Mat UK Energy Materials Review

Material R&D Priorities for Wind Power Generation

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1 INTRODUCTION

The wind energy industry has its origins over 20 years ago with the manufacture of wind turbines on a commercial scale starting in the 1980s. It is an industry that has been widely promoted and is currently the fastest growing sector in the power generation industry, with anticipated industry expansion rates consistently being exceeded since the early 1990s. As the wind energy industry has grown, electricity generated by wind power has shown a dramatic fall in cost. The average cost of production from a coastal turbine has decreased from approximately 8.8 € cents/kWh for a turbine installed in the mid-1980s to 4.1 € cents/kWh for a modern 1 MW turbine. This represents an improvement of over 50% in 15 years. In terms of price, wind power is already competitive with some new coal-fired power stations and in some areas can challenge gas, currently the cheapest option. However, despite this progress, wind power still has some way to go before it fulfills its potential as a large scale supplier of electricity.

After providing a brief overview of the wind power market, this report focusses on the design issues,materials used and technology/material trends for the major component parts of wind turbines. Recommendations for future materials research and development are provided.

2 OVERVIEW OF WIND POWER MARKET

2.1 DRIVERS

There are several key issues that have driven the growth of and demand for power generated by renewable sources, and in particular wind generated power. These issues include:

- Fossil fuel reserves are gradually being depleted
- The need to ensure security of power supply through reduced energy import dependence
- Electricity price rises
- The need to reduce emissions linked to global warming (CO_2, green house gases (GHGs))
- Government policy and direction
- Increased UK and global energy demand

2.2 CURRENT AND FUTURE MARKET SIZES

2.2.1 UK

The UK Government set a target of a 60% reduction in carbon emissions by 2050. Recognising the role of renewable energy sources in cutting CO_2 emissions, the Government has introduced legislation to encourage their uptake. The Renewables Obligation (RO) was introduced in April 2002 requiring all electricity suppliers to source 10% of their supply from renewables by 2010. In 2004 this target was revised to 15% of supply by 2015.

Wind energy is currently the most technically and economically developed renewable energy technology, and it is expected to make up around 75% of the 10% target by 2010. This equates to around 8,000 megawatts (MW) of capacity, which will be derived from onshore and offshore farms. Onshore this equates to a further 1,500 turbines (assuming an average size of 2 MW) in addition to 1,414 turbines that have already been installed. As offshore turbines are generally larger and more powerful (> 3 MW) than their onshore counterparts, fewer (1,300) will be needed.

The UK has recently broken the 2 GW threshold of electricity from wind power, around 1.5 % of the total UK electricity supply. This level of electricity from wind power has doubled in little more than a year.

2.2.2 EUROPEAN

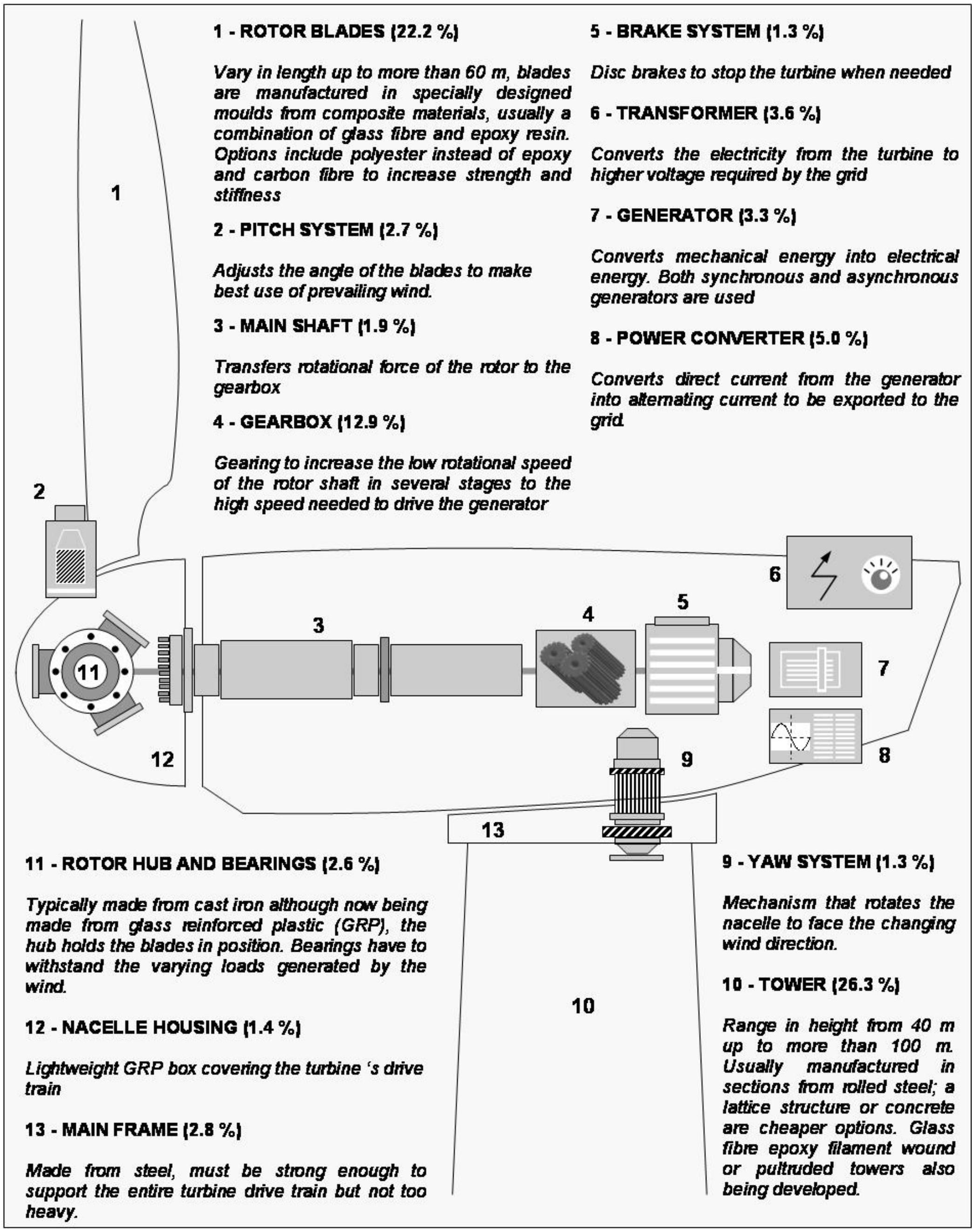
In 1997 the European Wind Energy Association (EWEA) adopted the targets set by the European Commission’s White Paper [1] on renewable sources of energy for 40 GW of wind energy capacity by 2010. This target was then revised three years later to 60 GW by 2010 [2]. However, this revised forecast has proved to be conservative with the expected growth rate being exceeded in reality. The latest EC figures [3] indicate that wind power capacity in Europe could reach 69.9 GW in 2010. The target now adopted by the EWEA for 2020 is for 180 GW of power, of which 70 GW would be generated by turbines located off-shore. In terms of Europe’s electricity consumption, the EWEA target would see wind energy contributing 5.5% in 2010 and 12.1% in 2020 [4]. This is equivalent to the electricity needs of more than 195 million people.

3 WIND TURBINE TECHNOLOGY

Many design developments have occurred since the commercialisation of wind technology in the early 1980s, however the basic configuration of the mainstream design has not changed significantly. Most wind turbines have upwind rotor blades and are actively yawed to ensure alignment with the wind direction. Figure 1 shows the components of a conventional wind turbine together with an indication of the percentage of the overall wind turbine cost.

The three-bladed wind turbine configuration is by far the most commonly used. It typically has a separate front bearing with a low speed main shaft connected to a gearbox that provides an output speed suitable for a four-pole generator. For the largest wind turbines, the blade pitch is varied continuously under active control to regulate power under high operational wind speeds. A nacelle housing encases the front bearing and pitch control system and the entire turbine drive train is supported on a mainframe construction mounted on the tower.

The drive train in Figure 1 shows the rotor attached to the main shaft driving the generator through the gearbox. Significant recent developments in basic design configuration have seen the advent of direct drive generators where the gearbox is removed and the rotor is used to drive the generator directly. Hybrid arrangements involving a single stage gearbox and multi-pole generators are also now appearing.



1 - ROTOR BLADES (22.2 %)

Vary in length up to more than 60 m, blades are manufactured in specially designed moulds from composite materials, usually a combination of glass fibre and epoxy resin. Options include polyester instead of epoxy and carbon fibre to increase strength and stiffness

2 - PITCH SYSTEM (2.7 %)

Adjusts the angle of the blades to make best use of prevailing wind.

3 - MAIN SHAFT (1.9 %)

Transfers rotational force of the rotor to the gearbox

4 - GEARBOX (12.9 %)

Gearing to increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator

5 - BRAKE SYSTEM (1.3 %)

Disc brakes to stop the turbine when needed

6 - TRANSFORMER (3.6 %)

Converts the electricity from the turbine to higher voltage required by the grid

7 - GENERATOR (3.3 %)

Converts mechanical energy into electrical energy. Both synchronous and asynchronous generators are used

8 - POWER CONVERTER (5.0 %)

Converts direct current from the generator into alternating current to be exported to the grid

11 - ROTOR HUB AND BEARINGS (2.6 %)

Typically made from cast iron although now being made from glass reinforced plastic (GRP), the hub holds the blades in position. Bearings have to withstand the varying loads generated by the wind.

12 - NACELLE HOUSING (1.4 %)

Lightweight GRP box covering the turbine 's drive train

13 - MAIN FRAME (2.8 %)

Made from steel, must be strong enough to support the entire turbine drive train but not too heavy.

9 - YAW SYSTEM (1.3 %)

Mechanism that rotates the nacelle to face the changing wind direction.

10 - TOWER (26.3 %)

Range in height from 40 m up to more than 100 m. Usually manufactured in sections from rolled steel; a lattice structure or concrete are cheaper options. Glass fibre epoxy filament wound or pultruded towers also being developed.

Note - percentages shown are contribution to overall cost based on a REpower MM92 turbine with 45.3 m length blades and 100 m tower. (Source - Wind Directions - January/February 2007 bulletin - "Focus on Supply Chain", European Wind Energy Association)

Figure 1: Components of a wind turbine and indicative percentage of overall cost

The main design drivers for current wind turbine technology are:

- Improved technology for low and high wind sites
- Grid compatibility
- Aerodynamic and acoustic performance
- Visual impact
- Offshore expansion

Although the proportion of offshore wind turbines is less than 1% of the total installed capacity, the latest wind turbine developments are driven by the offshore market. This means that the current technology driver is to make wind turbines as large as possible with the following issues key:

- Low mass turbine and nacelle arrangements
- Large blade technology and advanced composite engineering allowing enhanced exploitation of low wind sites (N.B. for high wind sites smaller blades, shorter towers and reinforced supporting structures are used)
- Design of offshore foundations, wind trubine erection and maintenance

Based on the current wind turbine architectures, it will be extremely difficult to build turbines with an output greater than 5 MW due to the cost of the turbine outstripping the energy output. The latest challenge is to overcome this and is an area where the use of new advanced materials, designs and manufacturing/production processes is seen as key. However, the use of new materials will neccessitate a significant amount of R&D if larger, more reliable designs are to be reaslied.

The following sections provide detail on the design issues,materials used and technology/material trends for the major component parts of wind turbines. Two cross-cutting themes, that are applicable to all materials and structures, namely Non-Destructive Inspection (NDI) and Structural Health Monitoring (SHM) are briefly detailed in Annex A.

3.1 BLADES

Wind turbine blades are complicated structures, comprising of a large number of materials, exposed to complex aerodynamic loading and environmental conditions. Historically the vast majority of wind turbine blades have been constructed from a combination of wood (e.g. birch, balsa), glass fibre-reinforced plastic (GRP) composites (initially glass fibre reinforced polyester systems were used but now epoxy-based resin systems predominate) and adhesives. (N.B. There has been recent interest in the use of natural fibre composites as sustainable alternatives to synthetic polymer matrix composites). Material selection is heavily influenced by the blade size, the number of blades, the turbine location and hence the weather conditions it is likely to experience, and the speeds the rotor is designed to operate at. As designs evolve with increasing importance placed on mass reduction, the overall relationship between blade mass and diameter is slightly less than cubic. It will be a challenge to maintain this trend (of less than cubic scaling through improved design concepts and materials) if rotors continue to get larger. Up scaling without radically changing design concepts and material properties will lead to higher internal material stresses. Such stresses can only be held at acceptable levels if materials are used with higher specific strengths or compliant components are incorporated into the design. If components bearing heavy dynamic loads are made of flexible materials then the forces acting upon them are not transferred to the supporting structure. In this way dynamic forces are averaged out leading to significantly lower fatigue loading of the relevant components.

The higher tip speeds of offshore wind turbines imply a reduction in the ratio of blade projected area to rotor swept area and hence slimmer blades. Reduced blade area will only allow reduced blade mass if materials of sufficiently high specific strength are available, hence the increased use of carbon fibre-reinforced plastics (CFRP) seen in modern, large blades. With increasing automation in blade manufacturing process from hand lay-up to resin transfer moulding (RTM) and pultrusion, which further reduces costs, the use of CFRP in blade construction has started to gain widespread acceptance.

Innovative composite sandwich structures for primary blade structures are also being increasingly used (skins from GRP/CFRP, core materials are typically PVC or BMI, balsa wood and less frequently honeycombs e.g. Nomex) for their inherent high stiffness and strength at low areal weights. However a major disadvantage of sandwich constructions compared to monolithic materials are that they are more prone to delamination and failure due to the presence of weak interfaces between adjacent materials with very different stiffness and strength properties.

Blades contain a multitude of joints (adhesive and mechanical) between similar and dissimilar materials. Localised shearing and bending effects can lead to severe induced through-thickness shear and normal stress concentrations that can significantly affect the static and fatigue strength of joined sub-components. It is likely that composite sandwich constructions and joints with improved damage tolerance (adhesives with increased performance) as well as crack stopper and load introductions techniques will be key requirements.

It is common practice to design large rotor blades constructed from fibre-reinforced plastics (FRPs) according to design codes and models based on first principles of composite material mechanics. Most commonly used models describing material properties are linear-elastic although in practice this is not the case. Such short-comings in the state-of-the-art numerical tools and existing composite material models result in high levels of uncertainty that lead to conservatism in design and blades of unnecessarily high weight and cost.

Wind turbine blades are subjected to severe fatigue loads. The severity lies not only in the magnitude of the forces but also the number of fatigue cycles the blade will see in its life time of 20 years or more i.e. typically 10^7 cycles. Although FRP materials have excellent fatigue properties, much work is still needed to understand how these materials perform under fatigue loading and particularly compression dominated fatigue. It is also crucial to be able to predict how these materials and structures will behave when they contain either imperfections introduced during manufacture/processing or damage induced during the service life. Again improved fatigue modelling, design criteria and design procedures are required if the use of materials that allow larger blades to be manufactured is to be realised.

3.2 NACELLE HOUSING

The nacelle housing provides an outer frame protecting the turbine machinery from the external environment. The nacelle is typically made of GRP with steel reinforcements and the housing is mounted through rubber dampers to the main frame with steel supports.

3.3 HUB

The hub serves as a base for the rotor blades as well as a means for housing the control systems for the pitch control system. The latest wind turbines have threaded bushes adhesively bonded into the root of the blade to allow the blade to be bolted to the hub. Hubs are typically fabricated from cast iron alloys due to the complicated component shape. The hub material must be highly resistant to metal fatigue, hence the reason why welded construction techniques are not used. In order to reduce the weight of the hub and increase fatigue performance, recent attempts have been made to manufacture a hub and shaft combination using preform-liquid composite (GRP) moulding processing. Another benefit of using a combined hub and shaft component is that the bolted connection between hub and shaft can be eliminated, thereby reducing weight, and manufacturing cost associated with the drilling of holes and tight geometrical tolerances. The use of composite materials allows directional tuning of material properties facilitating additional weight reductions. Although prototypes have been fabricated and products/techniques patented, the commercial use of FRP moulded hub and shaft components is currently some way off.

3.4 MAIN SHAFT

The main shaft of a wind turbine is typically forged from hardened and tempered steel. Future developments will look to fabricate shaft components from FRPs (Section 3.3) in order to reduce weight but their widespread use is likely to be in the long term.

3.5 GEARBOX

The gearbox is one of the most important components in a wind turbine. Situated between the main shaft and the generator, its role is to increase the slow rotational speed of the blades (in several stages) to the high speed needed to drive the generator. The trend toward larger wind turbines has led to expensive gearboxes that hinder their feasibility, although multi-generator drive train configurations can reduce the drive train cost for large wind turbines while increasing the energy capture and reliability.

Gears are typically fabricated from carbonised steel alloys and the teeth are case-hardened and polished to provide enhanced surface strength. The fatigue and wear properties of steel alloys used in gearboxes are critical.

Significant developments in the basic architecture of turbine power trains are now appearing in the form of direct drive generators where the gearbox is removed and the rotor drives the generator directly. Due to the historically problematic nature of gearboxes, both from a cost and maintenance perspective, the concept of removing them from the turbine is desirable. However, this will be an area for future development in the medium to long term.

3.6 TOWER AND FOUNDATIONS

Support towers are most commonly tubular steel tapering in both wall thickness and diameter from the base of the tower to the top. Concrete towers, concrete bases with steel upper sections and lattice structures are also used but are much less prevalent. Recent developments have seen GRP filament wound towers being trialled. The main advantage being lighter weight for ease of installation.

A current key area of research is that of cost effective foundation designs for offshore turbines. The general consensus is that steel is a far more competitive material than concrete for larger offshore wind farms. Most of the foundation designs will be economic until at least 15 metres water depth, and possibly beyond such depths. Corrosion is not a major concern with offshore steel structures. Experience from offshore oilrigs has shown that they can be adequately protected using cathodic (electrical) corrosion protection. Surface protection (paint) on offshore wind turbines is routinely delivered with a higher protection class than for onshore turbines.

3.7 GENERATORS

Recent developments in basic design configuration have seen the advent of direct drive generators where the gearbox is removed and the rotor is used to drive the generator directly. Hybrid arrangements involving a single stage gearbox and multi-pole generators are also now appearing.

Increasingly, superconductor generators that use HTS (high temperature superconductor) materials as replacements for copper coils in their rotors are being used. As HTS wire can carry much higher currents than copper wire, these windings are capable of producing much larger magnetic fields for a given volume. Hence superconductor generators can match the power output of a conventional generator but are around one-third of the size and half the weight. HTS generators can therefore be manufactured at much lower costs and transportation and installation costs are less. Also, the use of non-resistant HTS wire means that electrical losses are drastically reduced. HTS generators have lower sound emissions than conventional equipment, and as the windings are held at constant temperature are not subject to thermal fatigue.

4 OPERATING ENVIRONMENTS

As wind turbines require a good and constant wind supply they are normally situated in remote locations such as high ground or on shorelines. These sites have the disadvantage of being subjected to occasional strong winds and harsh environments, and so the turbine components must be robust enough to withstand these factors.

4.1 LOW TEMPERATURES

Low temperatues (down to –40 °C) can adversely affect the different materials used in wind turbine construction. Steel components become brittle at low temperatures and their energy absorbing and deformation prior to failure capabilities are reduced. Composite materials suffer due to differences in coefficients of thermal expansion (CTE) of the matrix and reinforcing fibres, resulting in thermally induced stresses that can lead to matrix microcracking which reduce the stiffness of the material and provide paths for moisture ingress.

Thermal shock can also cause damage to electrical equipment including the generator and yaw system. Gearboxes can suffer from long term exposure to cold weather as the viscosity of lubricants and hydraulic fluids increases with reduced temperature. Damage to gears will be caused when turbines are started after stationary periods as the oil is very thick. Seals and rubber mounts will also perish over time in cold climates.

Correct selection of materials for turbine components exposed to cold climates is therefore essential. Metals have been used in low temperatures for many years and materials such as nickel alloys and aluminium can improve the strength of steel at low temperatures. Composites have yet to see widespread applications in cold environments but differences in thermal expansion or contraction could be reduced by chosing fibre and matrix combinations with similar CTEs.

4.2 HOT/WET

In hot environments the blades are made with composite material systems using epoxy resins (the norm anyway) that can withstand heat and ultraviolet light. Although blades are sealed against moisture ingress, should moisture find a path into the composite blade material through surface damage of a gel-coat or paint, then the glass transition temperature of the material can be reduced and mechanical performance can be impaired. Dimensional changes may also occur through swelling of material.

4.3 MARINE

The marine environment is particularly harsh as turbine components are subjected to salt spray from the sea. Paint sealants and nacelle designs that inhibit penetration of salty air are used to protect the turbine, generator, blades and support tower from corrosion. Further work is needed to understand the mechanisms and affects of long term salt spray exposure for turbine materials, especially composites.

The measurement and prediction of mechanical properties of materials subjected to long-term exposure under various environments is of particular interest and importance, with accelerated ageing techniques needed.

5. PRIORITIES FOR RESEARCH AND DEVELOPMENT

The European Wind Energy Association's (EWEA) Strategic Research Agenda [5] identified a number of showstoppers, barriers and bottlenecks to wind energy development. Showstoppers are issues of such importance that if not addressed could halt wind energy progress altogether. Barriers are physical limitations in current technology that should be overcome in the medium to short term and bottlenecks are issues that can be overcome through additional short to medium term R&D. The following is a distillation of the EWEA conclusions that are related to enabling materials technologies:

- Showstoppers – availability of robust, low maintenance onshore turbines as well as insufficient R&D into the development of increased reliability and availability of offshore turbines
- Barriers – (i) integrated design tools for very large wind turbines operating in extreme climates, (ii) state-of-the-art laboratories for accelerated testing of large components under realistic (climatological) conditions, (iii) standards and certification - development of design criteria for components and materials
- Bottlenecks – development of component level design tools and accelerated finalisation of ongoing standards

From the preceding sections and with the EWEA SRA findings in mind, the following areas have been identified as priorities where future materials R&D is required for wind power to fulfill its potential as a large scale supplier of electricity:

- Improved reliability and reduced uncertainty through the development of test and modelling methods for lifecycle analysis/fatigue performance of constituent materials, sub-components and major structures i.e. blades, - medium term
- Reductions in operating and maintenance (O&M) costs through development of structural health monitoring technologies, - medium-long term
- Development and application of NDI techniques for more accurate and rapid defect detection, - short-medium term
- Continued development of innovative material designs and processing techniques e.g. sandwich constructions, joints, FRP pre-forming and infusion techniques, -short-medium term
- Development of test and modelling methods for materials characterisation for harsh environments – short-medium term
- Development of standards and certification procedures – short-medium term

(N.B. Time frame: short (0-5 years), medium (5-10 years), long (10-20 years)

5.1 UK CAPABILITY GAPS

The UK has successfully acquired the skills and resources for developing commercial wind farms in a cost-effective manner. The UK also has expertise in wind farm developers and consultants. However there are significant gaps in the UK capability compared to the leading wind power nations. The following bullet points highlight some of these areas:

- Lack of large scale manufacturing capability in the UK:
    - There are two large blade manufacturers in the UK, both owned by foreign companies, who export blades mainly into the European market.
    - No established UK turbine manufacturers
- Lack of availability of test facilities for accelerated testing of large components (e.g. blades) under realistic environmental conditions. This is key especially with the ‘up-scaling’ trend in blade design.

+ to be completed

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ANNEX A

NON-DESTRUCTIVE INSPECTION (NDI)

With information as to the maximum allowable size of defects/damage available, the detection of defects is of key importance. With turbine components increasing in size, especially the blades, challenges exist in developing and adapting suitable NDI techniques for accurate defect detection. For example, a major disadvantage of sandwich constructions used in blade structures is that manufacturing defects cannot always be detected using conventional, commonly used techniques. Rapid inspection is also an issue as blade size and therefore the volume of material to be inspected increases. Typically, visual inspection and tap testing have been routinely used. However, with reductions in design conservatism required if the up-scaling trend is to continue then more accurate techniques are needed. The most promising techniques for inspection are X-ray, ultrasound and shearography. Specific challenges that need to be overcome include:

- Techniques need to be developed that can detect defects located deep within sandwich constructions
- There is insufficient knowledge on the sensitivity and reliability of many NDI techniques when applied to composite materials to enable detectability limits and probabilities of detection to be defined

STRUCTURAL HEALTH MONITORING (SHM)

Effective structural health monitoring of wind turbine components is a challenge as it is inhibited by accessibility, both in terms of being able to effectively inspect structures such as blades due to component geometry, and also due to the often remote locations of the turbines when in-service. This latter aspect has become increasingly significant recently with the trend towards offshore wind farms. Development of on-line, remote sensor systems (e.g. fibre optics, acoustic emission, accelerometers etc.) would be extremely valuable in combating these issues. Blade failures are extremely rare, however turbines and blades are still relatively young and failures have occurred. The long-term performance is of considerable interest, especially with rapidly changing sizes resulting in frequent ‘new’ blades and designs. Essential to defining what performance indicators need to be measured/monitored, is a full understanding of the behaviour of the parent materials and the likely failure modes that may be seen in-service.