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Review Article

Trends in the Design, Manufacture and Evaluation of Wind Turbine Blades

Paul S. Veers,*Thomas D. Ashwill, Herbert J. Sutherland, Daniel L. Laird and Donald W. Lobitz, Wind Energy Technology Department, Sandia National Laboratories, Albuquerque, New Mexico, USA
Dayton A. Griffin, Global Energy Concepts, LLC, Kirkland, Washington, USA
John F. Mandell, Department of Chemical Engineering, Montana State University, Bozeman, Montana, USA
Walter D. Musial, National Wind Technology Center, National Renewable Energy Laboratory, Golden, Colorado, USA
Kevin Jackson, Dynamic Design Engineering, Inc, Davis, California, USA
Michael Zuteck, MDZ Consulting, Clear Lake Shores, Texas, USA
Antonio Miravete, Composites Engineering and Applications Center, University of Houston, Houston, Texas, USA
Stephen W. Tsai, Department of Aeronautics and Astronautics, Stanford University, Stanford, California, USA
James L. Richmond, MDEC, Newbury Park, California, USA

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Wind turbine blades continue to be the target of technological improvements by the use of better designs, materials, manufacturing, analysis and testing. As the size of turbines has grown over the past decade, designers have restrained the associated growth in blade weight to less than would have been possible through simple scaling-up of past approaches. These past improvements are briefly summarized. Manufacturing trends and design drivers are presented, as are the ways these design drivers have changed. Issues related to blade material choices are described, first for the currently dominant glass fibre technology and then for the potential use of carbon fibres. Some possible directions for future blade design options are presented, namely new planforms, aerofoils and aeroelastic tailoring. The significant improvement in sophistication of stress analysis and full-scale blade testing are also discussed. Copyright © 2003 John Wiley & Sons, Ltd.

Introduction

Both the size of wind turbine blades and the volume of commercial production have been steadily increasing to the point where typical peak output is now between 1 and 3 MW. Rotors of up to 80 m diameter are currently in production, and several turbine developers have prototypes with diameters in the 90–120 m range. It is estimated that over 5×10^7 kg of finished fibreglass laminate was used for the production of wind turbine blades in the year 2001, and that worldwide production volume will increase for the next several years (calculations based on the global wind energy market predictions of Reference 1). The growth in blade length and turbine size tends to make the blades a larger proportion of total system cost. Moreover, since the blades are one of the few wind turbine-specific components in the system, improvements in blade design, manufacturing and performance have been a primary target of research and development.

* Correspondence to: Paul S. Veers, Wind Energy Technology Department, Sandia National Laboratories, Albuquerque, New Mexico, USA. E-mail: psveers@sandia.gov

The growth trends and associated improvements in blade design and manufacturing have been produced by years of manufacturing experience as well as industry research and development. There has also been substantial research under government-funded programmes in both Europe and the United States. Investigations have focused on alternative blade design and material technologies. Technical challenges include restraining weight growth, improving power performance and mitigating loads, facilitating transportation, designing for fatigue cycles of the order of 10^8–10^9 and reducing design margins.

Because the blades themselves represent only 10%–15% of system capital cost, the ability to reduce cost of energy (COE) through improvements in blade cost are constrained. However, if an innovative blade design can result in a 10%–20% decrease in loading, substantial savings may be realized for several major components such as the tower, drive train and blades themselves. A modest cost premium in the blades may still result in improved COE as the result of other system economies.

Design and Manufacturing

Historic Blade Structure and Manufacturing Methods

Figure 1 is a section view illustrating a typical structural architecture for wind turbine blades. The spar cap is a relatively thick laminate with primarily unidirectional fibres to carry the flapwise bending loads. Blade skins are typically double-bias or triaxial fibreglass, with balsa or foam core used as needed for buckling resistance. Historically, wind turbine blades have been constructed using either all-fibreglass laminate or, in a few cases, fibreglass construction with selective use of carbon for local reinforcement. For blade sizes up to 30 m the most common manufacturing approach has been an open mould with wet lay-up. The most notable exception to that approach is Vestas Wind Systems, which has a long history of using prepreg fibreglass in its blade manufacturing process.

Growth Trends for Blade Mass

Figure 2 shows a plot of blade mass versus rotor radius for turbine sizes ranging from 750 kW to 4·5 MW. A simple scaling of similar blades would imply that the mass grows as a cubic power of radius. However, the trend line in Figure 2 indicates that the growth in blade mass with size has maintained a significantly lower exponent ($R^{2.3}$ for the data set shown). Inspection of Figure 2 shows a relatively large degree of scatter in the blade mass data. This is primarily attributed to two causes, namely the materials/manufacturing approach and the design criteria for the blades.

Additional insight is obtained by investigating mass growth trends for a particular manufacturer at a fixed design class. For the Vestas blades the mass difference between the V66 and V80 scales as $R^{2.7}$. This value is

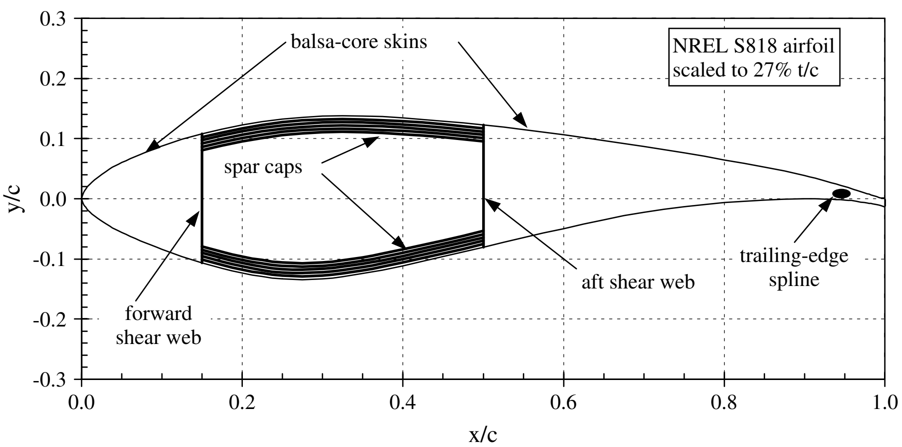

Figure 1. Common structural architecture for wind turbine blade

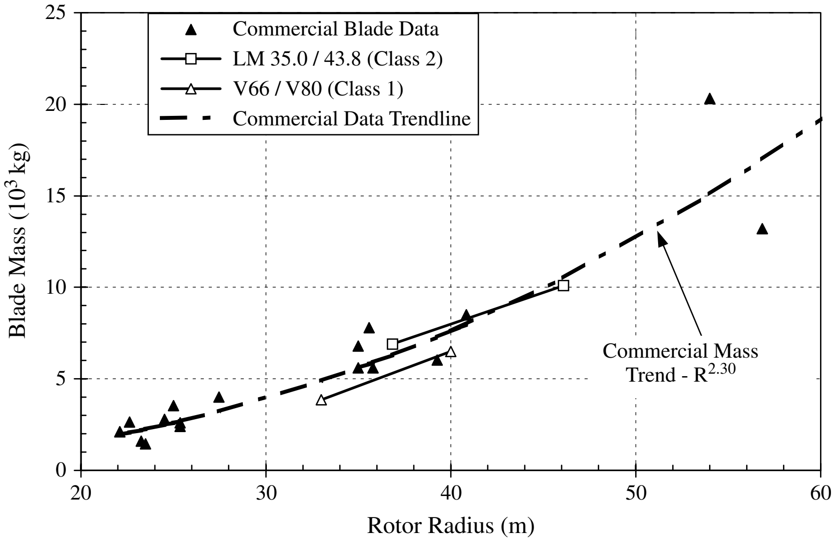

Figure 2. Mass growth for commercial MW-scale blade designs (primarily fibreglass)

much closer to the cubic scaling relationship. Because the V66 is already a lightweight design using relatively high-performing prepreg material, limited opportunity for additional weight savings from material performance remained for the larger blade (assuming no change in fibre type). The fact that the growth rate was held to a lower-than-cubic value is likely attributable to the use of thicker aerofoil sections. In contrast, the mass difference between the LM 35·0 and LM 43·8, at IEC Class 2, scales as $R^{1\cdot 7}$, which is substantially lower than the overall industry trend. The implication is that LM has taken advantage of significant improvement in material performance between these designs, in conjunction with the use of thicker aerofoil sections.

Reference 2 provides a detailed discussion of blade mass growth trends for commercial blades and the underlying evolution of aerodynamic/structural designs, materials and manufacturing processes. A major contributor to restraining mass growth in the data shown is the use of aerofoils with higher thickness-to-chord (*t*/*c*) ratios in the larger blades. Over the 25–50 m size range, increases in Reynolds number have allowed the use of higher-*t*/*c* foils with minimal adverse effects on aerodynamic performance. Structural efficiency may be further improved by the use of thicker aerofoils, but the trade-offs in aerodynamic performance must also be considered.[3]

The data presented in Figure 2 are limited to blades that are primarily fibreglass (either all glass or with selective use of carbon). Blades with carbon spars such as the Vestas V90 and DeWind 40 m are not included in the trend line. Material-related contributions to the restrained mass growth are attributed mainly to aspects such as improved laminate consistency, better fibre alignment and increased fibre volume fractions.

General Manufacturing Trends

A large number of turbine system manufacturers are currently moving towards in-house production of their own blades, and in doing so are using diverse materials and manufacturing methods. Nordex and GE Wind have both built blades in the 35–50 m length range using hand lay-up of primarily fibreglass structure in open-mould wet processes. NEG Micon is building 40 m blades with carbon augmented woodsolepoxy. TPI Composites is manufacturing 30 m blades using its SCRIMP™ vacuum-assisted resin transfer moulding (VARTM) process. Bonus has one of the more novel approaches in current use for large blades, where blades of length 30 m and greater are being produced using a dry preform with a single-shot infusion, eliminating the need for secondary bonding of the blade halves.

Some recent commercial blades now incorporate carbon fibre in the load-bearing spar structure. New Vestas V90 blades use carbon fibre spars. DeWind is using an innovative approach to produce 40 m carbon/fibreglass hybrid blades. In that process the spar cap is produced using prepreg carbon. After curing, the spar caps are then placed into a preform and infused into the fibreglass blade skins.

Design Drivers and Constraints for Large Blades

For conventional fibreglass construction, manufacturing costs are in the range of \$9–\$11 kg^{-1} (\$4–\$5 lb^{-1}) for finished blade structure.[2] Total system cost of energy (COE) is the primary figure of merit for evaluating any change in turbine design and manufacturing. For reference, blade costs typically represent 10%–15% of installed capital cost for the turbine system.[4] If alternative materials and processes are considered for turbine blades, cost increases must be offset by improvements in other system attributes such as power performance and/or loads.

Very few fundamental barriers have been identified for the cost-effective scaling of historic commercial blade designs and manufacturing methods over the size range of 80–120 m diameter.[5] The most substantial constraint is the transportation cost, which rises sharply for lengths above 46 m (150 ft) and becomes prohibitive for long haul of blades in excess of 61 m (200 ft).

In terms of manufacturing, it is expected that environmental considerations will prohibit the continued use of processes with high emissions of volatile gases, such as the open-mould wet lay-up that has been the wind industry norm. Another manufacturing challenge for large blades is bonding compounds. As blade sizes increase, it is natural for the gaps between fitted and bonded parts to grow as well. However, the bonding materials used for smaller blades do not scale well to increasing gap sizes, and blade tooling and production costs for large blades increase rapidly as dimensional tolerances decrease.

Gravity-induced loading is a design consideration but not an absolute constraint to scaling-up of the current conventional materials and blade designs. Nonetheless, materials and designs that reduce blade weight may be of benefit for MW-scale blades, as this would reduce the need for reinforcements in the regions of the trailing edge and blade root transition to accommodate the gravity-induced edgewise fatigue loads.

Changing Design Drivers

In 1992, blades were being designed for rotors 40 m in diameter on 500 kW turbines. Current designs feature 100 m rotors for turbines rated in the 3 MW range. As discussed above, the increase in rotor size has not been accompanied by a cubic increase in blade weight. The relative reduction in blade weight has been achieved by designs that push the design margins for blade materials and the blade structure. To achieve a reliable design within these reduced design margins, a new degree of sophistication had to be introduced into the design process. The analyses of the loads have significantly increased accuracy, failure analysis is required, and buckling stability predictions employ non-linear finite element analysis methods.

Ultimate Loads

Ultimate load cases for turbines are derived from the parked 50 year extreme wind case and from the maximum transient operating case. The designs of the earlier, smaller rotors were dominated by the 50 year extreme wind ultimate load case. As rotor size increased, the transient operating case became the ultimate load case design driver. Over the intervening years the analysis of these operating loads have achieved significantly greater accuracy; see the discussion in References 6 and 7.

Blade Root

As rotors have increased in size, the fatigue life of the root attachment has become critical. The large blade root diameters now have relatively thin root skins, making the root attachment analysis a complex 3D non-linear analysis. The large-diameter pitch bearings now in use are relatively flexible compared with smaller rotors and must be modelled with non-linear contact gap models for the ball bearings.

Laminate

The blade laminate has become less fatigue-critical as rotor diameter has increased owing to tower clearance requirements. The blade laminate fatigue life is usually lowest between the transition area and 50% span.

Tower Clearance

As rotor diameter has increased, tower clearance has become the dominant design driver for sizing the blade laminate. The basic upwind rotor–tower configuration has not changed with increasing rotor diameter. With blade deflection increasing with the cube of length and the operating load now often exceeding the 50 year extreme wind load, it's apparent that tower clearance becomes a design driver as rotor diameter increases.

Blade Materials

While a large number of materials have been used successfully for wind turbine blades,[8] blade designs are primarily based on fibreglass composites. The increasing rotor size of current designs, with its changing design drivers, is leading designers to examine other materials and to use current materials in innovative ways.

Fibreglass Materials

Two major databases have come from the study of fibreglass composites that are typical of the materials and loads for turbine blades the European FACT database[9,10] and the US DOE/MSU composite material fatigue database.[11,12] The former is best characterized as a study of a few materials in great depth, while the latter is best characterized as a study of many materials in not as much depth. These databases continue to be updated and expanded, see e.g. References 13 and 14.

These databases and their associated research and testing programmes have led to major advancements in the understanding of the fatigue of composites. Extensive testing has demonstrated that fibre architecture and fibre content can dramatically reduce fatigue life if they produce areas with the fibre volume beyond a critical level. Similar reductions in fatigue life are observed in structural details such as ply drops, bonded stiffeners and sandwich panel terminations.[13,14] Typical cases of the first are shown below in Figure 5. With glass laminates, delamination at ply drops was a major problem when fatigue tested.[11–13] Data demonstrate that major strength reductions can occur in these cases. The data also suggest that large knockdowns can be reduced or avoided by dropping only a single ply at a time; further improvement could be realized by reducing the fraction of plies dropped at a particular location and by surrounding the ply drops with more continuous plies.[15,16] We should emphasize that the specimens shown in this illustration are relatively thin laminates compared with those in blades.

Testing under spectral loading has demonstrated that a linear damage assessment such as Miner's rule is non-conservative (often by a factor of 10 on predicted service lifetime) when based on constant-amplitude coupon data. Moreover, the spectral data have demonstrated that the high-count, low-amplitude fatigue cycles typical of the fatigue spectrum imposed upon turbine blades are more damaging then previously thought.[17]

Known deficiencies in these databases have led to a major new EC-funded programme, entitled 'Optimat blades' (http://www.wmc.citg.tudelft.nl/optimat_blades/index.htm). The project has an extensive set of European participants (10 R&D institutes, two certification authorities and six industrial partners). The project is scheduled to run for 52 months and is funded at 5 million Euros. There are six primary research tasks: variable amplitude loading; multiaxial stress states; extreme (environmental) conditions; thick laminates and repair; residual strength and condition assessment; and design recommendations. These tasks will centre on the testing of a fibreglass/polyester composite material. Late in the programme they may test carbon composites. Many of these tasks parallel current US programmes. Of particular note are the studies of variable-amplitude loading, extreme conditions and residual strength.[12,17]

The examination of carbon fibre composites has also begun.[13,18] The initial studies indicated that the critical problem with carbon fibres, from a fatigue standpoint, is fibre alignment. Small misalignments can produce a dramatic reduction in fatigue strength. Thus manufacturing processes are critical to the introduction of carbon fibres into blade designs.

Carbon Fibres

The increase in rotor size has led designers to examine materials other than glass composites for turbine blades. One material that has come to the forefront is carbon fibre. Current commercial designs have been primarily limited to selective reinforcement or bulk replacement of fibreglass in otherwise conventional blade designs. Higher-risk, innovative designs are mostly being pursued under government-funded research and development (in co-operation with industry).

There are three fundamental ways that carbon fibre may be used in wind turbine blade designs bulk replacement of load-bearing fibreglass materials, selective reinforcement; and new, total blade designs. In the first two cases, carbon fibres may prove cost-effective in a blade design that is otherwise conventional. In the third case, these fibres offer the potential for design innovations that can improve the performance and reduce loads.

Carbon fibres have several obvious advantages over glass in blade applications: higher modulus (by a factor of three), lower density (by a factor of two-thirds), higher tensile strength and reduced fatigue sensitivity.[12] The obvious disadvantage is increased cost, but this disadvantage will be mitigated somewhat by a reduction in blade weight. Early results from test programmes show that the strain-related properties of lower-cost varieties of carbon composites, particularly in compression,[13,15] are significant poorer than those of aerospace–grade materials, and that these materials are very sensitive to reinforcement architecture, manufacturing method and structural detail geometry. The baseline ultimate compressive strain for large-tow carbon fibre laminates fabricated from low-cost prepreg (vacuum bag, no resin bleeding), with relatively straight fibres, is around 1·0%–1·2%.[15] Low-cost fibres, with their larger tow size and thicker plies formed using RTM techniques, result in ultimate compressive strains around 0·6%–0·8%. While acceptable for blades, the prepreg values for compressive strain to failure provide little cushion against other factors that reduce their compressive strength, e.g. misalign fibres, manufacturing processes and structural details. RTM laminates have significantly less cushion.

Fibre waviness and misalignment have long been recognized as having the potential to cause major reductions in compressive strength for laminates with otherwise straight fibres.[15] Blade structures produced at minimum cost, with relatively heterogeneous microstructures, are particularly prone to this type of flaw. Fibre waviness in blade structures has three main causes: waviness introduced in processing, as by resin flow in an infusion process causing fibre wash (Figure 3); waviness inherent in woven or stitched fabrics (Figure 4); and fibre misalignment associated with flaws and structural details (Figure 5).

Process-induced waviness as shown in Figure 3 may be either through the thickness or in the plane. In severe cases like that shown, both tensile and compressive properties can be reduced to a small fraction of baseline values, as the failure mode becomes matrix-dominated.[13,15,16] Loosely constrained unidirectional fabrics are most susceptible to this problem, but also have the most nearly straight fibres in the absence of fibre wash.[15] Similar types of fibre waviness may occur in prepreg laminates with some geometries owing to

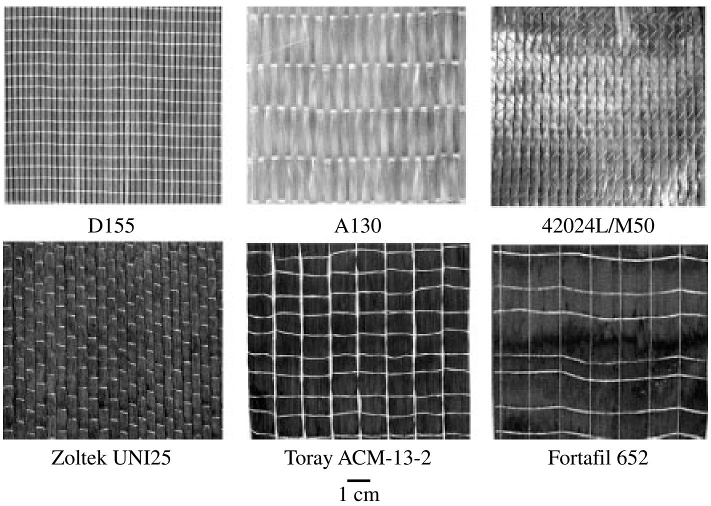

Figure 3. Glass (top) and carbon (bottom) fabrics used in this study

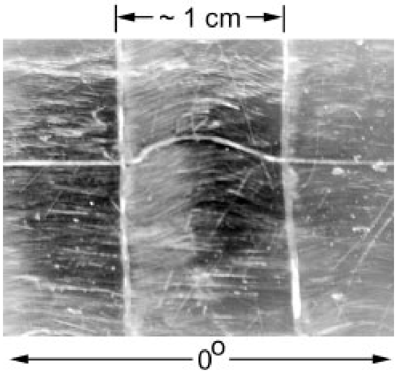

Figure 4. In-plane waviness in a single-ply laminate of Fortafil 652 carbon fibre/epoxy processed by RTM[4]

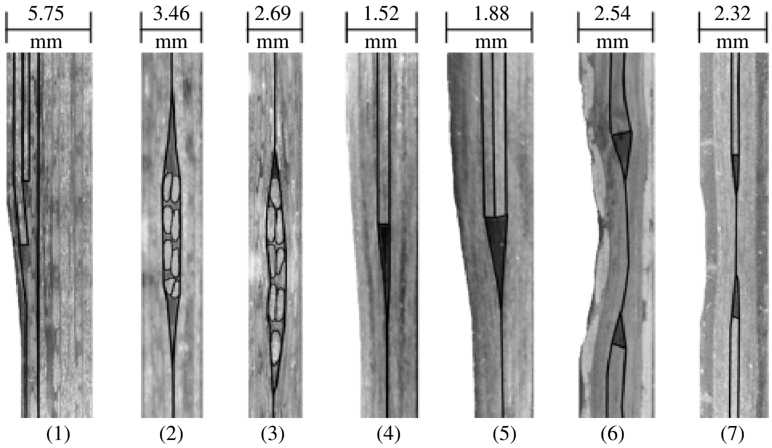

Figure 5. Enhanced cross-sectional views of materials containing ply drops, joints and inclusions: (1)–(3) glass fabrics processed by RTM, (4)–(7) prepreg laminates with Carbon 0° plies

consolidation, as with tubes having circumferentially oriented plies. An insidious form of through-thickness waviness is introduced when attempts are made to produce unidirectional fabrics which are more easy to handle and less prone to distortion, as with weaving strands over a small bead or stitching strands to a mat or to plies of other orientation. Although the fibre misalignment produced by the weave geometry is small, it predisposes the fibres to a buckling mode.[15]

Like glass composites, the final origin of fibre misalignment considered here is that associated with many types of flaws and structural details. Examples are ply drops and ply joints, see Figure 5. Data demonstrate that major strength reductions can occur in these cases. Fatigue testing has not yet been conducted on these carbon materials with ply drops.

One note of encouragement concerning wavy fabrics is that experience with glass fibres indicates that knockdowns are usually not additive, so that a woven fabric would not necessarily suffer additionally from details such as ply drops;[11–13] however, this has not yet been established for carbon.

An additional factor in compressive strength is the matrix. Epoxy resin has been shown to increase compressive strength by 10%–15% percent when compared with vinyl ester resin. The compression fatigue testing of these laminates showed relatively good fatigue resistance relative to similar glass laminates.[11,12]

In summary, the limited data available to date for low cost forms of carbon fibre laminates suggest that the static ultimate compressive strain may limit designs. Processing methods, which provide the greatest control over fibre straightness, are favoured, suggesting that prepreg manufacturing techniques are the best for carbon fibre composites. Fibre misalignment associated with ply drops and joints in prepreg laminates, while damaging, may produce acceptable knockdowns if conservative design practices are adopted.

Other Materials

The search for materials that lead to more efficient designs for large blades is forcing a re-examination of 'old' materials as well as the 'new' materials (such as carbon). Two of the most promising are S-glass and carbon/wood hybrids.[19]

Most turbine blade designs use E-glass. Its stronger cousin is S-glass. This speciality glass fibre, originally designed for marine applications, has significantly better properties than E-glass, but its higher cost has limited its use in turbine blades. However, as rotor size increases, the enhanced properties of S-glass offer an alternative to carbon fibres. It provides most of the benefit of carbon without the very high cost. Moreover, with the mass production of the fibres required by the turbine blade industry, the cost of S-glass will come down significantly.

Carbon/wood hybrids also offer unique material characteristics suitable for very large turbine blades. Their biggest problem is the supply of high-quality veneer. Joining of these hybrid materials is also a technical challenge.

Some Anticipated Trends in Design Concepts

Blade Geometry

The emergence of the three-bladed upwind configuration as the dominant rotor architecture has played a major role in the way that blade geometry has evolved, since it puts a limit on acceptable blade deflection. The need to efficiently provide high stiffness at low weight and cost has driven the search for better inboard blade aerofoils. This is a difficult design challenge, because the aerofoils are asked to provide high lift at low Reynolds numbers, a goal that clashes with large structural thickness. The challenge is made even more difficult by the desire for insensitivity to roughness from blade soiling. The early SERI and later NREL special-purpose inboard aerofoils addressed these concerns, and more recent work at Delft and elsewhere has further pursued these objectives. The authors believe that further progress can be made with the concept of 'flatback' aerofoils using a large flat trailing edge to enhance maximum lift. One key for furthering these developments will be the refinement and validation of codes that can adequately address rotational effects in the inner rotor, which have a major effect on maximum achievable lift coefficients, and perhaps the effects of roughness as well.

A trend which is not yet apparent in the inner rotor, but which could soon become common, may be the use of a substantial region of constant chord in the maximum chord region. This is anticipated because the growth in blade size is approaching the point where maximum chord will exceed maximum dimensions for overload shipping by road. It would of course be possible to use a small trailing edge piece bonded on in the field to restore full chord length, but the use of flatback aerofoils and a region of constrained maximum chord appears to present a possible solution that eliminates potentially difficult or expensive field work. Figure 6 shows an aerofoil that retains a short chord while achieving a thick section by placing a flat on the trailing edge. While this is a very-high-drag aerofoil, it retains high lift in a clean condition. Net performance may be minimally impacted because of its inboard location. Performance enhancements may also be possible with some attention to trailing edge enhancements or control surfaces.

Another region of the blade where structural and aerodynamic requirements pose a particular technical challenge is the region near 75% span. Here the desire is for high L/D, which would normally imply the use of moderate-thickness aerofoils. However, this region of the blade is where most of the deflection occurs, and increased thickness is very effective in providing stiffness at least weight and cost. The desire is again to find aerofoils that retain high L/D with increased t/c and that these aerofoils be as insensitive as possible to surface roughness, since the outer blade region is where soiling and erosion are most likely to occur.

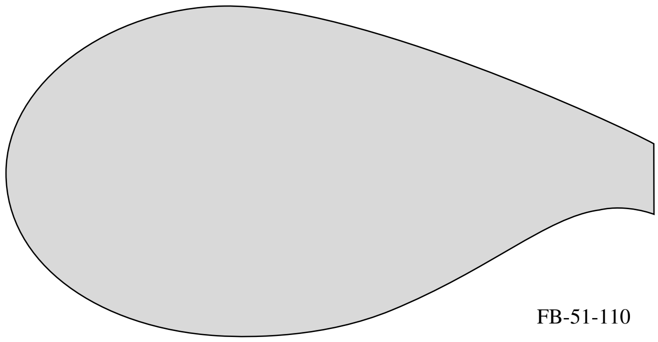

Figure 6. Example of a type of aerofoil called a 'flatback' created in response to a systems analysis of blade inboard structural characteristics, manufacturability and performance

An alternative way of providing increased tower clearance is to mould the blades with an upwind pre-bend in the outer blade. Such blades will be more nearly straight at or near peak load, thereby increasing clearance. This may be a technically excellent solution, but it does make the operation of loading materials into the mould more difficult, as it is no longer a relatively constant height above the shop floor. For a large amount of pre-bend, shipping could also become more difficult. Both of these could lead to increased costs, especially for very large blades.

Twist-coupled Blades

Whenever wind turbine blades twist, there is a direct influence on the angle of attack, changing loads and affecting output power. This is directly exploited in classic pitch control used not only in wind turbines but in rotors of all types. When the pitch changes are rapid enough, they can affect not only average loads and power but also vibratory loads, influencing fatigue life throughout the system. Even quite small angles of twist can have significant impact.

The prospect of installing blades that twist as they bend and/or extend, called aeroelastic tailoring, also provides opportunities for enhanced energy capture and/or load mitigation.[20–24] Although this coupling can be achieved in either an active or a passive manner, the passive approach is much more attractive owing to its simplicity and economy. As an example, a blade design might employ coupling between bending and twisting, so that as the blade bends owing to the action of the aerodynamic loads, it also twists, modifying the aerodynamic performance in some way. From a practical point of view, this coupling can be effected by using biased lay-ups in the blade skins and/or spars wherein the bias on the upper surface mirrors that on the lower one.[23]

Simulations with the rotor turning in turbulent winds showed substantial increases in fatigue damage for twist/coupling towards stall. Moreover, for a range of wind speeds in the stall regime, stall flutter is predicted. In contrast, when the blades twist towards feather, fatigue damage is reduced and stall flutter is not observed. The prospect of classical flutter, however, is modestly increased for reasonable levels of coupling.

In a recent study[24] on for variable-speed pitch-controlled rotors, dynamic computer simulations with turbulent inflow showed that twist coupling to feather substantially decreases fatigue damage over all wind speeds, without reducing average power. Maximum loads also decrease modestly. A simulated time history segment of the out-of-plane root bending moment for such a rotor, with and without twist coupling, is shown in Figure 7. By contrast, for constant speed stall-controlled and variable-speed stall-controlled rotors, significant decreases in fatigue damage are only observed at lower wind speeds, with smaller decreases at higher wind speeds. As a general observation, whenever a rotor is operating in the linear aerodynamic range (lower wind speeds for stall control and all wind speeds for pitch control), substantial reductions in fatigue damage are realized. This appears to be the most promising benefit of the twist-coupled blade and the motivation for continued efforts in its development.

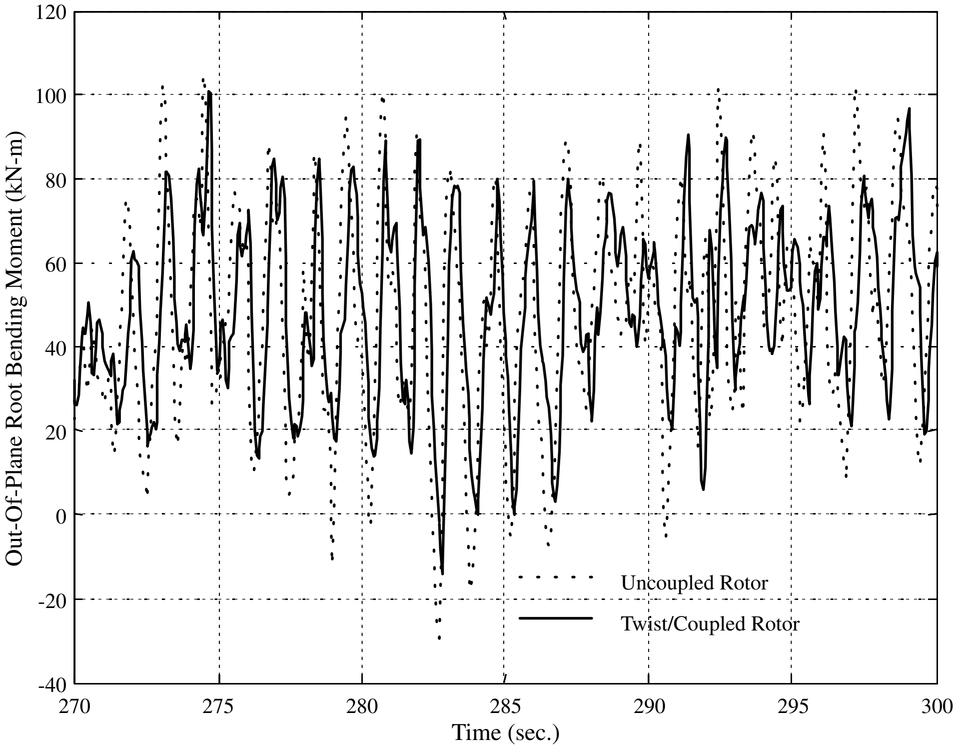

Figure 7. Comparison of the uncoupled and twist/coupled time histories of the out-of-plane root bending moment for the variable-speed pitch-controlled rotor for an average wind speed of 20 m s^{-1} at a high turbulence level

Blade Structural Analysis

Multi-MW-sized blades are now requiring blade designers to consider the structure of the blade earlier in the design process. It is no longer practical to simply determine the blade envelope based on aerodynamic performance. As the structure of the blade becomes a more dominant design criterion, the blade design process must better integrate both aerodynamic and structural concerns. The current drive towards blade designs with higher thickness-to-chord (t/c) ratios is a result of this effort.[18]

Full Blade Section Analysis

Preliminary structural analyses are the domain of section analysis owing to the insignificant computational expense and quick set-up time for the analyst. This approach treats the blade as a classical beam with all the associated implications of the assumption that plane sections remain plane. Three-dimensional distortions of the blade shell structure are not accounted for. Section analysis is usually performed with a custom code created by the designer. These are often elaborate spreadsheets.

A more comprehensive approach to section analysis has been developed at NREL.[25] Given the blade geometry and a design load, ultimate strength and buckling resistance criteria are used to compute the required thickness of the load-bearing composite laminates. Some assumptions are made about the blade architecture, though an arbitrary number of shear webs may be specified. Recently, this approach has been modified to work in conjunction with an aerodynamic performance code to accomplish a simultaneous aerodynamic/structural blade optimization. In a separate effort, work is in progress to link the optimizing section analysis and a finite element analysis (FEA) model generator called NuMAD such that much of the NuMAD/FEA model could be generated by the input provided to the section analysis. Thus the optimized blade design provided by the section analysis could be quickly converted to a full three-dimensional FEA model.

Full Blade Shell Modelling

A full three-dimensional FEA of a blade can be used to determine response that cannot be captured by a section analysis. Non-beam behaviour, such as cross-sectional warping, can be modelled with shell elements to predict local distortions and stress concentrations as well as local buckling strength. While FEA is more costly, it provides a level of detail needed for advanced or final blade designs. Large, commercial FEA codes are generally used. While many organizations in the US wind industry use ANSYS®, both Cosmos™ and Nastran are also used. NuMAD is a code developed at Sandia National Laboratories to greatly simplify the task of generating a three-dimensional finite element model of a wind turbine blade.[26] Second-order layered shell elements are used; a typical mesh for the blade model is shown in Figure 8.

Beam property extraction (BPE) functionality was recently added to NuMAD so that one-dimensional beam element properties may be produced for use with ADAMS®, BLADED or similar system dynamics and control codes. These one-dimensional beam elements must accurately represent all the mechanical properties of the full three-dimensional blade, including shear deformation, coupling between the various forces and moments, and offsets of the elastic, mass and shear centres. Previous attempts at capturing all of this information by examining the sections alone have been prone to approximations and omission of important aspects.

The BPE algorithms, developed by Global Energy Concepts and Sandia National Laboratories, use FEA displacement results from a suite of unit tip load solutions to extract the stiffness matrices for the equivalent beam elements. This information is then used to generate the complete aeroelastic model for the system dynamics model. Thus the highly detailed 3D shell model with thousands of degrees of freedom can be used to capture the equivalent beam behaviour of the blade with only tens of degrees of freedom.

Blade Root Detail Modelling

The blade root is a highly loaded and structurally complicated region. Most root connections consist of embedded studs or T-bolts in a thick composite structure used to bolt the blade to the hub. Either of these connections places a multiaxial stress state on the material and forces the composite matrix to carry significant shear loads. Without detailed stress analysis, large safety factors and structural redundancy are needed to insure a reliable connection.

The T-bolt type (Figure 9, right) is one of the most efficient joints for large blade roots, because there are no bonded joints, and therefore may provide long-term performance. The high-strength bolts (from 30 to 55 in number for MW-sized blades) are not vulnerable to corrosion problems. The pins act as nuts and perform as high-strength mechanical elements. The pre-stressed bolts transmit the load to the bushing.

A detailed stress analysis requires the using of submodelling (Figure 9, left). In order to get a high degree of accuracy, the model is extended up to the bearing, where the contact between the spherical balls and the cage is simulated by means of gap elements and constraints between specific nodes. The analysis also

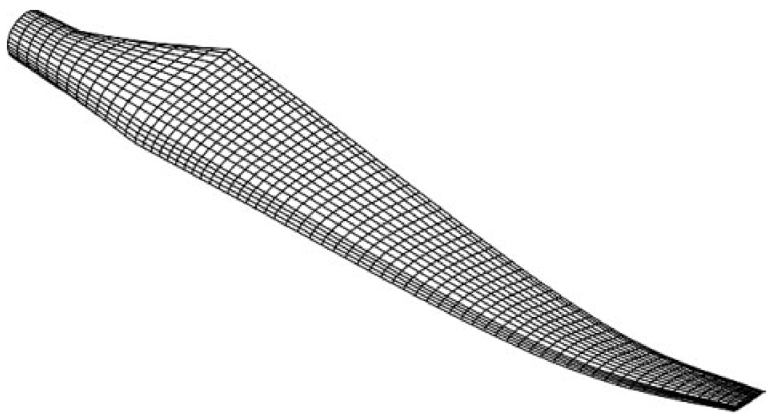

Figure 8. Typical FEA model generated by NuMAD/ANSYS®

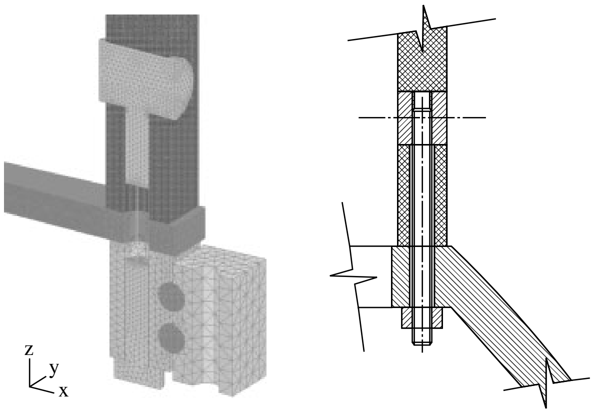

Figure 9. Submodelling finite element mesh (left) and joint scheme (right)

includes the pre-stress state of the bolt, which can be modelled by means of a stress loading along the bolt. The contact stresses in the three submodels (bolt head–laminate, bolt base–plate and plate–bearing) require special treatment using surface–surface or non-linear gap elements.

Finally, special attention must be paid to the mesh density in the stress concentration areas and the type of finite element used. Hexahedral elements are preferred to tetrahedral owing to the geometry and stress distribution over the composite blade root. The resulting detailed stress state predictions will impact the material selection and detailed design for durability of the joint.

Full-Scale Blade Testing

Inevitably, some structural details (joints, bonds, ply drops, etc.), material properties and characteristics of the manufacturing process are not fully understood before the fabrication stage. Full-scale testing has become the prudent means of reducing the risk of undetected structural problems in production. The internationally recognized IEC 88/102/CD certification design standard requires manufacturers to test wind turbine blades for both static strength and fatigue whenever a new design or manufacturing process is introduced.[27] In Denmark, where national standards dictate turbine certification, both static testing and fatigue testing are required.[28] The German certifying body, Germanischer Lloyd, requires only static test.[29]

Static testing is conducted to demonstrate the blade's ability to carry the extreme design load. The highest load cases, factored to include all the required safety margins, are applied to the blade span in each of the primary loading directions to demonstrate buckling stability and to verify the blade stiffness and maximum tip displacement. In addition, some laboratories recommend an ultimate strength test to failure to determine the design margin beyond the design load and to understand the probable failure mode and failure location. Although it is good practice, a test to failure is not required. Static test loads are applied using hydraulic actuators, cranes, winches and other loading devices.[30]

Fatigue testing is conducted to verify a blade's ability to withstand its operating load spectrum over a design life of 20–30 years. The operating load spectrum is comprises up to 10^9 load cycles occurring simultaneously both in the rotational plane (lead–lag) and perpendicular to the rotational plane (flap). The load spectrum is compressed into an equivalent damage load history of 10^6–10^7 cycles that can be applied in no more than a few months using linear damage principles.[31–33] Methods for applying these test loads range from forced loading with hydraulic actuators to resonance testing.[30]

Forced loading systems generally employ a servo-hydraulic system with actuators to exercise the blade in the flap and lead–lag directions.[34,35] as shown in Figure 10. Tests are conducted at frequencies below the blade's first fundamental flap natural frequency. The two primary advantages of a forced hydraulic loading system are the ability to apply biaxial loading, and a higher degree of load accuracy because the actuator

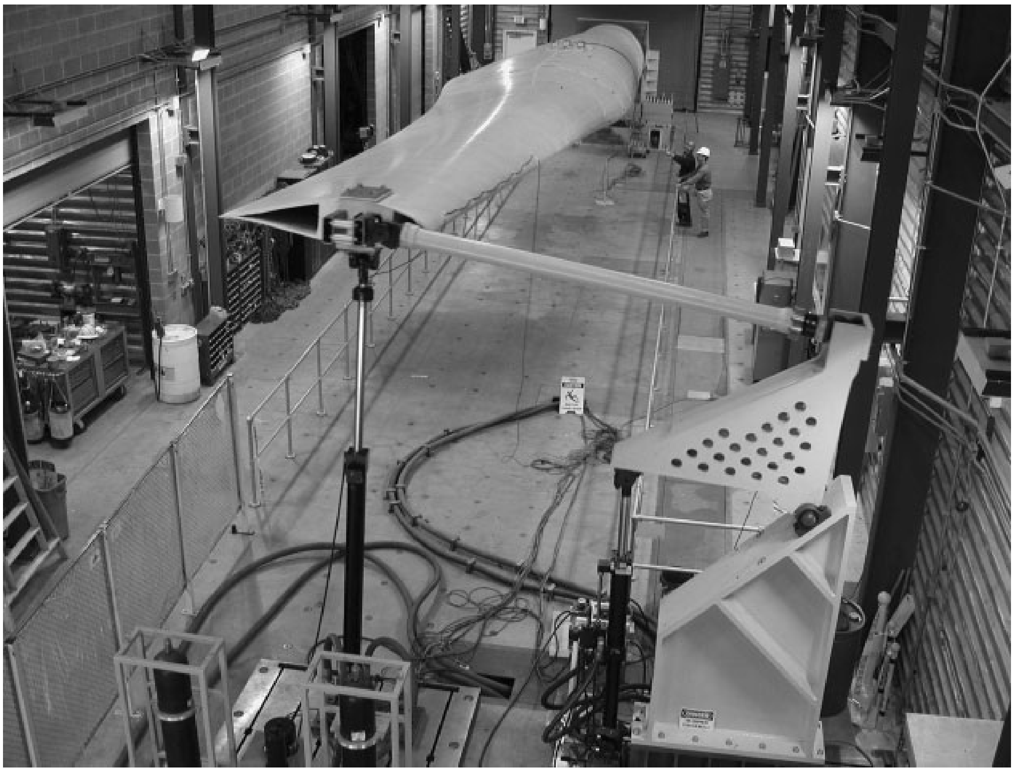

Figure 10. Two-axis forced hydraulic load fatigue test at the National Renewable Energy Laboratory, Golden, CO, USA (photo credit: Scott Hughes)

is physically coupled to the blade. The forced loading system requires large forces and displacements from hydraulic actuators. As the actuator sizes increase, so do the hydraulic pumping requirements. Consequently, substantial equipment costs are incurred for larger blades, while the pumping energy costs increase with the cube of blade length. White and Musial[36] have proposed a new method that combines forced loading and resonant loading, which may overcome test equipment and energy costs for multi-MW blades without sacrificing accuracy.

Resonance testing methods achieve test loads by exciting the fundamental natural frequency in the load direction. Most conventional resonance systems use an electric motor to rotate an eccentric mass attached to the blade, as shown in Figure 11. This method has several advantages. First, relatively little energy is required

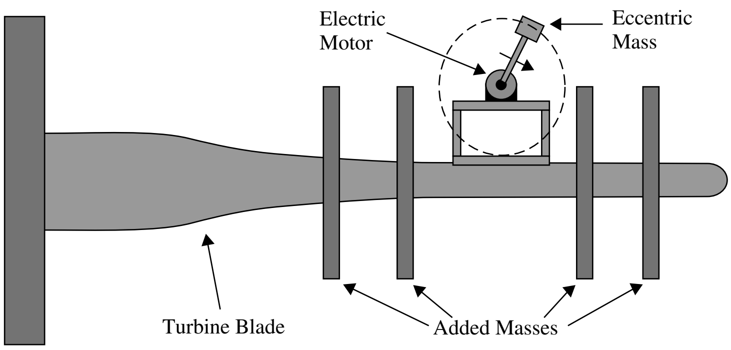

Figure 11. Schematic diagram of eccentric mass resonance fatigue testing system

to excite the blade. By cycling at the natural frequency, the test can be run faster than with forced hydraulic loading. In addition, the bending moment distribution along the blade can be adjusted to allow most of the blade span to be tested.

Typical resonant systems do not allow dual-axis loading, which many experts consider unrepresentative of the actual operating conditions. The eccentric mass can also add unwanted axial forces and moments, which may ultimately limit the accuracy of some blade tests.

Large-blade test facilities that use the fatigue test methods described are currently operating in the United States, Denmark and The Netherlands. Forced hydraulic loading is used generally in the USA and The Netherlands, while resonant testing is preferred in Denmark.

Blade testing becomes more important as machines get bigger and more costly. As blade lengths continue to grow, overcoming barriers to scaling blade testing technologies will be essential if the wind industry is to compete in the global energy markets.

Summary of Trends

In recent years, commercial wind turbines have grown to the point where typical rated power is between 1 and 3 MW and the blades are 30–50 m long. The corresponding blade weight increase has become a critical design concern for these large rotors. To keep blade weight growth below the cubic power of radius, designers have reduced margins, incorporated new materials, used more efficient manufacturing processes and explored innovative design concepts. Meanwhile, blades have maintained a design fatigue life of 20–30 years within the constraints of certification load and material safety factors. Ongoing research topics include the optimal use of commercial carbon fibres, load mitigation through aeroelastic tailoring, development of improved blade design criteria, and innovative blade geometry. New trends include the use of carbon and carbon hybrid materials and longer blades, more slender in the chord direction, with higher-thickness aerofoils for increased structural efficiency. If low-cost commercial-grade advanced materials, such as carbon fibre, become available in reliable quantities with guaranteed long-term pricing, blade design will change from heavy blades using low-cost glass to lightweight blades using higher-cost carbon. Innovations in rotor and blade designs are verified and improved with detailed stress analysis and with both static and fatigue testing. Analysis and testing of blades have grown in frequency and sophistication to the point where design margins may be reduced and additional cost benefits realized. The larger the blades become, the more expensive full-scale testing will become and the more the industry will benefit from detailed analysis and subscale testing.

References

1. BTM Consult ApS. A towering performance—latest BTM report on the wind industry. *Renewable Energy World* 2001; (July–August): 69–87.
2. Griffin DA. Blade system design studies Volume I: Composite technologies for large wind turbine blades. *SAND2002-1879*, Sandia National Laboratories, Albuquerque, NM, 2002.
3. TPI Composites. Parametric study for large wind turbine blades, WindPACT blade system design studies. *SAND2002-2519*, Sandia National Laboratories, Albuquerque, NM, 2002.
4. Malcolm DJ, Hansen AC. WindPACT turbine rotor design study: June 2000–June 2002. *NICH Report SR-500-32495*, National Renewable Energy Laboratory, Golden, CO 2002.
5. Griffin DA. WindPACT turbine design scaling studies technical area 1—composite blades for 80- to 120-meter rotor. *NREL/SR-500-29492*, National Renewable Energy Laboratory, Golden, CO, 2001.
6. Wright A, Tangler J, Fingersh L, Sutherland H. Recent progress in the advancement of wind turbine technology. In *Advances in Solar Energy*, vol. 14, Goswami DY (ed.). American Solar Energy Society: Boulder, CO, USA, 2001; 101–165.
7. Molenaar D-P. *Cost Effective Design and Operation of Variable Speed Wind Turbines*. Delft University Press: Delft, 2003.
8. Sutherland HJ. A summary of the fatigue properties of wind turbine materials. *Wind Energy* 2000; **3**: 1–34.
9. De Smet BJ, Bach PW. Database FACT: fatigue of composites for wind turbines. *ECN-C-94-045*, ECN, Petten, 1994.
10. Kensche CW (ed). Fatigue of materials and components for wind turbine rotor blades. *EUR 16684*, European Commission, Luxembourg, 1996.

11. Mandell JF, Samborsky DD. DOE/MSU composite material fatigue database: test methods, materials, and analysis. *SAND97-3002*, Sandia National Laboratories, Albuquerque, NM, 1997.
12. Mandell JF, Samborsky DD. DOE/MSU composite material fatigue database, 2003 update, Internal Report, Sandia National Laboratories, Albuquerque, NM, 2003.
13. Mandell JF, Samborsky DD, Cairns DS. Fatigue of composite materials and substructures for wind turbine blade. *Contractor Report SAND2002-0771*, Sandia National Laboratories, Albuquerque, NM, 2002.
14. Van Leeuwen H, van Delft D, Heijdra J, Braam H, Jorgensen E, Lekou D, Vionis P. Comparing fatigue strength from full scale blade tests with coupon-based predictions. *2002 AIAA/ASME Wind Energy Symposium*, Reno, NV, 2002; 1–9.
15. Mandell JF, Samborsky DD, Wang L. Effects of fiber waviness on composites for wind turbine blades. *SAMPLE Proceedings*, Long Beach, CA, 2003, in publication.
16. Adams D, Bell S. *Computer Science and Technology* 1995; **53**: 207–212.
17. Wahl N, Samborsky D, Mandell J, Cairns D. Spectrum fatigue lifetime and residual strength for fiberglass laminates in tension. *2000 AIAA/ASME Wind Energy Symposium*, Reno, NV, 2000; 49–59.
18. Joosse P, van Delft D, Kensche C, Soendergaard D, van den Berg R, Hagg F. Cost effective large blade components by using carbon fibres, *2002 AIAA/ASME Wind Energy Symposium*, Reno, NV, 2002; 47–55.
19. TPI Composites. Innovative design approaches for large wind turbine blades. *SAND 2003-0723*, Sandia National Laboratories, Albuquerque, NM, 2003.
20. Lobitz DW, Veers PS, Migliore PG. Enhanced performance of HAWTs using adaptive blades. *Proceedings of 1996, ASME Wind Energy Symposium*, Houston, TX, 1996; 41–45.
21. Lobitz DW, Veers PS. Aeroelastic behavior of twist-coupled HAWT blades. *Proceedings of 1998 ASME Wind Energy Symposium*, Reno, NV, 1998; 75–83.
22. Lobitz DW, Laino DJ. Load mitigation with twist-coupled HAWT blades. *Proceedings of 1999 ASME Wind Energy Symposium*, Reno, NV, 1999; 124–134.
23. Ong CH, Tsai SW. Design, manufacture and testing of a bend-twist D-spar. *Proceedings of 1999 ASME Wind Energy Symposium*, NV, 1999; 43–52.
24. Lobitz DW, Veers PS. Load mitigation with bending/twist-coupled blades on rotors using modern control strategies. *Wind Energy* 2003; **6**: 105–117.
25. Bir GS, Migliore PG. A computerized method for preliminary structural design of composite wind turbine blades. *Paper AIAA-2001-0022*, 2002.
26. Laird DL. NuMAD user's manual. *SAND2001-2375*, Sandia National Laboratories, Albuquerque, NM, 2001.
27. *Wind Turbine Certification*. 1998.
28. Danish Energy Agency. *Type Approval Scheme for Wind Turbines: Recommendation for Design Documentation and Test of Wind Turbine Blades*. Danish Energy Agency: Copenhagen, Denmark, 2002.
29. Germanischer Lloyd. *Rules and Regulations IV—Non-marine Technology—Part 1—Wind Energy*. Germanischer Lloyd: Hamburg, Germany, 1998; chap. 5.
30. *Testing of Rotor Blades*. IEC 88/84/CD (IEC 61400-23), 1998.
31. Van Grol H, Bulder B. *Reference Procedure to Establish Fatigue Stresses for Large Size Wind Turbines: a State of the Art Report. Volume I. Main Body of the Report and Annexes*. Netherlands Energy Research Foundation ECN: Petten, 1994.
32. Van Grol H, Bulder B. *Reference Procedure to Establish Fatigue Stresses for Large Size Wind Turbines: a State of the Art Report. Volume II. Tables and Figures*. Netherlands Energy Research Foundation ECN: Petten, 1994.
33. Larwood S, Musial W, Freebury G, Beattie A. NedWind 25 blade testing at NREL for the European standards measurement and testing program. *NREL/TP-500-29103*, National Renewable Energy Laboratory, Golden, CO, 2001.
34. Hughes S, Musial W. Wind turbine blade fatigue test plan for Enron 37B rotor blade. *NWTC Document NWTC-ST-EW-FAT-04-TP*, National Renewable Energy Laboratory, Golden, CO, 2002.
35. Hughes S, Musial W. Implementation of two-axis servo-hydraulic system for full-scale fatigue testing of wind turbine blades. *WindPower '99*, 1999, Paper 24.
36. White DL, Musial WD. Efficient method for fatigue testing multi-megawatt composite wind turbine blades using resonant excitation. *SAMPE Proceedings*, Long Beach, CA, 2003, Paper 196.

