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Reliability of Wind Turbine Blades: An Overview of Materials Testing

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Abstract

The structural reliability of wind turbine components can have a profound impact on both the profitability and reputation of a wind turbine manufacturer or supplier of wind turbine components. The issue of reliability is of critical concern when large wind farm co-operatives are considered, and when wind turbines are located in remote regions where the cost of inspections and repairs can be very high. From a structural viewpoint, wind turbine blades are subjected to very complex loading histories with coupled deformation modes. The long-term reliability of wind turbine blades requires an understanding of how damage develops in composite structures, composite materials and adhesives. Designing reliable wind turbine blades also requires the further development of laboratory scale and full scale test methods to evaluate the structural response and durability of new materials under various loading and environmental conditions. This paper highlights recent advances in methods used to characterize adhesive joints in wind turbine blades and the manner in which laboratory data is used to predict the structural response of wind turbine blades.

Keywords: wind turbine, blades, composites, adhesive, reliability.

Introduction

Within the past few years there has been a dramatic increase in the size and power output of wind turbines. The largest installed turbines now have rotor diameters of 126 m and power outputs of 5 MW. Even larger installations are expected in the near future. An increase in rotor diameter is accompanied by a corresponding increase in the load levels experienced by the blades, input shaft, gearbox and generator, as well as by the tower and nacelle. Because of the higher loads, the materials used for larger wind turbine blades will require extensive laboratory testing to ensure that new blade designs will continue to provide long term reliability. A recent study [1] has shown that 90% of the uncertainty concerning fatigue life predictions for wind turbine blades can be attributed to uncertainties related to material properties. Thus improvements in the manner in which test data is generated and interpreted, as well as improvements in analysis methods, will lead to significantly less uncertainty in life prediction for wind turbine blades. Ultimately, if uncertainties in material properties can be reduced, safety factors used in design can be reduced, resulting in more efficient use of materials and lower costs.

Wind turbine blades, which are constructed using fiber-reinforced composites, will experience a multitude of events that can affect reliability, including random cyclic loading, daily and seasonal temperature and humidity changes and, for colder climates, sleet and ice impact. For very warm climates, long-term exposure can cause degradation of composite structures and adhesives. For the safe and cost-effective operation of wind turbines, it is necessary to understand how these variables, acting in isolation or in parallel, can affect reliability. It is also important to understand how manufacturing-related defects and repairs. This understanding is of particular importance for the wind power industry since decisions related to the cost of wind energy, at both the governmental and industry level, are based upon the assumption of reliable operation over a period of 20 to 30 years. The issue of long-term reliability is of critical concern for wind turbines located in remote regions, where the cost of inspections and repairs can be very high both for the end user and the wind turbine manufacturer.

Wind Turbine Blade Construction, Materials and Damage Modes

Figure 1 shows the typical construction of a wind turbine blade used for large wind turbines (1 MW or larger output) [2-5]. The aerodynamic shell that defines the blade profile is typically constructed using fiber-reinforced polymeric composites and sandwich structures with lightweight PVC foam or balsa wood cores. The aeroshell is attached to an internal composite beam (spar), which is typically in the form of a hollow box beam or integral shear webs. The internal beam, which makes extensive use of unidirectional fibers aligned with the blade axis, is the primary load bearing component of a blade and is subjected to a very complicated multiaxis loading history. The primary function of the internal beam is to provide both bending stiffness and torsional rigidity to the blade. High-strength fiber-reinforced polymer composites are used extensively for the aeroshell and internal beams of wind turbine blades. For most blade designs, high-toughness adhesives are used to bond the aeroshell to the internal beam and for bonding of laminates at the leading and trailing edges (see Fig. 1). Because of cost considerations, as well as extensive design experience, glass fibers are used in the majority of wind turbine blades. However, to reduce static and cyclic deflections and improve buckling resistance, blade manufacturers are increasingly considering, and incorporating, carbon fibers and fiberglass/carbon hybrids into large wind turbine blades. In the longer term, it is expected that the cost of carbon fibers will decrease significantly as manufacturers increase production of carbon fibers, in particular lower-cost large tow carbon fibers. This could eventually lead to wind turbine blades that make extensive use of carbon fibers in both the internal beams and aerodynamic shell. As an interim measure, wind turbine blades will selectively utilize carbon fibers (in particular for internal beams) to take advantage of their higher stiffness.

Wind turbine blades are manufactured using procedures similar to those used for composite aircraft structures and composite boat hulls; namely, hand lay-up, pre-preg technology and vacuum assisted resin transfer molding [3,4]. One of the keys to improving reliability is the degree of quality control that is exercised in the selection of raw materials (e.g., resin and fibers) and the quality control used during blade manufacturing. However, it would be virtually impossible (and cost prohibitive) to manufacture a blade that is completely free of defects. It is therefore necessary to develop guidelines to determine allowable flaw sizes (for example debonds along adhesive joints) and for repair schemes that can be used during the manufacturing stage of wind turbine blades. In addition to the further refinement of models used to predict the life of wind turbine blades, an important goal of research in blade technology is to develop new blade structures and materials that are inherently tolerant to flaws.

During rotation, a blade is subjected to large edgewise and flapwise bending moments which introduce cyclic stresses in the aeroshell, adhesive joints and internal beam. The stress state developed in the composites and adhesive joints varies with position along a blade and also with position within a cross-section. Failure modes observed in when a wind turbine blade was tested to failure are shown in Figs. 2a and b [2]. The damage modes in the aeroshell and spar include delamination between composite plies and debonding along adhesive joints.

Testing of Wind Turbine Blades, Composite Materials and Adhesive Joints

For wind turbine blades, various levels of testing are required for the qualification of new materials and for the certification of new blade designs and blade repairs. Guidelines and standards (for example, IEC 61400 [7,8], Risø/DNV [5], Det Norske Veritas [9,10] and Germanische Lloyd [11,12]), which have been developed primarily in Europe, describe the types of coupon and full-scale blade testing required for blade certification (Tadich *et al.* [13] and Skamris *et al.* [14] give excellent overviews of the guidelines and standards developed in Europe for wind turbines). With the phenomenal growth in wind turbine installations, and the rapid change in composite materials blade size and design, the certification procedures and standards used for laboratory testing of composites, will require periodic updates to ensure that they continue to provide the best possible guidance.

Risø National Laboratory in Denmark has a long history of research in wind energy and the reliability analysis of composite structures used for wind turbines and has been very active in the development of improved test methods for characterizing the mechanical behavior of composites and adhesive joints [3]. Because of space limitations, this paper will focus primarily on an experimental technique developed at Risø by Sørensen and co-workers [6,15-16] to investigate the mixed-mode fracture behavior of adhesive joints and sandwich structures used in wind turbine blades.

Mixed-Mode Crack Growth Resistance of Adhesive Joints. The majority of composite blades contain adhesive joints. If a composite joint is properly designed, the adhesive can play a very beneficial role as its compliance allows for dimensional mismatch (e.g., from thermal expansion) and reduces stress concentrations at locations where elastic modulus mismatch is present (e.g., between a blade aeroshell and internal beam) to be accommodated. For all blades, defects or cracking between composite plies (delaminations) or in the vicinity of geometry changes (e.g., between an aeroshell and internal shear webs) can occur.

Figures 3a and b show typical adhesive locations for a blade manufactured with an integrated shear web. Of particular concern is the fracture resistance (toughness) and defect tolerance of adhesive joints. For wind turbines blades, adhesive joints are subjected to mixed Mode I/Mode II loading. The multiaxis loading at an interface can be characterized by the mode mixity (ψ), which is a measure of the ratio of Mode I and Mode II crack tip loading [17]. The fracture resistance of adhesive joints varies with mode mixity. Thus, an interface flaw along an adhesive joint could be harmless if located in one region of a blade, but the same size flaw may propagate if located in a region with different mode mixity or a higher stress state. It is therefore important that the techniques used to evaluate the crack growth resistance of adhesive interfaces allow a wide range of mode mixities to be investigated. Furthermore, it is important that the technique allows the reliability of adhesives to be investigated for both static and cyclic loading histories. Various test approaches have been developed for testing the fracture resistance of adhesive joints, including edge-notch flexure [18,19], double cantilever beam (DCB) [20-24], mixed-mode bending (MMB) [25] and flexure specimens designed with unequal beam lengths or center-span cracks for mixed-mode testing [26,27].

At Risø, a generalized mixed-mode DCB specimen and test configuration has been developed to more accurately characterize the fracture resistance of adhesive joints [15] and sandwich structures [16] in wind turbine blades. The specimen, referred to as a DCB-UBM (DCB – Uneven Bending Moments) and the test frame used for specimen loading are shown in Figures 4a-d. By applying unequal bending moments to the two beams of the DCB-UBM specimen, this loading arrangement allows for a full range of mixed-mode loading conditions to be achieved. The primary advantages of the DCB-UBM configuration are: (1) it allows stable crack growth for the entire mode mixity range between Mode I and Mode II, (2) it is suitable for characterizing large-scale bridging zones which are typical of delamination in fiber-reinforced composites and debonding of adhesively bonded composites and, (3) the fracture energy, which is characterized by the J integral for large-scale fiber-bridging, can be obtained in a straightforward closed-form solution (other approaches, for example DCB specimens loaded by forces at the beam ends, require measurement of beam rotation [21] or numerical solutions to quantify test results).

Figure 5a shows results obtained from a recent investigation of the influence of mode mixity on the interface fracture resistance of adhesively bonded laminates used in wind turbine blades. As is typical for adhesive joints, the crack growth resistance is lowest for Mode I loading and increases significantly as Mode II loading is approached. Results such as these are being used to quantify the mixed-mode behavior of adhesive joints and to develop engineering guidelines for allowable flaw sizes along adhesive joints. These approaches also allow developing cohesive laws for interface joints which are used for numerical simulations in blade design and reliability analysis.

Because the cost and time associated with full scale testing of blades is very significant, one goal of laboratory testing is to develop data and insight that can be used to predict the structural response and reliability of much larger structures. Thus it is important to determine if results obtained from laboratory experiments can be used to understand and predict the behavior of larger structures. Sørensen and Jacobsen [28] have recently compared results obtained using DCB-UBM specimens with experimental results from much larger (2 m) flexure specimens. The flexure specimens (see inset in Figure 5b), were manufactured by adhesively bonding two beams of different lengths (this specimen geometry is a modification of that proposed by Charalambides et al [26]). Although the flexure specimens do not allow a wide range of mode mixities to be examined, they are relatively easy to manufacture and test in large sizes and thus provide a convenient geometry to study scaling effects in adhesive joints. Figure 5b compares the critical moment predicted using fracture resistance data generated from experiments with DCB-UMB specimens and the 2 m long flexure specimens. Very good agreement was observed and provides confidence that laboratory test results obtained using DCB-UBM specimens can be used to predict the behavior of adhesively bonded joints in larger structures. Further advances in the reliability analysis of wind turbine blades will require an improved understanding of the behavior of adhesive joints and composite materials under mixed-mode cyclic loading and for random fatigue loading histories.

Conclusions

The composites and adhesives used in large wind turbine blades are subjected to complex multiaxis loading histories. With the increasing size and complexity of new blade designs, laboratory testing will take on increasing importance. New test specimens and test approaches are being developed at Risø to provide more accurate data needed for the structural design and reliability analysis of wind turbine blades and to qualify new wind turbine materials and adhesives. One recent development is the DCB-UBM specimen which is used to determine the fracture resistance and defect tolerance of adhesive joints and laminates under mixed-mode loading conditions. This specimen geometry provides stable crack growth over a wide range of mode mixities and allows the effect of large-scale fiber bridging in composite materials and adhesive joints to be quantified. An important consideration of coupon testing is to ensure that laboratory results can be used to predict the response and reliability of larger structures. Test data obtained using the DCB-UBM specimen have been shown to accurately predict the crack growth resistance of much larger structures.

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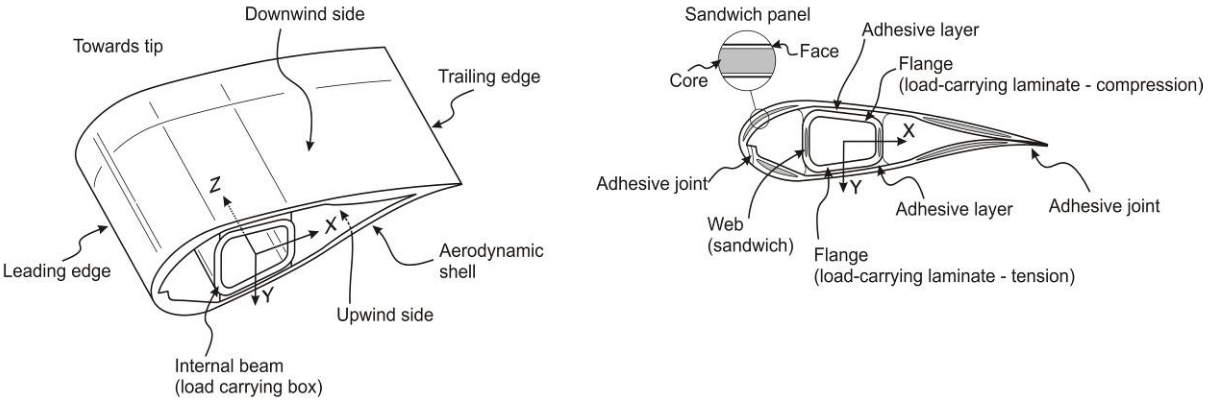
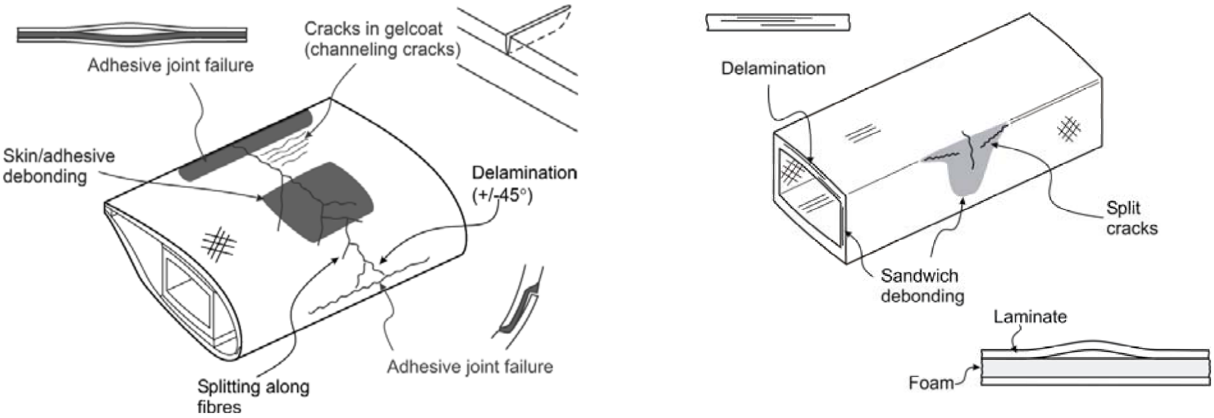
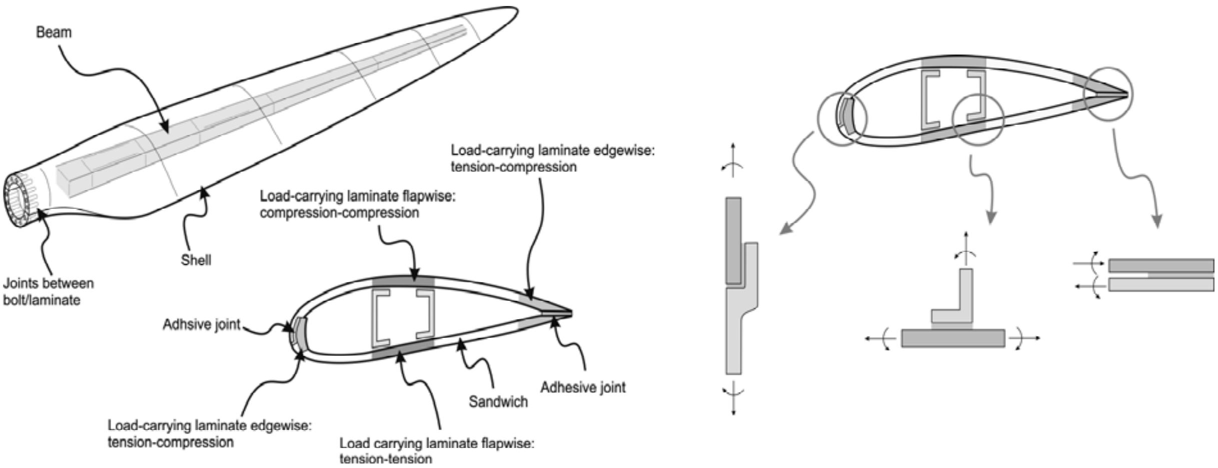


Figure 1. Typical construction of a wind turbine blade. The shape and construction of the internal beam (spar) varies considerably with manufacturer but is typically in the form of a box beam or one or more webs that may be adhesively bonded or form an integral part of the wing structure; adhesive joints may also be present along the leading and trailing edges and for core/facesheet bonding on sandwich panels. From Sørensen *et al* [2].



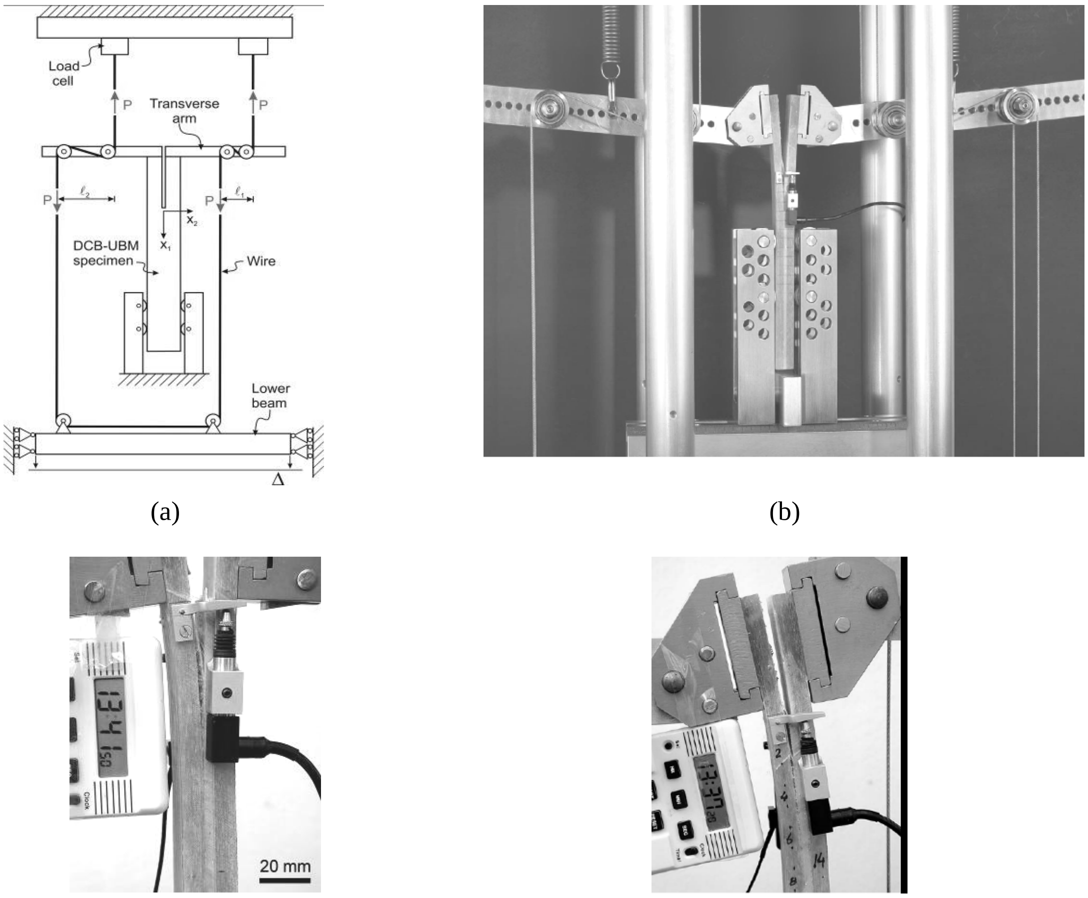
(a) (b)

Figures 2a,b. Damage modes observed in (a) composite aeroshell and (b) internal box beam when a wind turbine blade was tested to failure. From Sørensen *et al* [2].



(a) (b)

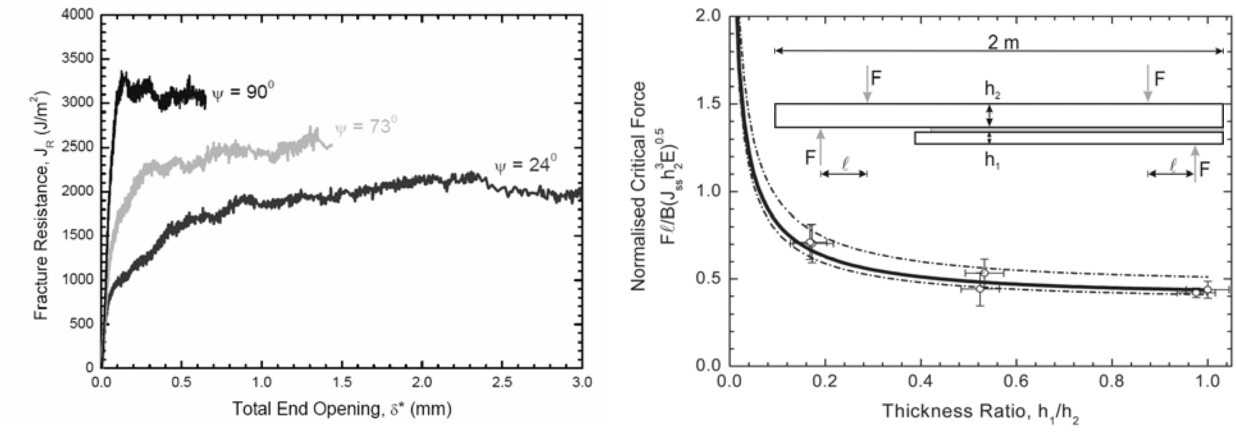
Figures 3a,b. (a) Schematic of a wind turbine blade showing primary loading modes (flapwise and edgewise). (b) Possible loading modes for adhesive joints along a blade cross section. From Sørensen and Jacobsen [6].



(a) (b)

(c) (d)

Figures 4a-d. (a) Loading arrangement used for DCB-UBM specimens. Moments are applied to the specimen by forming couples on each transverse arm (the force P is applied through a cable system). Mode mixity is changed by adjusting the distance (l_1 and l_2) between the rollers. (b) Test apparatus showing a 300 mm long adhesively bonded fibreglass-epoxy composite subjected to Mode I loading. (c) Adhesive joint failure for predominately Mode I loading. (d) Adhesive joint failure for predominately Mode II loading. Sørensen et al [6,15].



(a) (b)

Figures 5a,b. (a) Typical plot of fracture resistance versus crack opening displacement for an adhesively bonded fiberglass laminate subjected to different mode mixities [6]. (b) Critical force for crack propagation along an adhesive joint in 2 m long flexure specimens (the composite and adhesive were the same as that used for the DCB-UBM experiments shown in Fig. 5a) [28]. The data points shown were obtained from tests performed on 2 m long flexure specimens. The solid line shows a prediction for the critical force made *a priori* using steady-state fracture resistance data obtained from DCB-UBM specimens (the dashed lines are upper and lower error bounds for the UCB-UBM data). The agreement is very good and indicates that laboratory test results can be used to predict the behaviour of adhesive joints in larger composite structures with different geometries.