Application for Wind Turbine Blades

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Abstract The following text and images are taken from the five lectures given by Malcolm McGugan in the CISM "New Trends in Structural Health Monitoring" Advanced Professional Training Course on the 20th-24th of June, 2011 in Udine, Italy.

1 A look at the Wind Energy Industry

Wind power is an ancient technology that has been used by human civilisation for many thousands of years. The Mycenaean sea-trade culture of 1700BC was driven by the wind energy harnessed by their ships. Wind mills dating to the period around 200AD have been confirmed from ancient Persia to China. These early examples of the technology were based around a vertical axis and driven by reed mat sails. Later developments included horizontal axis mills with cloth sails. The most common tasks for early wind powered mills were pumping water and grinding corn.

By the 14th Century the Dutch were using wind mills to drain otherwise unusable areas of the Rhine Valley. There were 500 years of development in this technology that improved the aerodynamic lift in the sails, introduced cambered leading edges, optimised spar placement, measured the centre of gravity to balance the mill, innovated brakes, spoilers, flaps, and so on. This machine was a major factor in pre-Industrial Europe; irrigating, grinding grain, milling timber, processing spices and commodities, and more. But by the 17th century the steam engine began to take over these and other tasks.

At this point the US takes over the story of wind power development with the construction of electricity producing wind turbines. The wind turbine generator constructed by Charles Brush was discussed in a special edition of the Scientific American Journal in 1860. It consisted of a disc (17m in diameter) made of slated wood that was turned out of the wind by a huge tail fin in order to protect it from wind speeds that were too high for the fragile structure. Brush utilised a stepped gearbox (50:1 ratio) for his turbine and in good conditions generated up to 12kW of Direct Current.

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Figure 1. The Windmill De Kameel in Schiedam. Photograph by Martijn Janssen, GFDL.

The Brush wind turbine was limited, but in 1891 a Danish man, Poul La Cour, was showing that fast running turbines with fewer blades would generate electricity more efficiently, and by the 1920s there were electricity producing turbines of his design all over Denmark. But this first flowering of commercial wind powered turbines proved to be brief as the introduction of cheap, large, fossil fuel driven steam plants soon put them all out of business.

In the 1970s the events of the first oil crisis prompted governments around the world to support either the few remaining enthusiasts of wind power generation or the aerospace industry, according to availability in their respective countries. And while the aerospace designed turbines tended to be very fragile, the (mostly Danish) backyard industry succeeded by starting simply and slowly scaling up their designs and processes one step at a time in order to reach the sizes we see today. This means that the different designs which have existed earlier have now converged to what is often called the Danish design: three-bladed, upwind rotors, with a gearbox, on a tubular tower. And despite renewed enthusiasm for new and innovative wind powered devices, it is likely that the Danish design will be dominant for many years to come.

In order to stimulate the adoption of wind power, support schemes like the German Einspeisegesetz (Energy Feed Law) and similar laws in Denmark and Spain initially made these countries the top three for installed capacity. But by 2010 China, USA, and Germany are the countries with most installed capacity. 2010 was the first year where most of the new wind farm installations were in developing countries and emerging economies, led by China of course. This development shows that wind is not just a premium technology that can only be deployed at scale in rich countries.

Italy has almost 6GW of wind power installed at the end of 2010 which makes it the 3rd largest producer in Europe, and 6th in the world. Most of the new Italian capacity is to be found on Sicily, Calabria, and Molise. It could be noted that the only commercially exploited area that is not in the South is Liguria. Nationally there are 28,000 people employed in the Italian Wind Power Sector with 10,000 of these directly employed. 3.4 percent of Italys electricity requirement was met by the wind in 2010. In Denmark this figure is 24 percent. So far Denmark remains the country in the world with the highest penetration of Wind Power into the National Energy consumption.

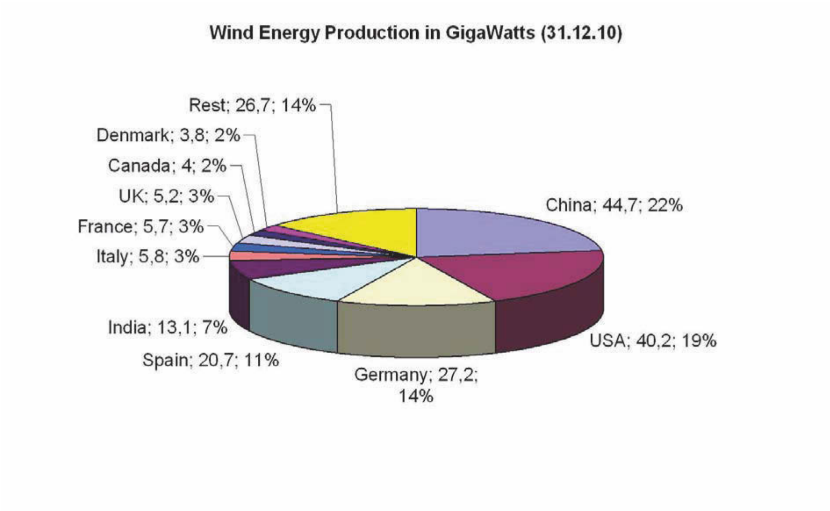

Figure 2. Pie Chart showing wind energy production by country - the global total is 200GW, figures from EWEA

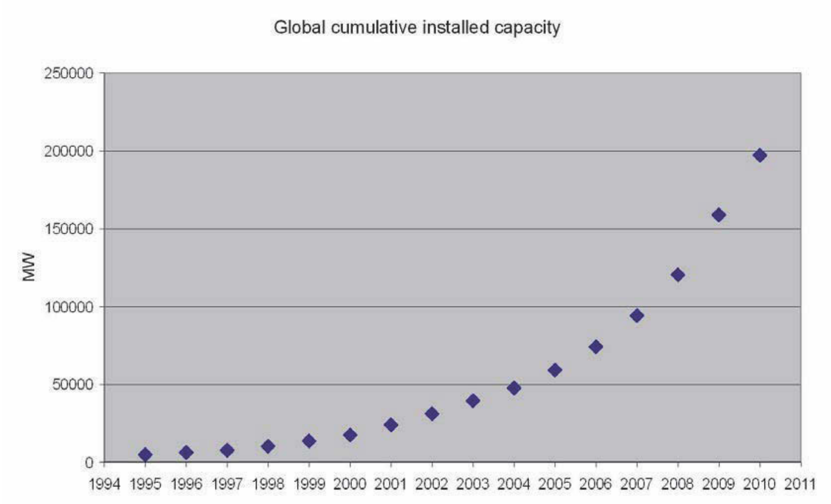

Figure 3. Graph showing installed global capacity from 1995 to 2010, figures from EWEA

Worldwide the level of installed wind power capacity approximately doubles every three years. While Europe is still the commercial area hosting the largest wind capacity, by the end of 2012 China will have overtaken that position. So the largest application focus for this industry is quickly moving East. So far, however, the new technology developments are still under development here in Europe. The challenge of offshore farms is being solved here (robust environment, scale, maintenance, deepwater, floating platforms, etc). The power network integration issues are being addressed here (transmission/distribution, smart networks, storage facilities, super grids). And the political targets for renewable energy are still most advanced here.

While the actions of the OPEC nations forty years ago were the impetus for the start of our modern drive to exploit wind power, the factors pushing us in this direction have not diminished. On the contrary, it can be easily proven that the worlds need for more wind energy is greater now than it has ever been. If we were to consider what these factors are we might start with the geopolitical perspective and list the following:-

- The world is facing an energy crisis
- Demand for power is increasing
- We now live in an era of energy uncertainty

- High oil prices are "here to stay"
- The effect of wind power as geopolitical leverage
- Climate change

The European nations need to ensure energy supplies has a major effect on the way we interact with our neighbours. Fossil fuel resources have lead to military confrontations and heavily skew the relationships the EU maintains with Saudi Arabia and Russia. On the 9th of March 2007 the EU Heads of State adopted binding targets for renewable energy (20% of the total energy mix by 2020, later increased to 31%). Since then several individual countries have chosen to publicly announce even more challenging targets as a way of maintaining their leading position in the new energy technologies; for example the Danish national target is now to achieve 50% of all power from renewable energy by 2020 and 100% by 2050. Within the next few decades it is only wind (among the many renewable sources available) that is mature enough and capable of contributing significantly to reaching these targets so quickly.

Of course political will on its own is not enough. Fortunately the technological developments in wind power generation encourage those in the Industry to agree that the targets set by politicians are challenging, but achievable. This technological perspective could be illustrated by pointing out that a modern turbine in 2010 produces 180 times more electricity than its counterpart could in 1990, and at half the cost. This improvement is expected to continue alongside corresponding improvements in wind farm control and power distribution networks.

Added to this are the many advantages that a "natural" energy source with no fuel (and therefore no waste products) has to offer society; Wind Energy is clean, free, indigenous and inexhaustible. Furthermore the globe is wealthy in wind resource. Wind power involves no issues regarding fuel, geopolitical risk, external energy dependence, energy imports, fuel costs, fuel price risk, exploration, extraction, refining, pipelines, resource constraints, air pollution, CO2 emissions, or radioactive waste.

These geopolitical, technological, and societal perspectives support an industry that has quickly become a proven technology area and is now poised at a period of massive potential growth. Across Europe and the World, huge wind farm developments have been planned. The towers, turbines and blades themselves are all becoming larger (to catch more wind) as modern materials permit more ambitious designs to become reality. The locations of these new farms are increasingly remote (offshore), and this in turn promotes the strong interest in SHM technology within the industry.

The desire to place wind farms offshore is due to the better use of space (Europe in particular is a crowded continent) and the improved wind regime.

In general moving 10km offshore improves the wind resource by 70%, and a doubling of the average wind speed at a particular location gives a potential eight times higher energy output. However against these advantages is the fact that the offshore environment is incredibly tough and difficult (expensive) to visit.

Trends in the Wind Energy Industry

- an increase in installed capacity world-wide
- an increase in the physical size of the structures
- new materials and designs
- an increase in the size of proposed wind farms
- a tendency to place wind farms offshore
- higher requirements of reliability and easier maintenance

The operation and maintenance of wind farms today is presenting an increasing challenge due to the trends summarised in the list above. It is a set of practical problems that have increased the relative cost of maintenance within the industry, problems encountered when employing traditional scheduled-based inspection maintenance of turbines placed inconveniently on many tall towers located in remote/inaccessible areas. A growing problem particularly exists with the maintenance of offshore wind turbines and the operation of a centralised maintenance group covering wind farms located in several countries.

The solution to this problem involves the use of remote sensing to reliably report equipment faults and structural health information. This has the potential to hugely improve maintenance performance under these difficult conditions and so affect the profitability of the farm. Sensor and communication technology have advanced rapidly over the last decade allowing this ambition to become a realistic goal for the offshore wind farm operator.

Wind energy can be an important industry for establishing Structural Health Monitoring as an applied industry. The industry is growing rapidly and is under pressure to adopt remote sensing. The prospect for the extensive use of sensor technology is apparent. And a further important factor in identifying the wind energy sector as the best prospect for adoption of monitoring technology lies in the pioneering culture that exists within this young industry, in contrast to that which exists in more traditional areas of structural engineering. All stages in the rapid development of the wind turbine structure design have required new approaches to solve challenging engineering problems. This is a sector that encourages the rapid integration of new ideas and approaches. A far more conservative point of view exists among civil sector engineers due to the greater emphasis on minimising risks, generally tighter constraints on budgets, and a huge reserve of good engineering practice and already established material and design information.

2 Condition Monitoring of Wind Turbine Blades

The design and manufacture process produces two items, a structure and a set of general instructions for how that structure is to be maintained and repaired during the prescribed service lifetime. These generic maintenance guidelines are then applied to each structure. The frequency of inspections is determined by the guidelines provided by the manufacturer, the occurrence of special loading conditions (such as severe storms for instance), and the requirements of insurance or certification bodies. Not only the blades but also the maintenance of all the other structural components in an industrial wind energy installation is organised along similar principles.

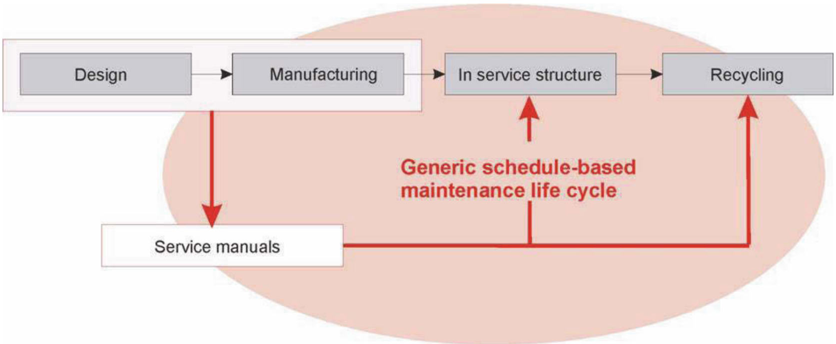

Figure 4. A traditional lifecycle paradigm

Also illustrated is a structure lifecycle controlled by a SHM system and we can compare this with the traditional paradigm. The most obvious difference is the presence of information feedback loops at every stage in the structure lifecycle. This structure response data, which is not available in traditional systems, is the means by which optimisation at each stage is made possible. A further key difference is that as all structures are sensorised, the data obtained is specific for each. This allows decision making based on the particular status of the structure, taking into account the manufacture, service life, repair history and so on.

Through the use of a successful SHM system it becomes possible to closely control the lifecycle of each individual structure. The user interface presents all the information necessary to make qualified decisions. The wind

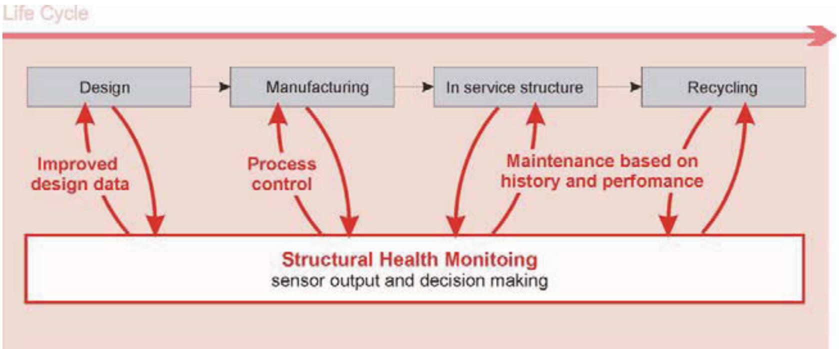

Figure 5. An SHM based lifecycle paradigm

energy industry has been identified as one of the best prospects for adoption of SHM principles that currently exists.

A Structural Health Monitoring System should:-

- remotely identify the presence of damage within a structure
- locate the damage within the structure
- assess the "severity" of the defect
- issue a prognosis of the damage development

In the list above Structural Health Monitoring (SHM) is defined as the ability to remotely (i.e. without direct inspection) identify the presence of damage within a structure. Furthermore, the application of SHM assumes a desire to further locate the damage within the structure, assess the "severity" of the defect, and issue a prognosis of the damage development in a way that allows a recommendation of action.

People have been building structures for thousands of years, and we can see that SHM, as the term is defined, has only become technologically feasible fairly recently due to remarkable advances in sensor development, data handling, networking, communication systems, computing power and by establishing a deeper understanding of the mechanisms involved in material degradation and failure. The adoption of a SHM approach to physical asset management however, is not dependent on an innovation within any single one of these technological disciplines, rather it is dependent on an exploitation of a set combination of them all with respect to a particular monitoring challenge. These technologies could therefore be said to represent the platforms upon which SHM systems can be created.

SHM is massively multi-disciplinary and working to develop this technology as an industrial application it can seem to be a very thin thread with

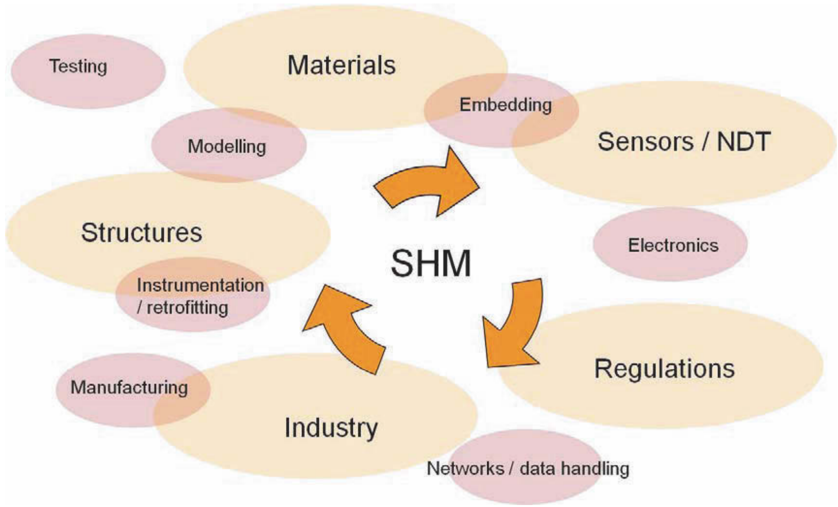

Figure 6. Technological platforms upon which an SHMS can be built

which to bind such large and independent research areas together. But in certain situations it becomes possible to position SHM as a central part of the strategies for these different groups. Where there is a need to demonstrate a high degree of integration and co-operation across disciplines then SHM can act as a kind of grand objective that leads to coherent research and allows a combination of resources to compete for new funding and new facilities.

When considering the specific issue of applying some form of SHM on wind turbine blades we need to consider the problem in relation to the current operation and maintenance procedures and ask what problems exist with traditional techniques?

Inspecting the condition of an in-situ wind turbine blade involves a considerable marshalling of resources. The timing of the work is critical and depends on favourable weather conditions. For this reason the inspection crew is often "on-standby" for when a suitable opportunity might present itself. When this occurs the turbine is place out of service and the blades are locked in the Y orientation, which presents the lowest arm for inspection. The most robust technique is visual inspection. Even with a highly skilled inspector, it is clear that this is a time consuming and inexact process, checking for damage/defects and cracks in the blade structure through the surface gel coat layer. Such inspections are considered worthwhile however as although the prospect of a catastrophic failure in a blade is remote, if it occurs it will certainly affect the remaining two blades, most likely the turbine machinery, and possibly even the entire tower structure. For this reason the default response to any detected defect is either to repair or replace the blade.

The inspection/maintenance procedure that is established for offshore wind farms will be crucial in determining the profitability of the industry. If the profitability is low then exploitation of the offshore resource will be compromised, and the national objectives with respect to adopting renewable energy cannot be made.

However there is encouragement to be found in the fact that the capability requirement for a practical SHMS for turbine blades in the wind energy industry is considerably lower than one that would be accepted for an aerospace application, for example. An aerospace application is always likely to demand something towards the very limit of what sensor and signal analysis is capable of providing in laboratory conditions with a millimetre precise mapping of laminate defects in the structural composite. Whereas a more technologically ready system, using commercial off the shelf components, that only provides a coarse set of information about structural condition is still likely to be commercially viable for wind turbine blades.

So let us consider the general idea behind how a modern offshore wind farm should be managed. The management system must integrate information from many different sources; an example of how this can be done is illustrated in Figure 7 where each component or system in the turbine can extract the relevant data from embedded sensor systems and/or other data sources and deliver this collated information to database and to a management system. The management program organises the many information streams from throughout the wind farm and presents daily reports, updates, alarms, etc. to the various users of the system. In such a modular system all that the Structural Health Monitoring System (for the turbine blade) needs to do is to provide output that fits into the pre-existing industrial communications framework. There is currently great activity inside the Wind Energy industry to ensure data tools conform to IEC standards in such a way those companies wanting to develop sensor inputs for wind farm operators are able to manufacture hardware that is instantly compatible in any wind farm.

The amount of information (data) generated by the monitoring systems in a wind turbine has always been increasing over time, and this is expected to continue. The graph in Figure 8 shows how as the amount of data increases, the options for control and optimisation of the turbine function also increases. This graph shows the measurement data generated for a

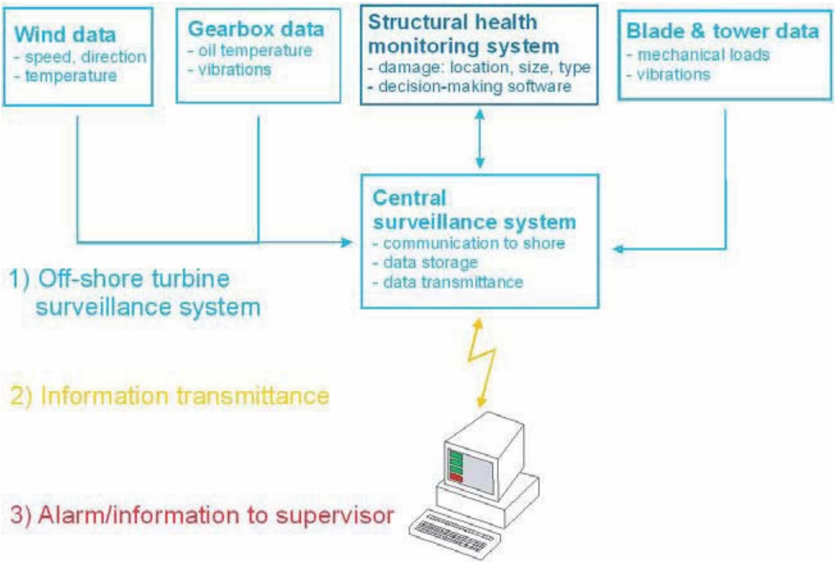

Figure 7. SHMS information embedded in a general wind farm surveillance system

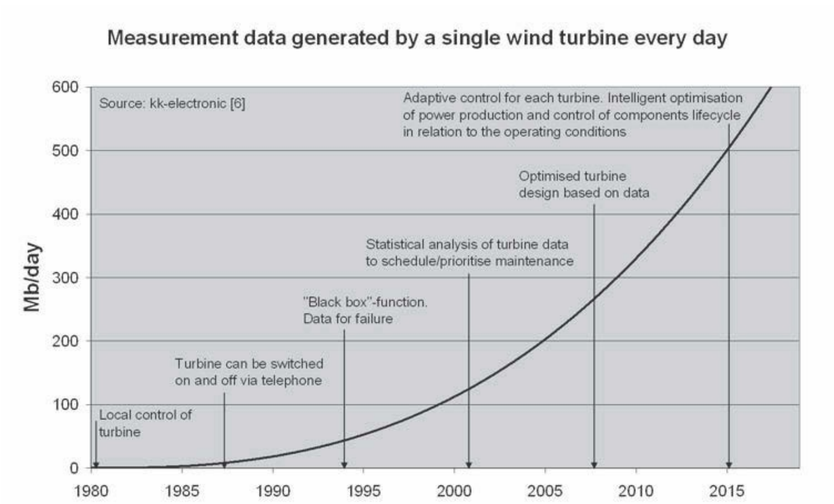

Figure 8. Graph showing increase in data generated by wind turbine - source KK-Electronics

single turbine, currently about 350MB per day. Projecting the trend only a few years into the future we see the electronic suppliers expect over 500MB of data per day (per turbine) and the possibility for "adaptive control for each turbine and intelligent optimisation of power production and control of components lifecycle in relation to the operating condition."

Most of the data represented in the curve shown in Figure 8 comes from wind and temperature measurements, pressure readings for the generator, gears and electronics, status checks on the brakes, relays and fire alarms and so on. Added to this will be some vibration and strain readings from the drive train components and tower structure. The physical network for gathering and controlling all these measurements and combining them into information that is relayed to a central control system is therefore already in place. And the development of a SHMS for the blade structure can then exploit this already present infrastructure to organise and transmit the data/information generated by the sensors in the blade. This is not something that can be expected for SHM implementations in all applications. It should also be noted that these "parametric" data streams are invaluable when interpreting the meaning of the sensors with respect to the operating conditions of the structure.

Later in this text the challenge of using sensors to understand the damage processes taking place in the polymer composite materials and turbine blade structures is discussed in more detail. As well as using specimen and component testing under laboratory conditions, the sensor data is also interpreted from measurements taken in full-scale structure tests, and finally from operating turbine blades. As the application of sensor systems moves from the small scale laboratory investigations (material properties), to full scale controlled loading of the entire structure (structure response), and then to in-situ measurement, the capability requirement of the system also changes. The practical application of sensors in a robust working environment that can be achieved at a financial cost low enough to be replicated across a fleet of similar structures is a significantly different challenge to the testing of material specimens and structural sub-components under laboratory conditions using the best available measurement and inspection technologies.

One of the conclusions of the research work addressing the challenge of moving research on the effect of defects/damage in materials and structures into an application technology has been that in the case of wind turbine blades the material damage processes and the structural geometry and loading conditions are so complex and challenging that it is not likely that a single sensor type will be sufficient to give a complete understanding of the "health" of the entire structure. In order to have confidence about the remote condition assessment from a wind turbine blade it will be necessary to create a synergy by combining different sensor/measurement technologies in one implementation.

Sensor fusion is the term used to imply a combination of disparate data sources (rather than direct fusion of information from several similar SHM sensors for example) to create a level of information that is somehow "better" (more accurate, more reliable, more complete, synergistically developing an emergent view) than any of the sources considered alone could generate. These other sources of data could include other types of sensors mounted on the blade (or elsewhere) as well as parametric data (including environmental and operational data), historical data, a priori information (e.g. about structural/material characteristics), and soft/virtual sensors (from software algorithms).

Considering only the data from sensors mounted on the blade we can characterise different types based on their structural range as follows:-

POINT sensors - This type includes strain gauges returning information about the material response at a precise point on the structure, or crack detectors in the leading or trailing edges of the blade that indicate the presence (or absence) of a crack.

LOCAL sensors - This type includes a passive Acoustic Emission sensor that returns information about the level of stress wave activity in a volume of the blade structure, a distributed strain fibre optic that returns strain measurements along the length of a fibre, or an active acoustoultrasonic instrumentation that interrogates the condition of a "hot-spot" and give warning of new structural discontinuities.

GLOBAL sensors - This type includes system identification via information from accelerometers and rotation sensors determining modal properties of the entire structure and variations due to the presence of damage.

The fact that there are many different damage types to be characterised and many sensor types under investigation suggests that no single sensor can be utilised to deliver all the information about potential damage of interest that can occur throughout the structure. A combination of sensor inputs is required, and this input can be optimised based on the best available understanding of the structure responses and damage types of interest. The sensor combination chosen is therefore based on the capabilities of the different techniques, "fusing" the best characteristics of each technique in such a way that they complement each other and their limitations are compensated for.

Note that a definitive matrix of sensor technique advantages/disadvantages with respect to polymer composite structures does not yet exist so predicting the ideal sensor fusion for this application is not straightforward.

So, an array of sensors is available within a linked communication network. Each sensor is unique and supplies local data. In a monitoring system for a large offshore wind farm there will be thousands of unique sensors available in the array. The raw data from these sensors can be processed by three modules to give information to Management, Maintenance and Design functions concerned with the structure operation. This information is interpreted within an expert system to aid decision making. The interpretation of this data requires correlation between the sensor data within the frame of an expert system.

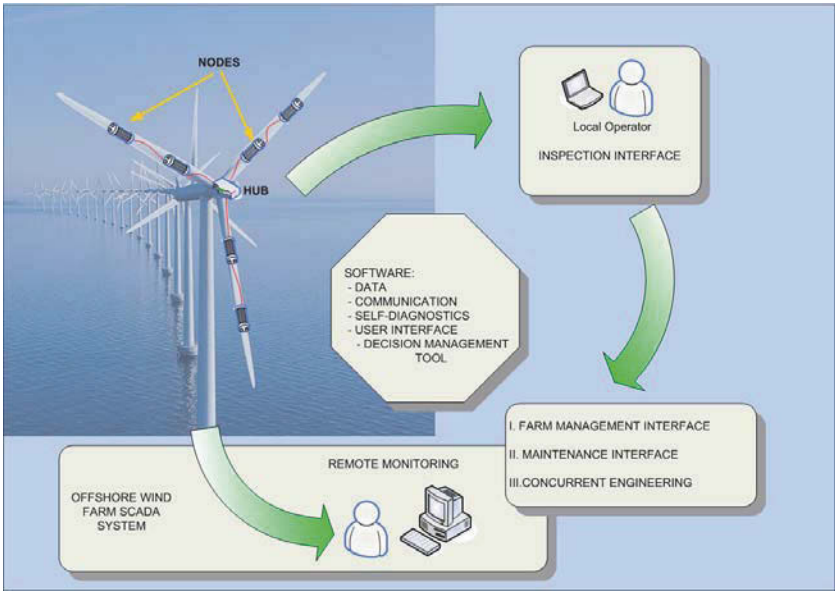

Figure 9. Sensor data extracted (locally and remotely) to three functional modules

The same sensor array is available to each module, but each module uses the data to generate different information. This information is utilised (possibly within expert systems / decision making systems) by the Management, Maintenance and Design functions.

The first module generates information on the operating parameters of the wind farm. This information will be utilised within management tools seeking to optimise output from the farm and from individual turbines. The second module generates structural health information for key plant in the wind farm. This information is primarily available in order to improve the maintenance/repair functions associated with the structure. The third module permits a concurrent engineering approach by generating information on structural response for comparison with the responses predicted by design. This information is primarily available to designers of components within the structure in order to continually improve their designs.

The benefits of such an organisation includes the fact that a huge amount of available "data" can be presented in a user relevant "information" interface and that several independently running management systems can be integrated into one. As the specific device manager software is open source, newly developed sensor types and/or analysis techniques can be quickly implemented. The data communication system is open and on-line at all times, therefore all structural/environmental changes and management/maintenance updates are visible in real-time. The remote interface with system output and controls (remote warnings and confirmations) is possible via all types of media. The in-service response data improves subsequent production run or design. Maintenance scheduling is improved by early fault recognition, localisation and diagnosis. And an improved management feedback and control allow profit optimisation.

The trends in the wind energy industry make it increasingly attractive to implement full condition monitoring of the blade in operation as the consequences of a failure is increasing for large turbines placed offshore and there is a need to integrate condition monitoring of the blades into the overall monitoring standards. Although many monitoring systems are now being evaluated, there are still challenges to overcome before a system is ready and these include the integration of different systems, the issue of system robustness/reliability, and avoidance of false alarm indications.

The concept of damage control in wind turbine blade structures that are monitored needs to be addressed now as the ability to remotely detect the occurrence of damage assumes a strategy for assessing the severity of detected changes and acting accordingly. Condition monitoring systems for operating wind turbine blades could be expected to provide the following capability:-

1. identify that damage evolution takes place
2. identify the location of damage
3. identify the damage type
4. identify the size of damage

In this way the need for manual inspection for operating turbines can be reduced, and the maintenance resources available can be more effectively deployed to respond to specific identified problems in the structure condition.

Various sensor types can be imagined that could contribute to such a remote damage detection/assessment system including point sensors (e.g. strain gauges), area or local sensors (e.g. acoustic emission sensors), and global sensors (e.g. accelerometers).

The data combination provided by the sensor network allows the remote surveillance system to provide an alert that this particular structure requires attention. This attention could include an on-site inspection that would give the full diagnostic result for that structure. And by combining the full structural information thus achieved with models of material/structural behaviour determined by previous experimentation, the final prognostic step can be taken that provides a suitable response by the operator. Illustrated in Figure 10, such a concept presupposes that the damage state can be assessed at a stage where the correct response will prolong safe structural life and/or prevent structural failure.

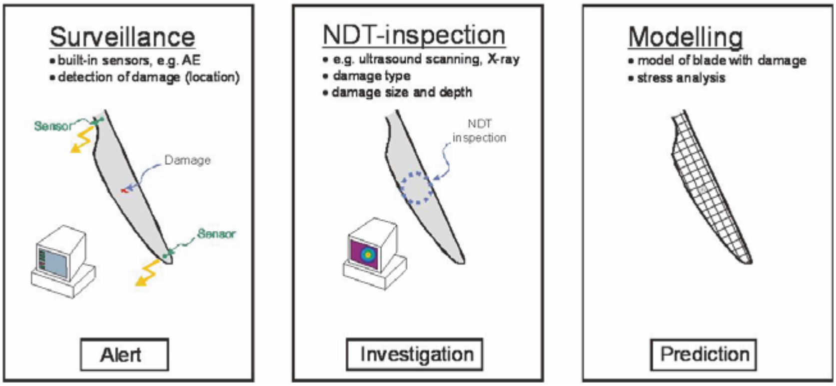

Figure 10. The Alert, Investigation, and Prediction stages in this damage control concept

Figure 11 shows the anticipated response of the structure under normal operation against the projected response (and premature failure) of a structure containing an unrecognised damage. Note that the y-axis places the sensor detection limit earlier than the visual, and of course earlier than the critical, damage state.

Figure 12 projects the effect of two possible responses to a detected damage, either a full repair to return the structure to the designed/expected damage evolution, or a change in the aeroload experienced by this particular structure in order to achieve the expected service life with no further intervention necessary.

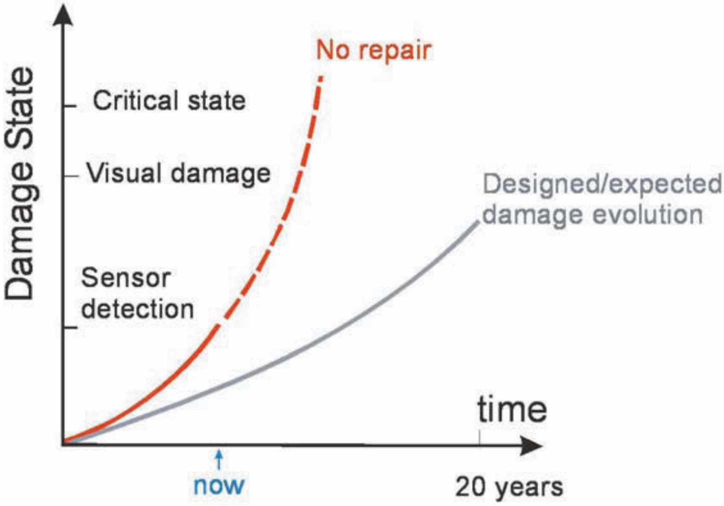

Figure 11. Damage state development for a healthy and a damaged structure

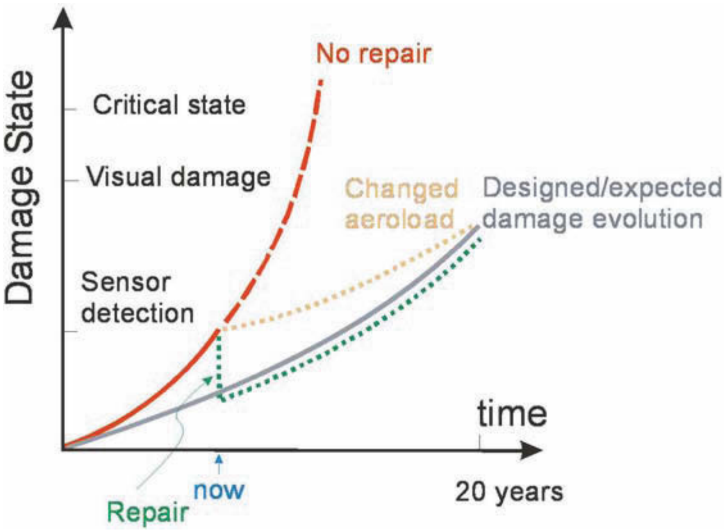

Figure 12. The effect of repair and of changed operation in achieving a full life cycle for the damaged structure

The possibility of making such decisions in the future is dependent on two things. Firstly the demonstration of sensors that can remotely indicate the presence and development of critical damage types, and secondly models that integrate the local material damage evolution within the global structural response.

Once present these two techniques allow knowledge-based decision making such as:-

1. The damage is stable therefore continue use of blade
2. The damage growth is slow therefore change the aerodynamical loads
3. The damage growth is fast therefore repair the blade
4. The damage is large (un-repairable) therefore replace the blade

This concept of turbine blade damage control for large remote wind farms requires a suitable interface relevant for the "non-technical" operators aiming to maximise the productivity from their assets. A relevant example could be the sensors and diagnostic processes in a modern car. Here also we find a network of sensors based on advanced technologies that are "hidden" behind a simple user interface. The underlying knowledge that controls the sensor network is not relevant to the user who requires only a clear indication of the overall damage state (or condition). Warning indications result in expert intervention where the system can provide a more detailed level of information relevant to the particular repair requirement.

3 Damage in Polymer Composite Materials

The wind turbine blades being produced have become larger over the years and this creates several technical challenges.

Figure 13 shows a scatter plot of the lengths of various wind turbine blades against their weight. As the length of the blade design is increased it can be seen that the weight of the blade increases more sharply. The scaling factor for aerodynamical forces is L^2, while the scaling factor for gravitational forces is theoretically L^3 (in practise $L^{2.25}$). The fact is proven that with larger lengths of wind turbine blades, (saving weight) becomes increasingly important in order to break the trend seen in the figure and achieve blade lengths of 80m, 100m, or more.

Another consequence of the increasing size of wind turbine blades is found in the manufacturing reproducibility and cost of fabrication. Blades are assembled from relatively few, but increasingly large, parts glued together. A large blade part has a high cost value it is therefore unattractive to be forced to discard such a part if it is sub-standard in any way. For this reason quality control becomes more important as blade size increases.

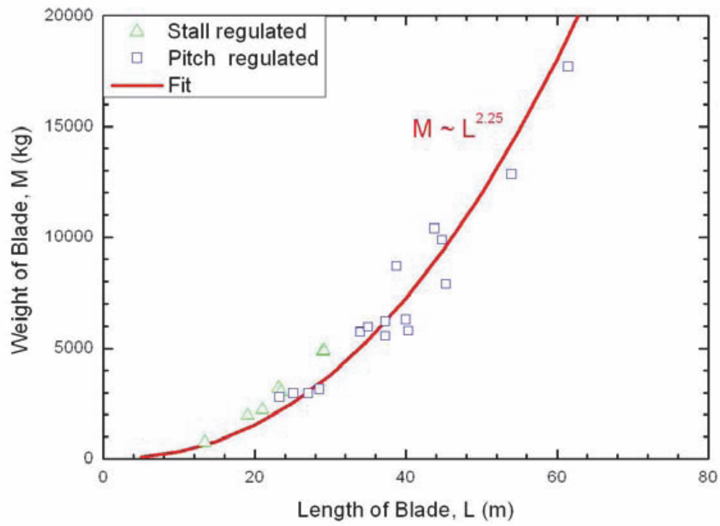

Figure 13. Blade length vs weight (LM Glasfiber A/S)

As the largest wind turbines are most likely to be placed offshore, the access to these structures is difficult and costly. Two further technical challenges are therefore to reduce the requirement for on-site maintenance, and develop reliable modelling tools for damage assessment and repair.

Looking at the response to these technical challenges we can see that in order to save weight we must develop better (stronger, lighter) materials and develop better structural design solutions. In order to improve quality control we must increase our understanding (and control) of the manufacturing process and the ways that different production defects can develop into damage (propagating cracks/fracture). To reduce the need for visual inspection of the composite structure we must investigate the response of various embedded SHM sensors to the initiation and growth of damage, as well as continuing to develop the correct Non-destructive evaluation hardware. And to provide correct modelling tools we need to further investigate the properties that govern the behaviour of cracks in these complex materials.

These are the considerations that underpin the research focus for the polymer composite material mechanics (AFM-KOM) research group at Risoe DTU. They are also shown in Figure 6 as the technological platforms to the top and the left hand sides of the illustration.

Within the KOM group the behaviour of fibre reinforced polymer matrix materials can be studied (and modelled) at all length scales using test facilities capable of testing single fibre specimens under microscopic analysis, mesoscale testing of all standard mechanical properties as well as specially designed test fixtures for more precise measurements of response or for studying fracture mechanics under various conditions, Sub-component testing, and full-scale blade testing.

Of particular interest is the response of the material (or structure) in the presence of various types of defect or damage. The way that damage initiates and grows can be revealed during the testing using sensors and scanners in order to correlate with the fracture mechanical models.

The laws governing the behaviour of the material is the same at all scales, stress-strain, and traction-separation.

Looking more closely at modern wind turbine blades, we see they are structurally advanced constructions utilizing sandwich design composite materials, gelcoat films and adhesive joints. Although there is a variety of wind turbine designs (reflecting different manufacturing processes and material selection), the functionality of wind turbine blades can be understood by considering the blade as a load-carrying beam enclosed by a shell. The primary purpose of the shell is to give the blade an aerodynamic shape, creating aerodynamic forces that cause the wind turbine blade to rotate and thus extracts energy from the wind to make electrical power. The aerodynamic forces are transmitted to the wind turbine hub through the load-carrying beam of the blade. Thus, the primary load-carrying part of a wind turbine blade is the load-carrying beam, sometimes called the main spar.

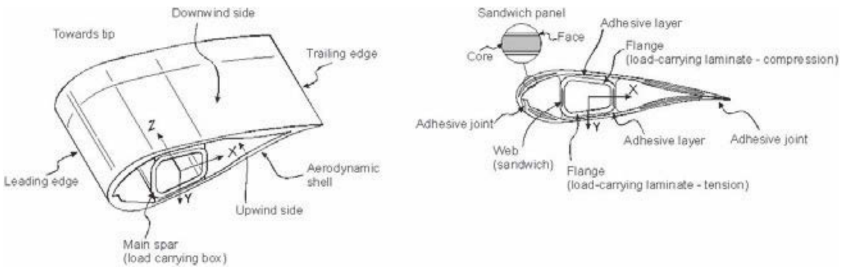

Figure 14. Cross section of a typical wind turbine blade

Looking at a typical cross section, we can conclude that wind turbine blades are made of several structural parts and can potentially fail in a number of ways. The details of damage evolution can easily differ from one blade design to another. However, the assumption that many failure modes may develop before a blade actually fractures remains plausible irrespective of different design details of different blade manufactures.

An overview of the types of damage observed in one wind turbine blade tested to failure is given by Debel (2004) and categorised as follows.

Type 1: Damage formation and growth in the adhesive layer joining skin and main spar flanges (skin/adhesive debonding and/or main spar/adhesive layer debonding)

Type 2: Damage formation and growth in the adhesive layer joining the up- and downwind skins along leading and/or trailing edges (adhesive joint failure between skins)

Type 3: Damage formation and growth at the interface between face and core in sandwich panels in skins and main spar web (sandwich panel face/core debonding)

Type 4: Internal damage formation and growth in laminates in skin and/or main spar flanges, under a tensile or compression load (delamination driven by a tensional or a buckling load)

Type 5: Splitting and fracture of separate fibres in laminates of the skin and main spar (fibre failure in tension; laminate failure in compression)

Type 6: Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive debonding induced by buckling, a specific type 1 case)

Type 7: Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (gel-coat cracking and gel-coat/skin debonding).

And illustrated by Sorensen et al. (2004) in the following sketches:-

It is clear that any attempt to detect the initiation and development of such a wide range of potential damage types along the entire length of a large wind turbine blade would require sensor instrumentation so extensive as to be scarcely feasible. In order to guide and focus the sensor installation therefore, it is necessary to work with the current research on initiation and growth of different material damage types and the structural failure modes this damage can cause. Only in this way is it possible to establish the critical damage types and the critical structural locations that will focus the sensor instrumentation effort required to monitor and assess structural health in a particular blade.

It requires a lot of understanding to assess the severity of damage in a wind turbine blade. Such an understanding does not exist at present. Never the less, it is of great importance to develop approaches that will allow an

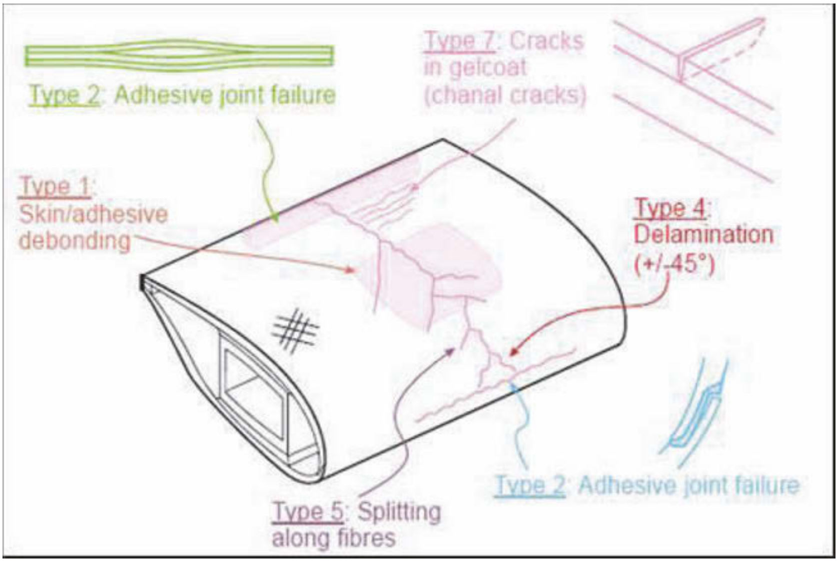

Figure 15. Damage types identified on the suction/compression face of a wind turbine blade tested to failure

inspector of a wind turbine blade to evaluate how serious any observed damage is. It is thus a long-term goal of the AFM-KOM group to establish a framework that enables reliable analyses of any set of damage given the position, size and type of that damage.

This framework can begin by taking the observed damage categories listed previously and assigning them to a general structural failure mode and a location within the structure.

Taking this approach further it is possible to consider each structural failure mode in terms of the basic material damage modes that control it. At first it may seem that this has uncovered an increase in the complexity of the problem of characterisation as the term adhesive joint failure or laminate failure both cover a range of different basic damage modes. However the table in Figure 18 shows that several structural failure modes actually belong within the same family of basic damage modes. This implies that the same concepts and criteria (once understood in the laboratory) can be used for characterising a range of different structural failure modes.

This then is the research approach taken by materials research groups like AFM-KOM at Risoe DTU. The observed damage is categorised and assigned a specific structural failure mode which is then rendered into the

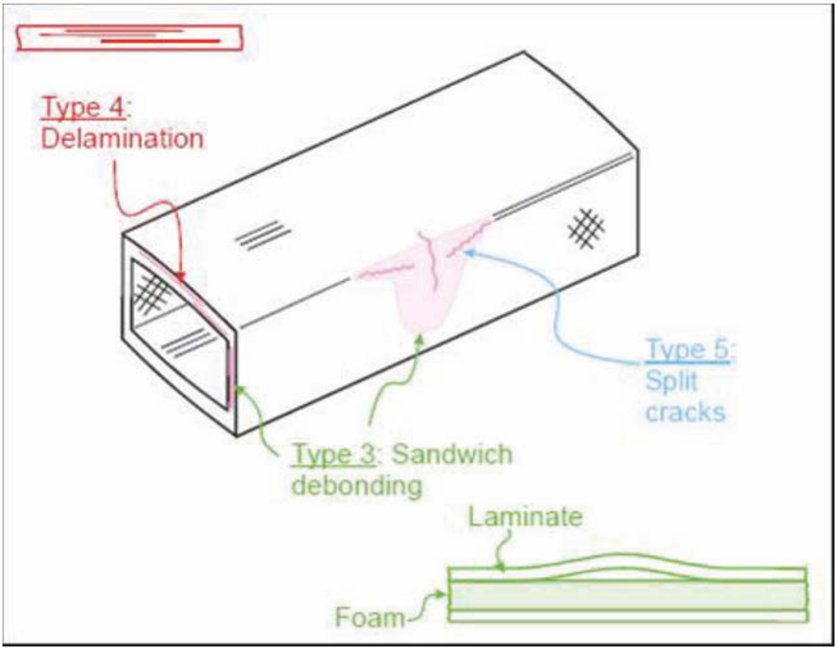

Figure 16. Damage types found in the main spar section of a wind turbine blade tested to failure

Structural failure mode	Location in wind turbine blade
Adhesive joint failure (type 1 and 2)	upwind/downwind skins at leading and trailing edges skin/main spar joint
Sandwich face/core delamination (type 3)	skins webs in main spar (e.g. buckling driven delamination)
Laminate failure (type 4 and 5)	skins main spar (e.g. buckling driven delamination)
Gelcoat/skin delamination (type 6)	upwind/downwind skins
Gelcoat cracking (type 7)	upwind/downwind skins

Figure 17. Table showing structural failure modes and their position in the wind turbine blade

Structural failure mode	Basic damage modes
Adhesive joint failure	crack in adhesive layer laminate/adhesive interface cracking interface cracking with fibre bridging
Sandwich face/core delamination	interface cracking interface cracking with fibre bridging
Laminate failure	tensile failure (fibre fracture mode) - damage zone compressive failure (fibre fracture mode)- damage zone tensile failure (matrix fracture mode) - cracking shear failure splitting crack (crack parallel with fibre direction) delamination crack between plies
Gelcoat/skin delamination	interface cracking interface cracking with fibre bridging
Gelcoat cracking	thin film cracking

Figure 18. Table showing the basic damage modes assigned to the observed structural failures

basic damage modes involved. It is these basic damage modes which are investigated in the test laboratories to establish the material properties that control the initiation and growth of these modes and provide the micro and meso scale models that determine their behaviour within a structural context.

So let us now consider the critical damage modes. Fibre reinforced polymer composites are damage tolerant. This implies that a structure manufactured with these materials will not fail as the result of the growth of a single crack (such as is the case with brittle materials like glass and ceramics). Rather, structural failure in a polymer composite wind turbine blade involves the progression of several damage mechanisms with the global collapse occurring when a damage mode at a particular structural location has reached a critical size (at which point the fracture growth becomes unstable). Considering this damage tolerance property and the size of wind turbine blades it is clear that research into the damage modes of interest for these structures focuses on understanding the mechanisms by which different damage modes can progress (crack propagation - is it stable, unstable, or arrested/stopped?) rather than the micro-structural details that describe how/why the damage formed in the first place (crack initiation - from existing flaws/defects).

A wind turbine blade under operation is subjected to varying aerodynamic loads due to the fluctuation in the local wind speed, plus gravitational and aerodynamic effects resulting from the turbine rotation. When characterising the critical damage modes for structural material used in the blades it is necessary to consider two types of loadings: Very high static loading ("an extreme wind load") and various types of cyclic loads. The wind turbine blade must be able to survive a few extreme loads (however the number of extreme wind load events is small), but also a huge number of cyclic loads (where the load level is relative low however).

Therefore, researchers consider two cases for damage evolution: static growth and fatigue (dynamic) damage. The material properties which describe damage evolution under static loading and under fatigue loading are not the same.

Damage mode	Loading regime	Material property of interest
Damage zone	Static	Tensile strength σ_{11u}^{+}
		Compressive strength in the fibre direction σ_{11u}^{-}
		Composite shear strength τ_{12u}
	Fatigue	Maximum applied stress σmax
		Number of cycles to failure *Nf*
Crack propagation	Static	Critical mode I stress intensity factor *KIc*
		Critical mode I energy release rate G*Ic*
	Fatigue	$\frac{da}{dN} = A\left(\frac{G_{max}}{G_{Ic}}\right)^{n}$
Crack experiencing fibre bridging	Static	Mode mixity G*c*= G*c*(ψ)
	Fatigue	? Not yet entirely clear... See Meeking et al. (1990), Cox & Marshall (1991), Cox (1993), Sørensen & Jacobsen (2002), and Sørensen 2011.

Figure 19. Table showing the modes of damage in polymer fibre composite laminates and examples of the corresponding material properties governing growth criteria under static and fatigue loading regimes

<u>Static</u>

For a damage mode that develops a damage zone (where the failure process zone constitutes a considerable volume) the damage is usually described in terms of a critical stress value, i.e., by a maximum stress criterion (tensile or compressive strength).

The onset of growth of a crack (crack propagation) can be described in term of a maximum stress intensity factor (fracture toughness) or a maximum energy release rate (fracture energy).

A crack experiencing fibre bridging requires modelling of the bridging fibres. This can be done by a cohesive law (a stress-opening law). A cohesive law describes the relationship between the local crack opening and the local stress across the failure process zone. In the general case, the cohesive stresses can be normal and shear stresses; we then talk about mixed mode cohesive laws.

Fatigue

For materials that fail by a damage zone, such as composites loaded in the fibre direction, the strength properties under cyclic loading can be described by a so-called S-N curve, which is the relationship between the maximum applied stress, and the number of cycles to failure.

For materials that fail by cyclic crack growth, the crack growth rate, da/dN, should be measured as a function of the applied energy release rate.

For materials experiencing large-scale-bridging under cyclic crack growth, the situation is more complicated. The cohesive laws that operate under cyclic loading are likely to be different from those present under monotonic crack opening. Thus, the cohesive laws should be characterised as a function of the number of cycles. Precisely how this should be done is not quite clear, although a few ideas have been developed (see McMeeking and Evens (1990), Cox and Marshall (1991), Cox (1993), Sorensen and Jacobsen (2002) and Sorensen (2011)).

For a review of the materials testing guidelines, standards and techniques that can generate these material properties relevant to certifying and repairing new wind turbine blade designs see Holmes et al. (2007).

Many parameters that affect the growth of damage in a wind turbine blade are known with a high degree of accuracy (structural dimensions and the materials elastic properties for example) while others are subject to uncertainties. Among these uncertain parameters are naturally varying aerodynamic forces. But fracture properties of the materials are another uncertain element when considering damage growth, partially due to scatter in material properties, but also because the many possible modes of fracture failure are not fully characterised and modelled.

The table in Figure 19 shows that damage in composite structural materials is considered as two separate classes. The first is a distributed damage within a volume of material that can be described in terms of a critical stress value (tensile or compressive strength) and number of cycles. The second is a distinct crack present in the structure (either within the laminate structure or at an adhesive interface) that can be described in terms of a maximum stress intensity factor (fracture toughness) or a maximum energy release rate (fracture energy) governing its' propagation.

In general the first class is better understood by materials scientists and structural engineers and is a well defined consideration in the design and maintenance procedures for wind turbine blades. The second however is a topic of current research aiming to describe and model the growth patterns of various types of cracking possible in complex laminate composite components, and the effect of the presence of such defects in a dynamically loaded structure. For this reason such failure modes represent a much greater risk for the owner of a wind turbine blade and should be the focus of useable SHM hardware development. This in turn helps us define the laboratory testing required; to optimise our monitoring effort to detect interface failures at an early stage in key structural locations.

One very significant damage event in sandwich composite materials is skin/core debonding, where the exterior layer of laminated composite material becomes detached from the lightweight core material. Once initiated, such damage has the potential to grow quickly and compromise structural performance. The speed at which this damage grows depends on many material and structural factors such as where the damage is located in the structure, how large it is, the external loading, the material quality and so on. Clearly one of the most significant factors determining the growth rate is the energy uptake required to advance the crack front.

The interface between skin and core in a sandwich composite structure is often characterised as a "resin rich layer", where there is little or no reinforcement of the polymer resin matrix by the glass or carbon fibres. Consequently, if damage is initiated between the skin and core, the energy uptake required to propagate the damage through this layer is low. This is known as debonding of the skin from the core.

There is a laminated structure within the skin material formed by the layers of fabric reinforcement held in place by the polymer resin matrix. Damage can also form between two layers of the composite material and this is known as delamination. By comparison with skin/core debonding however, there is likely to be far more fibre reinforcement between two laminate layers in the skin material itself than there is between the skin and core. This fibre bridging between skin laminate layers is the reason that the energy required to propagate a delamination is generally far greater than the energy required to propagate a debond.

There is a practical challenge regarding the inspection and maintenance

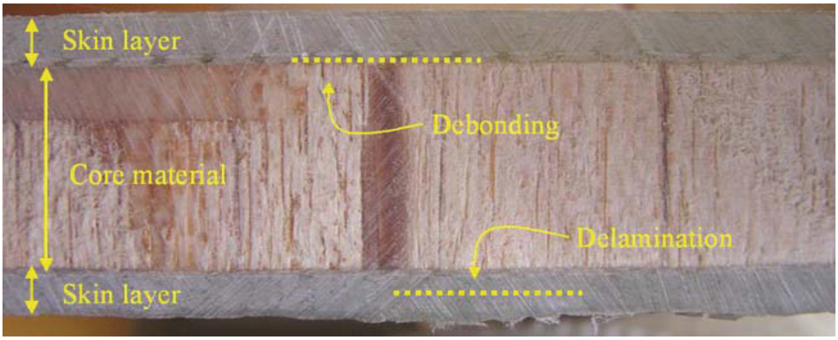

Figure 20. Through thickness profile of a sandwich core panel (GRP skin/Balsa wood core)

of these structures. This might be difficult (or impossible) to detect during a visual inspection, but could have serious implications if the damage grows over time until the structure/panel is at risk of failing under operational loads.

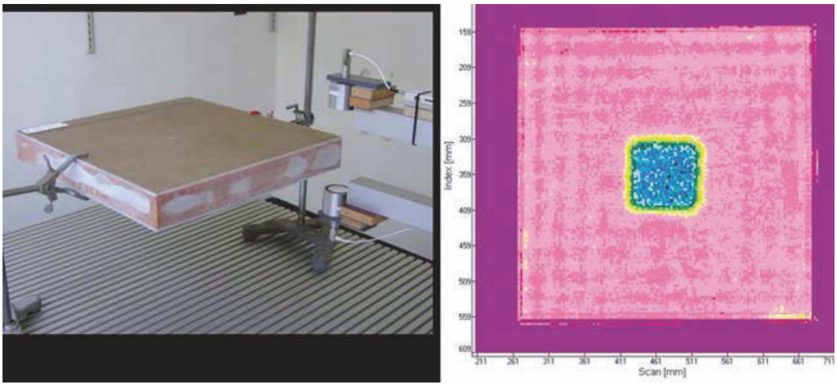

Figure 21. Inspecting a damaged sandwich core GRP panel with through transmission, air-coupled Ultrasonics

Damage of this kind (both delamination and debonding) has traditionally been detected during routine inspection using non-destructive techniques such as pulse echo ultrasonic inspection. However, such an inspection is not always able to distinguish between debonds and delaminations as both create a similar "loss of transmission" in the returned ultrasound signal and the difference in depth between a possible debond or delamination can be a matter of millimetres. But making such a distinction is not always a priority however, as a common philosophy for maintenance of sandwich FRP structures is that all detected damage should be repaired.

Over time, there has been an adoption of damage tolerance approaches to the maintenance of large GRP structures, in order to extend service life and to avoid invasive repair procedures. A successful damage tolerance assessment requires detailed information, including the energy uptake of the damage. These two paths of crack advance (debond and delamination) have significantly different fracture resistances. Obviously this difference has a critical influence on any damage tolerance assessment based on fracture mechanics, therefore, distinguishing between a debond and a delamination becomes necessary.

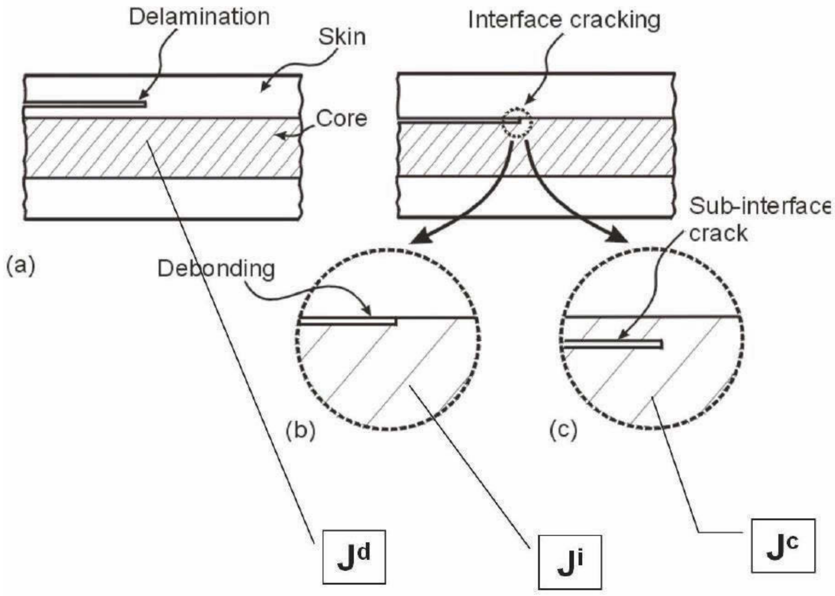

Figure 22. Crack propagation in sandwich GRP. J^d (delamination) J^i (interface/debond) and J^c (core)

The high stiffness to weight ratio of fibre reinforced polymer sandwich panels, and the ease with which this stiffness can be predicted, has contributed to their popularity. A more complex area that designers need to deal with however, is the relationship between the growth of damage/defects in the skin (or skin/core interface) and the presence of shear stresses in the panel.

Cracking in FRP sandwich structures occurs along weak planes. The criterion for crack growth is that the energy release rate reaches a critical value, the fracture energy of the crack front. The cracking occurring in these materials is mixed mode, meaning there is both normal and shear stresses present at the crack tip. The fracture resistance is affected by the degree of mode mixity.

As illustrated in Figure 22, crack propagation can occur in three different places; As delamination, as an interface crack, and in the core material. It is important to distinguish between them because the resistance to fracture can be very different for the three cracking planes.

In some systems, crack growth in the laminate and at the interface is associated with crack bridging. This is fibres or fibre bundles bridging the two crack faces. Crack bridging results in substantial increases in fracture Energy and can range from J_0^d (no fibre bridging) to J_{ss}^d (fully developed bridging zone). These are considered material properties in fracture mechanics calculations.

So it follows that the "severity" of a crack in a sandwich structure does not only depend on the size of the crack, but also on factors like position (both in the structure and through the thickness of the sandwich), the level of mode mixity at the crack tip, and the degree of fibre bridging associated with the crack front.

In order to determine the cohesive laws that govern the propagation of cracks in materials it is necessary to obtain data from stable crack growth experiments. Most test methodologies involving shear loading at the crack tip give unstable crack growth, however the DCB-UBM (Dual Cantilever Beam - Uneven Bending Moment) specimen configuration used at Risoe DTU allows stable crack growth in any mixity from Mode I (simple opening) to almost pure Mode II (in-plane shear).

The use of a wire and roller arrangement ensures that identical forces exist in the loading wire, but that the moment can be controlled by changing the distances in the loading arms. A support allows the specimen to move up and down in the test machine, but not to rotate. This ensures no axial forces as the crack propagates.

By controlling the mode mixity at a crack front in a sandwich core test specimen it is possible to control the J integral for the damage growth and even the amount of fibre bridging behind the crack tip. This allows the researchers to generate experimental data that can be used in validating models describing crack growth under different conditions, and direct measurement of specific crack characteristics with monitoring sensors.

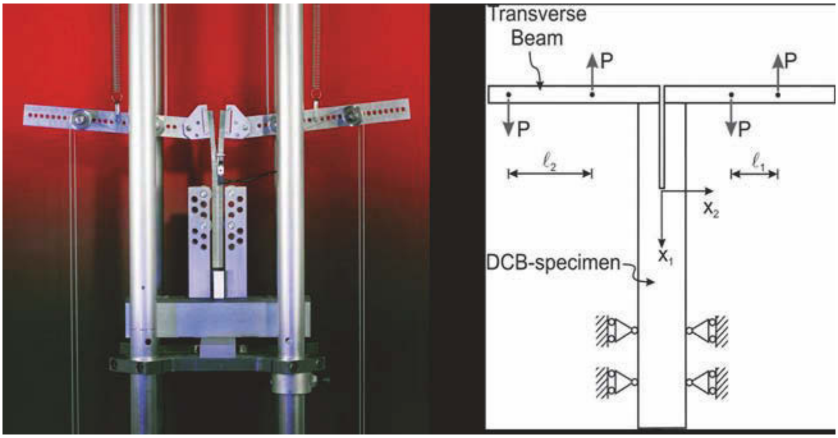

Figure 23. The DCB-UBM specimen configuration - Even bending moment

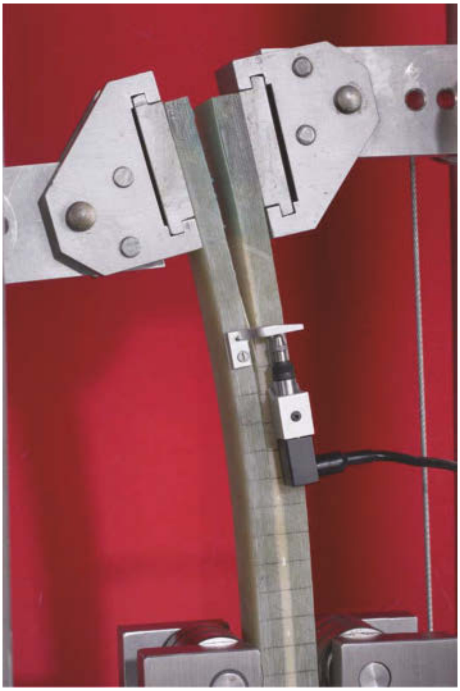

Figure 24. The DCB-UBM applying a mixed mode (uneven) bending moment

One of the techniques used to investigate damage in fibre reinforced polymer composites is AE (Acoustic Emission). In Laboratory testing AE can be used to mark the initiation of damage, localise and characterise the crack growth activity, and identify the failure mechanisms. In large scale structure testing AE is used to provide feedback during loading, focus inspection at "active" areas of the structure, and ultimately provide a more efficient structure test. While for in-situ measurements AE can provide an "exception analysis" that identifies problem structures and locations at an early stage.

In the crack growth tests conducted with the DCB-UBM machine a two sensor AE linear array localises the crack growth and the extent of the crack bridging zone behind the crack tip.

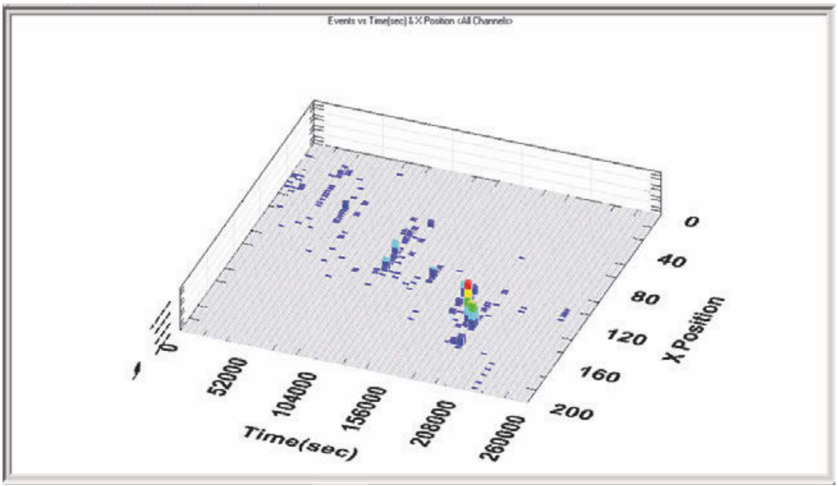

Figure 25. AE localisation showing the crack advance over time and extent of cohesive zone behind the tip

A test series was conducted to assess the extent of fibre bridging present behind the crack tip during loading using only AE output. Essentially this would be a way of estimating the J value in real time. Identical DCB specimens (GRP skins, polymeric foam core) were tested, and by using the DCM-UBM test machine it was possible to grow a crack along the skin/core interface; J^i. But by careful alteration of the mode mixity it was possible to vary between the J_0^i (no fibre bridging) and the J_{ss}^i (full scale fibre bridging) values of the crack front. In this way it was possible to vary the amount of fibre bridging present and assess its significance for the damage propagation.

H1309					
AE Hits	36102				
Cum counts	859580	Average NRG/hit	17.08		
Cum NRG	616714	Average counts/hit	23.8	**Average NRG/count**	**0.718**
Time (s)	415				
H1310					
AE Hits	23853				
Cum counts	530724	Average NRG/hit	22.20		
Cum NRG	529508	Average counts/hit	22.25	**Average NRG/count**	**0.998**
Time (s)	310				
H1311					
AE Hits	1324				
Cum counts	40589	Average NRG/hit	40.09		
Cum NRG	53083	Average counts/hit	30.66	**Average NRG/count**	**1.308**
Time (s)	180				

Figure 26. Table showing the AE data for different degrees of fibre bridging behind the crack tip

The AE data recorded in the three test specimens varied due to the different energy uptake values for the crack growth, both in the general activity during the test and also in the characteristics of the recorded waveforms. Differences in the general AE activity recorded during the tests reflected the type of crack growth taking place in each specimen. A huge number of low intensity hits were recorded for H1309 (Fully developed bridging zone, micro cracking) and the crack growth was controlled and grew only very slowly. By comparison, H1311 (crack in the resin rich layer, no fibre bridging, macro-cracking) had far fewer AE hits but each individual hit contained far more energy. The crack growth here was less stable (due to resin plasticity) and progressed entirely during two sudden "jumps" forward, the AE trace reflected this. H1310 was an intermediate case with an intermediate number of hits, energy per hit and length of test/crack growth. And although the AE trace (and crack growth) during the test was generally stable, it could be seen from the AE that the crack growth was in fact via a series of "mini-jumps".

A key observation is that simply observing total AE activity or cumulated AE energy release is not sufficient to determine the "severity" of a defect in a sandwich GRP material. The crack growth involving fibre bridging (H1309) generates a huge number of AE events, and far more energy is released overall than in the other specimens. However this does not correlate with the length of crack growth in this specimen. More significant is the amount of energy released per event detected, and the energy released per count (a function of the event duration).

It was proposed that by calculating a real time figure for average energy per count during the course of the test, it would be possible to estimate the relative amount of fibre bridging in any similar specimen at any time during the crack growth; lower ratios for average energy per count indicating a greater degree of fibre bridging. In a DCB test where the crack type changes (from skin/core debonding to skin delamination or vice versa) due to a change in applied moment, we suggested we could immediately detect this event using only AE sensor data.

This kind of monitoring could be used (initially) to automatically control the loading arms on the DCB-UBM test machine in order to maintain a certain crack pattern in a specimen, or perhaps in the future to adjust a structure loading pattern in order to prevent damage.

4 Structural Testing of Wind Turbine Blades

Wind turbines in Denmark must be certified in accordance with the Danish approval system at an accredited test centre. The rotor blades are the most critical parts of a wind turbine. Failure of a rotor blade in service often involves damage of the entire turbine. The economical consequences of a rotor failure can be devastating to a wind turbine project, wherever situated on the globe. Although the blade design and loading calculations are simulated thoroughly on computers, there is still a strong need to verify these calculations by full-scale blade tests. In addition, vital information concerning manufacturing issues can be brought to light by these tests.

The static tests specified for accreditation involve a determination of various physical properties of the blade (weight, centre of gravity, natural frequencies), a flapwise proof test, an edgewise proof test, a torsional proof test and a visual inspection. The fatigue tests involve instrumentation by many surface strain gauges followed by a static load calibration check. Then a fatigue loading (usually produced by an eccentric mass exciter) for a predetermined number of cycles. Every 1,000,000 cycles the static load calibration check must be performed again. An optional post-fatigue static test to determine residual strength can also be included as a final step. These tests enable certifying bodies to compare measured data to the calculated data of the design criteria. The entire test process is reported using a standard format and the tested design is accorded a pass or fail based on these specified measurements.

Static blade tests are performed in order to determine the structural properties of a blade including stiffness data and strain distribution. Static tests may be carried out as a single point load application, but more usually via multipoint load application from carefully fabricated loading clamps. The load may be applied in horizontal or vertical direction depending on the test facility.

Dynamic blade tests are performed in order to determine the fatigue properties of the blade; the duration of a test may be several months. Surveillance, inspection and calibration of the test setup will take place at regular intervals.

Resistance strain gauges applied to the blade skin and internal blade structure provide response data in static load condition and over the duration of the dynamic testing. Non-linearity of the response in strain gauges positioned along the length of the blade can indicate that buckling of the blade skin is taking place. The slope of the strain graph as load increases is also essential information for the verification of the structural blade design. And the length-wise strain distribution under static load can be used to reveal any high gradients that will reduce the fatigue life of the blade.

The condition monitoring techniques specified by current certification authorities are surface strain measurement, displacement transducers, the output of the load cells, and visual inspections. However, in order to extract more data from these (rather expensive) full-scale tests, blade manufacturers have begun to use more and more sophisticated condition monitoring techniques and to perform more demanding and complex loaded tests on their new blades. This includes non-standard testing designed to get extra information about the design and manufacturing issues for the structure and to check actual response against models that can predict the onset of non-linear behaviour.

The increase in the production rate (and scale) of wind turbine blades has generated a need for improved and faster quality inspection at manufacture and during/after structural testing. A wide range of techniques are available and the most common are summarised by Drewry and Georgiou (2007) and Amenabara et al. (2011). The simplest and most robust technique available is a visual inspection by an experienced employee. A manual inspection of this kind can include the use of miniature cameras or endoscopes, and the use of tap testing (manual and/or computer aided) to investigate hidden structural irregularities such as skin/beam disbonding and so on.

The results of tap testing can be used to justify the application of an ultrasonic inspection, or to confirm the findings of such an inspection. Ultrasonic inspection can reveal hidden defects effectively; it is a reliable and repeatable technique and the most widespread non-destructive composite inspection method in the industry. The main advantage is its ability to locate and characterise hidden defects (or damage) like delaminations and laminate dry spots. The main disadvantage is usually the issue of applying the technique quickly over the large surface areas of a modern wind turbine blade. Commercial services offering blade inspection tend therefore to focus on the use of arrays or automated robotic systems to optimise the technique applicability, for example the NDT systems used by FORCE A/S technology (www.forcetechnology.com).

Infrared thermography is also a technique in widespread use for detecting flaws in adhesive joints and research/innovation groups are currently optimising hardware for commercial applications in wind turbine blade manufacture, for example the Fraunhofer-Allianz Vision groups Thermographic Testing of Rotor Blades in Wind Turbine Generators (www.fraunhofer.de).

Commercial Shearography systems are available that are designed for use of wind turbine blades, for example Dantech Dynamics Wind turbine Blade Inspection using Shearography (www.dantecdynamics.com).

Back scatter X-ray technology is also a system being developed for this application, for example InnospeXion ApS back-scatter x-ray technology for the detection of sub-surface defects accessible from one side (www.innospexion.dk).

Many of these NDT techniques (with some practical modifications) can also be applied to blades that are undergoing proof testing in order to document the initiation and development of damage, or even applied to search for problems on blades mounted on the towers. However the disadvantage of transporting personnel and hardware to carry out full structure inspection in such harsh conditions is the driving force for the development of embedded systems that can give early warning of problems and focus inspection effort where it is needed.

There are some key differences between NDT (non-destructive test) hardware and SHM (structural health monitoring) hardware.

- NDT hardware is used consecutively on a series of different structures. The cost of the system relative to the cost of the structure can be high.
- SHM hardware is used continuously on a specific structure for the remainder of that structures operating life. The cost of the system relative to the cost of the structure must be low.

Most SHM hardware is trialled for effectiveness in detecting damage initiation and growth during blade tests. The more successful techniques can in some cases be modified and made suitable for long term demonstration on operating blades (that is made cheap and robust). The next step in the development of such SHM hardware that is successful in both controlled tests and normal operation would be a prototype product development and integration with the relevant communication/data tools and SCADA systems.

For example, Acoustic Emission techniques have been used to good effect to document structural integrity and any damage initiation/development in connection with full scale blade tests during extreme static loading by Jorgensen et al. (2004), in fatigue series by Wei and McCarty (1993) and Beattie (1997), and for standard certification tests (AEGIS project, 1998-2002). The perspectives in mounting AE sensors on an operating turbine blade have also been a research topic investigated for the industry by Blanch and Dutton (2003).

Risoe DTU has a long history of investigation in this area (SHM for wind turbine blades) and the summary reports by Sorensen et al. (2002) and McGugan et al. (2008) detail the sensor types investigated (Acoustic emission, Fibre optic, and accelerometers), the monitoring approach (Ultrasonic and X-ray), and the laboratory and full-scale testing undertaken.

More recently, static loading tests at the Risoe DTU Blade test Facility (established 2008) have showcased the effectiveness of various measurement techniques in characterising the deformation behaviour and damage evolution of wind turbine blade structures. These techniques include Digital Image Correlation, Vacuum hood shearography, acoustic emission, ultrasonics, resistance strain gauges, and mechanical displacement measurements. See Jensen et al. (2008) and Nielsen et al. (2010).

Improvements in Optical Backscatter Reflectometry techniques now permit resolutions at which a single fibre optic can provide a distributed strain measurement along its' entire length with obvious advantages over multiple point measurement (whether from traditional resistance strain or fibre Bragg gratings). See Guemes et al. (2010).

Large EU sponsored projects such as UPWIND (www.upwind.eu) have included instrumentation for all wind turbine structures, including fibre optic strain systems for the operating blades, in a dedicated work package looking at condition monitoring (WP7). And indeed this is the technology type that it is most common to find offered as an extra feature in commercial blades, the inclusion of embedded (in fact bonded) fibre Bragg-grating strain systems and crack detectors.

It is clear that many different techniques are used in the industry but that simple and robust inspection methods are preferred for quality control purposes with the most successful NDT equipment (ultrasonic inspection) hampered by problems covering the large surface areas and complex geometries of the structure.

In-situ inspection is even more limited in application, and embedded sensor technology hardly used at all. In general the application of these technologies is most widespread in structural testing to understand structural response and damage progression; however modified forms of portable inspection and robust sensor systems have been used in blades, generally as a response to a known but uncharacterised problem. The extent of research in the area suggests that the industry focus on more reliable (and larger) structures will prompt new technological solutions involving combinations of sensor systems that can begin to provide remote structural data and hence maintenance optimisation.

So the idea that by concentrating the use of sensors and monitoring systems during structure testing, where the demand for them is apparent, we can also develop the techniques that will be most efficient when applied as SHM on operating blades. For example, stress wave analysis or acoustic emission gives the possibility of locating small cracks and imperfections in the structure. By use of the acoustic emission detection system during fatigue test and static test it becomes possible monitor the initiation and development of defects, and stop the test before damage extends to a size that will cause the blade to fail.

The acoustic emission detection system is a set of piezo-electric transducers positioned on the blade in a pre-defined pattern. The sensors are connected to a data acquisition system that samples the transducer signal. Knowing the position of the sensors, it becomes possible to locate the area of the signal source (the damage). Hence the system is set up to register "first hit" among all sensors; any signal will be determined to originate from the zone of a single sensor. With a closer pattern of sensors it becomes possible to make accurate determinations of the origin of the damage using time of flight information between two (linear location) or more (planer location) sensors.

An important objective for a development engineer working to develop SHM is to first demonstrate the practical benefits accruing to the test centre from using sensor technology as simply an aid for the test personnel when carrying out their regular work. This includes the following points.

- Increased safety
- Instinctive sensor feedback
- Minimise "unwanted" damage events
- More focused "faster" inspections
- Identify onset of different damage modes during testing
- Inspections closer to ultimate failure load
- Improved ratio of "working" to "resting" time in the rig

When carrying out tests on such large structures it is paramount that all personnel must kept safe. For this reason, the test operatives have no way of visually checking the blade during loading for evidence of damage development. Video links and stress-strain curves have previously been the only information available. The audio feedback from the AE sensors and the clear visual displays showing where "damage" is developing in the blade give the operator a much more meaningful indication of or "feel for" how the test is proceeding. Errors such as unwanted damage are much less likely to go undetected. This allows alterations to be made, if necessary, to ensure a good test. The process of visually or ultrasonically inspecting a 50m long blade for damage following a proof load becomes much less time consuming when a good indication already exists of where to begin looking. Different damage types occurring during the course of the test can often be identified during the actual load process. The predictive use of AE activity during load holds means that a full NDT inspection of the structure can be carried out at a damage level almost immediately before failure. Often this will give much more information about the root causes of the failure than is possible from only inspecting the destroyed structure. A net result of this will be that the ratio between "working time" and "resting time" while the blade is in the rig will be improved, thus saving money.

An example of a static blade test where AE measurements were used to follow the damage condition and modify the load application is given in Jorgensen et al. (2004) and summarised here.

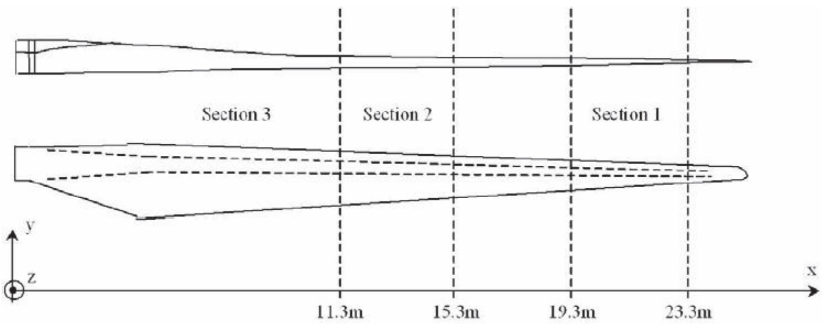

Figure 27. A Blade to be tested statically in three separate sections

The blade was tested in three sections, giving the opportunity to investigate three independent failures. The sections to test were decided based on knowledge of compression strength and geometry and these sections were loaded and supported in such a way that ultimate failure would occur in a particular area and in a particular way (one that involved the central spar "bulging" as predicted by new non-linear modeling analysis).

A step loading approach was taken whereby the load was increased and held for a short time, then either unloaded and the blade inspected or the load increased another step depending on the AE response from the attached sensors.

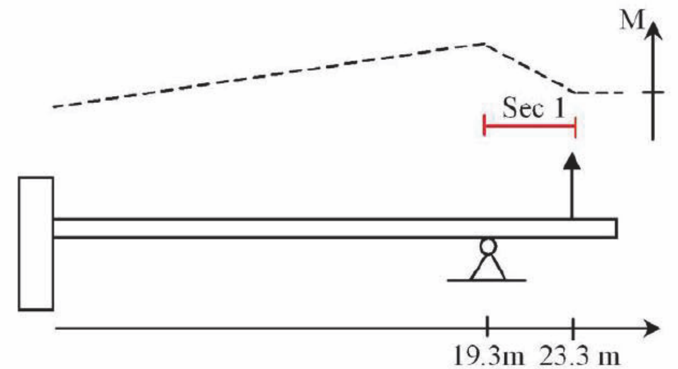

Figure 28. The Load schematic for blade section 1

Strength calculations for the section 1 loading scheme predicted blade failure at the 20.1m chord of the blade (x = 20.1m). AE sensors were used to monitor the level of activity at the 19.3m holding yoke and the activity at the 23.3 loading yoke in order to give a visual indicator to the test operatives that the loading was proceeding as expected and that no unwanted damage types were occurring. An array of sensors was also positioned on the compression face of the blade around the 20.1m chord in order to generate an activity localisation around the predicted failure.

The blade was loaded as shown in Figure 29 several times with AE activity recorded for each load. During these multiple loadings a form of the Kaiser effect was observed, in which acoustic emissions are not observed during the reloading of a material until the stress exceeds its previous high value. When the blade was loaded to failure it was observed that the fracture line at the 20.1m chord corresponded to the AE localisation data obtained as the structure approached failure.

Figure 31 shows that a slightly more complex loading scheme was used on blade section 2 with two "loading" yokes and one "clamping" yoke. This time the strength calculations predicted failure at the 12m chord of the blade. So guards were placed at the "clamping" yoke marked 1 (at 11.3m) and at the "loading" yoke marked 2 (at 15.3m). And the localisation sensors positioned at 3 (12m chord).

However, at the expected failure point (12m chord), almost no acoustic emission activity was detected, whereas guard sensor 2 which had been

Figure 29. Static blade test deflection

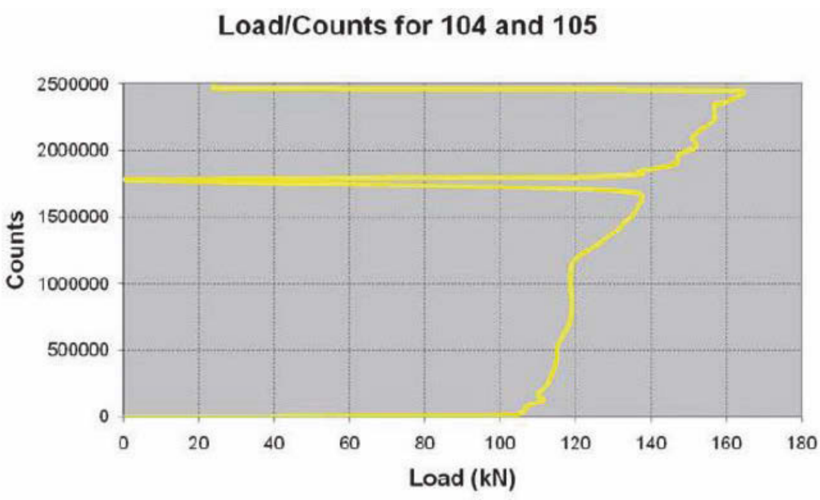

Figure 30. Cumulated AE activity against load showing the Kaiser effect

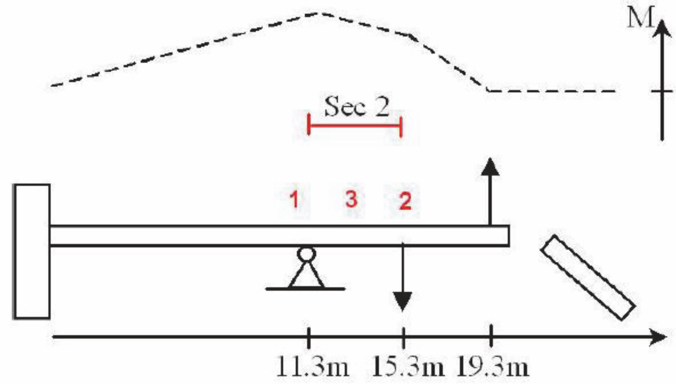

Figure 31. The Load schematic for blade section 2

positioned at the 15.3m loading yoke successfully warned, very early in the test, that failure would in fact occur here. This was an example where the model prediction was incorrect.

The static load was applied in a stepwise manner in order to assess the amount of acoustic emission and decide if the load should be increased further or the blade unloaded. Figure 32 shows that after each increase in the load ("step up") there is a burst of acoustic emission activity. As the load is held the activity level dies down and the load can be increased again to the next "step". At each step up and load hold the amount of AE increases and the time taken for the activity to die down becomes longer. This is a common technique when using acoustic emission to monitor a structural test.

On the final step load in test 201 (Figure 32) the AE activity is so great and takes so long to die down again that is was decided to stop the test and inspect the area. In this way it was possible to characterise the damage condition in the blade very close to failure load by using the sensor output to predict how close the loaded structure was to failure. In this case the test operators were able to predict failure load for this section with a less than 2% error as on the subsequent reload of the blade failure occurred as soon as the load was increased above the previous "step" level; see Figure 33.

The fact that the blade failed at section 2 by the 15.3m loading yoke was unwanted but, due to the warning from the AE sensors, not a surprise. At the moment of failure the broken blade "sprang back" against the clamping yoke at 11.3m. At this point it was observed that the guard sensor placed at the clamping yoke signalled AE activity, where it had previously been

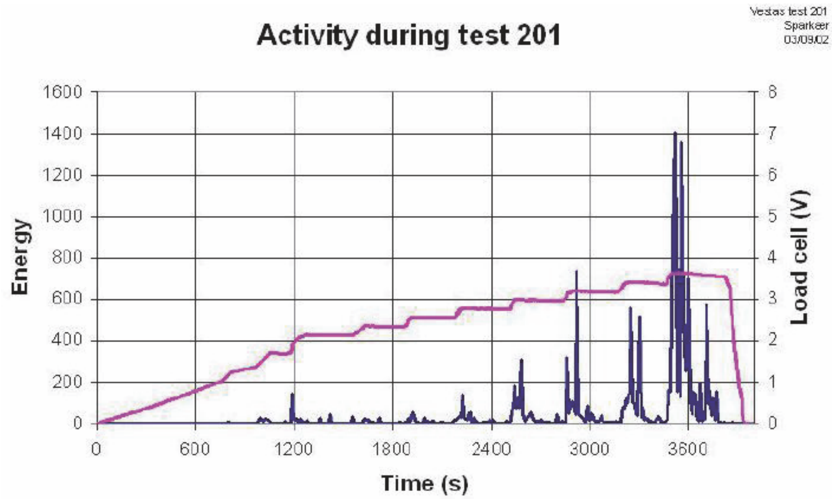

Figure 32. Showing bursts of AE activity at each "step" of test 201

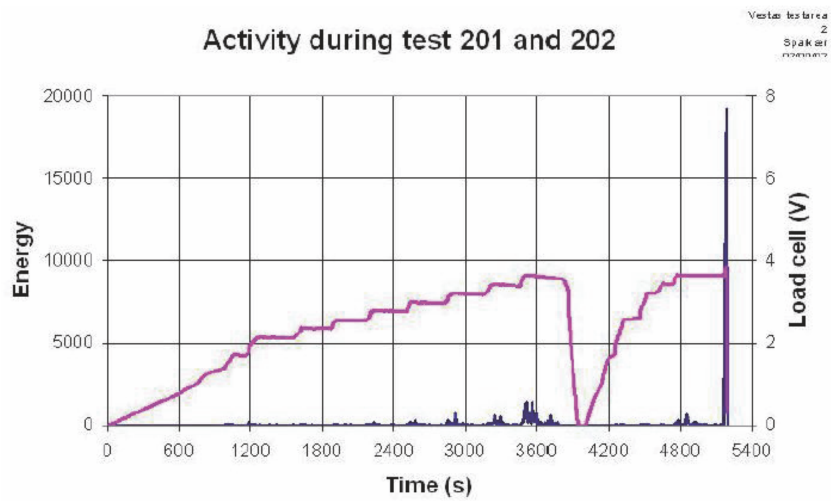

Figure 33. Showing bursts of AE activity at each "step" of tests 201 and 202

silent. This prompted a close inspection of the blade at this area. From outside the blade nothing could be seen.

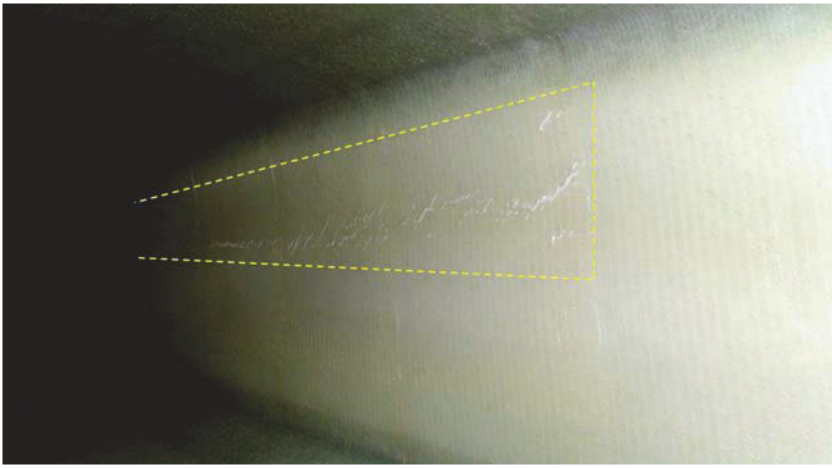

Figure 34. Image from inside the blade showing damage

But by climbing inside the blade central spar and crawling out to the 11m chord it was possible to see lateral cracking on both sides of the spar that were certainly caused when the blade "sprang back" against the clamping yoke at the moment of failure out at 15.3m.

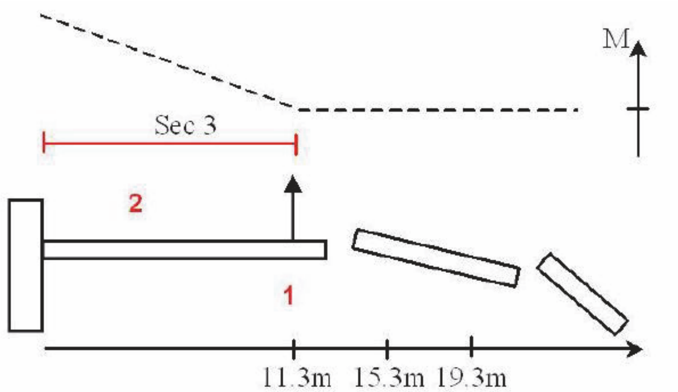

Figure 35. The Load schematic for blade section 3

This damage became very significant in the third and final blade section test. As shown in Figure 35 this was a simple static loading from a single loading yoke. The greatest bending moment is found at the root of the blade, but due to the thickness of the structural material at the root it was predicted by the model that the failure cord would be at 5.5m. AE monitoring was positioned at this predicted failure point and at the loading yoke (11.3m).

Figure 36. Alternate test configuration with reinforced loading section

The test began as expected but suddenly a great deal of AE activity registered at the loading yoke and the blade was quickly unloaded. An attempt was made to load up again but this time there was immediate activity (even at very low loads) from the AE sensor at the 11.3m loading yoke. By marking the extent of the lateral cracking inside the blade it was shown that this damage was growing and it was clear that the blade will not break as planned, the test as it was currently configured must be abandoned.

As the structure had been saved from premature failure by the AE monitoring it was possible to enact a change in the test configuration and try the loading again.

It was decided to change the loading angle (see Figure 36) and reinforced the blade around the loading yoke by using a solid plug. When loading again with this new configuration the AE sensor at the 11.3m loading yoke was silent (the lateral cracking now longer growing) and activity began at the 5.5m instrumentation indicating that the test is proceeding correctly. Note that there was no other way to predict where the blade was going to break during loading (only info is from the bending calculations made beforehand) and without the AE detecting the unwanted damage, and confirming it was active when reloaded, it is certain the test would have broken the blade at the loading point instead of at S2, and the results from this structure test would have been worthless.

5 Future work; Smart blades?

Wind turbine blades manufactured today deflect in such a way that the worst of extreme wind blast loading is avoided. This is simply due to the passive properties of the construction material, anisotropic, non-symmetrical laminates, that can be utilized to create a controlled bending and twisting under normal wind loading.

In addition to this passive response, there are also benefits to be gained from the performance of a wind turbine blade that can actively adapt its' aerodynamic profile to the conditions. Much as a bird of prey can hang motionless in the air due to slight wing adjustments, an adaptive blade can draw more energy out of the available wind and avoid peak loading from potentially damaging gusts. This saves materials and at the same time increases the potential operating lifetime as the mechanical loads on the wind become smaller. An adaptable blade will be less buffeted in a gusting environment.

In order to do this the trailing edge profile of the blade (possibly fabricated from tough rubber material) should be altered using piezoelements or pneumatic actuators linked to sensor feedbacks measuring the characteristics of the wind and the turbulent flow immediately approaching the blades. Such measurements could be realized by further development of the LIDAR (LIght Detection And Ranging) systems used in the windscanner project (www.windscanner.dk).

The structural design of wind turbine blades is also an area where significant changes will be made as the trend towards still larger structures continues. Figure 37 illustrates the multi-scale approach to testing of wind turbine blades. The smaller images inside the triangle are of tests that have been developed and carried out by Risoe DTU over the last few years. At present the certification agencies regulating structural materials used in the wind energy sector require documentation only for the top and bottom levels of this pyramid; that is small test specimens measuring material properties and full-scale blade tests measuring structural response. It is the objective of the Risoe DTU groups collaborating on blade materials and structures to systematise the sub-component testing (the levels in-between specimen and full scale) in such a way that it can also be used in the design and certification process.

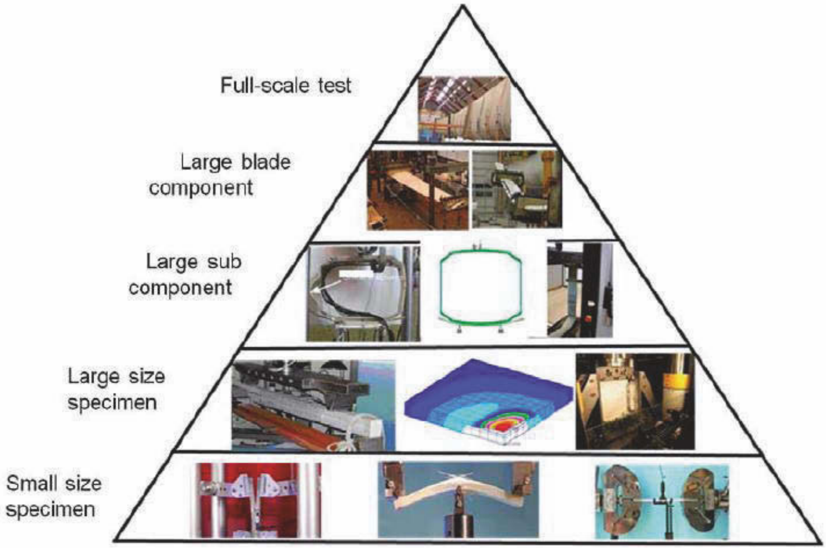

Figure 37. Test triangle for materials and structures at different scales

In order to be more complete this diagram should also include a sub-level corresponding to mechanical testing of specimens at the micro scale (perhaps approaching the nanoscale). Testing of this kind, that measures fibre pull-out and other interface effects, are carried out at Risoe DTU and the models for behaviour at this scale are also of importance when taking such a multi-scale view.

The breadth of scale under consideration here is not simply a practical issue of best mechanical testing methods. To characterise the responses at different scales we see different modelling processes implemented, and different sensor types and configuration adopted. The challenge posed by considering such a multi-scale triangle/pyramid is to develop a solution where the effect of small-scale local deviations in material properties (whether caused by the presence of damage/defects or due to design) distributed around the structure can be integrated with the full-scale models in a consistent way thus providing a tool for identifying and characterising material failure modes and locations that are critical for any given blade design. Such a tool can be used in the design and qualification stages of new blade types, and could later be used to assist maintenance decision making for the blades once in operation by predicting damage growth patterns and calculating the remaining life of any particular turbine blade based on its current health status and its operating environment.

A major ambition for the future is the establishing of test facilities at DTU that are capable of carrying out testing of sub-component structures under realistic boundary conditions. This requires the use of sensor data and NDT input to characterise the response of the sub-component in terms that can then be fed into models describing the effect of the sub-component response within the framework of the structure it will be a part of. This model is then used to recalculate the boundary conditions around the sub-component and hence correct the loading profile.

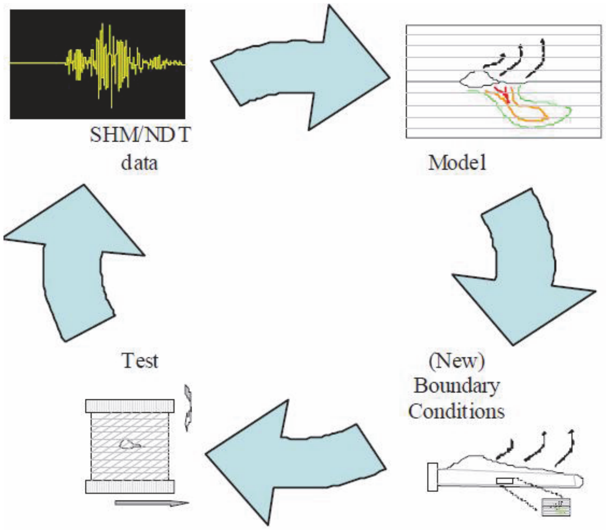

Figure 38. Hybrid testing of a sub-component with sensor feedback and boundary control

Such a facility would allow examples of the type of "smart structure" ambitions of designers who wish to create operating structures that can use embedded sensor data to inform the structure on how to automatically respond to operating loads; whether it be an adaption in order to optimise operating output under different conditions, a safeguarding of the structural integrity by avoiding potentially damaging load conditions and thus maximise total operating life, or as input to a condition based maintenance regime.

Figure 38 illustrates how an eventual hybrid test might proceed with sensor data from the test feeding into damage growth models that then update a structural response model, which supplies new boundary conditions for application on the sub-component test actuators, and so on. This gives a more realistic investigation of the sub-components mechanical properties in its' structural context.

Very often the emphasis on future developments is dominated by current research, technical progress and the possibilities that these offer to current procedures. However these advances are not enough in and of themselves to enable a change in an established industry. The argument in this section has been that the changes identified as specific to the wind energy industry allow better opportunities for new ideas like Structural Health Monitoring to be adopted than has been the case in other industries (Aerospace, civil, and military) that have followed the technology with interest for many years.

One positive way to consider this situation is with reference to the ideas first put forward by Christensen (2003) in the Innovators Dilemma. Here one can read about the possible need for an "enabling application" which successfully uses a lower capability type technology, and thereby promotes that technology's State of the Art (SOTA) in such a way that it later becomes competitive at the higher technology capability level. There are difficulties in successfully identifying Christensens enabling and disruptive type applications before the fact, but a good case can be made for offshore wind turbine blade monitoring currently being one of the best candidates for an SHM enabling application. Key terms include:-

- Sustaining technologies - improve product performance
- Disruptive technologies - "different value proposition"
- Enabling technology - "pilot" the technology, demonstrate reliability, validate cost benefits, reduce "program" risks prior to wide-scale application on an emerging program.

Sustaining technologies are those that improve the performance of an established product or procedure. The improvement can be large, but it is always evolutionary in nature (doing something "better"). The vast majority of all technological improvements (also in the aerospace structural maintenance industry) are sustaining in nature.

Disruptive technologies, on the other hand, "bring to a market a very different value proposition than had been available previously. Generally, disruptive technologies underperform established products in mainstream markets. But they have other features that a few fringe (and generally new) customers value."

Christiansen goes on to suggest that once established in a few fringe or niche markets, disruptive technologies can then quickly go on to become fully performance competitive in the wider market, where initially they underperformed with respect to established procedures and/or products.

The question could then be asked if SHM is disruptive with respect to current NDT and Inspection? If so, then in assessing technological possibilities for SHMS, we can use Christensens findings to judge the way that these new technological possibilities are most likely to be enabled.

The repair and maintenance procedures for (for example) military aircraft are well established and highly optimised. Advances in the procedures are without doubt of a "sustaining" nature as described by Christensen. However, there are a few areas where difficulties in the maintenance procedures are recognised.

For example:-

- Physical access to areas of inspection
- Adoption of new materials
- New operational requirements

The sustaining technology approach to the difficulties listed above might include the decision to alter designs to allow easier access to structural components in question, performing qualification trials for the materials and specifying in-service structural assessments, and so on.

The general approach identified by a SHMS approach would require "hot spot" monitoring of only the structural components in question, rather than attempting an ambitious "general" structural health assessment. The precise nature of the reason for adopting this hypothetical "hot spot" monitoring in an operational platform is not made clear, but it would most likely be due to one of the reasons listed above.

It should be recognised that the output of the "hot spot" monitoring from an SHMS does not need to equal the quality of output expected from using traditional inspection techniques on the same structural area. The reason for this is that the SHMS is offering a different "value proposition". A successful SHMS would allow operators the confidence of focussing traditional inspection effort (which is relatively expensive and time consuming) only on the platforms that contain structural areas that require it.

These characteristics would seem to cast SHM as a "disruptive" technology in the area of physical asset management with respect to traditional inspection techniques.

A true enabling application is one that involves mass production and associated economies of scale. One possible argument against the idea that successful adoption of SHM on aerospace structural "hot spots" will inevitably lead to full structure monitoring on aircraft, is that the mass production (of sensors) would not be achieved here. Similarly in other aerospace, the emphasis is on sustaining technology advances and optimisation rather than whole structure sensorisation, with only small potential applications for SHM in suspect structural areas, e.g. around the tail rivets on commercial airliners or on the insulation tiles on the Space shuttle. These small applications however may not require the mass production of sensors necessary to qualify for the epithet, "enabling" as it is defined by Christensen.

A brief consideration can made of other potential "enabling" applications for SHMS in other industrial sectors.

The application of sensor technology in civil engineering is progressing only very slowly, due to the well-established and optimised principles of building being employed. Where new materials and/or designs are adopted, there is a slightly greater interest, also where older buildings with historical value are monitored or buildings are placed in earthquake zones. Many new buildings are constructed with an in-built wireless communication system, and sensors/actuators designed to deliver automated energy savings. So although the damage detection technology is not employed, relevant SHM "sensor communication infrastructure systems" are common in modern civil engineering.

In the early 90s, helicopter-monitoring systems developed very rapidly when safety problems in the industry (serious problems which almost crippled the industry) required an immediate advance in the technology employed. In particular, the advances in vibration monitoring sensors were strong and allowed these sensors to later become widely applied in all (industrial) rotating machinery, including wind turbine gearboxes and drive trains. However, the development ceased when the required level of safety through monitoring and data-fusion had been achieved. No further SHM technology developments are expected here in the short to medium term.

SCADA systems for offshore wind farms are under pressure to deliver a far more comprehensive and integrated information flow to operators, including live structural health updates on turbine machinery, foundation piles, blades, etc. The repair and maintenance strategy adopted for the forthcoming round of large offshore installations has been identified as being a decisive factor in their financial success (or otherwise) and hence of the renewable energy strategy for Europe. The scale of this construction operation and the demands (industrial and political) for extra reliability in such a treacherous ocean environment make this a good prospect for a SHM enabling application in the next decade. This would also be a bonus for European competitiveness as this continent is ahead in wind power development and would therefore benefit most from such a SHM breakthrough.

Other possible enabling application could be computer (games) technology and/or human/machine interface technologies like augmented reality.

In the United States, sensor research and development is generally more advanced than in either Europe or Asia, but what this high technology American industry has so far lacked is an application that demands significant numbers of their products. The most common application for structure monitoring sensors is in Aerospace, where the volume of demand is not high, and within civil infrastructure, where a high level of confidence in design and materials have restricted the use of the relatively expensive sensors.

Adoption of SHM technology within the European wind energy industry would create a great demand for the hardware manufacturers and create a network of supporting industry and consultants on this continent. This concentration of expertise would form the base for the expansion of the technology into other sectors in Europe and around the world, re-exporting the "know-how" into diverse applications. The economies of scale would reduce hardware costs and the confidence from a successful application would win over more cautious engineers (in civil sectors for example).

Industries poised to follow the example of a pioneering European wind energy sector and embrace SHM technology include, Aerospace, Transport, Civil infrastructure, Earthquake construction, Historical building preservation and more.

It is the general feeling among experts, such as Patrick Goggin of Boeing Phantom Works (Goggin et al. (2003)), that a breakthrough application ("enabling application") is necessary in order to stimulate a more general adoption and development of SHM ideas and techniques throughout industry. The rapid manufacturing growth within the wind energy sector, and the trend towards large offshore farms, make this the most promising global candidate for fulfilling the requirements of an SHM enabling application.

With reference to Figure 39; a technology can be monitored thru time, and the CAPABILITY of the technology can be compared to the CAPABILITY REQUIRED for different applications. The technical requirements for SHM on aerospace is currently "not available". Hopefully the rate of improvement in the technology is rising faster than the requirement for the application but this cannot be known. Perhaps it never reaches the required level and arrives at the future scenario of SOTA2. But if Christensen is correct then by "discovering" an application that can match with the current level of SHM capability, the SOTA development curve is improved to such

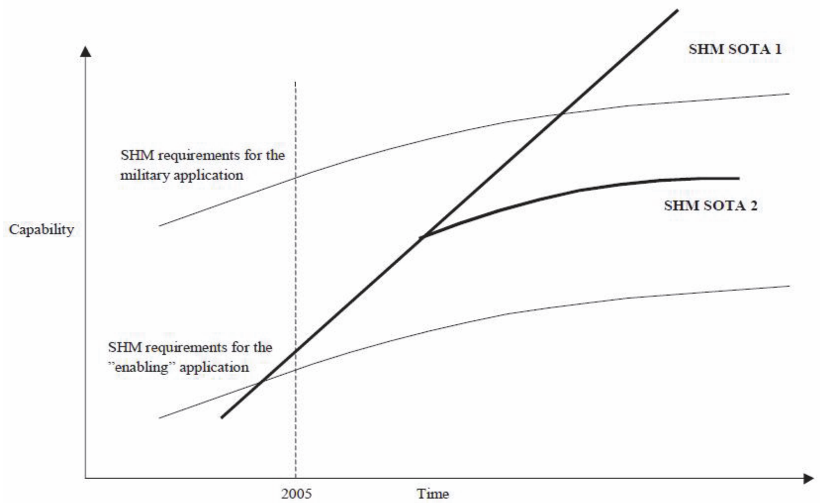

Figure 39. Clayton Christensens "Innovators Dilemma", Christensen (2003)

an extent that we do in fact manage to overtake the high capability requirement in the future; SOTA1.

A final consideration that may be fruitful when considering the best way to promote the use of Structural Health Monitoring could be biological systems; in particular the evolutionary approach to sensor development. In many presentations of the technology of Structural Health Monitoring it is common to compare the function of a sensor network in a biological phenotype (a human being) to that which is being proposed in the SHMS. However the consideration of how such a system came to be expressed (that is, the history recorded in the genotype) is not made.

It is possible that useful insights can be found by considering how small (but measurable) improvements in the performance of biological sensors through an evolutionary process are made in a competitive environment; particularly where the ultimate objective is a "high capability" system that cannot be achieved without demonstrating small but incontrovertible improvements at no (or limited) cost.

To summarise we can list the following concluding statements:-

- Developments in the wind energy industry demand new approaches
- Challenges exist for the effective structural performance of larger blades
- Opportunity exists for SHM and other "smart" solutions to speak to

these challenges
- Modular monitoring systems are envisaged to harness the synergy required to cover all significant damage types
- Implementation strategy will be critical in any successful adoption of SHMS
- Structural Health Monitoring is a form of Information Technology
- Management and Organisation of the developments are as much an issue as any technical challenges

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