Structural Health Monitoring for the Advanced Maintenance of Wind Turbines: A review

K. Kalkanis*, S.D. Kaminaris, C.S. Psomopoulos, G.C. Ioannidis, G. Kanderakis

Abstract— Wind energy has been developed rapidly throughout the world. However, as more wind parks are built worldwide, the number of accidents recorded regarding wind turbines increases as well. As the most critical and expensive components of the wind turbine system, wind turbine blades often suffer damage. Presently in situ blade inspection is carried out every 3 to 6 month visually or with manual operatives involved in dangerous abseiling. Only limited, crude repairs are performed in situ. In most cases a damaged blade is dismantled & transported to a factory with specialized composite repair facilities, making the operation downtime very high, especially with the increasing trend towards remote offshore location of turbines. These factors generate very high maintenance costs, amounting to over 30% of overall operating costs when allowing for lost revenue. The trend is for turbines to grow in size and number to the globally set targets and their deployment becomes more widespread and remote, maintenance costs will escalate. The ideal solution is for Structural Health Monitoring (SHM) of blades so as to minimize the need for extensive repairs, thus eliminating all transport costs and associated downtime. This review will underline the most promising emerging and established technologies on the topic.

Keywords—Sensing techniques, Structural Health Monitoring, Wind Turbine Blades, Data Acquisition, Fibre Optics.

I. Introduction

Critical components in the blade industry are susceptible various failure modes caused by environmental and/or loading conditions. Furthermore, nearly all engineering structures experience some form of alternating stress, and are exposed to harmful environments during their service life. This plays a significant role in the fatigue of composite structural materials**.** Blade failure arises from a number of possible sources and results in either entire blades or blade fragments being propelled from the turbine.

Wind turbines operate autonomously and can possess reliability issues attributed to manufacturing defects, fatigue, or extreme weather conditions. Being one of the most critical and vulnerable parts of the modern wind turbines, blades can suffer holes or cracks that can lead to blade failure and loss of energy revenue generation. Low level reliability and subsequent damage leads to excessive repair costs that raises the cost of the wind generated energy. In order to help identify damage in wind turbine blades, several approaches have been used in the wind industry most of which require transducer integration, have not been effective, or require inspection.

There are various causes for wind turbine failure emanating from the fabrication stage such as inadequate quality control and extending to in service induced damage such as unforeseen loading and general fatigue failure [1, 2]. During manufacture of the composite blade many inherent faults can make their way to the final product with devastating consequences. These include broken reinforcement fibers, resin rich areas, inadequate curing-low level of polymerization, insufficient adhesive bonding which may lead to development of micro-cracks within the matrix, debonding between fibers and matrix separation of different layers of a laminate (Delamination) [3,4].

As far as in service failure, it can involve bending loads while in standstill [5], braking system failure rendering the turbine spinning uncontrolled until catastrophic failure, lightning, highly stressed trailing edge components when in stall.

It is inescapable that in order to increase the use of renewable power sources, more powerful wind energy plants will be built in the years to follow. Downtimes of these plants will have to be as short as possible via maintenance optimization. Additionally older plants will be repowered and new areas will be considered for wind power use. It is a certainty that in the future people will live nearer to wind turbines, which means that accident avoidance will have to reach higher levels of effectiveness.

The magnitude of wind turbines has become physically larger so as to meet the rising capacity needs, a fact which generates problems as far as maintenance and repair procedures are concerned. It is operationally difficult and hazardous to perform inspection and maintenance. Furthermore, the usually remote location of the wind turbine generates added difficulty. It is deemed obligatory to monitor turbine blades so as to obtain operational performance reassurance. Health Monitoring of such structures has gained much interest lately as it offers enhanced safety, optimized inspection cycles by the use of non-destructive testing techniques, minimization of downtime and avoidance of extended damage. The wind turbines must be routinely monitored to ensure good condition to ultimately provide reliable power generation [6]. Various

K. Kalkanis is with the University of West Attica, Dept. of Electrical and Electronics Engineering, Campus II, 250 Thivon str & P. Ralli Ave, GR-12244, Egaleo, Greece. *Corresponding author: E-mail: k.kalkanis@puas.gr, Tel +302105381575, Fax: +302105381321

S.D. Kaminaris, C.S. Psomopoulos and G.C. Ioannidisis are with the University of West Attica, Dept. of Electrical and Electronics Engineering, Campus II, 250 Thivon str & P. Ralli Ave, GR-12244, Egaleo, Greece.

G. Kanderakis is with GMI AERO, 9 Rue Buffault 75009 Paris France.

existing measurement techniques, including fibre-optics, and the acoustics emission, can detect and identify defects on composite wind turbine blades [7].

II. STRUCTURAL HEALTH MONITORING

In general, the development of successful SHM methods depends on two key factors, namely, sensing technology and the associated signal analysis and interpretation algorithm [8]. Due to the current economic developments in all areas of our society and in particular to the creation and subsequent implementation of complex and costly constructions, there is an attempt to maximize the cost-effectiveness ratio, while maintaining the originally planned-designed lifetime. The effort to monitor structural integrity / health monitoring has thus appeared in the area of modern day engineering.

Structural Health Monitoring systems can be divided into two main categories:

• Load spectrum monitoring systems: These systems record load spectra of structures in their operational use and calculate the cumulative fatigue damage by using pre-existing analytical / numerical models [9]. These systems are called Operational Load Monitoring Systems.

• Health monitoring systems: These systems record the precise field parameter values (strain, temperature, etc.) and are integrated into the constructions [10], with the ability to determine a failure event, size, its location and impact. These systems are distinguished in:

(1) Integrated, which consist of sensors, built-in structural integrity logic and feedback capabilities to external stimuli

(2) Semi- integrated, which incorporate only sensory and structural integrity logic.

A major problem in the predictive and fault tracking process in one construction is the measurement of field parameters capable of being associated with any occurring failure and yielding the characteristics of the failure [11]. In the case of health monitoring systems, the major component capable of describing the above is strain. Of course, the process of linking a failure to field parameters depends directly on the monitoring technique used and the desired result. In line with modern developments in the field of structural integrity monitoring, two main techniques have been identified: the local and global monitoring technique.
Local techniques are usually optical or based on local field measurements using X-rays, strain gauges, optical fibers, etc., require prior knowledge of both the nature of the failure and the monitoring area and require effort and time when applied to large scale projects [10]. On the other hand, global techniques (vibration monitoring techniques) can monitor changes in the dynamic characteristics of a structure under the influence of dynamic loads and detect any failure in both small and large-scale structures, but not matching the precision offered by local techniques.
It is therefore common practice to supplement these techniques when it is necessary to monitor the health integrity of a large scale structure.
The implementation of an operating monitoring system, whether universal or local, is based on the following stages - levels that are distinguished by the desired accuracy in detecting a failure [12,13]:

• SHM Level 1: Confirm the existence of a failure in the construction
• SHM Level 2: Spatial localization detection
• SHM Level 3: Quantification of failure
• SHM Level 4: Calculate the remaining construction life in service

The SHM information gathered could be used in a condition based maintenance program

- Minimize the time needed for inspection of components,
- Prevent unnecessary replacement of components,
- Prevent failures and
- Allow utility companies to be confident of power availability.

In addition, SHM may allow the use of lighter blades that would provide higher performance with less conservative margins of safety [14].
Furthermore, a wind turbine with lighter blades can respond to wind alterations, thus capture more energy [15].

All loading factors, including environmental stimulate [16, 17] factors result in accumulated fatigue damage, which can cause catastrophic damage to the wind turbine. Thus, much research effort is now focused on real-time monitoring techniques including vibration based, optical fiber sensing, and piezoelectric techniques.

In such value added, large structures, algorithms are utilized, capable of processing the harvested signals from the sensors for SHM, and can be further extended to the prediction of failure, estimation of the remaining service life so as to determine the actions required.

In order to develop a general-purpose algorithm for the designated applications, efforts are needed to ensure that the whole system does not become complex in defining the relationship between subsystems, components and subassemblies [18]. A fault prediction algorithm has the primary function of this system which allows early warnings of structural defects to prevent major component failures. Many faults can be detected while the defective component is still operational.

The ability of mounting a sensor network at selected locations in order to be able to consistently, reliably and accurately receive data about its behavior when operating loads. Comparing these elements with the standard behavior of the construction (according to the results of the simulation and the other calculations made during the design phase) it now is possible to "continuously diagnose" the structural integrity of the construction and to reveal any structural faults or mechanical and electrical malfunctions.

In this way, the engineer is given the opportunity to reduce the uncertainty encountered during the initial design phase of construction (and thus the safety factors - and the added cost). In addition, he is able to diagnose any construction errors (failure to meet material specifications, poor construction, etc.) in time (immediately after loading), which could then evolve into factors of premature construction failure. And all this, without the need to withdraw the construction from use, as in the case of Non Destructive Testing techniques, and with relatively low direct costs.
Thus necessary repair actions can be planned for the most appropriate time without the need to bring an immediate halt to the system at the point of total failure. [19].

III. DAMAGE DETECTION TECHNIQUES-SENSOR PLACEMENT

When a critical section of a structure is under consideration for SHM, the number of data output to the signal processing system tend to reach great volumes due to the increased number of sensors. In order to receive a manageable volume of data, [20, 21] a Structural Neural System (SNS) for SHM is proposed.

According to the level of detail required by a health monitoring and damage identification system, four levels of logic implementation can be used as in [12]. In [21] the use of neural networks and genetic algorithms was studied in order to implement a structural integrity logic (four levels of implementation) concept in terms of health monitoring of a composite patch repair. In that respect, various learning algorithms were examined and compared using the data set defined in experiments considering Two major potential failures: the repaired crack extension despite the repair and debond of the adhesive bonding of the composite onto the metallic structure. In order to design the best solutions available for each level of implementation, two main network types were used: a classification network and a function approximation network. Each network was used for a specific level of implementation. Thus, for levels 1 and 2 a classification network was used while for levels 3 and 4 a function approximation multilayer perceptron network was used.
For the implementation of the capability to identify and verify fault that occurred in a composite patch repair, due to the lack of experimental data, the learning data set used was produced using the finite element method, for the model presented in Figure 1.

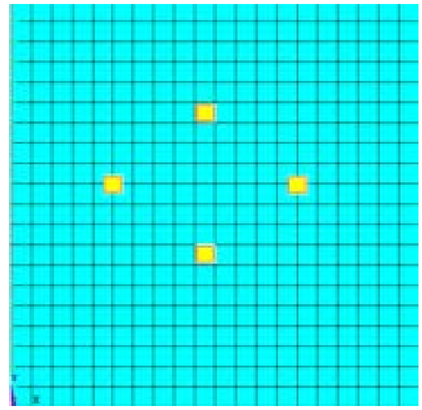

Figure 1: The structure FE model and the assumed sensor positions.

Three types of failure were modelled as typical failures that can occur in a composite patch, which are:

- Crack
- Local disturbance
- Delamination

The data set consisted of 500 exemplars (data points). The Neural Network used for the algorithm evaluation was consisted of 10 to 30 hidden processing elements and the test was performed with 1000 to 5000 epochs (iterations).
A typical classification multilayer perceptron was used to locate the potential damage occurred within a composite patch. Due to the monitoring capabilities initially provided, three classes of failures were assumed for the case of a composite patch, which are presented in Figure 2.

Figure 2: Classes of failure for SHM Level 2 on a composite patch repaired substrate.

Having completed the training process as well as the validation of the network architectures, the optimum network architecture for each SHM Level is then submitted to a "live" process, during which online strain data taken from the sensors can be fed to the networks. The network outputs for this "unknown" data set were close enough (Figure 3) to the expected causes.

SHM's are now being established in new turbine blades using mainly embedded or fiber sensors [22, 23]. Placement of the sensor is of outmost importance so as to deliver useful readings from the SHM system [24]. Reliable data regarding the impending failure or damage of certain components can only be acquired by optimally placing sensors mainly at critical loci, to reduce the number of data acquisitioned and stored. It should be stated that composite materials fracture mechanics is much more difficult to address compared to isotropic and homogenous materials [25].
Fiber Bragg Grating (FBG) sensors are able of measuring strain and fluctuations in temperature at selected spatial locations, thus detecting failure modes, including delamination

between plies or on the substrate surface. FBG sensors can be patched on the surface of the blades or embedded into laminate composites [26-28]. They exhibit excellent sensing and mechanical performance compatible with online monitoring [28-31], environmental stability and immunity to electromagnetic interference. The disadvantages presented include measurement limited to local deformation and active crack sensing only when in close proximity [32].

A. Fibre Optics Method

A predominant requirement for a sensible construction is to quickly and accurately detect the measured quantity (mechanical voltage, temperature, torque) while simultaneously transmitting it to the construction control devices. At the same time, the measurement should be independent of external factors such as electromagnetic radiation, etc., have a satisfactory analysis and ease of adaptation (internally or externally) to whole construction. It has thus been found that such advantageous attributes are the use of optical fibers and optical sensors for the detection of measured quantities.

The method of constructing optical sensors is based on the proper integration of fiber sensing capabilities, which essentially translates into detecting changes in light transmission characteristics such as intensity, phase, polarization, frequency, etc. caused by the change in measured field sizes. Depending on the physical and geometric characteristics of the sensors, the optical sensors are distinguished in different categories.

Categorization of optical sensors is based on the configuration of the optical sensor with respect to the optical fiber. Optical sensors that are internally incorporated into the carrier fiber are called intrinsic sensors, while sensors that are externally integrated or at the interface between optical fiber and other device, by appropriate methods (such as fusion splicing, welding or other mechanical connection) are called extrinsic sensors. The basic requirement of an optical sensor layout is to measure a field parameter in an area of interest. Depending on the range of this area, the following types of sensors are defined:

- If the measuring range is point, the sensor is called a point sensor. Most of the optical sensors that measure temperature, pressure, strain, etc. operate with this philosophy.

- If the measurement area is point and distributed at the same time, the sensor is called semi-distributed. This sensor is used in case of measurement in specific small distributed areas (e.g. chemical processes).

The Bragg gratings are manufactured by the controlled and periodic ultraviolet radiation incident to the core of the optical fiber. Usually it is achieved by using a laser and it is possible to precisely determine the length of the sensors and the period of the refractive index (λ) of the reflected wavelength. Multiple sensors with different reflected wavelengths can be created on the same fiber.

Optical fibres are also used as sensors in SHM in various forms. FBG sensors can be interrogated with different types of opto-electronic instrumentation, and the resulting information, typically the electrical output signal produced by a photo detector, has to be acquired, sampled and elaborated by means of a dedicated electronic system [33]. The FBG has certain useful characteristics as follows [34].

(a) The sensor is a modified fibre. It has the same size as the original fibre. This is in marked contrast to many other types of optical fibre sensors which are either bigger, weaker or both.

(b) The responses to strain and temperature are linear and additive and the FBG itself is calibration-free.

(c) Multiple gratings can be combined in a single fibre by taking advantage of multiplexing techniques inspired by the telecommunications industry. These systems are able to simultaneously read large numbers of sensors on a very few fibres, leading to reduced cabling requirements and easier installation.

Although FBG is used to measure strain, a distribution of FBG over the structure can be used to detect traverse crack evolution [35] and impact damage [36]. The impact event can be detected in real time by measuring both the abrupt change of strain and the time delay in the strain changes between the sensors. By using the difference in arrival time of the strain response, the position of the impact event can be located and further analysis can be conducted.

It has been shown that Acoustic Emission (AE) waves generated during standard pencil-lead breakage or actual damage will propagate on a structure and then modulate the pitch of the FBG [37, 38]. This ability makes the FBG viable to detect structural damage as early as at its onset.

A specimen is usually heated using flash lamps chamber, and a fibre optic sensor is used to measure changes in the thermal conductivity of a sample due to impact damage. Furthermore, and in the case of a composite to composite repair, it is worth noting that the FBG’s find successful application [39, 40].

In [11] experimental investigation, supported initially by numerical analysis, addressed the capability of sensing during the curing cycle of a structural repair guaranteeing cure quality. Results have exhibited identification and completion of cure leading to reduction of repair and downtime costs. The sensors were further used post curing for structural integrity where results proved that the optical fibres can render a general state of the strain field inside the patches and possible crack propagation in real time.

B Ultrasonic methods (UT)

Ultrasonic testing has proved its effectiveness in a variety of applications including determination of material homogeneity, deterioration in mechanical properties of material in time, interlaminar loss of traction locate discontinuities, porosity, delamination and low velocity impact inflicted damage [12,41, 42].

The technique relies on generation of ultrasonic pulses via a piezoelectric element. Multiple cross-sections of different phases are performed within the material by propagation of the pulse resulting to development of longitudinal and transverse waves. The return of the waves to the piezoelectric element creates an electrical signal thus determining the time needed to return. In flawed areas where the material may have failed, a pulse velocity drop is observed which corresponds to the calculation of the magnitude of the failure (Figure 5). Unfortunately the method is rather slow and acquires experienced investigators for interpretation of results.

C Acoustic Emissions (AE)

Piezoelectric transducer sensor arrays capture the stress waves passively generated and emitted by active damage to identify the type or location of the damage [43-47].

The acoustic emissions technique detects the transient elastic waves produced by redistribution of the stress field. When a structure is loaded, shifts are created that lead to energy release in the form of waves propagating to the surface.

Acoustic tracking and analysis provides useful information on the origin and the severity of a failure.

AEs are differentiated in relation to other methods in two ways:

1) Sensors receive the energy emitted by the failure.

2) Control is almost always performed during the operation of the structure, so AEs focus on dynamic phenomena such as crack propagation or detachment.

Of course, this second point implies difficulty in taking measurements in high noise environments, which is added to the signal noise. A negative feature of AEs is that only qualitatively they can recognize the failures in the monitored structure. For the quantification it is necessary to use other NDT methods.

Basically, acoustic emissions are generated by stresses that in turn cause strains either elastic or plastic. The most visible AEs are observed when the material receives plastic deformations. At that time, the individual planes slide between them. These displacements create elastic waves (ultrasound). The amount of energy, range and waveform released by an acoustic transmission are related to the size and speed that distinguishes the failure.

The identification and consequently the conversion of these waves into electrical signals is the principle of operating the AEs. Analysis of these signals provides useful information on discontinuities within a structure under investigation.

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As far as wave type and speed are concerned, acoustic sources, i.e. failures, lie through the time it takes the wave to cross the material and reach the sensor. It is therefore very important to accurately calculate the velocity of the waves, which depends on the material under consideration.

In signal analysis, the sensor is attached onto the structure and monitors the signals resulting from the imposed stresses. When a signal is successfully recorded, various parameters are collected such as amplitude, rise time and duration [12].

AE systems are able to locate where a signal originates through the wave velocity and the difference they reach the different sensor locations. Of course, this logic assumes that speed remains constant, which is often not the case, due to reflections or waveform conversion. Monitoring during loading of wind turbine blades has offered considerable advantages towards the understanding of the complex damage mechanisms [48-50]. In addition, the characteristics of an AE event concentrating at a certain point and taking into account the increase in intensity, can be utilized by pattern recognition software for damage evaluation [49, 50].

D Thermal Imaging Method

Thermal imaging method is a subsurface defects or anomalies detection method owing to temperature differences observed on the investigated surface, such as the wind turbine blade, during monitoring by using infrared sensors or cameras [51], detecting differences in thermal diffusivity and hence indicating material irregularity or damage.

The thermal imaging method can be categorized by the thermal excitation method of the test subject using either passive or active methods. Thermography is an infrared imaging method used to evaluate leakage due to stresses, heat conduction leakage and structural detachment. It offers high-resolution and real-time images (Figure 6), and the ability to record results on magnetic media (video). It is emphasized, however, that this method is only applicable to small parts, since the supply of the required heat to large pieces is difficult and expensive. Of course, this damage detection technique can be a local technique [52] or a global technique because it is possible to assess the damage from a single or full-field measurement [53], depending on the resolution of the camera.

In active thermography, heat is applied to the test piece via optical flash lamps, heat lamps, hot or cold air guns, and surface temperatures are monitored by an infrared camera, as the heat leaks the material. In reflecting method, heat is applied to the surface being monitored. Relatively hot areas indicate possible internal defects. In heat transmission, heat is applied to the camera opposite side of the block, and the relatively cooler areas indicate areas with a poor heat transfer coefficient. However, while heat delivery is the most common process, its removal can also be used to generate temperature potential for examination. Passive Thermography, without an external calorific source, can be used if thermal differences can be created in the material in other ways, such as electric heating.

Thermographic methods are particularly suitable for use with materials having a low thermal coefficient, such as ceramics and polymers. Heat spreads slowly on such materials, and results in less time accuracy than the camera monitoring the phenomenon. In addition, interference with initial thermal stimulation may affect near-surface effects, so slow heat transfer helps to minimize false indication.

Also surfaces with a high degree of thermal conductivity offer better results. Thus layers in black, often applied to the surface of the material for better radiation. Defects such as delamination perpendicular to the convection of heat are most likely to be detected by thermography. Other imperfections that prevent convection, such as liquids trapped in cellular composite materials, can also be readily identified. The clarity of the method decreases with depth, because the thermal energy dissipates towards all dimensions and not to the investigation's favour. Furthermore, differences in thickness and composition can be detected by Transmission Thermography.

The disadvantages of the method are the cost of equipment, the dependence on the surface radiation coefficient, and more generally the low signal to noise ratio. Advantages include the technology maturity, speed, use without contact with the item and flexibility in measurement. Further increase in sensitivity to infrared cameras and optimization of thermal imposition will further develop the thermographic method as well as the associated technologies mature [12]. Thermography techniques have several advantages for finding sub-surface voids, laminations and other concrete failures. The obvious advantage is the speed at which this examination is carried out. At the same time it is a control method that does not cause environmental problems and does not require special security measures. The most important advantage is that a material area is being studied in its entirety rather than point.

Certainly a very significant disadvantage of the method is that the depth and thickness of a failure are difficult to record and require multiple measurements. Furthermore in active thermography, overzealous application of the heat source can cause charring to thermoset and melting in thermoplastic matrices [54].

Finally, if all types of loading are not included in the test program, it is possible for a major flaw to go undetected [55].

The passive approach is not common in wind turbine SHM and more modifications are required before it becomes a promising method. Thermoelastic stress analysis is useful during fatigue test of a wind turbine blade as the measurement of surface stress distribution on a blade during cyclic loading is possible. Furthermore stress concentrations and damage are identified.

E Electrical resistance-based damage detection methods

This electrical resistance-based damage detection method is different from the resistance-based damage detection method. Researchers have [56, 57] utilized the conductive property of the CFRP and proposed an electrical impedance tomography damage detection method and demonstrated that the principle can be used to detect fatigue damage.

The electrical resistance gradually increased as the stiffness reduced and showed a very abrupt change when the final fatigue failure was imminent. It has been shown that matrix cracking, delamination and fibre breakage can be detected using this method.

In [58], several inductive contactless strain-sensing methods were investigated. Magnetostrictive wires were embedded inside composite laminates to act as both structural and sensing elements with no obligation of connecting the sensing element to the measuring device. Using a single transducer (which is connected to the measuring device), we can acquire strain measurements at any point. The experimental results (Figure 7) showed that the minimum detectable strain value could be around 0.25 mStrain and the resolution up to 0.1 mStrain. Using these wires as strain-sensing elements could enable inspections at regular maintenance intervals in order to retrieve the structure's 'strain signature'. The retrieved strain signature is then compared to previous readings in order to trace potential differences and/or anomalies.

Eddy currents are one of many methods of non-destructive testing based on the phenomenon of electromagnetism. They are created through the process of electromagnetic induction. When a coil is leaking from an alternating current, it creates a magnetic field. When a conductor enters the alternating magnetic field then it is leaking from electricity.

Eddy currents are electric currents that flow in a circular path and are so named because of the vortices created when liquid or gas flows in a circular current around obstacles when conditions are ideal. Flaws, such as cracks, are detected when they disrupt the eddy current and weaken it. The advantages of the method include its sensitivity to small cracks and other imperfections, the ease of finding superficial and sub-surface imperfections, the fact that it is carried out by portable equipment and that it offers immediate results. At the same time the test specimen requires minimal preparation, while the sensor does not need to come into contact with the surface. Finally, it is noted that because of the basic equipment required for the method, it makes it very flexible in terms of the geometric complexity of the parts that can be controlled [12].

However, there are significant drawbacks to the method as it applies only to conductive materials. Furthermore the sensor must be close to the surface under investigation, which must not be rough. In addition, special training and skill is required. Finally, a significant downside on the implementation of the method is the reduced depth of penetration and the fact that deficiencies such as the delaminations parallel to the sensor coil go undetected.

F Radiography Method

X-ray inspection is a very useful tool for component inspection. With this method it is easy and fast to inspect the bulk of any material, even those containing cellular composite, for imperfections such as improper lay-up, cracks, precipitations, damage, foreign bodies and humidity. Moreover, it is an effective method for disclosing layer detachments in multilayer composites.

The method essentially uses a gamma X or X-ray source to provide powerful energy to the piece. A portion of the energy is absorbed by the component being examined while the rest passes through it and is imprinted on the special film located on the other side of the component, illustrating the difference between its regions (Figure 8). This is essentially one 2D shadow of the entire volume of the piece. X-ray assessment is based on the comparison of photographic density differences with known object characteristics or data extracted from radiographs of the same acceptable quality items.

Its disadvantages include the high, but not prohibitive, cost of the negative (film). The method can be applied using portable devices, but very strict safety rules must be observed due to the hazardous radiation emitted.

It is also slow and exhibits no sensitivity to several types of imperfections [12]. Cracks can not be perceived unless they are parallel to the direction of the rays; small cracks in dense areas are usually not perceptible even if they are in the right direction; Minor discontinuities such as inclusions in forged materials, flakes, micropores, microtips can not be detected unless they are isolated sufficiently to provide a satisfactory total contrast.

A variant of the method is real-time systems. The advantages they offer are the faster scanning speed and drastic reduction in operating costs due to the non-use of films (the results are captured on-screen.)

X-rays can penetrate a large number of materials including composites. Typically images are obtained as shadows revealing variations in the integrated attenuation of x-rays along the propagation paths. Thus under the normal mode of operation, x-rays cannot reveal cracks oriented parallel to the rays [59]. However, the energy needed is low and safety requirements can be easily satisfied with remote-controlled positioning units. Xray sources can be small, air cooled and easily implemented for various applications. This method is capable of detecting missing glue between laminates, cracks and voids in the laminates, non-intended orientation of fibres or kink band.

Some microfocus sources enable detection of defects less than 10 μm. This method can be used for real-time x-ray inspection for quality control during or shortly after wind turbine blade production. If novel, very compact detectors and small x-ray sources can be developed, in-service non-rotating SHM for the wind turbine is possible.

An advantage of x-rays is that images are obtained in parallel (not by scanning) as in the thermographic approach and hence it is fast, provided that some *a priori* knowledge of damage location is obtained. The problems lie within the interpretation of the x-ray images and safety reasons.

IV. Conclusions

The wind energy market has a huge potential for energy delivery and is considered a true means to combat climate change and ensure energy security and it is forecasted that the wind sector will become a 21st century industry for the production of energy all over the world.

To successfully improve this technology, manufacturers of wind power technologies are aware of the challenges ahead, which include the improvement of overall performance and reduction of maintenance costs so as to provide competitive technologies. Therefore international efforts have commenced in order to foster cooperation in the sector and define key topics for the European wind initiative that are expected to impact the structure and potential of the European wind energy sector.

A very potent action is the generation and implementation of complete in situ systems for damage identification and location. Considering that adding the SHM sensor system to a wind turbine structure may adversely affect the performance of the turbine, the number and location of sensors are an important issue. Methods that are to be implemented for in-service wind turbines should demonstrate that they can perform adequately with optimal number of measurement locations, and under the constraint that these locations be selected without apriori knowledge of the damage location.

The fibre optic strain monitoring and/or damage detection methods can be selected to obtain global load conditions and the AE events damage detection method based on built-in sensors is most appropriate for early warning of the generation of damage or to identify a failure sign.

FBG has also been developed and can be embedded into composite laminae without compromise in strength. The eddy current method application is limited on composite components. The most demanding factor toward structural health monitoring and damage detection are the actual application of the above techniques. These approaches should be tailored for online monitoring of wind blades.

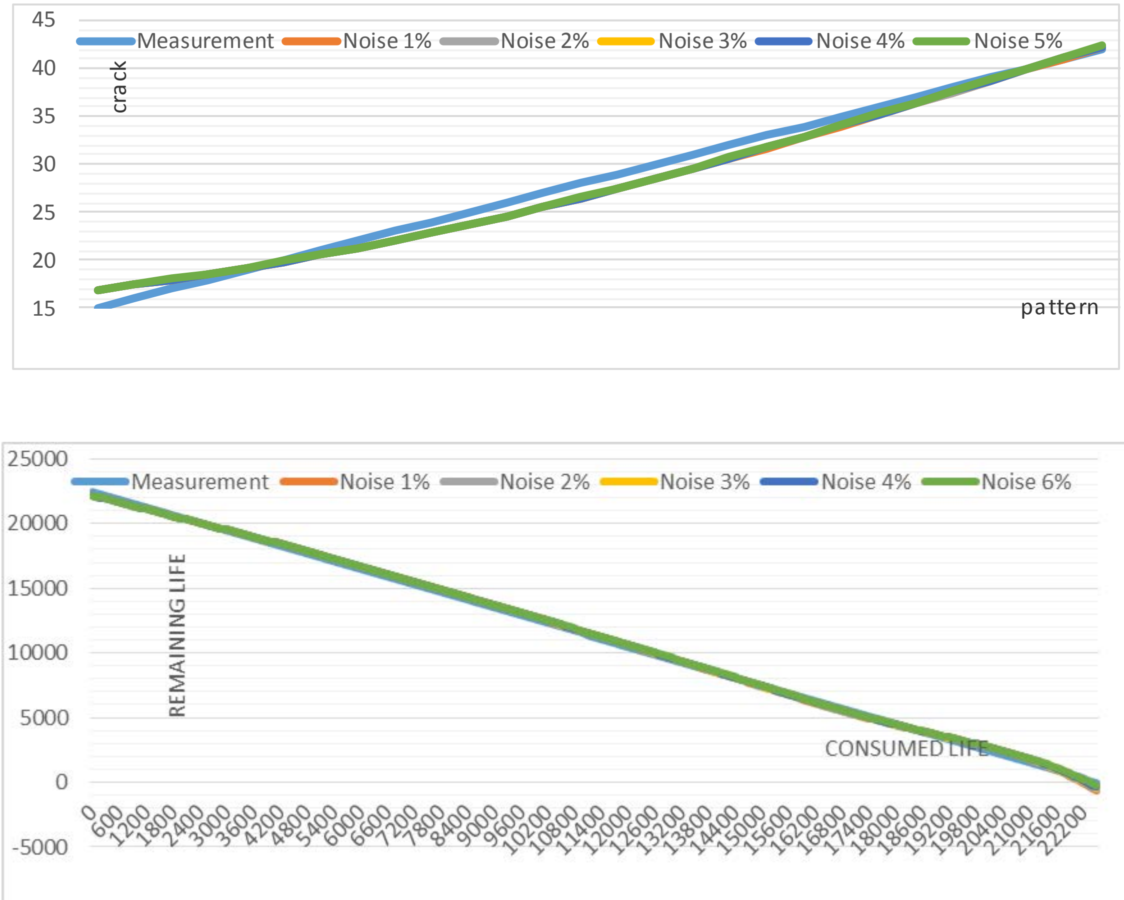


Figure 3: Neural Network output stability testing SHM Level 3 and 4.

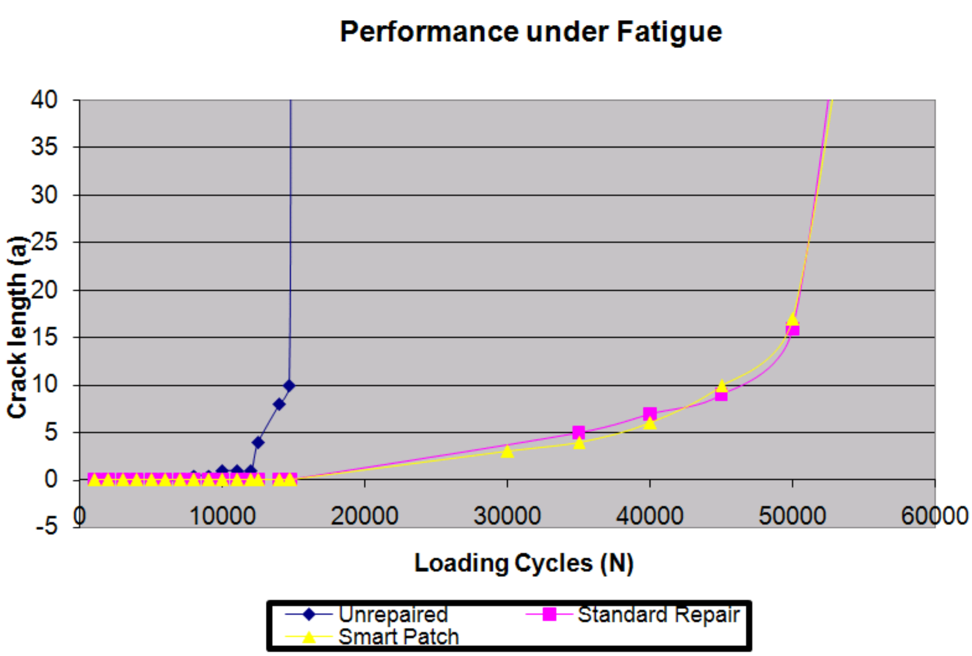


Figure 4: Crack initiation and propagation in relation to the loading cycles.

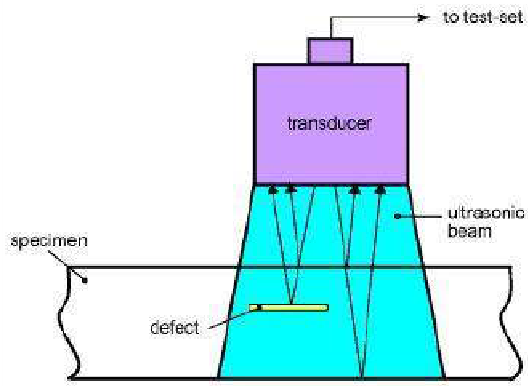


Figure 5: Ultrasonic Testing principle. Taken from [54].

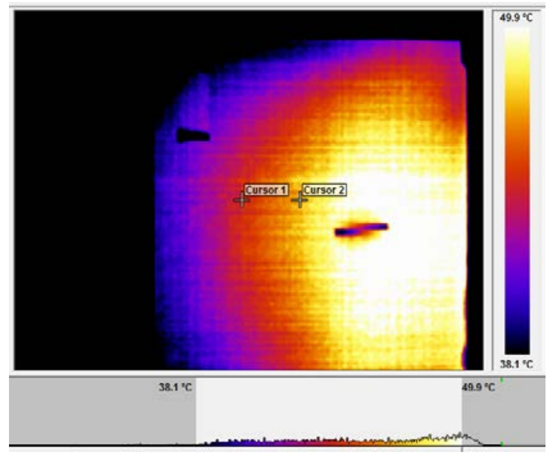
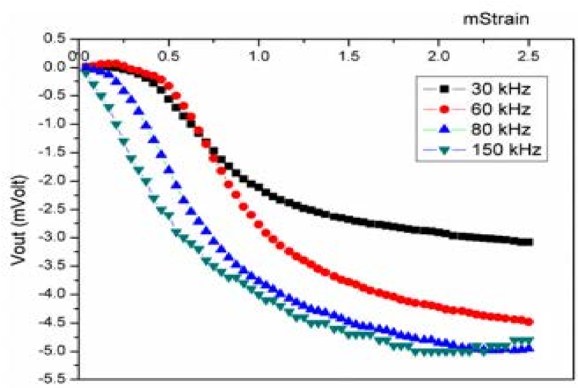
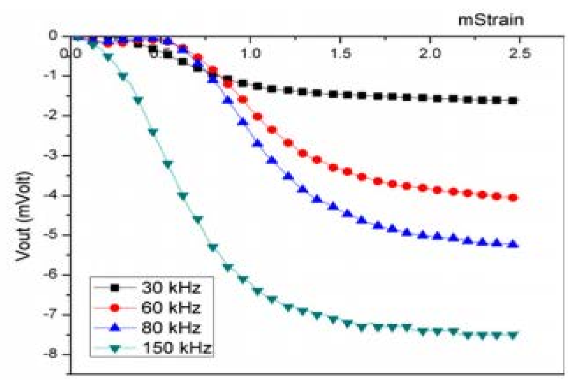


Figure 6: Active thermography image (resolution at 240x180 pixels) of an epoxy-carbon fibre panel having sustained a low velocity impact incident [12].



a)

Figure 7 (a): Results from the coaxial coil transducer (induced voltage difference versus strain) for $Co_{78}Si_7B_{15}$ wires. [58]



b)

Figure 7 (b): Results from the coaxial coil transducer (induced voltage difference versus strain) for $Fe_{78}Si_7B_{15}$ wires. [58]

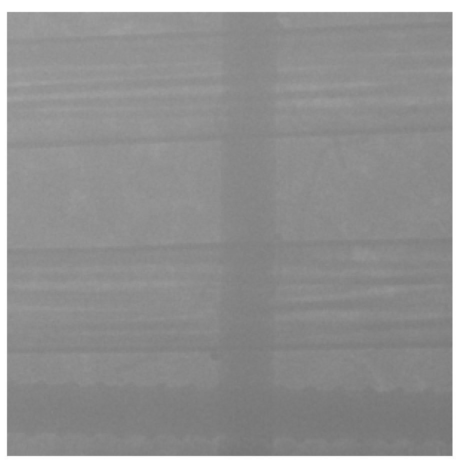


Figure 8: Image detail showing reinforcement bar and conduit with ties. The time required for the image was 10 seconds with 300keV x-ray source. Concrete slab approximately 20cm. (Image courtesy of Penhall Technologies, USA).

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