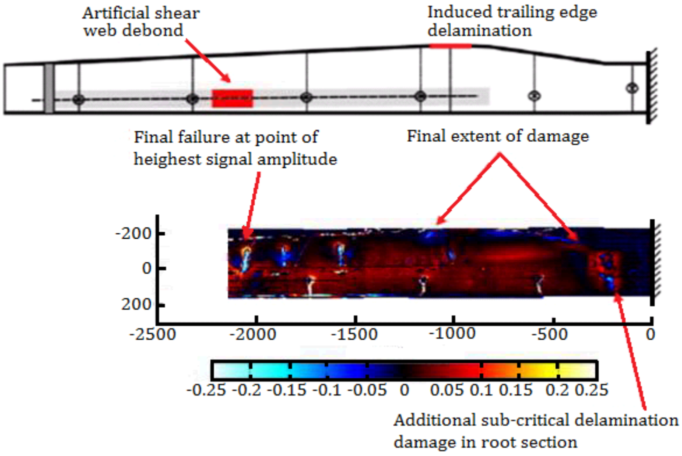


Fig. 24 Detecting defects in blade by thermography

4) Ultrasonic Detection:

Ultrasound is a well-established method for investigating the inner defects of composite structures, such as wind turbine blades. The basic principle of the technique is that an ultrasonic wave is passed through the material and is then reflected and/or mode converted by a defect. Ultrasound probing will typically reveal planar cracks (e.g. delamination) oriented perpendicular to the direction of sound wave propagation. The transmit time and/or amplitude of the feedback ultrasonic signals will be monitored. The transmit time can be used to determine the position of the defect relative to the position of the transducer, while the amplitude can be used to assess the severity (or size) of the defect. At present, the ultrasound-based blade monitoring techniques have been commercialized. Fig. 25 shows a blade ultrasonic detection system developed by a Danish company named Force Technology.

In the system, four ultrasonic transducers are used. A special control system was designed to ensure that transducers can properly touch the varying blade profile at different positions. A camera was installed in the front of the system, avoiding the system goes over the blade. The defects (e.g. cracks, delamination, etc.) can be successfully detected and easily observable from a 3D testing image. However, like other ultrasonic detection systems, this system also requires special couplant with low attenuation to enhance the detecting capability of the ultrasonic transducers. This constrain significantly limits the onsite application of ultrasonic techniques in wind farms.

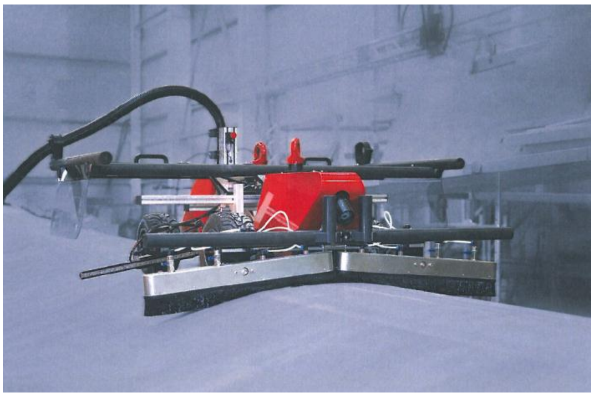


Fig. 25 Ultrasonic detection system for wind turbine blade

5) Fibre Optics:

An optical fibre is a glass or plastic fibre designed to guide light along its length. Optical fibres are widely used in fibre-optic communication, which permits transmission over longer distance with less loss and at higher data rates than other forms of wired and wireless communications. Moreover, they are immune to electromagnetic interference. In application, the optical fibre will be attached to the test specimen. The optical power of a light source will reduce when it goes through the optical fibre. The reduction depends on the strain of the fibre. This principle is adopted to sense the strain in the structure being tested. In wind industry, this technique was developed for evaluating the structural health condition of wind turbine blades through measuring the strains and therefore bending moments in root sections of the blades. Currently, many companies across the world are developing such kind of techniques and systems for application in wind farms. One of the proven systems is the Rotor Monitoring System (RMS) developed by Moog Insensys, as shown in Fig. 26. Up to date, RMS has been utilized for accomplishing multiple health detection items of wind turbine blades, such as ice detection, rotor imbalance detection, lightning strike detection, and blade damage detection.

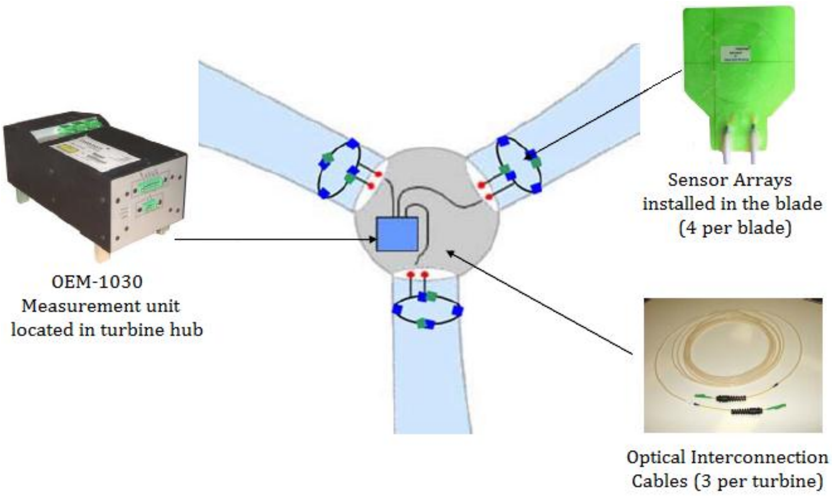


Fig. 26 Typical configuration of Insensys RMS system

6) Laser Doppler Vibrometer:

The laser Doppler vibrometers are a type of non-contact velocity transducers based on analysing the Doppler effect on a laser beam emerging from a solid surface. Previously, laser Doppler vibrometers have been widely used for monitoring the vibration of rotating machinery. Such technique was further applied to monitoring the variation in the relative distance between wind turbine blades and tower [22]. This is because that approximately 63.4% of the structural damages in wind turbines leading to catastrophic accidents are due to the sudden deformity or displacement change between the blades and the tower [19]. The LDS system developed in [22] consists of a sensor head and controller. It employs triangulation measurement principles, whereby the laser emitter projects an infrared laser beam that creates a spot on the rotating blade surface. Reflected light from the surface is detected by the light receiver inside the sensor head. Therefore, LDS system does not need any special surface preparation to detect the reflected light. The displacement values of the blades are acquired through use of a DAQ system (NI, Terminal block 2120 and Digitizer PCI 6221) in real time to monitor abnormal blade deflection. The displacement is continuously monitored by impinging the laser beam of the non-contact LDS at the rotating blades in an operating condition of a wind turbine. Damage such as nacelle tilt, bolt loosening, or blade mass loss causes measurement irregularities or changes, indicating the detection of any possible damage. The installation of the LDS system on a wind turbine is illustrated in Fig. 27.

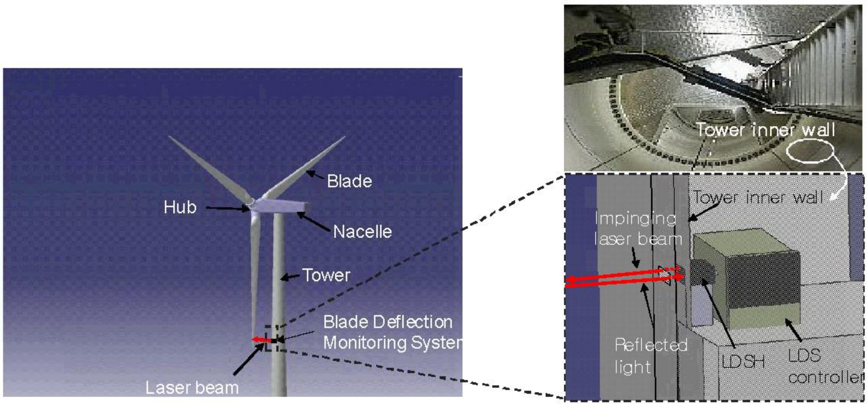
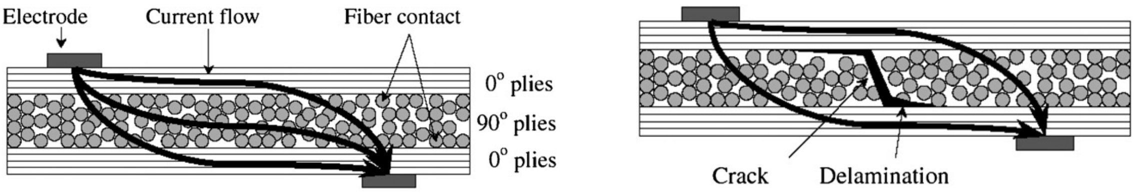


Fig. 27 The blade deflection monitoring system installed on a wind turbine

7) Electrical Resistance-based Damage Detection:

Carbon fibres used in wind turbine blades have high electric conductivity while the polymer matrix of a carbon-fibre-reinforced plastic (CFRP) is an insulating resistor. In practice, CFRP laminates have finite electrical resistance in every direction. The electrical resistance in the transverse direction is much larger than in the direction of the fibre orientation. If a delamination crack propagates in the resin-rich interlaminate, the crack breaks the fibre-contact-network between the plies. The breakage of the contact network causes an increase in the electrical resistance of the carbon/epoxy-laminated composites, which enables delamination crack detection by measuring the electrical resistance change in a CFRP composite laminate. A delamination crack is detected using the electrical resistance change between the two mounted electrodes, as shown in Fig. 28.



(a) Electrical network structure of the fibre in a CFRP laminate

(b) The electrical network is broken with delamination and matrix cracking

Fig. 28 Schema of a practical structure of a carbon/epoxy composite when an electrical current is applied [16]

A wireless delamination detection system is composed of a sensor module that has a ceramic oscillator connected to the electrodes mounted on the composite surface and its receiver. The ceramic oscillator of the sensor module is used for wirelessly transmitting the electrical resistance change data as the oscillating frequency changes to its receiver. The oscillating frequency of the sensor circuit increases with the increase of electrical resistance of CFRP laminates, indicating the occurrence of delamination in the CFRP laminates.

8) Mechanical Strain Gauge:

Mechanical strain gauges are popularly used in static and fatigue testing of full scale wind turbine blades. As shown in Fig. 29, they are glued to the surface of the blade being tested to provide accurate measurement of the bending and stretching loads of the blade. At present, mechanical strain gauge might be the cheapest and the most reliable approach for fault detection, lifetime forecasting and protecting against high stress levels of wind turbine blades. However, owing to the inherent reliability issues of the material mechanical strain gauges can be used in laboratory testing but unsuited to onsite applications.

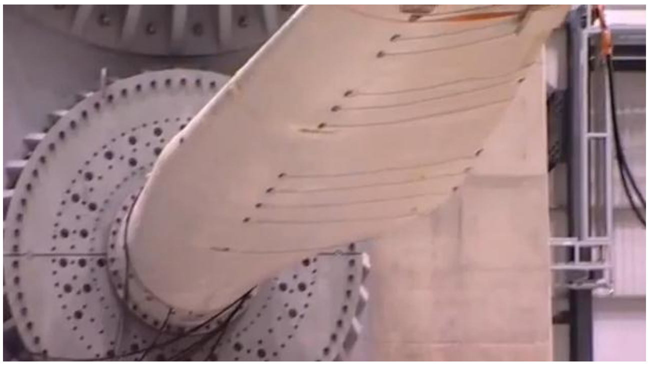


Fig. 29 The array of mechanical strain gauges in fatigue testing of a wind turbine blade

B. Performance Monitoring

In spite of the great effort already done, the majority of the aforementioned Non-destructive testing techniques are still not ideal for performing the online monitoring of wind turbine blades in operation. In addition, some blade defects, e.g. rough surface of the blade caused by ice/snow, insect remains or dusts, are not actually the structural damage of blades. They however do significantly degenerate the energy capture efficiency of the blade. For these reasons, instead of spending lots of money and attention to conduct the structural damage detection, the operator would rather to make more effort on improving the capacity factor of wind turbines by taking advantage of available resources in wind farm. The data collected by the wind farm Supervisory Control and Data Acquisition (SCADA) system is one of the most valuable resources available to utilize. The SCADA system is originally designed for operating wind turbines, ensuring they are conforming to the designed power curve and protecting the turbines in extreme weather and loading conditions. It measures the operating and performance parameters from those key subassemblies or components of the turbines regularly (usually at 10 minutes intervals). Through analysing these SCADA data, the operator can count the electric power generated by the turbines and understand their operating/health conditions approximately. Owing to being collected by using a low sampling rate, the SCADA data can hardly be applied to performing condition monitoring using conventional spectral analysis approaches. They however may be used to carry out some simple condition monitoring tasks of those key components of the turbines if a suitable algorithm is available [23, 24, 25]. Researches have shown that many correlation relations among wind turbine operating/performance parameters can be used for assessing blade conditions or early detecting the faults in blades. For instance, a total of 6 parameters, i.e. wind speed, rotor speed, generator power, generator speed, gearbox vibration and gearbox oil level, are proposed for condition monitoring a wind turbine blade in operation [23]. The judging procedures are:

Step 1: Check the correlation between generator speed and generator power to assess the health condition of generator;

Step 2: If generator is fine, check the correlation between rotor speed and generator speed, the correlation between rotor speed and gearbox vibration and temperature, as well as the gearbox lube oil level against time, to assess the health condition of gearbox and coupling;

Step 3: If above correlations are well maintained, the miscorrelation between wind speed and rotor speed, and the miscorrelation between wind speed and shaft torque would indicate something wrong with one or more blades of the turbine.

Owing to the shortage of wind turbine SCADA data, the kinds of blade performance/condition monitoring techniques have not been fully demonstrated, although their preliminary application results are promising [23]. To facilitating understanding, the wind speed - rotor torque correlation curves obtained before and after the presence of a blade defect are shown in Fig. 30. From this figure, it can be clearly seen that the torque-speed curve gradually sinks over time. And from this phenomenon, it can be inferred that the energy capture efficiency of the blade is degenerating gradually with the growth of defect.

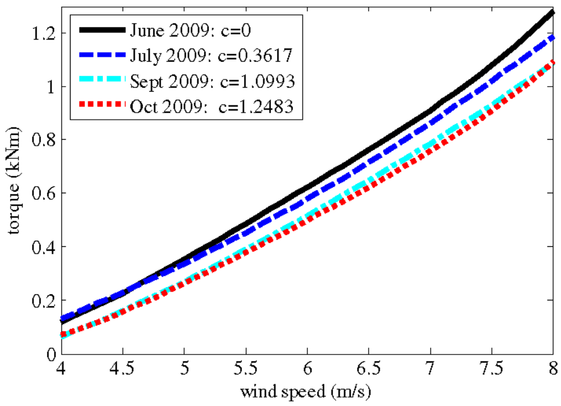


Fig. 30 The correlation between wind speed and shaft torque [23]

The influences of ice, snow, dust and insect remains on the energy capture efficiency of wind turbine blade are often reported. They are characterized by either gradual or sudden change of wind speed – power curves. All these environmental factors take negative effect on blade's performance mainly through changing the surface roughness of the blade. A successful surface roughness assessment technique or device is still sought for today. At the moment, the assessment of the blade surface roughness is still accomplished by the means of visual inspection.

VI. GENERAL SUMMARY

A. Single-axis Fatigue Testing

Fatigue testing of wind turbine blades has developed to its present capabilities of testing over 60 m long blades, and delivers an important part of the proving process for wind turbine performance. Several different fatigue testing methods are possible, which can broadly be classified as either forced displacement or resonant testing. Both testing methods are currently used in performing fatigue testing of wind turbine blades. Each of them has both advantages and disadvantages. To benefit the future R&D work, their major limitations are summarized as follows:

1) Forced Displacement Testing:

Forced displacement as a testing method requires equipment that is able to physically move the blade through the required deflections. As blades get longer the deflections required also rise and the demands made on testing equipment, particularly hydraulic cylinders, become much higher. With hydraulic cylinders the key factors to consider are the stroke length to achieve the required deflection, and the hydraulic fluid flow rates needed. Stroke lengths may rise to several metres, and the hydraulic fluid flow rates required, to support these stroke lengths, can rise to thousands litres per minute (1000L/min). Long stroke length, high load hydraulic cylinders are expensive and the cylinders themselves are subjected to fatigue wear due to the testing.

The cost of pumping large amounts of hydraulic fluid is a major consideration for a forced displacement testing. This cost is mainly the cost of energy for moving the hydraulic fluid and for providing cooling for the fluid. There is a direct relationship between the amount of deflection needed and the quantity of energy required, and with a forced actuation system there are very limited means of reducing this energy cost.

For a forced displacement system the blade needs to be able to take the loads that are input from the actuation equipment. These loads can rise to high levels if only one or two load points are used, which requires the blade to be reinforced at these loading points. Blade reinforcement will alter the blade performance and behaviour, and whilst this should not be an issue for the fatigue test, if further static testing is required after the fatigue test, then this reinforcement may interfere with obtaining valid static test results.

A forced displacement system using hydraulic actuators requires robust and fail-safe control systems, since the very nature of hydraulic systems means that they have the potential to move very rapidly with high forces, with the possibility of severely overloading the blade. Hence, once the hydraulic cylinder is connected to the blade, there is the risk that any control system malfunction or operator error could damage the blade.

2) Resonant Testing:

The main limitation of resonant testing methods is that they can only be performed at the first natural frequency of the blade plus test equipment system. This means that it is not possible to alter the duration of testing time, and as blades get longer, natural frequencies become lower and testing times increase and become longer. In addition, for a resonant testing method the testing equipment is normally mounted on the blade, which introduces an amount of static mass as well as the dynamic moving mass that excites the blade. This added mass also reduces the natural frequency.

The equipment that is mounted on the blade is subjected to the movement of the blade and in particular the accelerations as the blade cyclically oscillates, reversing direction through each cycle. On longer blades these accelerations can reach high levels and exciter equipment needs to be designed to accommodate these accelerations and induced forces.

With resonant testing the damping forces due to aerodynamic resistance, particularly in the flap orientation, become very significant for long blades. These aerodynamic damping forces arise because of the large deflections that blades are subjected to, and the resultant large volumes of air that are displaced by each sweep of the blade. The energy input to sustain resonance on long blades needs to be carefully considered, and the test apparatus designed appropriately to ensure effective transfer of energy from the exciter system to the blade under test.

For rotating mass excitation the only significant variable is the amount of dynamic mass and just adding more can lead to a case of diminishing returns. With oscillating mass it is possible to vary both mass and amplitude of mass movement, giving greater flexibility, but also creating other interactions between moving mass and the accelerations that can be sustained by the test equipment.

B. Dual-axis Fatigue Testing

In contrast to single-axis fatigue testing, dual-axis testing shows the following advantages:

- provide a better test of the blade by combining load cases;
- reduce the time of testing by combining the flapwise and edgewise testings to run in parallel rather than sequentially.

However, despite the quick progress and innovations in developing new dual-axis testing methods and facilities, many issues still remain to solve in this field, namely:

- flapwise and edgewise loads are not applied in a predictable order;
- the number of load cycles applied in flap and edge develop at different rates;
- loads onto the non-major blade axes are difficult to define prior to the start of the test;
- the number of load cycles applied to non-major blade axes only becomes known as the testing proceeds;

• blade manufacturers at present have procedures for developing damage equivalent loads (DEL) for a single-axis fatigue testing, and these DELs are used to define the load level for the single-axis fatigue testing. These procedures are not easily adaptable to the resonant dual-axis testing method;

• the material property data requirements for the DEL analysis on a dual-axis testing are not the same as those for a single-axis fatigue testing, and blade manufacturers will need to invest in more material testing if they wish to exploit resonant dual-axis testing.

At present, both testing organizations and universities are performing research activities aiming to investigate the various points detailed above. Once these issues are solved successfully, it is believed that dual-axis testing will be popularly adopted in the full-scale testing of wind turbine blades attributed to its superiorities to single-axis testing.

C. Blade Lightning Strike Testing

It is well-known that wind turbines are frequently struck by direct lightning strikes. The risk of suffering struck has proved to increase with the increasing size of wind turbines. This fact cannot only be explained by the increase in collection area, but apparently the amount of upward initiated flashes from these relatively high structures has increased drastically as well. Fortunately, both research and experience accumulated over the last decades have shown that wind turbine can be effectively protected against lightning strike by applying the well-known and proven lightning protection techniques. This is the case for the electrical and control systems, and also for most of the wind turbine structures. The exceptions are the blades for which new protection systems have had to be developed and tested.

At present, many testing bodies have either partially or fully possessing the capability of performing the lightning strike testing of wind turbine blades. Moreover, lightning strike accidents of wind turbines are often reported [19]. However, there are still not many requests from blade manufacturers for this type of testing. So, it can be said that today static and fatigue testings are still the mainstream items of blade testing, because most blade failures stem from the damages resulted by ultimate loads in severe weather conditions or long-term fatigue loads in a normal operating condition.

D. Blade Condition Monitoring

Many techniques for non-destructive testing were performed in assessing the health condition of wind turbine blades. These techniques are either simple or complicated, either cheap or costly. Most of them have shown promising testing results in laboratory and some of them have been commercialized and adopted for monitoring blade during static and/or fatigue testing. However, few of them are really suited to onsite application in wind farm. Among these techniques, fibre optic strain gauge measurement is a best proven technique in wind industry. It was originally designed for controlling the bending moment loads of the blades and protecting them from being damaged when overloaded. Now, its application has been further extended to detecting the failures of turbine rotor. Despite these achievements, to fulfil a successful structural health monitoring of a long blade (> 60 m length) by the approach of fibre optic strain gauge measurement is still a challenging issue, especially under constantly varying loading and operating conditions of wind turbines.

Performance monitoring of blades by taking advantage of wind turbine SCADA data is a cost-effective and therefore promising technique. The IEC 61400 standard has specified the parameters that are essential to be collected by wind turbine SCADA system. If the additional values of these SCADA parameters and the knowledge behind them can be fully explored, many critical wind turbine failures, including blade failures, can be early detected in advance. Unfortunately, the wind industry today has not been fully standardized. The wind turbine design, the manufacturing process and the SCADA systems equipped in the turbines are different from manufacturer to manufacturer. Moreover, the SCADA data collected from wind turbines are currently being regarded as highly confidential properties of turbine suppliers. Access to these data cannot be made open to the public. Undoubtedly, all these restrictions have significantly delayed the progress in R&D for condition monitoring techniques.

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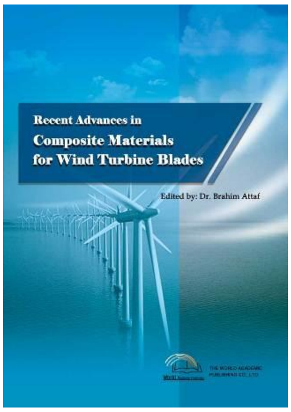

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This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, aerodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

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