# Wind rotor blade materials technology

**During the past three decades, there has been a rapid growth in the use of wind turbines for electric power generation. Although many small wind turbines in the kW range were in use during the first half of the twentieth century, they were primarily used to provide power to farms in rural regions of Europe and the United States.**

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These early wind turbines were manufactured with wooden or steel blades. The first MW scale wind turbine designed for electric power generation, the Smith-Putnam wind turbine, was installed in 1941 in Vermont (USA).[1] This wind turbine, with a 53 metre rotor constructed using two steel blades, had a potential power output of 1.25 MW. However, the bending stresses developed in the massive steel blades were exceedingly high and, as a consequence, fatigue failure near the blade root occurred in 1945 after only a few hundred hours of intermittent operation. Although the extensive use of steel for such large blades was not practical in an engineering sense, the well documented failure of this wind turbine is generally credited to pointing the way towards the incorporation of lighter weight materials into turbine blade design and greater emphasis on structural design. In particular, this early failure showed engineers that the very significant loads imposed on rotor blades and fatigue failure were critical design considerations for large horizontal axis wind turbines.

In the 1950s, a comparatively well thought out wind turbine, the so-called Gedser design, was developed in Denmark for electric power generation. The Gedser design, with a 24 metre rotor, incorporated three blades, tied together by a truss structure. The blades utilised a steel spar with a lower mass aluminium aeroshell that was supported by wood ribs. Although not as large as the earlier US wind turbine, the Gedser design proved to be far more reliable (for a 1950s era design) and was successfully used until retiring in the 1960s. However, the early development of wind energy in Europe and the US did not make significant progress until the 1970s, when political events such as the oil embargo provided the catalyst for forward looking governments and young entrepreneurs to examine ways to diversify energy sources. In 1976, the Danish Department of Commerce worked out an energy plan in which the main topic was to spread-out the Danish energy production across multiple resources. Among these resources, wind energy was mentioned for the first time in public strategies. One inspiration for this plan was that, in 1976, a group of students and teachers at the Tvind High School in Denmark had started construction of a large wind turbine (54 metre rotor diameter and 53 metre tower, maximum power 960 kW) for power generation. In the following years, the Danish Department of Commerce supported a Windmill Project with the aim to build two 600 kW wind turbines. The site for these two wind turbines was close to the town of Nibe and by 1980, the turbines were running. For many, this project is considered the beginning of the large-scale wind energy development in Europe, as well as global wind energy development. From the 1970s up to today, the size and power output of wind turbines has increased dramatically, with large wind turbines manufactured in 2008 typically producing 1.5 MW to 3 MW, and up to 5 MW for the largest wind turbines that are being marketed by several companies in Europe.

With the increasing worldwide energy demand, which has led to high oil prices and a depletion of oil reserves, as well as concern about $CO_2$, the need to develop clean and sustainable energy resources is critical. Currently, electric power production by wind energy provides less than two per cent of the world demand. However, in many European countries, this number is much higher; in Denmark, wind energy contributes more than 22 per cent of the total electric power production. The focus of this article is to highlight recent developments in rotor blade design and manufacturing and to describe the materials used in blade construction. New methods for testing and acquiring material data for wind turbine blades are also briefly addressed. The following reviews and references have been the inspiration for this article.[2,3,4,5,6]

## Current wind turbine blade design

The demand for larger wind turbines with very high reliability is one of the main driving forces for current research and development in blade design. The blades for current generation wind turbines are typically designed for a fatigue life in excess of 20 years (over $10^9$ cycles). In addition to low mass and fatigue resistance, stiffness is an important design consideration for blades. The blades must provide adequate stiffness to prevent contact with the tower during severe wind gusts.

Longer blades give more power and are more efficient to utilise, from manufacturing and financial viewpoints. Today, the longest blades, with a length of 61.5 metres, are manufactured by LM Glasfiber A/S for use on 5 MW wind turbines (a 5 MW wind turbine produces enough power for approximately 4500 homes). These blades were first installed in 2005 on a RePower 5 MW test turbine in Brunsbüttes, Germany and in 2006-2007 on two RePower demonstrator turbines placed in the North Sea, 15 miles off the East coast of Scotland near the Beatrice Oil Field.[7] Research has until now not found an optimisation level with respect to the length of rotor blades, and only material performance, the production technology and the transportation and building infrastructures claim a limitation on blade length.

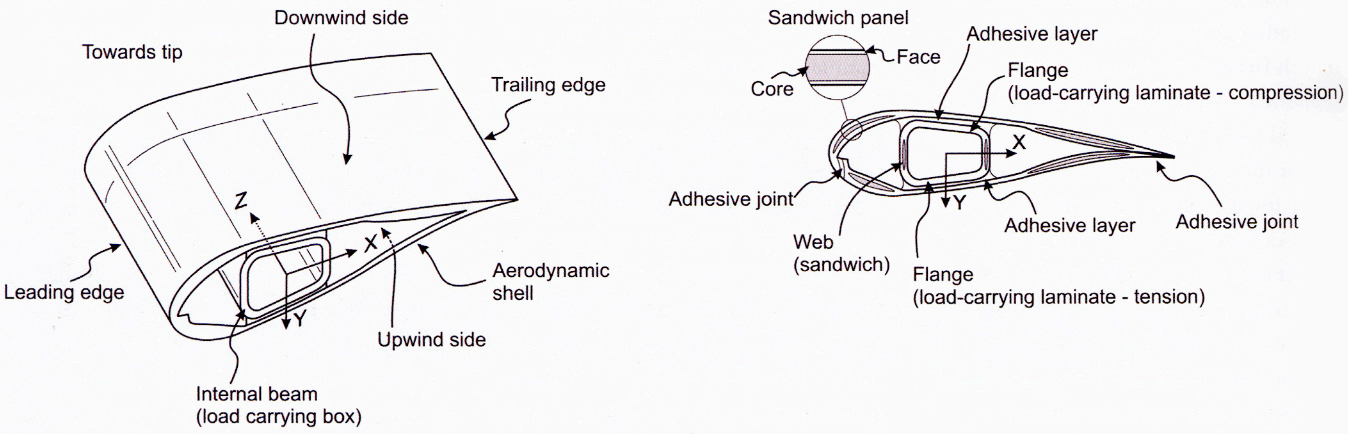
Because of their size, and the need for long-term reliable operation over a period of 20 - 25 years, wind turbine rotor blades present a very challenging engineering design, material utilisation and manufacturing problem. The dominate design used for horizontal axis wind turbines consists of a rotor with three blades. A three blade rotor is primarily chosen to give stability and good balance during rotation, avoiding skew loading of the main bearings and the main shaft driving the gearbox and generator used in most wind turbine installations.

The modern wind turbine blade is a complicated aerodynamic and engineering structure. As with aircraft wings, aerodynamic forces created by the movement of air past the surface of a wind turbine blade create lift and allow energy to be extracted from the wind. However, a wind turbine blade has a far more complex geometry, and is subjected to much different structural loads than those encountered for aircraft wings. The complex geometry and loading modes experienced by wind turbine blades and rotors, and the significantly larger number of fatigue cycles compared to aircraft wings (and helicopter blades), places tremendous demands on the materials used. The requirement to keep mass down with large turbine rotors, and the need to reduce costs without compromising reliability has led to the innovative use of both advanced polymeric composites and wood-composite hybrids.

A large rotor blade typically consists of a thick walled circular root section with metal bushings with bolts or studs for mounting the blade to the rotor hub. This root section is integrated into a continuously tapered longitudinal beam, the spar, which provides the stiffness and strength required to carry the wind load and the weight of the blade. Around the spar, the two aerodynamic-shaped shells, the suction side and the pressure side, form an optimised aerodynamic wing (Figure 1a, see page 38). The outer shells of the blade meet at the leading edge and the trailing edge. Inserted webs take up the torsional twist of the blade and help stabilise the blade against bending, shear loads and global buckling.

Several types of spar design are typically used. One design, shown in Figure 1a,b (page 38), consists of a separate spar (in the example shown, in the shape of a box beam). In a very general sense, the top and bottom sides of the spar react to longitudinal loads and the sides of the spar react to shear loads. The aerodynamic shaped shells (aeroshell) that comprise the exposed blade surface are typically adhesively bonded separately to the beam. This construction can enable a lighter design but with a more expensive fabrication cost. A second design (Figure 2, see page 39), which is probably the most widespread, integrates the aeroshell and the spar, and is constructed with one or more shear webs to take up and transfer shear loads.

Wind turbine blades used for large horizontal axis wind turbines are typically constructed using polymeric matrix composites and sandwich structures with low density polymer foam or balsa wood cores. Although most blades utilise glass fibre reinforcement, some of the more recent blade designs also incorporate carbon fibres; in particular for the spars. The primary motivation for the use of carbon fibres is their lower density, higher stiffness and higher tensile strength relative to glass fibres. With larger rotor diameters, it is expected that there will be an increased utilisation of carbon




**Figures 1a and b. (a) Cross-sections through a composite wind turbine blade that incorporates a box-shaped beam spar. (b) The aerodynamic shell is usually constructed of polymeric composites and is reinforced against buckling by using sandwich structures with balsa or PVC foam cores. The spar is manufactured using a glass or carbon reinforced polymeric composite and may contain regions with sandwich structures (PVC foam or balsa). Also shown are locations for adhesive joints which are utilised in the majority of large wind turbine blades. From Sørensen et al [8]**

fibres in the spars and selected regions of the aeroshell.

### Manufacturing technologies

Composite technology is well known in the ship building industry and it was a natural development for the ship building industry to become involved in early blade manufacturing. The earliest blades were often produced by placing glass-fibre reinforcements in open moulds and impregnating the fibres with polyester resin, using paint brushes and rollers. The aerodynamic shells were then adhesively bonded to the spars. As the blades became larger, webs were adhesively bonded between the two sides. Today, because of environmental and quality concerns, the use of open mould technology to manufacture blades has decreased significantly, and the majority of larger blades are made by vacuum assisted resin transfer moulding (VARTM). This approach consists of placing dry fibres in a mould, encapsulating and sealing off the fibre package, injecting the liquid resin into the fibres package and curing the component. The most important issue for this process is to ensure that all fibres are thoroughly wetted by the resin; in other words, there should be no areas with dry fibres in the final product. The VARTM techniques are used in two different concepts. In the first and most widely used method, the two halves of the blade are infused in separate moulds and subsequently assembled by adhesively joining the webs and the leading and the trailing edges. In another concept, developed by Siemens Wind Power (IntegralBlade® process), the fibres for the entire blade are placed inside a mould cavity and the resin is infused to complete the blade in one pass; this eliminates the additional processing required with adhesive bonding of blade sections. Other manufacturers, such as Vestas Wind Systems and Gamesa, utilise pre-preg technology in blade production.

### Materials

Blades for small local turbines can be made from metal, solid wood, solid polymers, or composites.

Larger rotor blades are typically made of composites consisting of fibre-reinforced plastics (resins) or wood. The materials are typically made from E-glass and carbon fibres impregnated with a thermosetting resin (polyester, vinylester or epoxy). Blades made of wood are normally impregnated with epoxy and reinforced with carbon fibres in selected regions.

The main spars are primarily constructed with unidirectional laminates to provide optimal stiffness and strength (compression and tensile) in the length direction of the blade. The aeroshell is typically made from sandwich constructions, in which the skin layers are either a biaxial (±45°) lay-up to transfer shear loads, or a triaxial (0°, 90°, ±45°) lay-up to react to multiaxial loadings. The fibre lay-ups are injected primarily with thermosetting polymers using the above mentioned manufacturing methods. The resins are low-viscosity epoxy, polyester or vinylester, which can be used for manufacture by the VARTM process. Until now, only a few prototype blades are based on thermoplastic resins.[9]

In addition to polymeric composites, other materials such as wood can be used for large wind turbine blades. For example, Vestas currently manufactures up to 50 metre long blades using birch reinforced with epoxy and carbon fibres. These wood-based blades have a lower mass than comparable size blades manufactured from polymer-based fibreglass composites. In the rapidly changing, highly competitive field of wind energy, other material combinations are also being explored for use in large horizontal axis wind turbines. For example, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, in collaboration with the International Centre for Bamboo and Rattan (ICBR) in China, is currently involved in research to develop and characterise a new generation of bamboo composites for horizontal axis wind turbines.[10] A distinct advantage of bamboo, compared to the use of wood such as birch, is the rapid growth rate of many bamboo species, where plants can reach harvestable size in as little as four to six years. The use of bamboo also has many environmental advantages, including a high carbon sequestering capacity.

As with other bio-based composites[11]

being developed for structural applications, bamboo and bamboo-based composites offer the potential for improved recycling compared to polymeric-matrix based blades.

## Materials testing and blade qualification

Wind turbine blades are designed toward stiffness and fatigue, and the composite materials required for the blades must undergo extensive mechanical testing, in particular in regards to fatigue loading of the blade materials and the adhesive joints that are commonly used in blade construction. The durability of post-manufacturing or in-service repairs must also be evaluated through mechanical testing.

For the composites used in wind turbine blades, material properties depend strongly on the fibre architecture and volume fraction, the polymer matrix chosen and the processing route. Stiffness, static strength and fatigue properties are typically measured by experiments performed using standardised test coupons and by the testing of sub-level components and full size blades. Strength and stiffness are typically determined under quasi-static loading, with fatigue testing performed under varying loading conditions. Properties are measured under tensile loads, compressive loads, shear loads or combinations of these under multiaxial loading modes. The data obtained by both coupon and full-scale blade testing is used to qualify the materials and to ascertain that the materials fulfil the design demands originated in the aero-elastic modelling of the blades under expected wind loads. Both coupon testing and subsequent full scale testing used for blade qualification can take many months to complete, and represent a considerable part of the cost associated with the development of new blades.

Various levels of testing are required for the qualification of new materials and for certification of new blade designs. Guidelines and standards, which have been developed primarily in Europe,

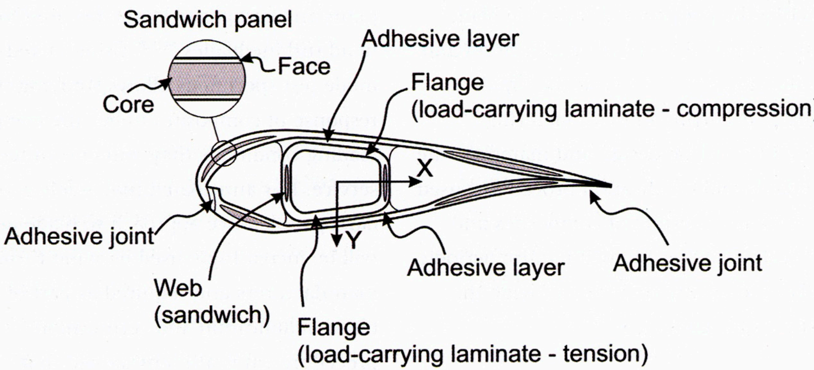



**Figure 2. Cross-section through a composite wind turbine blade incorporating an integral spar. The primary loading types and primary fiber lay-up (unidirectional or multidirectional) used to react to the loads are shown along with typical locations where sandwich structures are used to increase stiffnes and provide resistance to compressive buckling. Sandwich structures are sometimes also used in the spar. From Nijssen[5]**

describe the coupon and full-scale blade testing required for blade qualification and certification.[12,13,14,15,16,17] With the rapid changes occurring in manufacturing procedures, blade design and materials, the standards and certification procedures used for laboratory testing of composites and full-scale blade testing will require periodic updates to ensure that they provide the best possible guidance.

### A need for improved engineering-based analysis tools

In addition to the development of new materials and design approaches to improve blade reliability and reduce costs, the wind turbine industry is devoting considerable resources to improving the accuracy of calculations used to determine the structural loading of blades and to predict the effect of multiaxis cyclic loading on blade reliability. Independent of manufacturing approach, manufacturing-related flaws and in-service damage and crack growth between composite plies (delaminations) or along adhesive joints are possible and need to be accounted for both in the initial design stages and during turbine operation. Recently, there has been an increasing understanding by wind turbine manufacturers of the need to adopt defect and damage tolerance design approaches, where allowable sizes and growth rates of defects are determined for a given material and blade design. Damage tolerance approaches, which are based upon fracture mechanics, involve determining the growth rate and the maximum allowable defect size that can exist for the safe operation of a structure. With this information, the defects or in-service damage can be monitored, and maintenance and repairs can be made before the damage reaches a level that could potentially cause failure. These approaches have been used extensively in the aircraft industry, primarily for metallic components, but are being further developed for use with composite wind turbine structures. As a step in this direction, a generalised mixed-mode specimen and testing methodology was recently developed at Risø DTU to more accurately characterise the fracture resistance and defect tolerance of adhesive joints and composite laminates used for wind turbine blades.[18,19,20] Using mixed-mode test specimens allows studying the response of composites under the complex loading conditions they will encounter in service. It is anticipated that a defect and damage tolerance approach to blade design will be increasingly used by wind turbine manufacturers and required as part of blade qualification and certification procedures. It is also envisioned that structural health monitoring, where sensors in blades are used to determine both the loading history and possible damage development, will become more commonplace in the future. When coupled with an improved understanding of the growth rate of defects in blades, structural health monitoring will further enhance reliability and reduce turbine downtime for blade inspections.

### Conclusions

The field of wind energy is rapidly growing and has become very competitive. In the long term, companies that can consistently provide wind turbines with the greatest reliability at a competitive cost will be the most successful. This requires increasing innovation in blade design, material selection and manufacturing procedures. In addition to the development of new materials and improved quality control, it is important to further develop and utilise defect and damage tolerant approaches in blade design and as part of structural health monitoring and maintenance procedures.

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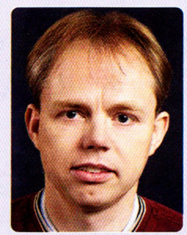

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