# MATERIALS AND STRUCTURES FOR WIND TURBINE ROTOR BLADES - AN OVERVIEW

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## SUMMARY

An overview is given of the use of composite materials in wind turbine blades, including common failure modes, strength-controlling material properties, test methods and modelling approaches at the materials scale, sub-component and component scale. Thoughts regarding future trends in the design, structural health monitoring and repair are given.

*Keywords: failure modes, fracture mechanics, fatigue, repair, testing, modelling*

## 1. BACKGROUND AND TRENDS

Wind turbine rotor blades are traditionally made of polymer matrix composite materials (laminates and sandwich structures). Rotor blades are the largest rotating components of a wind turbine. They should last for a minimum of 20 years. During this time they will be subjected to varying wind loads, as well as hot, cold and wet weather. Thus, they must be designed against different types of damage e.g. fatigue damage or damage due to extreme strong winds [1, 2].

The major trends in the development of new wind turbines are (a) development of *larger size* wind turbines, and (b) *offshore* placement in large wind turbine parks remote from land. Combined, the two trends lead to several challenges with respect to the development of future rotor blades:

1. The *weight* of wind turbine rotor blades increases progressively with increasing blade length. For future blades, the gravitation loads will exceed the aerodynamics loads. Thus, weight savings become of great importance. In the design phase, this can be achieved by better design of structural details and by the use of stronger and lighter materials. More accurate design methods are needed and *better material testing methods and material models* are needed to give a better description of the materials properties.
2. Since wind turbine blades traditionally are made of relative few parts being glued together, it becomes of great importance to ensure *high quality uniformity*. Blades that have manufacturing defects will be repaired, since large parts are costly and it is therefore very unattractive to discard them.
3. Since access to offshore wind turbines is difficult and costly, it is desirable to *reduce the need for manual inspection* as much as possible. Sensors that can

detect damage in the blades will be built-in, so that blade damage can be detected in proper time and inspection can be restricted to damaged blades.

4. Fourth, there must be *reliable modelling tools* available for modelling of the damage evolution in wind turbine blades, such that it becomes possible to make accurate assessments of the detected damage and thus make knowledge-based decisions regarding whether the blade should be replaced, repaired, or kept in use without being repaired.

This paper focuses at the damage development and failure mechanisms in wind turbine blades. The paper is organised as follows: First, a brief overview is given of modern blade design, common failure modes and the various length scales that can be useful in the analysis of materials and structures for wind turbine blades. Next, each of the four challenges listed above will be discussed in some detail. Many of these challenges set goals for development of knowledge in the area of material science and material mechanics.

## 2. BLADE DESIGN AND COMMON FAILURE MODES

### 2. 1. Blade manufacture and design

Due to the elongated shape, a wind turbine blade is essentially a load-carrying beam covered with an aerodynamically shaped shell. For weight saving reasons, the aerodynamic shell is made as sandwich structures consisting of composite face sheets enclosing sandwich core made of a light-weight material such as balsa wood or polymer foam. The load carrying parts are made of fatigue resistant composite materials such as glass fibre/polyester and carbon fibre/epoxy. The composites are usually made by the use of vacuum infusion or by the use of pre-pregs. A common manufacturing method is to make the two aeroshells in external moulds. A load-carrying beam or webs are then placed in between the aeroshells and the parts are then bonded together. Fig. 1 shows schematics of two common design principles. Note that the largest parts of the blade consist of sandwich structures. Close to the root, where the blade has fittings for the nacelle, the shape of the blade changes to a circular tube.

### 2.2. Overview of failure modes

Although full scale testing of each new blade model is done as a part the certification process, blades are rarely tested to failure. In some cases, rotor blades have been tested to failure to identify the damage and failure modes [3, 4]. Analyses of the fracture surfaces of wind turbines that have been tested to failure have revealed that failure involves a number of failure modes. The major ones are [3, 4]:

1. Skin/adhesive delamination
2. Adhesive joint failure of leading or trailing edges
3. Sandwich face/core delamination
4. Delamination of laminates

5. Failure in individual laminas (tension, compression, shear/splitting)
6. Skin layer/adhesive delamination due to buckling of the skin
7. Gelcoat damage (cracking and gelcoat/skin delamination)

These failure modes are shown schematically in Fig. 2. It is striking that very little damage was found that involved fibre failure. Lamina failure was mostly by splitting cracks running parallel to the fibres. The vast majority of damage was in the form of delamination along week interfaces, either in laminates, sandwich structures or adhesive joints.

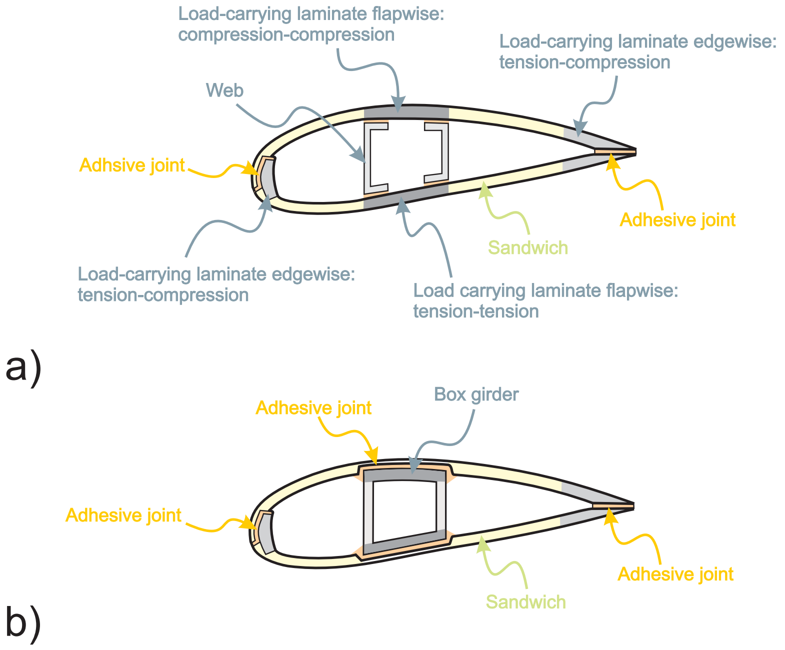
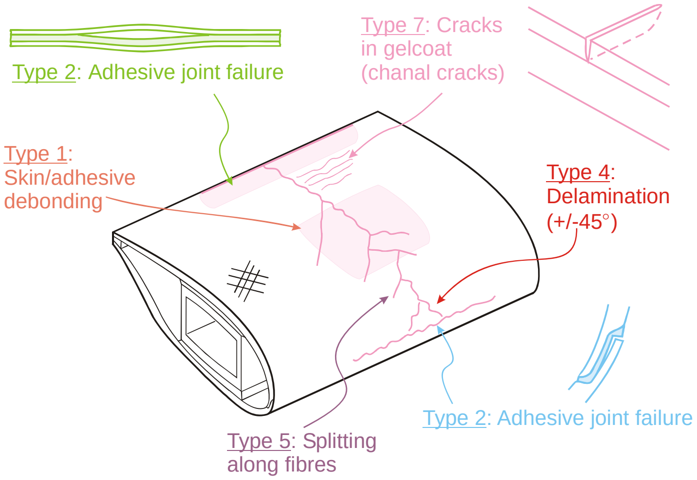


Figure 1: Schematics of the cross-section of two common design principles of wind turbine blades: (a) a design that uses load-carrying laminates in the aeroshell and webs for preventing buckling and (b) a design that uses a load-carrying box.



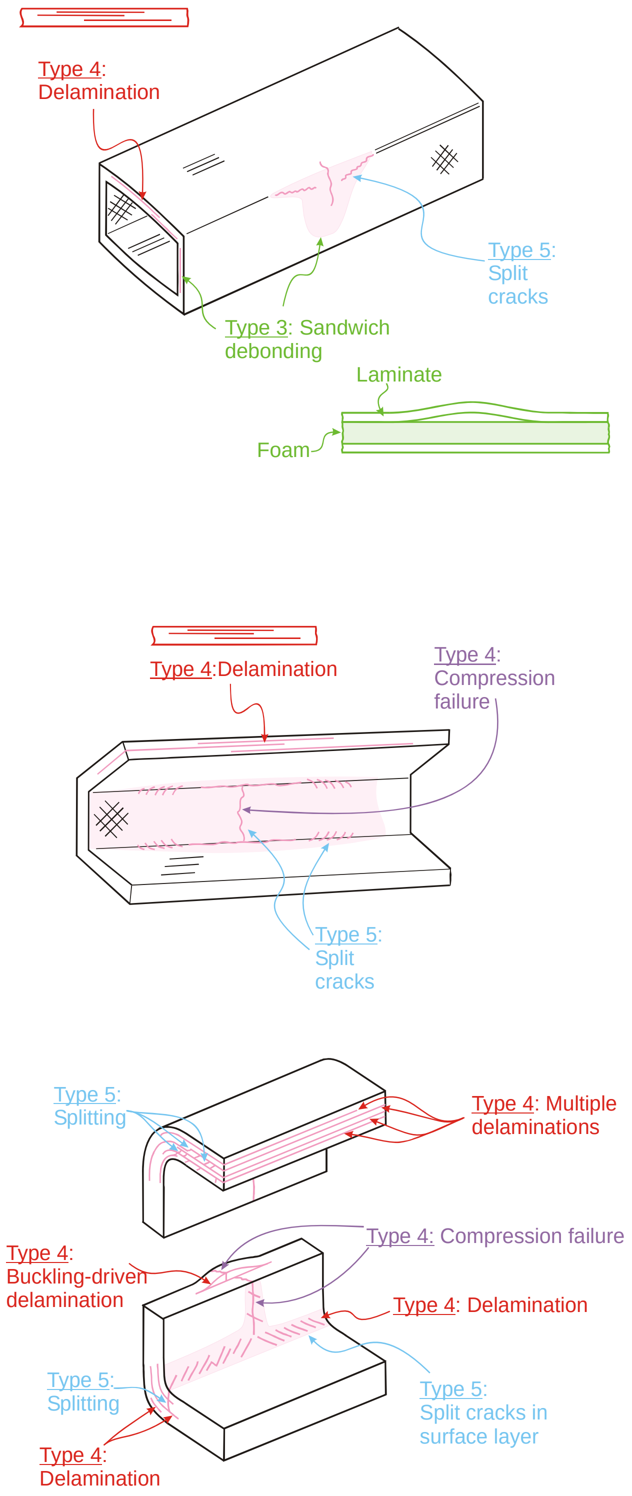


Figure 2: Sketch of observed failure modes in a wind turbine blade purposely tested to failure (from [3]).

### 2.3. Length scales

It is convenient to study wind turbine rotor blades at various length scales, from microscale (material), over macroscale (test specimen) to component scale (wind turbine rotor blade).

Currently, most testing is conducted using test coupons (materials testing for measurement of mechanical properties like stiffness and strength) and full scale testing. However, the trend is towards testing and modelling at all length scales, since it is of great importance to check that the materials have the presumed properties and that the structure behaves as predicted by models. Interestingly, this trend is the reverse of the trend in aerospace, where the aim is to reduce testing at various length scales to reduce costs (Robin Olsson, private correspondence).

At the macroscale, materials testing of composite materials for wind turbine rotor blades involves both static and cyclic loads, testing of the base materials (usually unidirectional layers), laminates, sandwich core materials, adhesives, gelcoats and interfaces between various layers. Strength and fatigue characterisation is made by traditional tension, compression and shear testing as well as fracture mechanics testing of interfaces. Recent developments include fracture mechanics approaches for determination of cohesive laws [5] for use in finite element simulations [6].

Mechanical testing can also be conducted at the microscale on specimens inside scanning electron microscopes using special loading devices [7]. This enables in situ observations of details of the microscale damage evolution. In addition, single fibre tests or single fibre fragmentation test can be used for characterising the mechanical properties of the fibres and the fibre/matrix interface [8]. The aim of such studies is to provide input to or compare behaviour with micromechanical models, e.g. made by the finite element method. Through parameter studies, micromechanical modelling is used for investigating the effect of microstructural parameters on the macroscopic properties.

## 3. CHALLENGES

### 3. 1. Better design methods

Models used for structural design can be split in two groups:

(A) Models of overall blade behaviour e.g. for analysis of blade deflection, effect of elastic deformation on the aerodynamic behaviour (aeroelasticity) and eigenfrequency [9].

(B) Models for analysis of strength of structural parts, e.g. models of details like adhesive joints, holes for receptors (for catching lightening flash) and ply-drops.

Obvious, the type (B) analysis requires a more detailed geometric description of the blade and requires knowledge of more materials properties, e.g. stiffness and strength data of all materials, interfaces between dissimilar materials and failure criteria for the various types of failure modes.

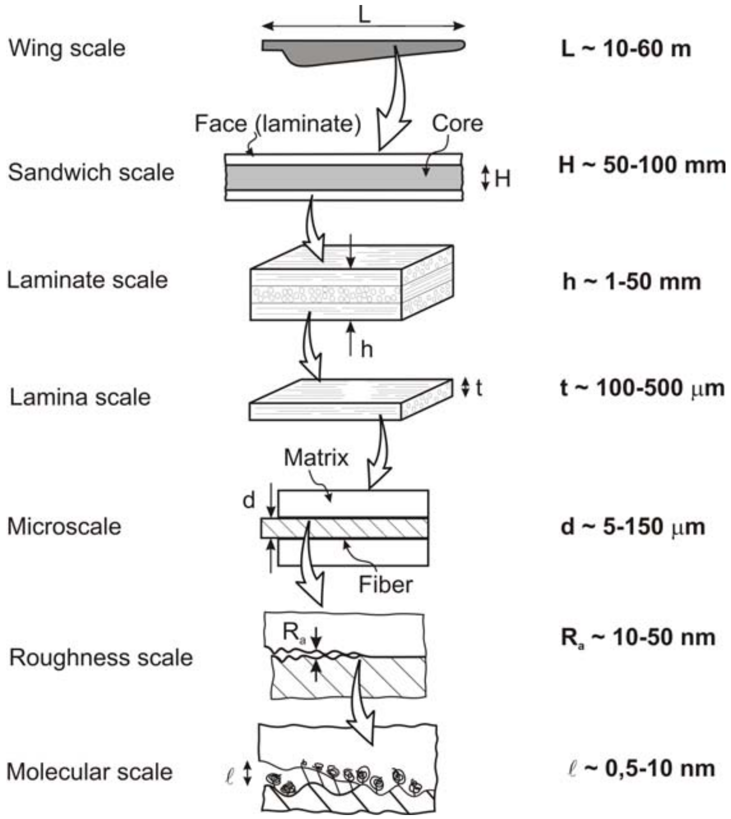


Figure 3: Design against failure of wind turbine blades can be considered at various length scales, from structural scale to various material length scales.

### 3.2. Better materials

As described in Section 2.2, wind turbine blades can fail by many different failure modes. Therefore, in the design phase (and in analysis of failure of wind turbine blades) it is necessary to use relevant failure criteria and the associated strength or fracture mechanics data must be known for the involved materials and interfaces. Fracture mechanics models of structural failures such as delamination and adhesive joint failure are under development [10]. In particular, the use of cohesive zone modelling allows modelling of delamination growth [6]. However, the accuracy of model predictions depends on the accuracy of the cohesive law input; determination of cohesive laws are limited [11]. Much more research is needed in this area. Failure of laminas is usually predicted using semi-empirical stress or strain based failure criteria such as Puch and Hashin [12]. These failure criteria operates on stresses in the lamina and do not include microscale parameters. A future research goal is to develop failure criteria that include microscale parameters. This link is required to add fundamental knowledge to the failure criterion and will provide insight into the area of development of stronger materials. Such models should be inspired by the real damage evolution at the microscale, which can be studied e.g. by the use of X-ray tomography [13]. The perspective is to reduce the sensitivity of materials to defects and damages by the development of materials that are more damage tolerant. An example is the use of materials that exhibits significant toughening due to large-scale fibre bridging [14].

However, there appears still to be potential for the development of materials that are more damage tolerant.

### 3.3. More uniform material quality

A more uniform material quality with less process-induced flaws can be obtained by reducing the variability in processing e.g. by increasing the quality control of raw materials and by increased use of automatisation for instance by the use of robots for accurate placement of plies and adhesives. A higher quality of the end-product can be ensured by the use of non-destructive techniques (NDT) such as X-ray imaging or ultra sound scanning for detection of flaws in the final blades. However, a complete understanding of how processing flaws develop into damages and cracks does not yet exist. Therefore, such criteria are to some extend empirical; rigorous criteria for flaws types and sizes cannot yet be prescribed.

### 3.4. Sensors for damage detection in blades in service

Structural health monitoring (SHM) is an approach where important parts of a structure are equipped with sensors that give output that allows the estimation of the residual strength or fatigue life of the component. The perspective is that by equipping wind turbine blades with sensors, manual inspection is only required for a few blades (those with sensor alerts). Thus, the cost of sensors and remote surveillance can be outbalanced by the cost savings of manual inspection [15]. The primary goals of SHM are (in order of importance): (1) to identify that damage evolution takes place, (2) the location of the damage, (3) the damage type, and (4) the size of the damage. The analogy to a modern car is obvious: A car has a number of build-in sensors. If a sensor detects an error, a red alarm light is turned on at the dash board. The driver takes the car to a workshop where the car mechanics has the knowledge and tools for repairing the car.

Several types of sensors can be used. The price and the type of information from various types of SHM sensors vary greatly. Sensors can be divided into point sensors, area sensors and global sensors [16]. *Point sensors* (e.g. foil strain gauges and optical fibres with Bragg grating) are very sensitive to stiffness changes, but measure only at the very positions where the sensors are placed. Thus, a total coverage of an entire wind turbine blade requires the use of a high number of point sensors; clearly this is not feasible. Point sensors will therefore be used in the most important areas only. *Area sensors* can detect damage in a much larger area (for instance, active and passive modes of acoustic emission can cover a few square meters around each sensor) and can be used for determining the location of damage. However, still relative many sensors are needed for full coverage of an entire wind turbine blade. *Global sensors* measures global responses of the blade (e.g. accelerometers that can be used for determining the eigenmodes). Obviously, the global blade response is less sensitive to damage and damage location. Furthermore, damage type identification is difficult to obtain by global sensors only. Therefore, most likely, a combination of point sensors, area sensors and global sensors will be required for high fidelity SHM.

It is of course very important that the sensors operate reliably over the entire projected life time of wind turbine so that false alarms are avoided and all significant damages are detected. It is therefore anticipated that sensors and surveillance systems will undergo extensive laboratory and pre-pilot testing prior to installation in commercial wind turbines.

An interesting perspective is that SHM may actually lead to a situation where more blades are allowed to develop damage, if the probability of damage detection by sensors is very high and reliably. The reason is that a decrease in the safety margin (so that slightly more blades develop damage) can lead to a significant reduction in the material consummation, and significant weight and cost savings.

### 3.5. Reliable methods for prediction of residual strength and fatigue life

But SHM cannot stand alone. Once a specific type (size and location) of damage is detected in a wind turbine blade, it is crucial to be able to assess the criticality of the damage. Approaches must be developed for modelling of each failure modes. The accuracy of the models should be assessed by case studies of simplified problems, such as the prediction of adhesive joint strength, accounting for a large-scale fracture process zone due to fibre cross-over bridging [17].

Modelling of an entire wind turbine blade for prediction of damage evolution is rather challenging, since the blade dimension is large, while high level of detailing is required for modelling of detailed damage evolution. This calls for either by multiscale modelling or by model refinement, e.g. by re-meshing parts of a 3D shell-model to 3D solid elements. Work is in progress in those areas [10].

### 3.6. Repair technology

Finally, if a certain type of damage has been identified, and a strength analysis has been carried out and it has been concluded that the damage decreases the residual strength (or fatigue life) significantly, the blade must be replaced or repaired. Again, since a very larger blades is very expensive, discarding the blade is not attractive. Consequently, repair will be preferred in those cases where it is possible to recreate most of the strength and fatigue lifetime. Repair of load-carrying composite is not new [18]. However, it seems that there is still a need for development of repair technology before the load-carrying capability can be fully retrieved. Typically, a repaired part only recovers maximum 80 % of the strength of an intact part [18]. Repair guidelines should be based on rigorous studies to ensure that the strength of the repaired structure is as high as possible. This may include the use of better (but more expensive) materials, such as nano fibre-reinforced resins or adhesives for adhesive joints.

## 4. SUMMARY AND CONCLUSIONS

This paper has presented an overview of the current state and future challenges in the area of structural design and materials for wind turbine blades. The current trend towards lager wind turbines placed offshore lead to several challenges for material science and mechanical engineering:

1. Weight savings become of increasing importance. Weight savings can be obtained by better design methods, better material models and better testing methods.
2. Blades that have manufacturing defects will be repaired, since large parts are costly and it is therefore very unattractive to discard them. Repair technology thus become of great importance.
3. Structural health monitoring and remote surveillance will be used increasingly to save costs for manual inspection. Calibration of various sensor types for various damage types is a crucial issue.
4. Reliable modelling tools must be developed for modelling of the damage evolution in wind turbine blades.

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