New advanced materials will enable the bigger wind turbines of the future

Sørensen, Bent F.; Mikkelsen, Lars P.

Published in:  

Link to article, DOI:  
10.11581/DTU.00000213

Publication date:  
2021

Document Version  
Publisher's PDF, also known as Version of record

Citation (APA):  

General rights  
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Chapter 13

New advanced materials will enable the bigger wind turbines of the future

Bent F. Sørensen and Lars P. Mikkelsen

Materials in a wind turbine rotor blade

It is obvious that material properties set limits to how wind turbines can be designed. More specifically, it is the mechanical properties of materials and interfaces between different materials that limit a wind turbine’s lifetime. These properties set design limits, which, together with costs, the characteristics of processing methods and processability, are the most important factors for load-carrying structures. In this chapter we will focus on materials for wind-turbine rotor blades. On the component level, the two main design criteria are (i) when subjected to the highest wind-induced loads, the wind-turbine rotor blade must never deflect so much that it can hit the tower; and (ii) the blade should last for 20-25 years of operation, during which it will be subjected to cyclic loading. The cyclic loads originate mainly from the blades rotating around the hub and the wind shear. This induces variation in the aerodynamic loads (flap-wise bending) and the direction of the gravitational loads (edge-wise bending). From a materials perspective, therefore, the most important properties are stiffness and avoiding the failure of materials and interfaces under cyclic loading, denoted fatigue failure.

As described in Chapter 12, a rotor blade is a light-weight component made mainly of composite materials. Most modern blades are constructed as an aerodynamic shell incorporating load-carrying spar caps and supported by one or more shear webs. The spar caps are made of composite materials consisting of long, aligned fibre composite materials in a polymer matrix [1]. The aerodynamic shell and the shear webs are typically made as sandwich structures with thin composite layers enclosing a light-weight core material (e.g. balsa wood or polymer foam). There are usually adhesive bond-lines at the leading and trailing edges and between the spar caps and the shear webs. In simple terms, the spar caps and shear webs act like a load-carrying beam [2]. The outer surface of the blade is covered by a paint or gelcoat. The key design challenges are to avoid fatigue damage in the load-carrying fibre composite materials (in-plane fatigue failure or delamination, cracking between layers in composite laminates) and debonding along adhesive bondlines. A particular type of damage is leading-edge erosion induced by rain.

The dominant manufacturing method is vacuum infusion [3,4]. The first step in the manufacturing process is to place fabrics of dry fibres in a mould shaped to give the final blade the desired aerodynamic form. The fibres in the spar caps are nearly all unidirectional, with the fibre direction being oriented along the length of the blade to provide maximum stiffness [4]. After placement of the fibres and the core materials, the mould is sealed off by vacuum bags to which a vacuum is applied, enabling resin in liquid form to be sucked in. The mould is heated up, and resin cures to form a solid matrix material forming an aeroshell with an integrated spar cap. After the aeroshells are consolidated, they are assembled and joined by adhesive bonding. An entire blade can thus be made from a very few large parts, namely an upper and a lower aero-shell and shear webs that are joined by adhesive bonding. This method of manufacture is a highly scalable process: longer blades require a longer mould and more inlets (for resin) and outlets (to create the vacuum), but there are no fundamental limitations as such.
The field of materials for wind-turbine rotor blades is constantly evolving, with new types of fibre and resins (for matrix materials and bondlines) being developed. The primary composite material used for the main spar is polymer matrix composites with glass fibre due to their relatively low cost, high stiffness-to-weight ratio and high fatigue life [4]. More recently, carbon fibres, which have a higher stiffness-to-weight ration but are also more costly, have been used both in ‘hybrid’ composites (mixtures of glass and carbon fibres) [5] and as pre-consolidated carbon-fibre planks manufactured by pultrusion. The main benefit of incorporating carbon fibres as pultruded planks in the spar caps of the wind-turbine blade is their very high degree of stiffness [6], obtained by a high fibre alignment and high fibre volume fraction in comparison with other manufacturing processes [7].

Scientifically, leading-edge erosion is a complicated problem (see Figure 1), which a lot of research is currently concerned to understand better. First, a raindrop impact is a dynamic event that requires advanced models to calculate the evolution of the stress field induced to the materials as a function of time. Secondly, although the mechanical properties (stress-strain laws and failure criteria for materials and interfaces) are likely to be rate-dependent, high-rate properties are not easy to measure. Thirdly, the damage initiation and damage evolution are largely controlled by microscale parameters, such as voids, particles and the mechanical properties of interfaces and layer materials [9].
State of the art and trends in industry and society

As noted earlier (Chapter 1), there are several major trends in wind energy:

- Upscaling (larger and larger turbines)
- Reduction in the cost of energy of off-shore wind
- Digitalization (increased use of larger numerical models and increasing amount of collected data)

Developments in materials research in composite materials can make important contributions toward the continuation of these trends.

Upscaling with bigger and bigger turbines seen from a materials perspective

Figure 2 shows a plot of the weight as a function of blade length for blades made over approximately the last two decades by a large wind turbine manufacturer. Blades up to 80 m in length were made of glass-fibre composites, and blades exceeding 80 m in length are made using glass-carbon hybrid composites. The data clearly show that blade mass increases progressively with blade length. A curve fitted to the data of the blades made of glass-fibre composites shows that the blade mass scales with the blade length at a power of about 2.25. Note that the two longest blades, which are made of hybrid composites, have a weight about 20% lower than the trend curve of glass fibre-based composites.

Figure 2. Blade weight is shown as a function of blade length (data from LM Wind Power). A curve is fitted to the blade data for blades smaller than 80 m that are made of glass-fibre composites.

The progressively increasing blade mass with increasing blade length has important consequences. First, given the current manufacturing approach to make blades in big parts, each part will include a large amount of material, and it will not be possible to make blade parts free of manufacturing-induced defects. And since a large part represents a large value (e.g. in terms of materials costs), it is not attractive to discard parts of blades or entire blades with severe manufacturing defects. As a result, the effects of manufacturing defects become increasingly important. Second, longer and heavier blades are more difficult to transport on roads. This issue could be addressed by making blades in parts to be joined after transportation (‘split blades’, see Chapter 8).

Materials research can contribute to reducing the effects of manufacturing defects. Since damage mostly takes place in terms of crack growth along interfaces (debonding along bond-lines and delamination in laminates), the effects of manufacturing defects can...
be reduced by novel damage-tolerant composite materials that possess a significant increase in fracture resistance with crack length (R-curve behaviour). It has been shown experimentally [10] and theoretically [11,12] that it is possible to multiply the fracture resistance by the generation of multiple cracks with fibre bridging. More research is needed to bring this approach to maturity, both in terms of materials characteristics and materials models (in terms of cohesive laws) and to establish and demonstrate design methods that use such damage-tolerant materials. Potentially, blade manufacturing can be made faster and more reproducible by automatization, for example by the use of robots for the placement of fibre fabrics and carbon fibre planks, as well as application of adhesives for bondlines. Complicated geometries could be manufactured by 3D printing.

Manufacturing blades in parts introduces a new critical problem: to make reliable joints of major load-carrying parts (spar caps). This will be a major challenge for materials, design, manufacturing and maintenance. Clearly, from a materials perspective, there is a great potential for research into material developments for reliable, strong and fatigue-resistant joints of the load-carrying spar.

Overall, the upscaling also leads to changes in the way composite structures fail. Scaling laws will show that the driving force for crack growth (the energy release rate) increases with increasing dimensions [13] when all other non-dimensional parameters are held constant. Then, for instance, in comparison with in-plane fatigue, which is usually designed using a maximum allowable strain value, delamination and debonding become the main damage types for larger structures.

Another trend is related to sustainability (see also Chapter 15). Wind turbines, of course, make ‘green’ electricity, i.e. without producing significant CO₂, but the materials currently used in blades are not sustainable or recyclable. One long-term goal must therefore be to develop sustainable composite materials for blades. Biobased fibres such as hemp and flax have a stiffness-to-weight ratio comparable to glass fibre [14] and are renewable. Therefore, they have the potential for use in structures designed for high stiffness and low weight. However, they also have lower tensile strengths and greater variation than conventional glass- and carbon-fibres [15]. They can be susceptible to water uptake, which can induce dimensional changes (swelling) [16]. This means that they cannot simply replace glass- and carbon-fibres; their mechanical properties and environmental resistance should be improved first.

In summary, the upscaling will continue in the coming decades, and research can contribute to this process through:

- The development of improved, more damage-tolerant materials (composites and adhesives)
- The development of improved manufacturing procedures and design methods for incorporating pre-cast carbon-fibre parts into blades
- The development of materials and interfaces for joints of major load-carrying parts like main spars (split blades)
- The development of bio-based fibres and resins with improved mechanical properties

**Reduction of the cost of energy from offshore wind: a materials perspective**

Making turbines (and thus blades) bigger – the ongoing upscaling mentioned above – has been one of the main reasons for the relatively fast decrease in the cost of energy as described in Chapter 1. For offshore wind, maintenance costs are relative high, since manual inspection is costly, as also discussed in Chapter 1.

An approach to reducing the need for manual inspections of turbine blades in the future could be to equip blades with sensors (e.g. strain sensors and acoustic emission sensors) and only inspect the blades when the sensors in it give off alarms [17], i.e., avoid regular inspections and thereby reduce inspection costs. However, before this becomes an accepted practice, the robustness of the sensors needs to be tested, and the sensors’ failure rates must be low.

The use of drones and robots can also reduce the need for manual inspections and thus save inspection costs. Inspection by drones is valuable for the detection of visual damage (e.g. leading-edge erosion), but non-visible (‘hidden’) damage such like delamination in the spar caps and debonds are unlikely to be found. Non-visible damage can, however, be found by advanced inspections (non-destructive testing, or NDT) methods such as ultrasound scanning. The development of robots that can crawl along the outside of blades and use ultrasound scanners is underway [18].

Having found damage, the key questions are whether the damage needs to be repaired or not, and, if
a repair is needed, how should it be done and how fast? The criticality of the damage can be assessed using fracture mechanics models of the damage. One example, namely the growth and arrest of a delamination crack from a ply-drop, has been analysed by a fracture mechanics model [13], but more research is needed for other types of damage. As mentioned earlier, the use of more damage-tolerant materials could reduce the need for repairs. Finally, doing a high-quality repair in the field is challenging. Much more research is needed to ensure that repairs to load-carrying parts are of high quality and reproducible, which could include non-destructive inspection of the repaired area. New adhesive materials and new surface treatments prior to bonding could also lead to better repairs.

A second approach to reducing the cost of energy is to use the turbines beyond their originally designed life time of 20-25 years. They would then produce electricity for a longer time period. For example, assume that 1% of all blades are anticipated to fail within a planned operational time of twenty years. Then, the remaining 99% of the blades have a life longer than twenty years. Imagine further that it is possible to do an inspection of all blades before they approach a service life of twenty years, thus identifying and taking out of service the 1% of blades with severe damage. The remaining 99% of the blades could then be used in service for, say, an additional ten years of electricity production. Achieving this aim requires research to establish the fundamental relationships between damage type and the blade's size and residual life [19].

In summary, there is a need for research in the following areas:

- Precise determination of what the damage is in a given blade (‘understand’ output from sensors and non-destructive testing)
- Models for precise predictions of how fast a particular type of damage will grow
- Reduce the need for repairs by making more damage-tolerant materials in blades so repairs are not needed so frequently
- Develop precise criteria for when repairs are needed and when they are not needed
- Establish scientific-based methodology for performing high-quality repairs and post-repair quality control of repairs

**Digitalization**

The adoption of a ‘digital twin’ is clearly applicable for wind-turbine rotor blades (see also Chapter 12). During the manufacturing stage, a number of process parameters (temperature, pressure, etc.) can be recorded. Most large blades are subjected to ultrasound scanning as part of their quality control after manufacturing. The primary purpose is to identify manufacturing defects that should be repaired before the blade is allowed to be installed on a turbine. However, such scanning data are also valuable later if the blade is subsequently scanned for damage detection after being mounted on a turbine. In the future, more measurements, e.g. of the blade geometry of individual blades, will allow a more detailed description of each blade. Furthermore, the blades can have built-in sensors for load, deformation (strains) and structural health monitoring (e.g., acoustic emission sensors) that can locate where damage growth within the blade is taking place [17]. All these data (processing conditions, manufacturing defects, geometry, load history, damage) can be combined into an individual 3D model of each blade.

At the blade scale (see more in Chapter 12), a digital twin would imply an individual model for each blade (the ‘physical’ twin), such that the damage state of each individual blade would be approached in a deterministic way. Based on the damage identified by sensors and scanning, the residual life would be predicted using models of damage growth. For future generations of blades, design philosophy could shift to a damage-tolerant approach, potentially leading to lighter designs than the current ‘no-damage’ design approach. It is thus not sufficient to have a 3D reproduction of each real blade. Physical-based models are required to simulate processing for the prediction of residual stresses (for example by cure kinetics) and predictions of damage growth to predict the residual life of the individual blade. Modelling each blade by taking into account the individual characteristics of its manufacture, defects and damage, and loading history will create a more deterministic approach to the variation in the residual life of turbine blades, thus reducing large uncertainties. It could become possible to utilize the life of each blade, using most blades for a significantly longer time than the original design life.

The concept of a digital twin can also extend to the microscale of composite materials. Precise digital models copying a real microstructure are already facilitating the investigation of materials and test specimens. In order to build precise numerical finite-element models of composite materials, efficient micro-structural segmentation tools are required. Figure 3 shows a full
3D cross-section obtained by X-ray computed tomography of a test specimen. The scanned volume, which contains more than 100,000 fibres, is segmented into local material orientation using such a segmentation tool [6]. Together with the local fibre volume fraction distribution [20], this is then mapped on to a finite element model of the component [21], based on which, for example, the distribution of local stress during the actual loading can be predicted.

The vision rests on several research challenges. One basis should be established for structural health monitoring (from sensor data to life prediction), including the monitoring and modelling of processing and damage growth. Furthermore, the accuracy of the model predictions should be investigated and documented, e.g. by well-controlled tests on 'elements', before being brought into the blades. From the materials perspective, the required research to achieve the digital twin are at the microscale and the macro/laminate and element scales:

- Models of residual stresses in composites and bond-lines
- More accurate materials laws enable better use of materials (more complicated composite materials and adhesives require new and more precise material models)
- Improved testing methods for the mechanical characterization of advanced composite materials must be developed
- Models for predicting how fast different damage types will grow

Discussion: trends in research

Microscale characterization of composite materials

In this section, we summarize the major trends in the research community. Materials science has always progressed through a combination of experimental and modelling work.

Probably the most important development in experimental studies of composite materials is the development of lab-based X-ray computed tomography (XCT) with a resolution of 1 micrometre or less. This has enabled investigations of, for example, fatigue damage in 3D in composite materials for wind turbine rotor blades [22]. It was found that failures of fibres in the load direction occur in a connected mode, i.e., there was a sharp 'front' separating a region of failed fibres from unbroken fibres (see Figure 4). This suggests that fibre failure occurred at the damage front being induced by the most recent broken fibre. This has inspired a micromechanical model for the prediction of fatigue damage and fatigue life from basic properties of fibres, matrixes and the fibre–matrix interface [23]. In order to use such predictive models in connection with the development of improved composite materials, it is necessary to characterize the mechanical properties of the microscale, such as the debonding and sliding friction of the fibre–matrix interface under static and cyclic loading. Thus, the mechanics characterization of fibre composites has moved to the microscale. In the future, there will be opportunities for XCT studies at much higher spatial and temporal resolutions, such as the X-ray synchro-
tron facility Max IV in Lund, Sweden. The higher resolutions can make the difference between qualitative observations of mechanisms and quantitative in-situ measurements of microscale parameters.

**Computational modelling**
In parallel with technical advances in XCT, the computational capabilities continue to increase, for example, by using large computer clusters. This will enable larger, more detailed and more accurate numerical models (e.g. by the finite element method), of damage at both the microscale (micromechanical models) and the macroscale (e.g. test specimens and elements tests) [3].

It is emphasized that the macroscale material properties are controlled at the microscale (properties of fibres, matrixes, interfaces and fibre distribution and architecture). However, models of, for example, blade damage must be made on a coarser scale, using ‘effective’ composite properties (e.g. laminate theory-based). It remains a challenge to establish consistent connections between models across length scales with different materials laws, particularly for damage and failure.

**Regulations**
Finally, it should be noted that, since wind energy is not a very regulated application area in terms of materials and component testing – unlike, for instance, aerospace – it is relatively cheap and fast to develop and to introduce new composite materials in rotor blades. This creates a quite agile environment for the design and manufacture of future wind-turbine rotor blades.

**Summary and conclusions**
Research into composite materials for wind-turbine rotor blades contributes critically to the development of very large wind-turbine rotor blades in the future in at least two ways. First, increasing the depth of knowledge of the behaviour of current materials will lead to better materials models and thereby allow future designs that utilize materials and interfaces close to their limits. Second, increasing understanding of how the life time of blades is controlled by basic materials properties at the microscale and how processing conditions influence these basic properties will enable the development of new composite materials with improved properties.

![Image](image-url) **Figure 4.** Fatigue damage observed in XCT in a specimen subjected to cyclic tensile loading in the fibre direction. Based on multiple scout and high-magnification scans of the same region in a specimen subjected to cyclic tensile-tensile loads, the evolution in the damage zone in the form of fibre failures are shown (a) after 47300 load cycles, (b) after 57300 cycles and (c) after 57300 cycles (after Jespersen and Mikkelsen [22]).
Chapter 13 – New advanced materials will enable the bigger wind turbines of the future

References


