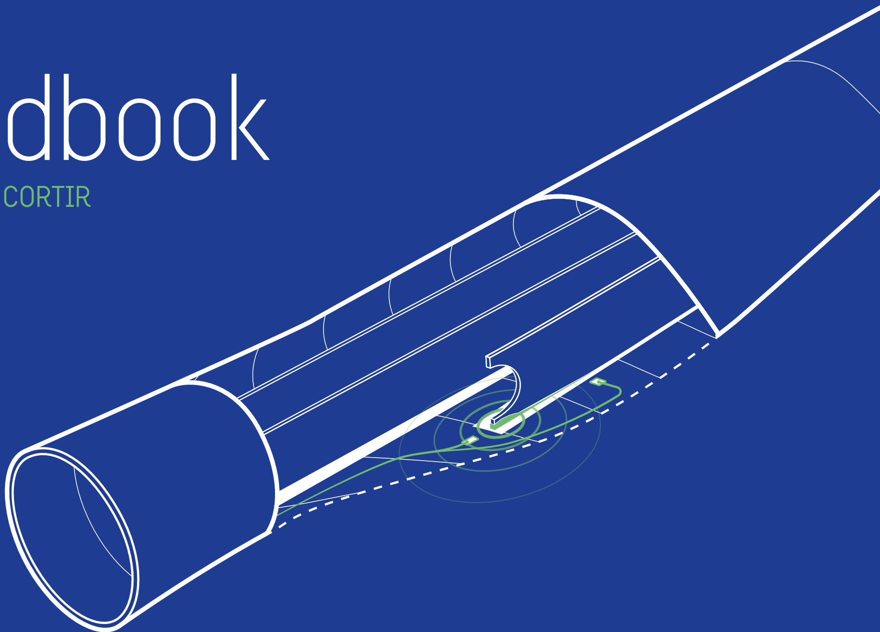
WIND TURBINE
BLADES

Handbook

Edition 2022 CORTIR



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Additionally, we would like to thank ReLife project partners for their contribution to further developing the handbook.

The Blade Handbook™ | A shared lingo of terms and definitions for wind turbine blades

Developed by Bladena and KIRT x THOMSEN in LEX, RATZ, EWIC and CORTIR Phase I & II projects mainly funded by EUDP (Energy Technology Development and Demonstration Programme)

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THE BLADE
HANDBOOK™

A shared lingo for the future of wind

CONTENTS

WHY A HANDBOOK

During the three EUDP projects LEX, RATZ and CORTIR Phase I & II, partners from all segments of the wind industry value chain have been involved in how to communicate with each other about wind turbine blades. In the industry many different ways of describing the same has been the reality. The reason for this handbook is to improve the common understanding of everyday blade related issues, to get a common language in the wind industry and to help newcomers to the industry with getting an overview. The present Blade Handbook is a direct further development of the RATZ Handbook.

Thus, this Blade Handbook is aimed at helping all parties involved in R&D of wind turbine blades to get a common understanding of words, process, levels and concepts.

PART I

1 | BLADE ANATOMY

Blade & cross section
Surface
Inside
Root
Load cases

2 | STRUCTURAL

Strain & Stress
Materials
Beam structure
Bending & Torsion
Local effects

3 | LOADS

Wind conditions
Turbulence
Aerodynamics
Structural dynamics

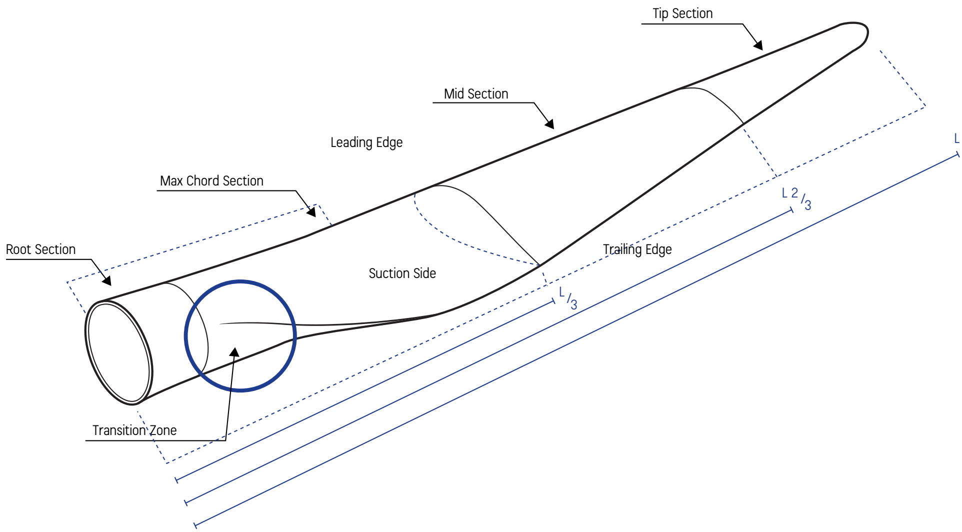
4 | VIBRATIONS

Aeroelastic instability

ANATOMY OF A BLADE

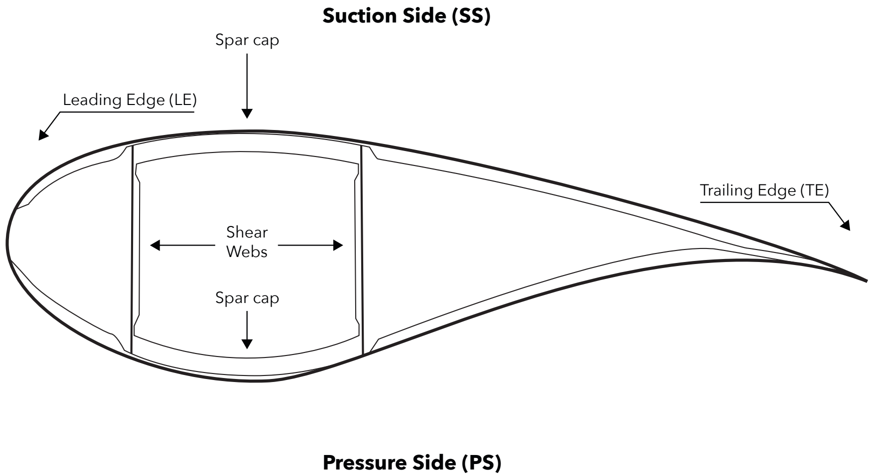
BLADE SECTIONS

A wind turbine blade is divided into different sections as shown

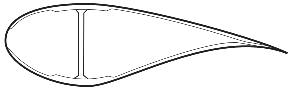


CROSS SECTION

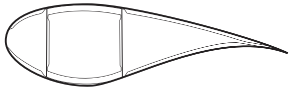
Blade cross section indicating main construction elements



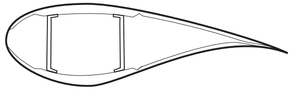
Types of cross sections



Closed shell



Box spar



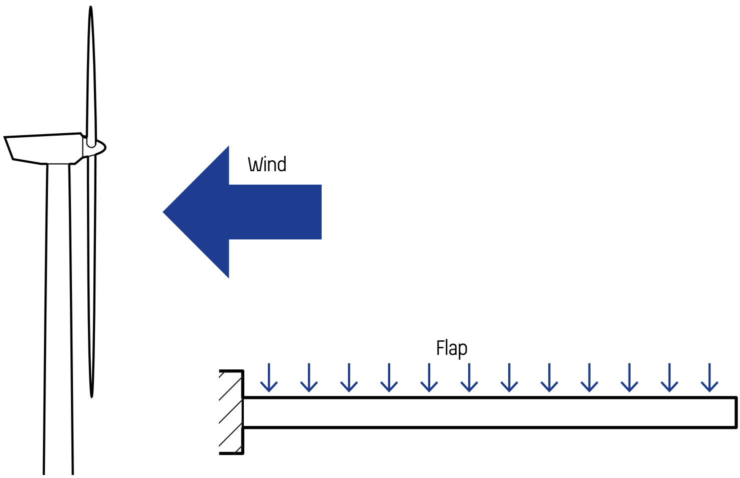
Load carrying shell

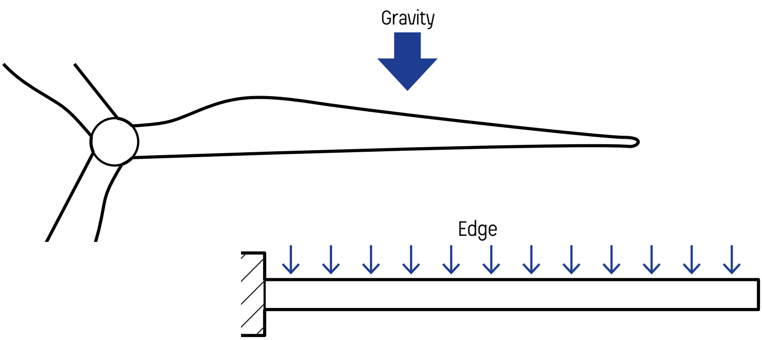
ANATOMY OF A BLADE

FUNCTION

The primary function of the blade is to capture the wind and transfer the load to the hub. This creates a bending moment on the root bearing, and a torque on the main hub.

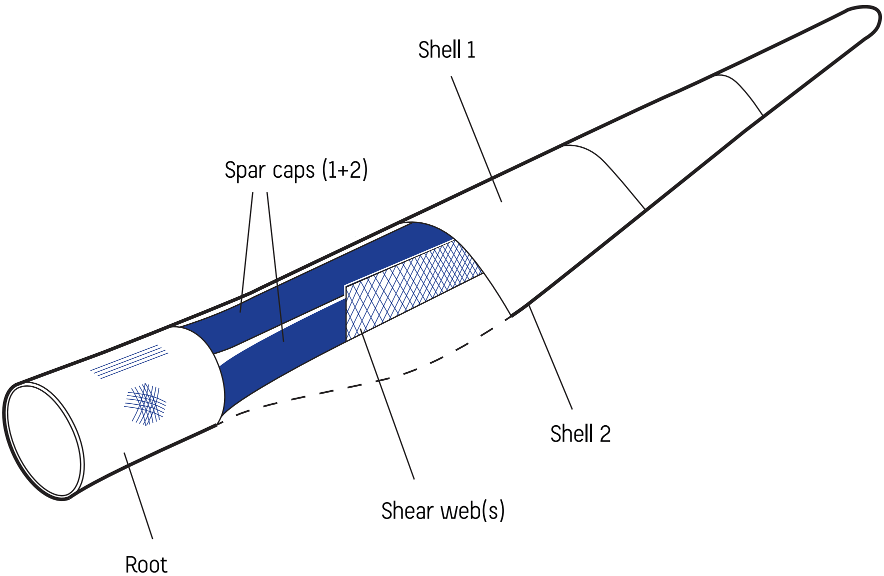
A blade can be regarded as a large cantilever beam





CONSTRUCTION

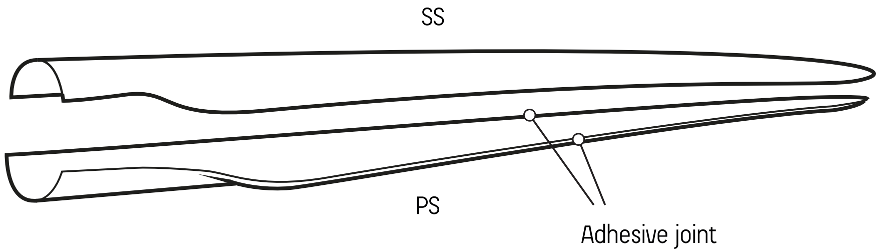
A blade can be segmented into 4 main parts, each parts fulfilling a specific function (shell, caps, shear webs, root).



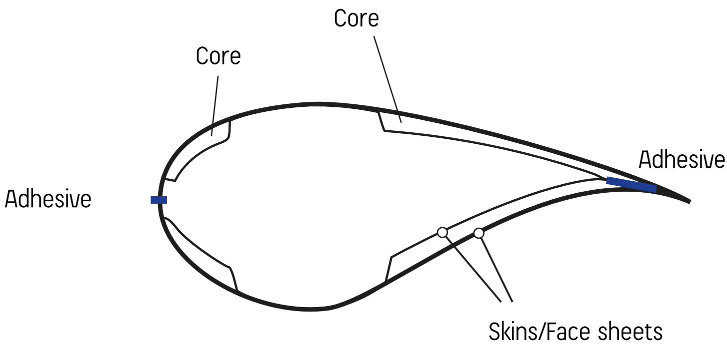
SURFACE

SHELLS

The SS and PS shells are large aerodynamic panels designed to transfer lift, created by the shells, to the spar caps.



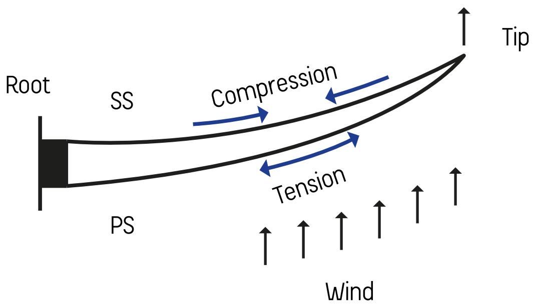
They are typically moulded in two blade shell tools (SS and PS moulds), and adhesively bonded to each other along their leading and trailing edge, and to the SS and PS spar caps in the middle. The shell skins are lightweight glass fiber skins (often 2 to 54 layers of triax material at 0, +45 and -45Deg), of low thickness; they therefore need to be stabilised by the use of a core (PVC or PET core, balsa, etc.). Without a core, they would buckle and would therefore not be able to keep their required profile.

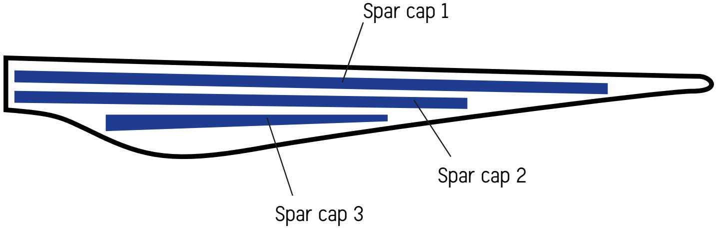


SPAR CAPS

The primary function of the spar caps is to pick up all the loads from the aerodynamic profile (PS caps working in tension, SS cap working in compression) from the tip to the root, and to transfer them in to the cylindrical root tube (working mainly in shear).

They are long, narrow and slender components; thick at the root end, thin at the tip end. They are mostly made of unidirectional fibers (0°) and some off-axis material (up to 20%), which makes them less sensitive to twist, torsion and other induced loads.



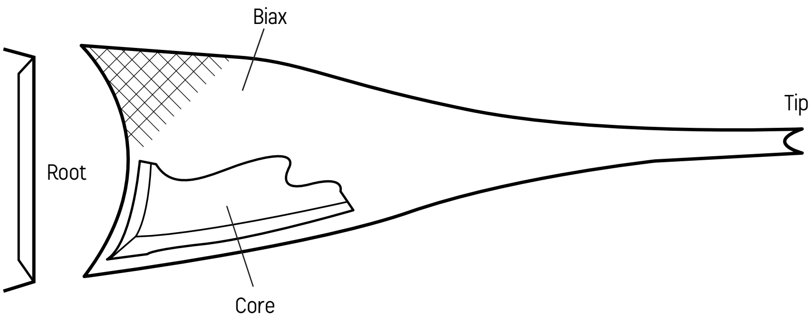


Several spar caps are found in large blades.

INSIDE

SHEAR WEBS

Shear webs are one of the simpler parts to design and manufacture. The primary function of the shear web(s) is to keep the PS and SS caps away from each other, allowing the blade to behave as a beam and retain its global stiffness.



They only carry shear loads, and the challenge from a design point of view is to stop them crushing and/or buckling.

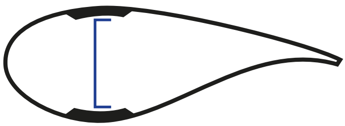
Construction is typically 2 to 8 plies of ±45° glass biax either side of a low density core (PVC, balsa, PET, etc.).

There can be one, two or three webs in a blade depending on length and design choices.

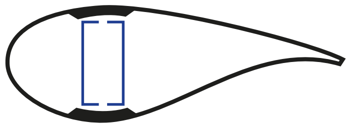
They sometime include feets or flanges, a transition where the skins join each others to facilitate the load transfer to the shells or spar caps.

SPAR CAPS

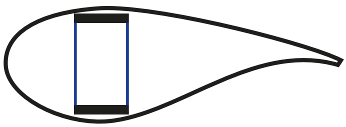
The scope of the spar caps is to increase the flapwise stiffness of the blade and to carry the shear loads from the webs to the root.



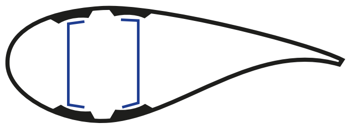
1 web, 2 caps



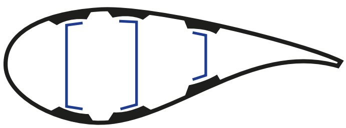
2 webs, 2 caps



Box spar



2 webs, 4 caps

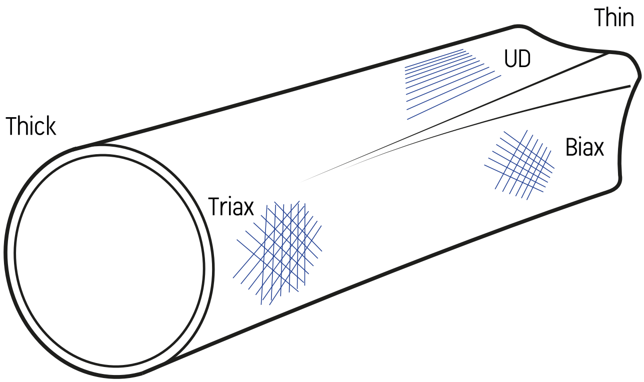


3 webs, 6 caps

ROOT

The primary function of the root is to transfer the bending moment of the blade to the root bearing in the most uniform way, without damaging it.

This is usually achieved by progressively re-directing the loads carried in the UD caps into the root tube, then into the metallic inserts that connect the root to the bearing.



The metallic inserts usually extend from the hub and between 10 to 20% of the blade length (R2.5 on a 25m blade, R9 on a 45m blade)

The root is typically a thick laminate, with a limited amount of fibers at 0° and most fibers at ± 45°.

The thickness is needed to accommodate the root bolts, that create weakness in the laminate.

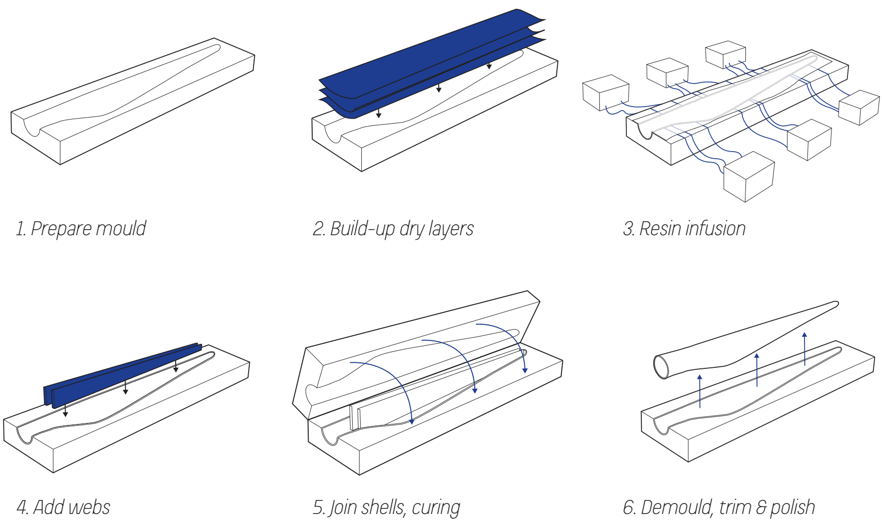
MANUFACTURING

The methods of manufacturing influence the lifetime of a wind turbine blade.

Blade manufacturing procedures can introduce conditions in the composite which strongly influence fatigue life and potential failures. These conditions include local variations in resin mixture homogeneity, local porosity variations, local fiber curvature and misalignment of fibers as well as local residual stresses. Such conditions are variables in all composite manufacturing processes and should be considered in design.

Regardless if the exact same manufacturing process is achieved with the exact same manufacturing conditions and materials, the composite specimen will never be completely identical to the previously manufactured composite specimen.

Typically if a blade has a pre-bend, the PS is the blind spot when the mould is closed. This increases the risk of manufacturing defects on the PS adhesive bondline.



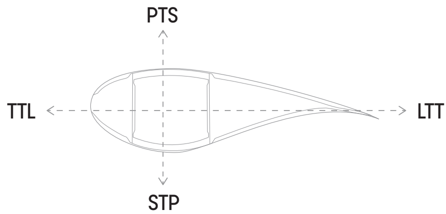
Generic steps of composite blade production

LOAD CASES

MAIN LOAD DIRECTIONS

FLAPWISE DIRECTION

- PTS - pressure side towards suction side
- STP - suction side towards pressure side

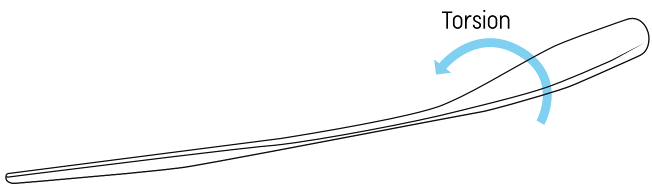


EDGEWISE DIRECTION

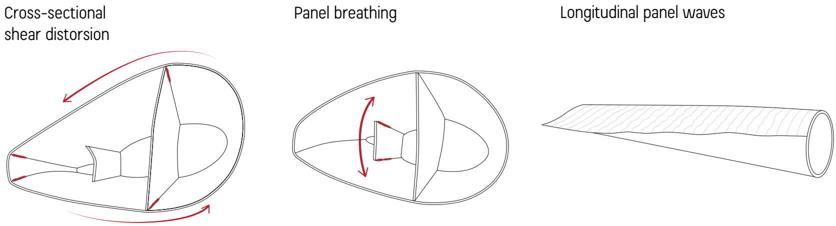
- TTL - trailing edge towards leading edge
- LTT - leading edge towards trailing edge

TORSIONAL LOAD (COMPONENT)

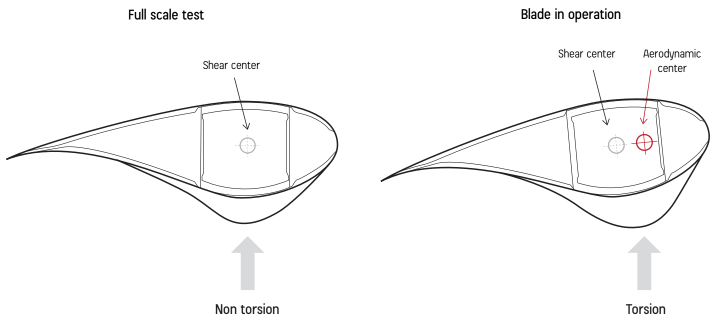
- Torsional load component generated by the combination of flapwise and edgewise loads, which increases exponentially with the blade length. The transition zone and max chord regions are mostly affected.



- Torsional loads are the main drivers for increased localized deformations in the transition zone and the max chord region of blades, hence driving structurally related failures.



- Torsion is not captured in full-scale testing. First, the loads are applied in the shear center; for that reason, the blade deflects in a pure flapwise or edgewise direction. Second, the stiff clamps used for load application do not allow the blade to deform locally, and therefore, the failure modes are not triggered.



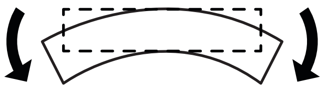
STRAIN & STRESS

When loading a structure, one can achieve direct response of stresses or strains. Strains are relative changes in length, and define the deformation of the structure. The stresses are the response of the material to the strains. The strain and stresses are coupled via the material model e.g. Hookes law.

AXIAL STRAIN

The strains are divided into axial strains (longitudinal and transverse strains) and shear strain. E.g. elongation of the individual fibers in the axial direction.

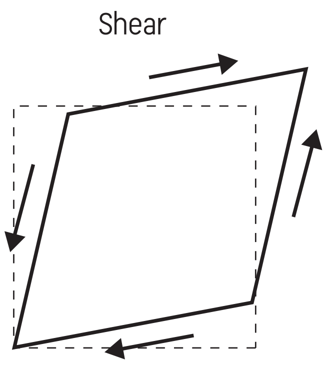
a) Axial strain due to axial load.



b) Axial strain due to bending.

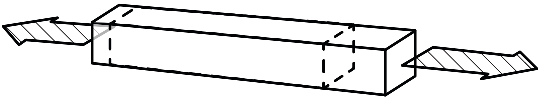
SHEAR STRAIN

The other type of strain is shear strains that changes the angles between fibers.

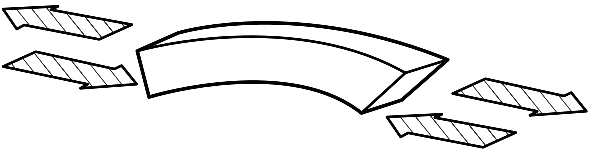


AXIAL STRESS

Similar to strains the stresses can be axial i.e. in the direction of the fiber. Axial stresses can be a result of bending of a beam or stretching a rod.



a) Axial stresses due to stretching a rod

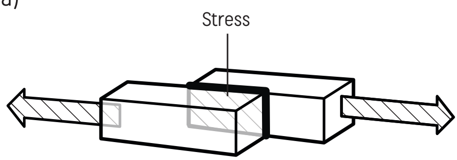


b) Axial stresses due to bending.

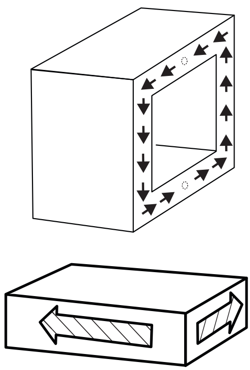
SHEAR STRESS

Another type of stress is shear stress and will be directed along the surfaces of the fibers. Shear stresses can be seen in overlap joints (a) or in torsion of a cross section (b).

a)



b)

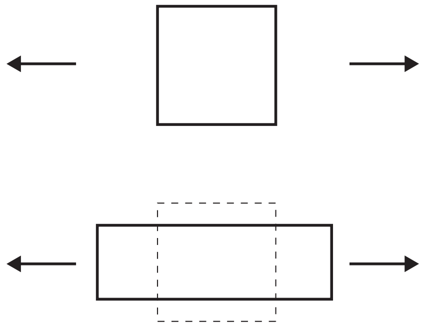


MATERIALS

ELASTIC BEHAVIOR

Materials can behave in many ways but for wind turbine blades the most important is the elastic behavior.

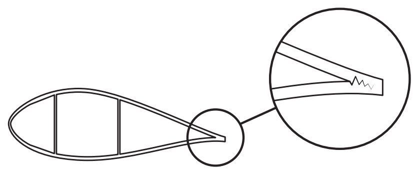
An isotropic material has equal properties in all directions. The properties are described by the Modulus of Elasticity (E) which defines the stress for a strain increment in a given direction and the Poisson ratio (ν) which defines the deformation perpendicular to the stress direction.



STATIC AND FATIGUE STRENGTH

Materials subjected to repeated loads may fail due to fatigue. The number of load cycles in a wind turbine blade is very large. The fatigue problems will often occur in bondlines where peeling stresses are high, due to bending in the panels, which will over time cause skin-debonding. Bending in the laminate will introduce interlaminar failure.

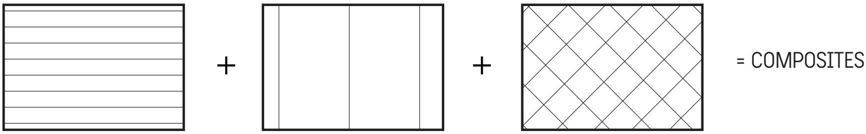
a) Load cycles over time.

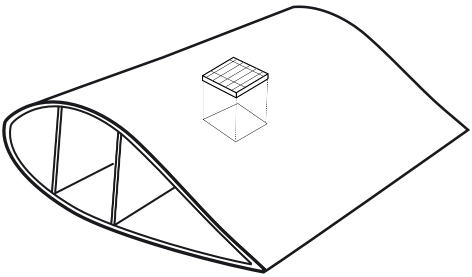


b) Example of fatigue cracks in the trailing edge due to peeling stresses.

COMPOSITES

Composites are a number of layers (laminas) bonded by a resin (matrix) creating an anisotropic material. An anisotropic material possesses directionally dependent material properties.



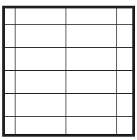


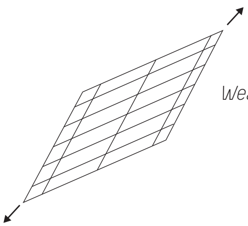
In composite materials the fibers can be arranged in many different ways, so that the strength and stiffness will depend on the direction in the material.

In a wind turbine blade there will be more fibers in the longitudinal blade direction in order to handle the bending of the blade. There will be fewer fibers in the transverse direction.

The directional differences makes the analysis more complicated as the secondary direction (the transverse) experience a small impact from the loads but also a low strength due to fewer fibers.

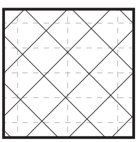
Fibers in 2 directions



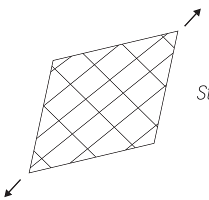


Weak in shear

Fibers in 2 directions



+ Biax (±45°)



Stronger in shear

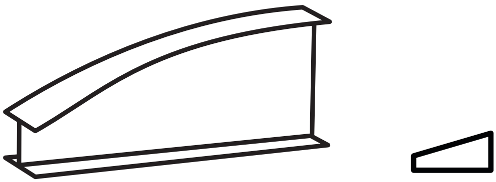
BEAM STRUCTURE

Wind turbine blades acts as a beam i.e. say a structure with a dominant length direction. Beams used in e.g. building design normally have constant cross-sections. For various design reasons the beam can also be tapered or twisted.

A

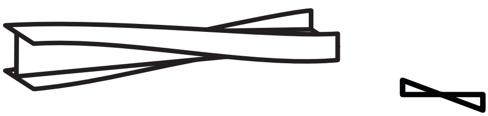
Constant

B



Tapered

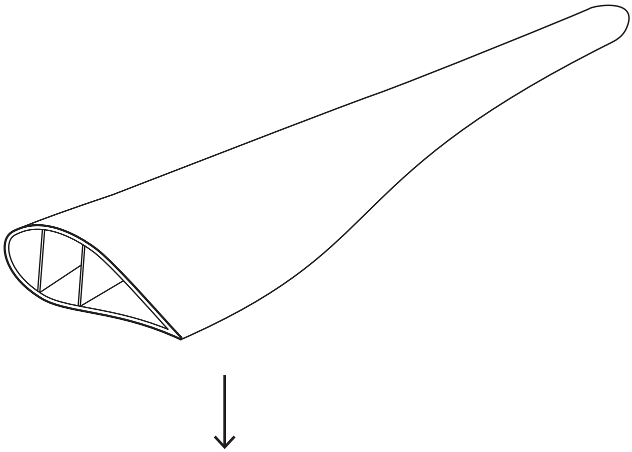
C

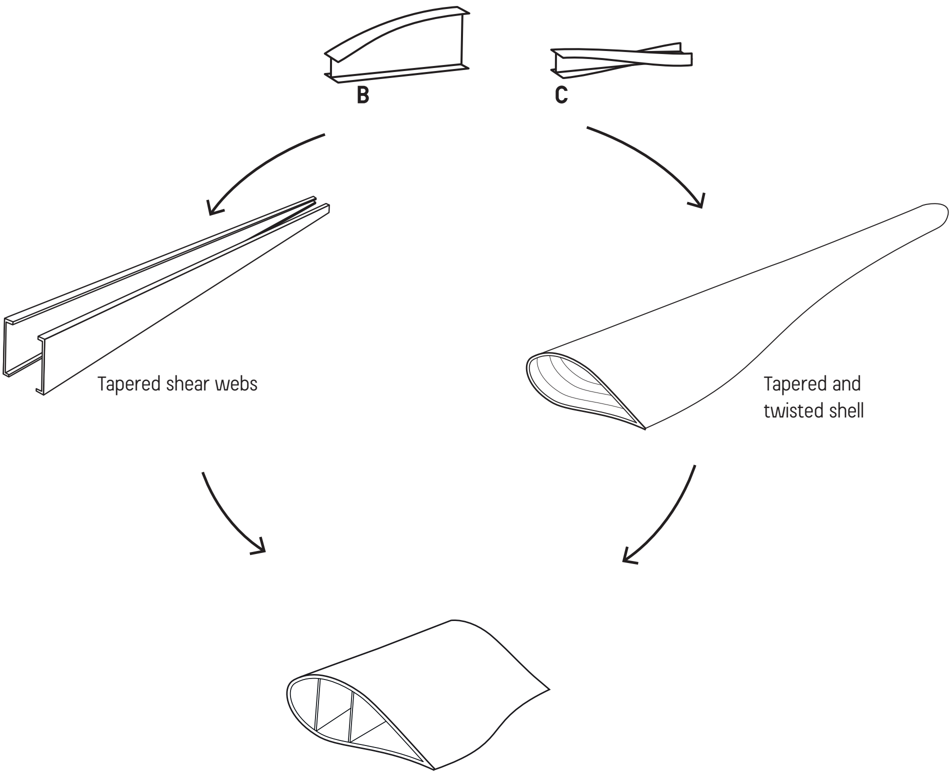


Twisted

IN A BLADE

A typical wind turbine blade will be both tapered and twisted. The shear webs are tapered longitudinally, while the aerodynamic shell is both tapered and twisted. The combination of the two results on a double tapered and twisted body.





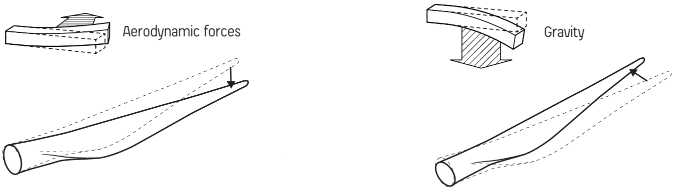
Together that is a PRE-TWISTED STRUCTURE
(eg. similar to a helicopter blade)

BENDING & TORSION

The load on a wind turbine blade in operation stems primarily from wind pressure, gravity and acceleration contributions e.g. centrifugal or inertial forces.

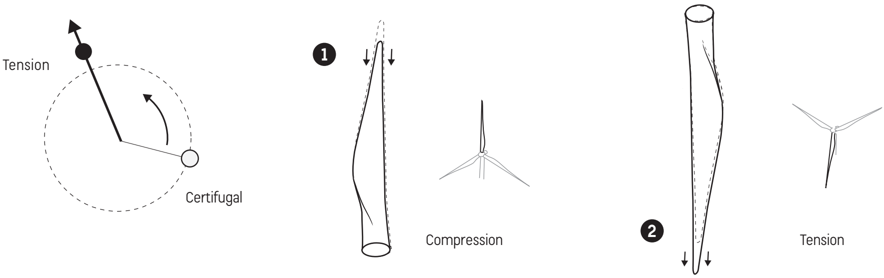
A. BENDING

The primary way of carrying the loads are through bending.



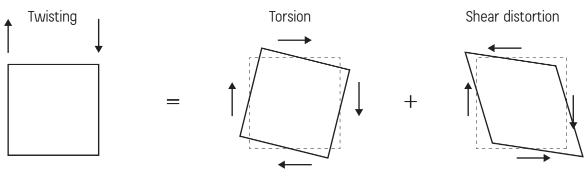
B. AXIAL FORCE

Gravity and centrifugal load creates an axial force which can be tension or compression.



C. TWISTING

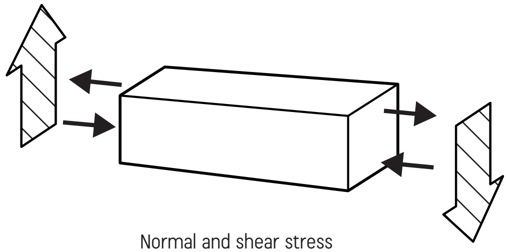
Wind loads act excentrical and creates twisting in the blade.



The twisting will give a rotation of the cross-section (Torsion) and a change in the cross-section (Shear distortion). Shear distortion becomes more dominant for larger wind turbine blades (60m+). The contribution is not covered by traditional beam theory, but will be seen in a Finite Element analysis.

BENDING + SHEAR FORCE → **NORMAL + SHEAR STRESS**

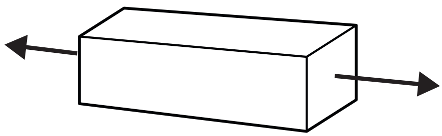
The bending moments create normal and shear stresses



Normal and shear stress

AXIAL FORCE → **NORMAL STRESS**

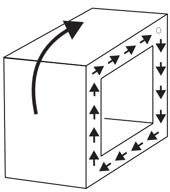
The axial force creates normal stresses

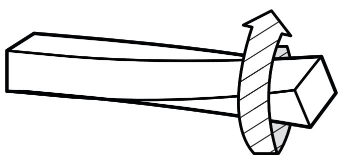


Normal stress

TORSION → **SHEAR STRESS**

The twisting moment creates primarily shear stresses in the blade. However the shear distortion may also create local bending and shear in the transverse plane of the blade, this may reduce the fatigue life of the blade. Torsional forces will increase the localized bending of the trailing edge panels in the max chord region.





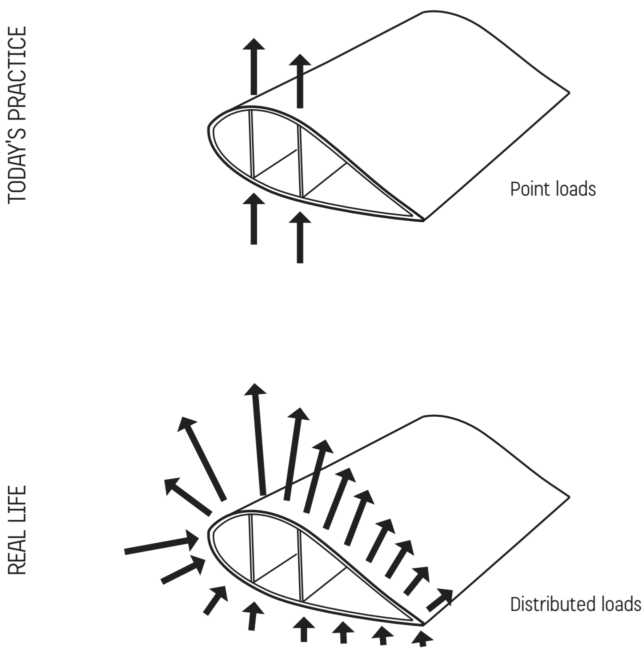
Shear stress

LOCAL EFFECTS

In classical beam theory the load perpendicular on the blade is not accounted for in detail. However wind load acting on the blade will create bending/shear in the transverse plane in the blade. These stresses may reduce the fatigue life of the blade.

BLADE TESTS TODAY VS REAL LIFE

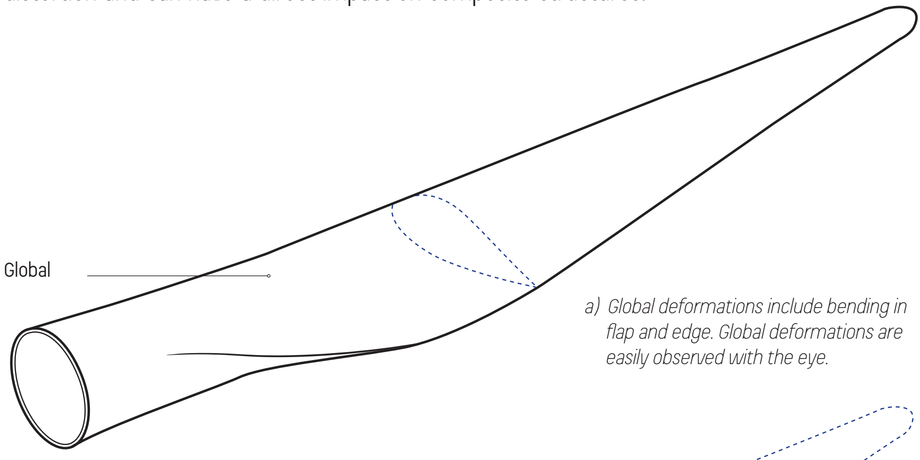
Wind loads are today referred directly to the stiff part of the structure, when load calculations and FEM analysis are being done, and this is not on the conservative side compared to a distributed pressure load closer resembling the actual load.



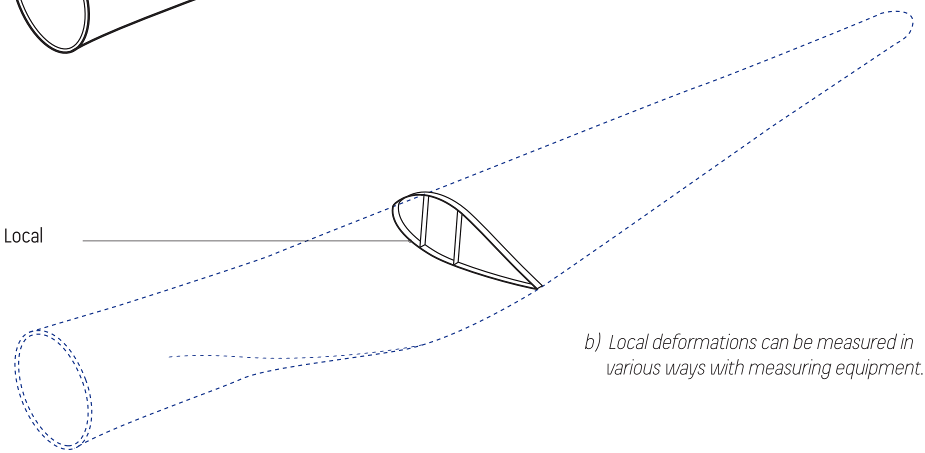
GLOBAL VS LOCAL

The wind load, gravity and centrifugal loads primarily give axial stresses in the blade direction and some shear stresses in the transverse plane.

The longitudinal stresses from the global deformation (bending) of the blade are far larger than the local stresses in the transverse plane. However, the blade design and material use successfully accommodate for the increased longitudinal stresses, while their transverse strength is typically weaker. Longitudinal stresses stem from the transfer of the load into the beam. The local stresses can e.g. be due to panel bending, buckling or cross sectional shear distortion and can have a direct impact on composite structures.



a) Global deformations include bending in flap and edge. Global deformations are easily observed with the eye.

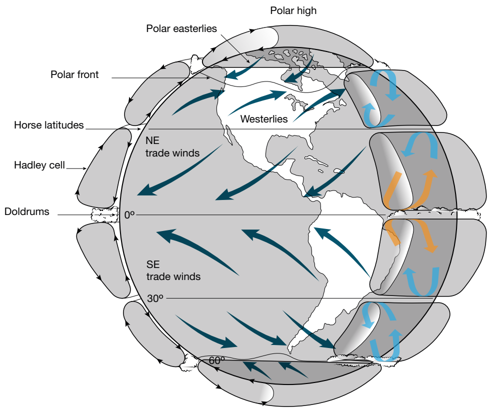


b) Local deformations can be measured in various ways with measuring equipment.

WIND CONDITIONS

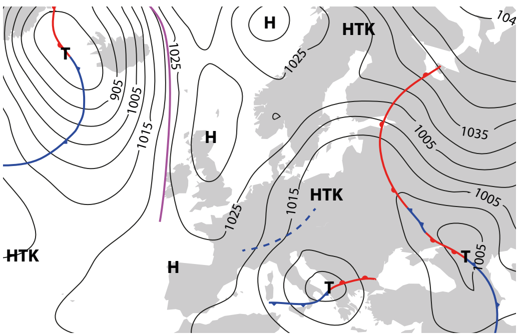
GLOBAL

The sun is the key source of the wind systems on the planet. The heat over equator causes rising air and flow near the surface from north and south. The Coriolis force "bends" the flow causing three layers of wind circulation zones on the Northern and Southern Hemisphere.



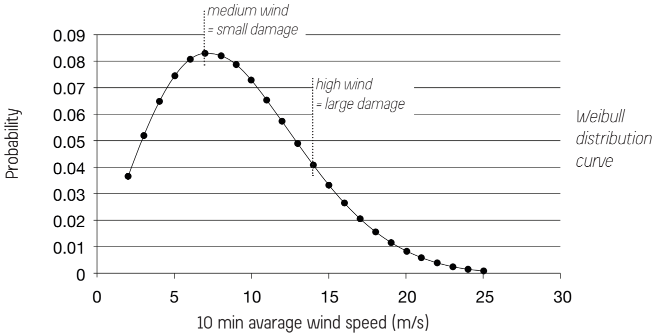
REGIONAL

More locally, but still on a large scale, the wind is driven from local high to low pressure regions. The flow is still "bent" due to the Coriolis force. These high and low pressure regions are responsible for the mean wind speed in timespans from hours to days.



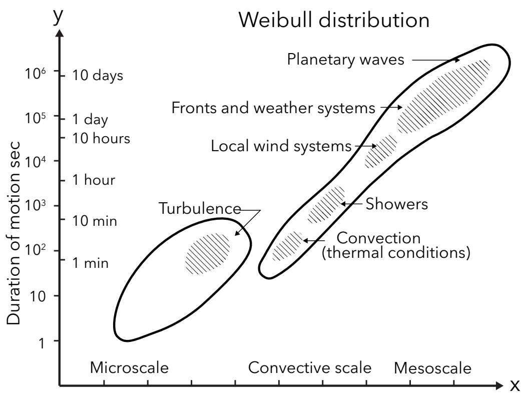
PROBABILITY

The probability density function of hours at a certain wind speed is typically given as a Weibull distribution.



SCALE & TIME

Weather system can roughly be classified into large system (meso-scale) driven by high and low pressure and a smaller scale (micro-scale) driven by local roughness of the surrounding terrain. The meso scale effects are important for the total power production, whereas the micro scale effects are important for the turbine load level. Notice the relation between vortex size in meters (x-axis) and duration in seconds/days (y-axis).

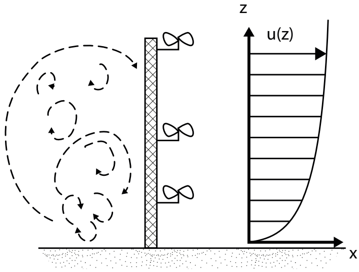


Courtesy Courtney, M, Troen, I. (1990). Wind Spectrum for one year of continuous 8Hz measurements. Pp 301-304, 9th symposium on Turbulence and diffusion.

TURBULENCE

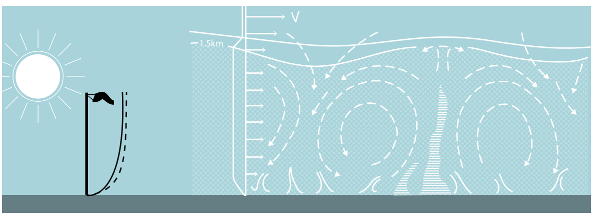
HEIGHTS

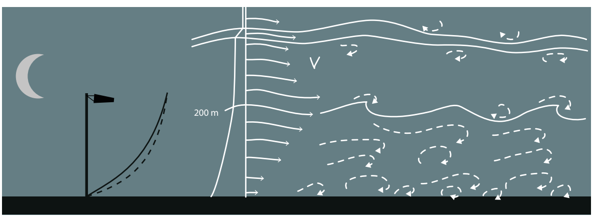
The type of terrain near the turbine has a friction level on the wind - also denoted a terrain roughness. The roughness causes a near surface boundary layer with increasing wind speed for increasing height.
The roughness also creates turbulent vortices with length scales increasing with height.



DAY VS NIGHT

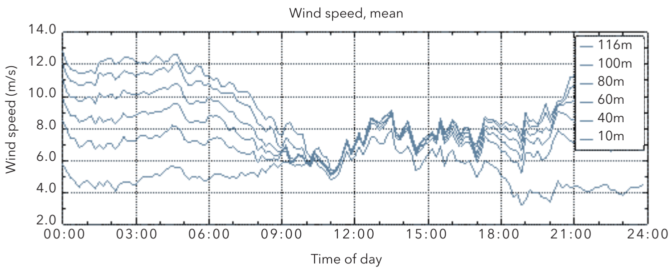
Temperature effects in the boundary layer has a direct impact on the turbulent flow. The mixing of warm and cold air near the surface causes unstable conditions yielding increased turbulent mixing - with a large shear in the mean wind speed.





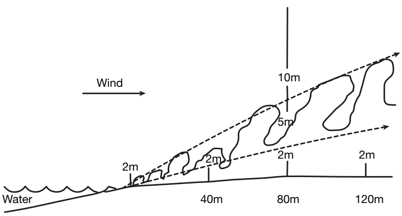
HEIGHT & TIME

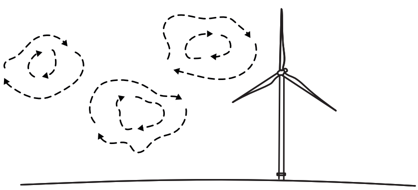
Measured wind speed in different heights at the Høvsøre test site. Cold temperature at night causes very stable conditions where the heating from the sun causes unstable conditions with a significant turbulent mixing.

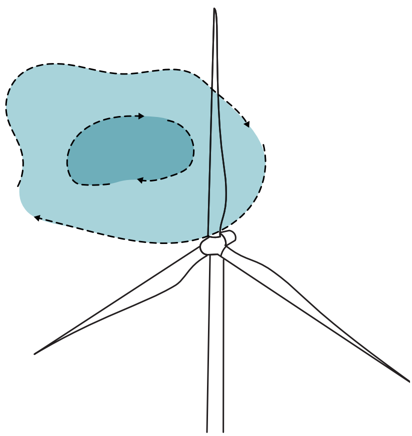


TERRAIN

A change in terrain roughness cause a change in tubulence regions with height. Here is an example of water - to - land change causing the lowest level to be dominated by high turbulence (land conditions), the highest level with low turbulence (water conditions) and an intermediate zone in between.



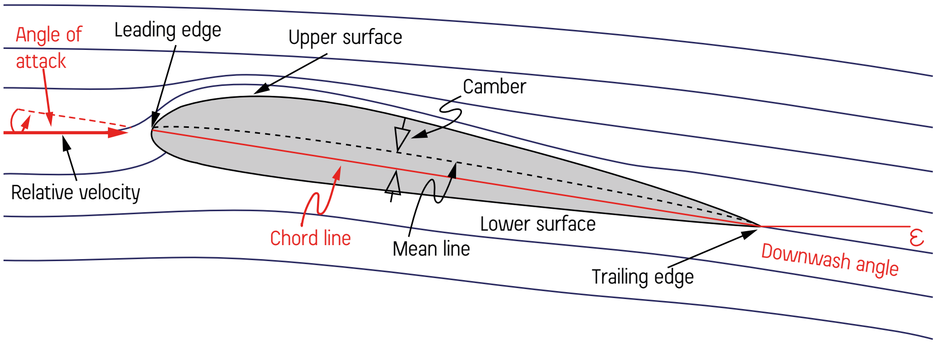




AERODYNAMICS

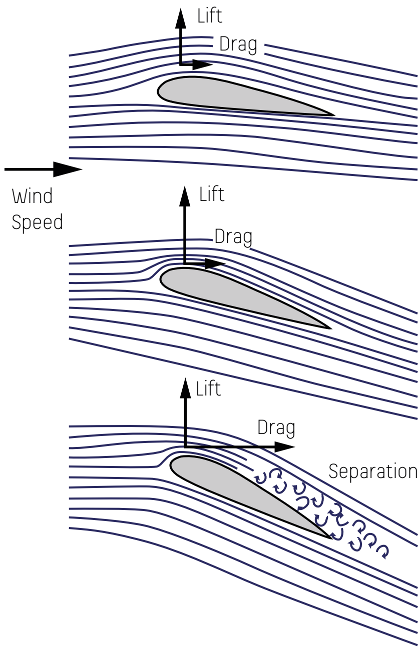
AIRFOIL TERMINOLOGY

2D airfoil terminology



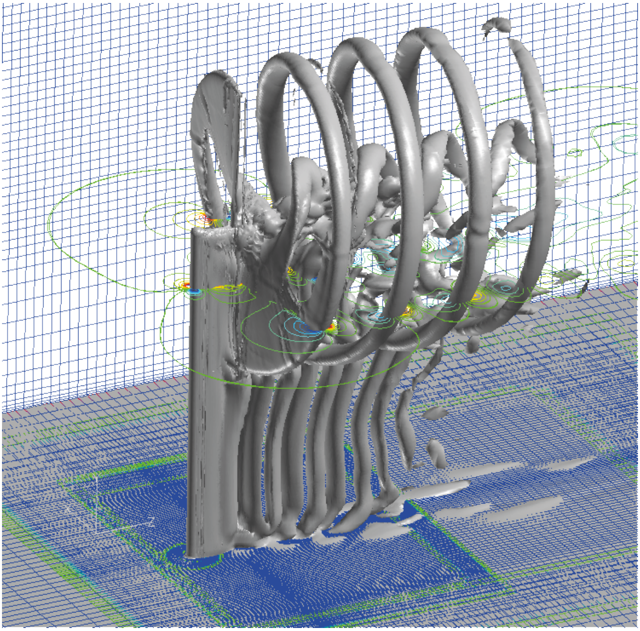
LIFT & DRAG

The presence of an airfoil in a flow will cause a bending of the air flow. As the air particles are forced downwards due to the pressure induced by the airfoil, there will be an equal sized reaction force from the flow to the airfoil. This is the lift force. For increasing angles of attack the lift force also increases until a point where separation occurs which lowers the lift and increase the drag force.



VORTEX

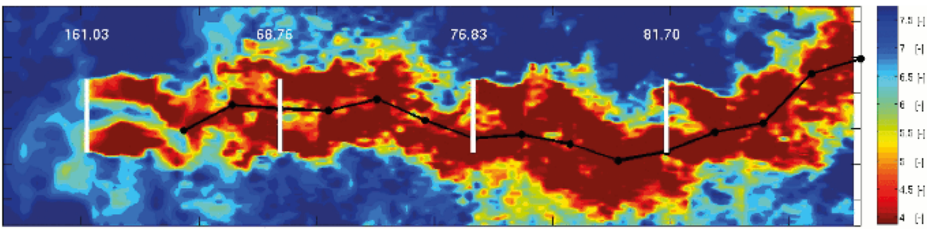
Detailed vortex system behind a turbine. (In this particular case a two-bladed downwind turbine). The tip and root vortex system can be seen as well as the tower shadow. Details of the aerodynamic rotor/tower interaction are seen on the right.



Courtesy Zahle, F., Sørensen, N. N., & Johansen, J. (2009). Wind Turbine Rotor-Tower Interaction Using an Incompressible Overset Grid Method. Wind Energy, 12(6), 594-619. 10.1002/we.327

1x wind turbine

WAKE EFFECT



Courtesy: Machefaux, E., Larsen, G. C., & Mann, J. (2015). Multiple Turbine Wakes. DTU Wind Energy. (DTU Wind Energy PhD; No. 0043(EN)).

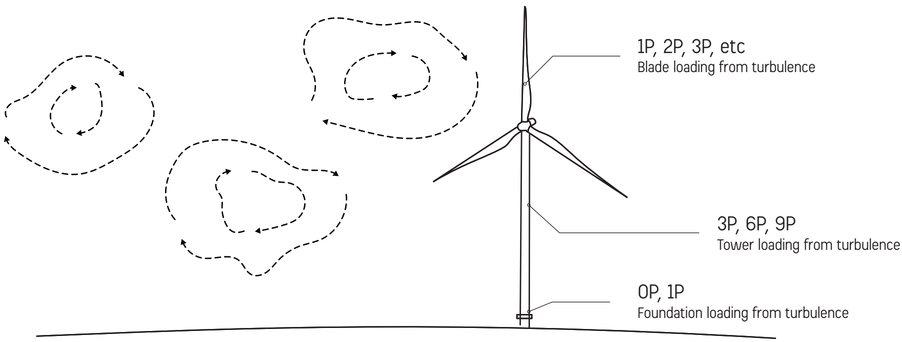
4x wind turbines

The wake effect is the aggregated influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the turbines on each other. This has a direct negative impact on the production and also causes increased load levels on the downwind turbines.

STRUCTURAL DYNAMICS

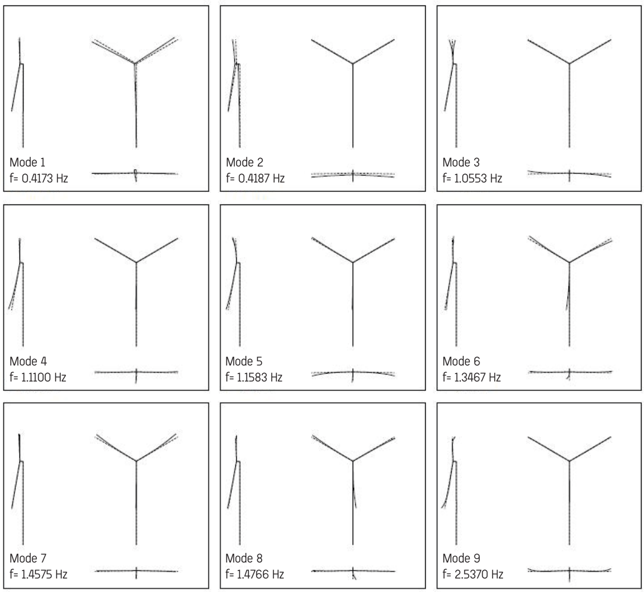
OPERATIONAL FREQUENCY

A wind turbine is a highly flexible structure. The blades deflect noticeable, but the tower and main shaft are also highly dynamic - and low damped dynamic systems.



MODE SHAPES

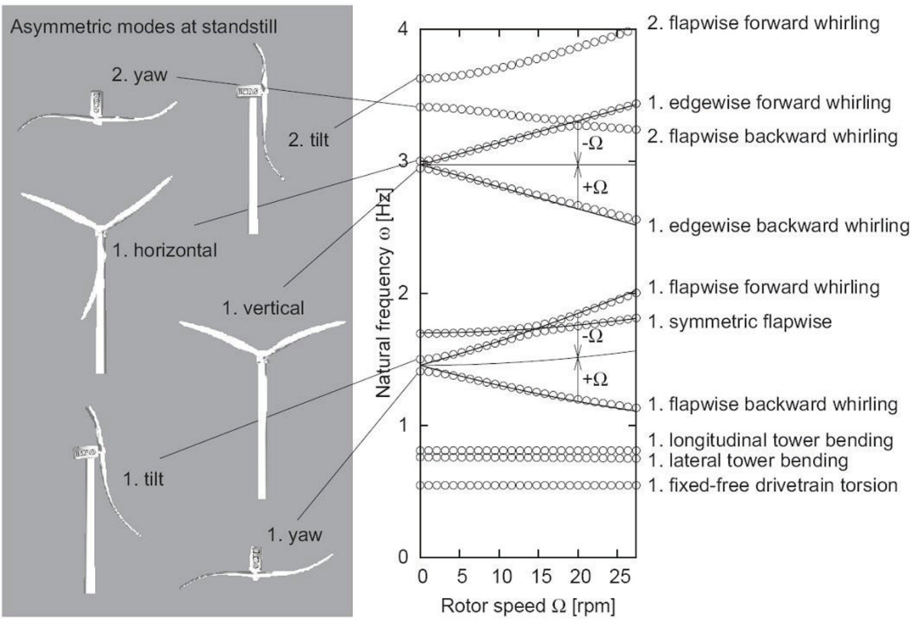
The order of mode shapes is more or less always the same. Frequencies decrease for larger turbines. The first two modes mainly consist of tower motion (lateral and logitudinal), the next three modes are dominated by blade flapwise bending, then two edgewise blade bending modes and above this the second blade bending modes appear. Mode shapes with frequencies above 5Hz do not normally contribute to dynamic loads on the structure.



Natural frequencies and modeshapes of a turbine in standstill with the rotor shaft locked.

NATURAL FREQUENCY DURING ROTATION

When the turbine rotates, the assymetric rotor modes change frequency. They enter whirl mode. The modes split up with +/- 1P seen from a fixed frame of reference (eg. the tower system). In a rotating coordinates system (following the blade) the blade frequencies remain the same as a standstill - but may be increased slightly due to centrifugal stiffening. The frequencies therefore appear differently depending on which component that is observed.



Courtesy Hansen, M. H. (2003). Improved modal dynamics of wind turbines to avoid stall-induced vibrations. Wind Energy, 6, 179-195. 10.1002/we.79

VIBRATIONS

NATURAL FREQUENCY

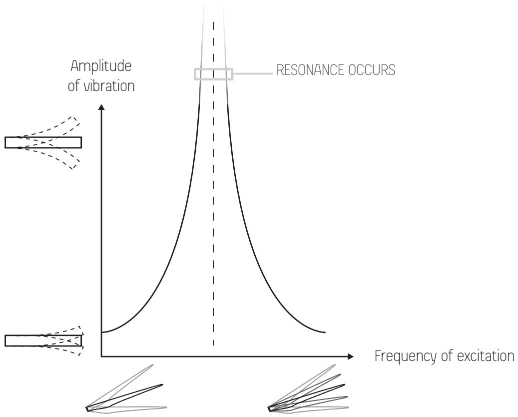
Blades have different natural frequencies depending on the direction of vibration i.e. flapwise, edgewise and twisting/torsion. Natural frequencies are the inherent frequencies which a blade will adopt its free vibrations when set in motion by a single impact or a momentarily displacement from its rest position, while not being influenced by other external forces. A blade has many different natural frequencies and each has its own distinct mode of vibration. However, the lower the frequency is - the larger the amplitude of that mode's vibration. Hence, in practice it is just a few of the lowest frequencies that are governing the overall vibration of the blade. The natural frequencies of a blade are given by the stiffness, mass-distribution and damping of the structure.

RESONANCE

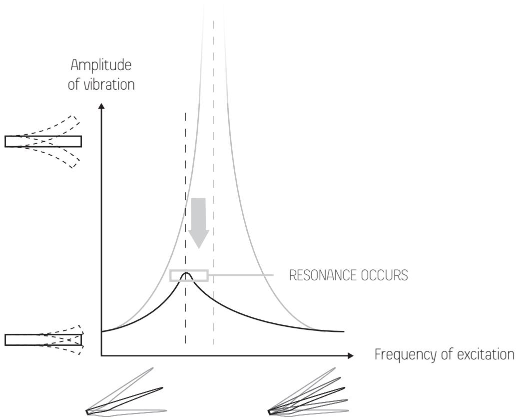
Resonance can occur when a blade is excited by external periodic forces at a frequency close to one of its natural frequencies. Small periodic forces at a resonant frequency can build up to produce large and violent oscillations of the structure. If the resonance occurs, the structure could in the worst case collapse.

DAMPING

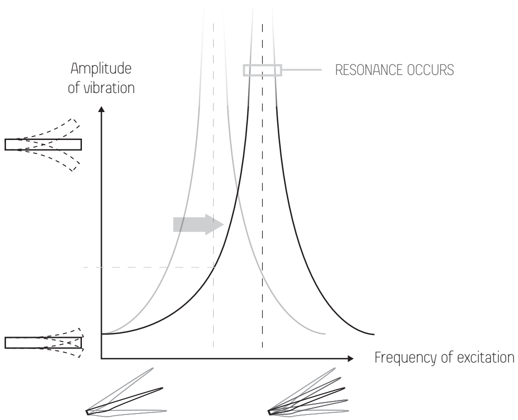
Damping reduces the amplitude of vibrations in a structure by dissipating energy from the system. Energy can be dissipated in the structure due to friction and generation of heat or by means of mechanical devices i.e. a viscous damper (dashpot).



NO DAMPING



WITH DAMPING



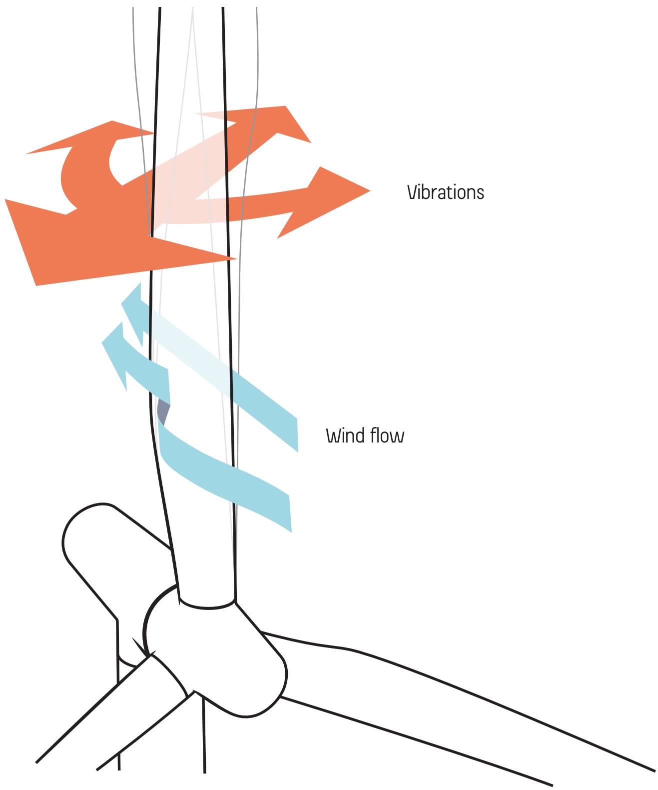
INCREASED
STIFFNESS

AEROELASTIC INSTABILITY

TWO PHENOMENAS

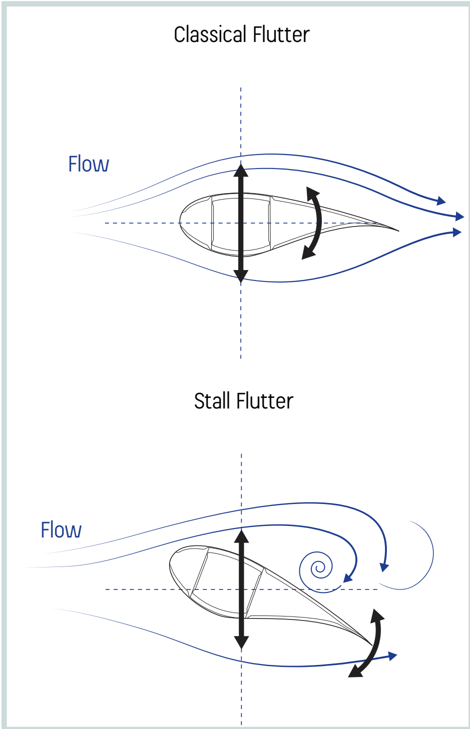
The phenomenon of aeroelastic instability, also called flutter, can occur due to the structural flexibility of wind turbines. Structural deformations induce changes in aerodynamic forces, i.e. operation above rated speed or during standstill or parked position. The additional aerodynamic forces cause an increase in the structural deformations, which lead to greater aerodynamic forces in a feedback process.

The additional forced vibrations interacting with one or two of the blade natural modes of vibration can result in violent self-feeding vibrations - such as classical flutter, stall flutter and galloping. Self-feeding vibrations might result in catastrophic structural blade failure, if resonance occurs.



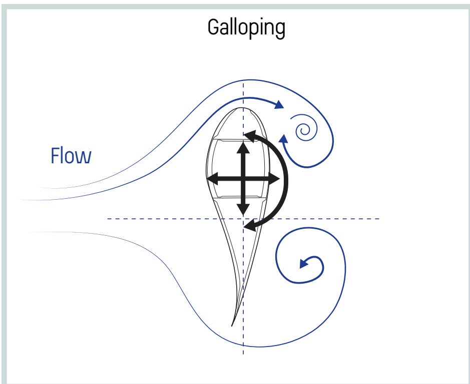
CLASSICAL FLUTTER involves the coupling between torsional- and flapwise-vibration.

STALL FLUTTER involves the coupling between separated and attached flow to the surface of the blade in a cyclic manner.



IN OPERATION

GALLOPING involves only separated flow over bluff structures.



PARKED / STANDSTILL

PART II

5 | FAILURES

Failure modes
Root causes
Safety margins

6 | TESTING

Hybrid testing/hybrid simulation

7 | DIGITAL TWIN

Validation process

8 | DAMAGE & DEFECTS

NDT

9 | FRACTURE MECHANICS

Fracture modes
Crack loading
Cohesion strength in composites

10 | L.E. EROSION & LIGHTN.

Leading edge erosion
Lightning

FAILURE MODES (A)

The following table presents the blade failure modes and the loads that could result in blade failure. Consequently, the failure criteria are ranked with respect to their importance on the certification standards.

Failure Mode / Loads	IEC 61400-5 : 2020	IEC 61400-23 : 2014	DNVGL-ST-0376 : 2015	Used in industry	Uncertainty on tools
A. Buckling (non-linear approach)	(4)	(2)	(4)	YES	LOW
B. Bondlines (Peeling test)	(2)	(1)	(3)	(YES)	MEDIUM
C. Skin debonding from core (Test)	(2)	(1)	(3)	(NO)	MEDIUM
D. Interlaminar failure (Bending test)	(2)	(1)	(2)	(NO)	LOW
E. Strain based (failure criteria)	(5)	(5)	(5)	YES	LOW
F. Torsional loading	(3)	(3)	(3)	(NO)	LOW
G. Flutter	(5)	(1)	(5)	(YES)	HIGH
H. Edgewise vibrations	(3)	(2)	(3)	(YES)	MEDIUM - HIGH
I. Shear web disbonding	(2)	(1)	(3)	(YES)	LOW

Definition of the numbers is presented in the list below:

(1) There is no reference in the standard

(2) Standards use "should be considered"

(3) "Should be considered", but stronger statements compared to (2)

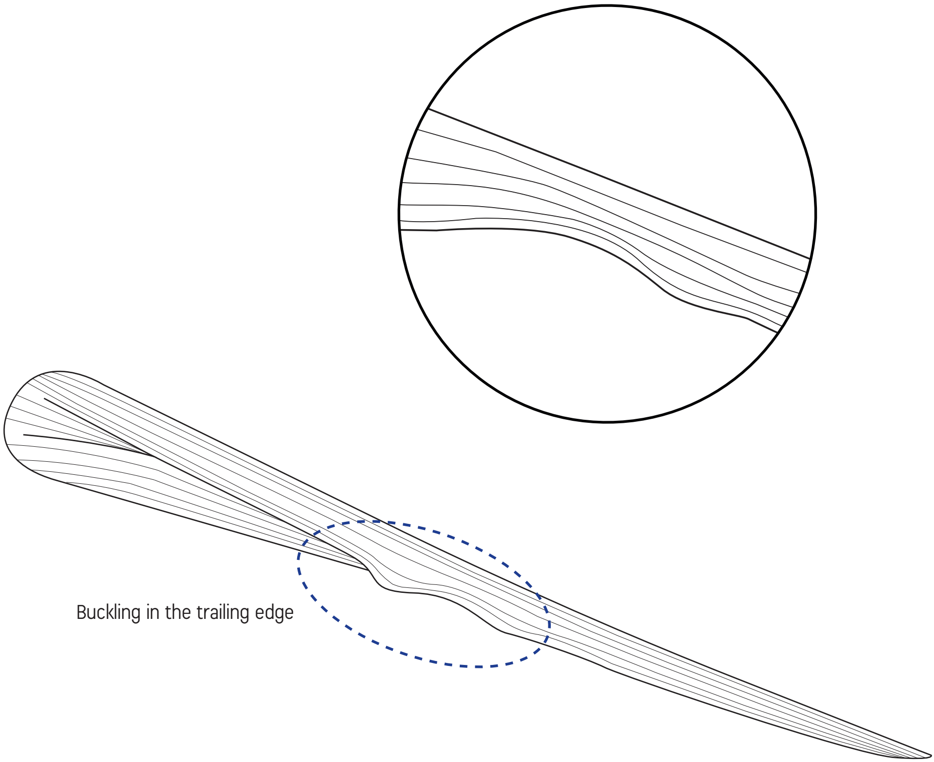
(4 Similar to required, but standards leave the door open for other approaches

(5) It is required in standards

A. BUCKLING

Buckling is a non-linear in-plane stability phenomenon. It can be predicted by non-linear FEM. Using a combined loading load case for both numerical simulations and testing will capture the phenomenon.

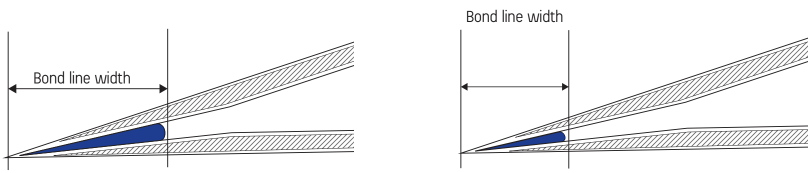
Premises of failure: The bending of the blade due to additional loads in the edgewise direction (inertial forces, added mass due to icing, etc.) and reduced buckling capacity of the blade in mid span creates premises for failure during operation.



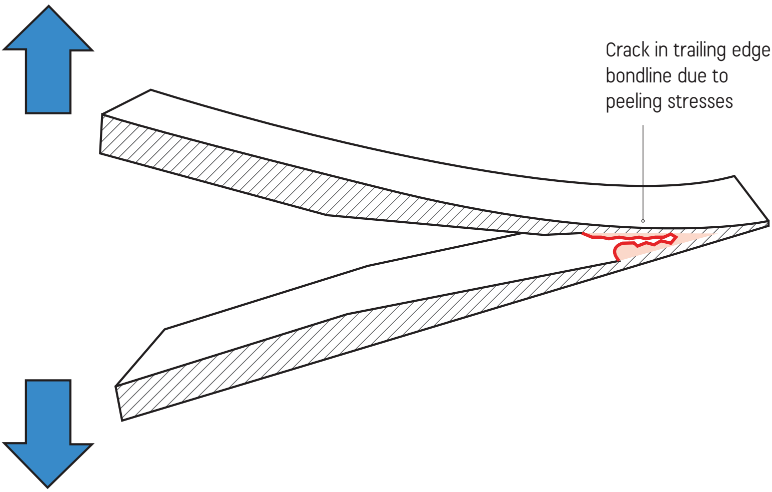
FAILURE MODES (B-C)

B. BONDLINES, TE

The magnitude of the peeling stresses is not influenced by the bond line width.
The peeling stresses will have the same magnitude regardless of the width of the bond lines.

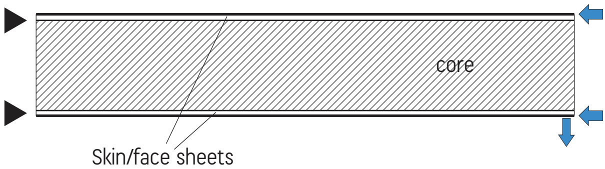


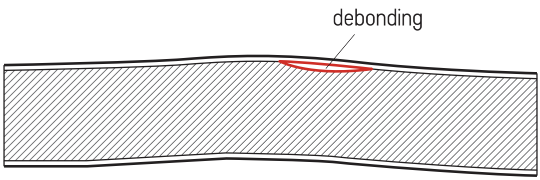
Different lengths of the bond line



C. SKIN DEBONDING

Skin debonding refers to the detachment of the skin from the core material. Full-scale testing or subcomponent test can be used to capture this.

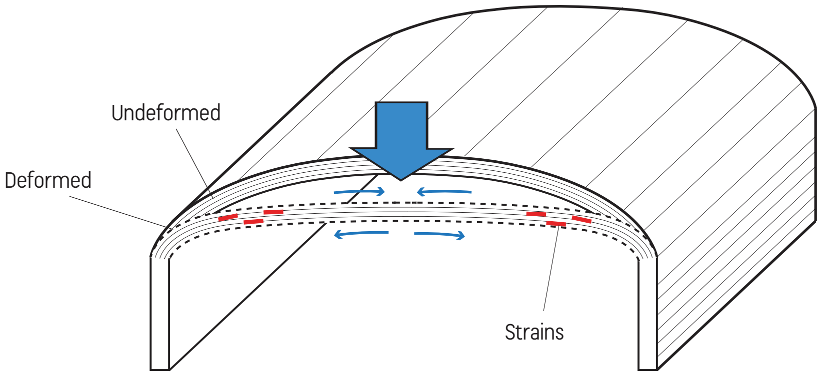




FAILURE MODES (D-E)

D. INTERLAMINAR FAILURE

Bending of the laminate causes interlaminar failure



E. STRAIN BASED FAILURE

Strain based failure criteria is not valid for wind turbine blades composites due to:

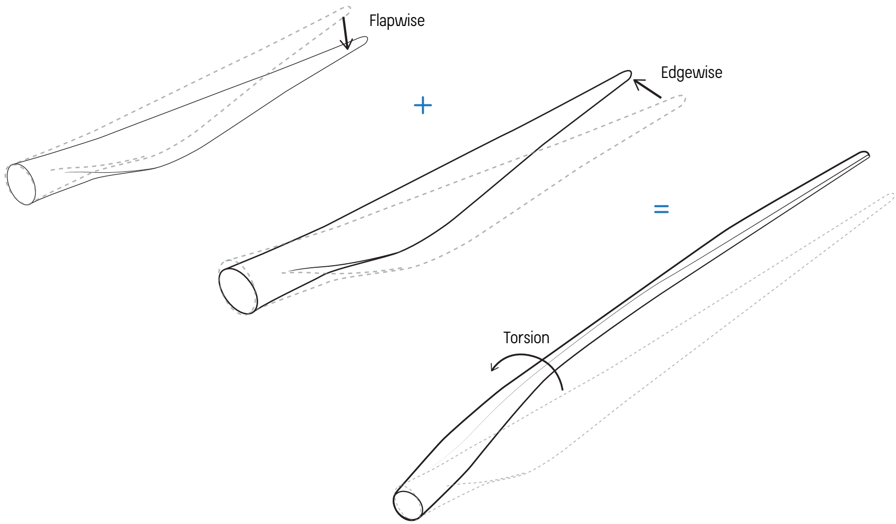
- In-plane strain levels are much lower than the actual capacity of the fibers
- Bending generates interlaminar stresses and peeling in bondlines that could cause failure

Wind turbine blades have thick laminates which are very strong in the fiber direction but very weak in out-of-plane direction that will lead to delamination. Due to the airfoil shape of wind turbine blades and the structural design with unsupported panels, the laminates experience bending that causes out-of-plane stresses. While in-plane loads are effectively carried by fibers, out-of-plane loads are controlled by matrix strength which it is sensitive to the presence of defects such as porosity and debonding. For wind turbine blades strain based failure criteria is not relevant since it does not identify the major blade failure modes (buckling, bondlines, skin debonding and interlaminar failure).

LOADS (F-G)

F. TORSIONAL LOADING

Torsion is a combined load, which is a result of flapwise and edgewise loads during operation, twisting the blade around its longitudinal axis.



Torsion, even if it is a realistic load scenario in the field, is not fully captured during the certification process. Blades are only tested with flapwise and edgewise loads applied, while torsion is only a "should be considered" condition.

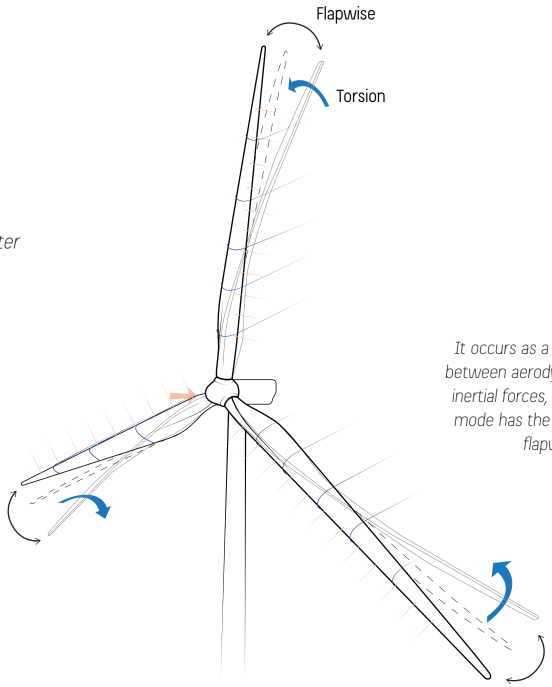
By not testing a blade under torsional loads, certain failure modes are not triggered. Therefore, any tolerances that were considered during the design and manufacturing process might be misleading with regards to the "true" structural integrity of the blade, making it more prone to failures.

G. FLUTTER

Flutter is an instability phenomenon encountered in long and slender flexible structures subjected to aerodynamic forces, such as wind turbine blades.

Flutter depends on:

- *Mass center*
- *Tip speed*
- *Aerodynamic center*
- *Torsional stiffness*
- *Bending stiffness*



It occurs as a result of interactions between aerodynamics, stiffness, and inertial forces, e.g., when a torsional mode has the same frequency of a flapwise mode.

If structural damping is insufficient in damping out the motions created by aerodynamic energy added to the blade, flutter occurs.

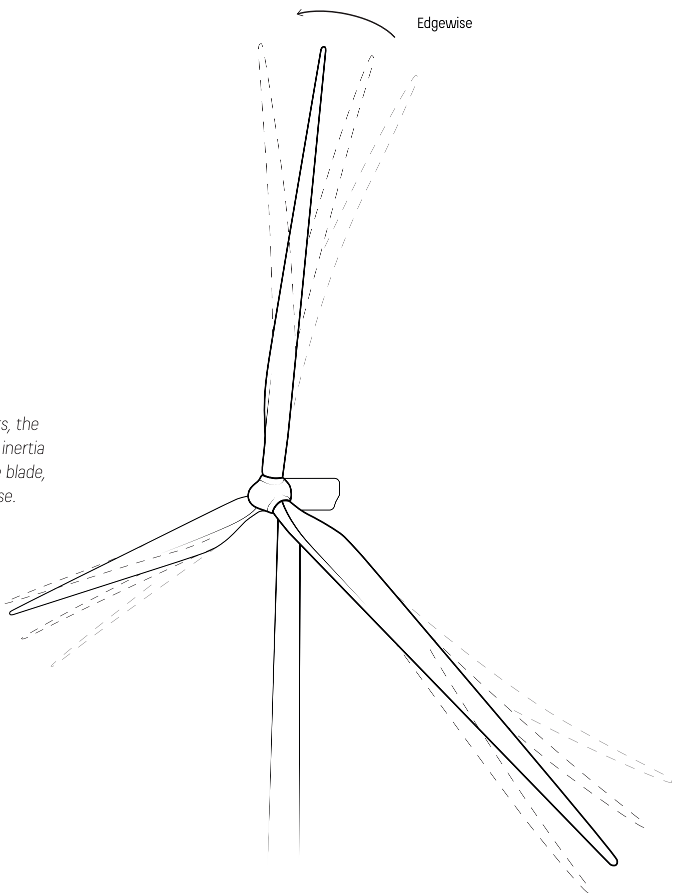
Blade tip speed and center of mass are two key parameters that influence flutter, hence larger blades are more prone to this failure mode due to the trend of increase in blade length.

LOADS (H-I)

H. EDGEWISE VIBRATIONS

Edgewise vibration is an aeroelastic instability phenomenon that results in large amplitude vibrations of a blade, leading to its failure. The edgewise vibration limit is very dependent on several parameters.

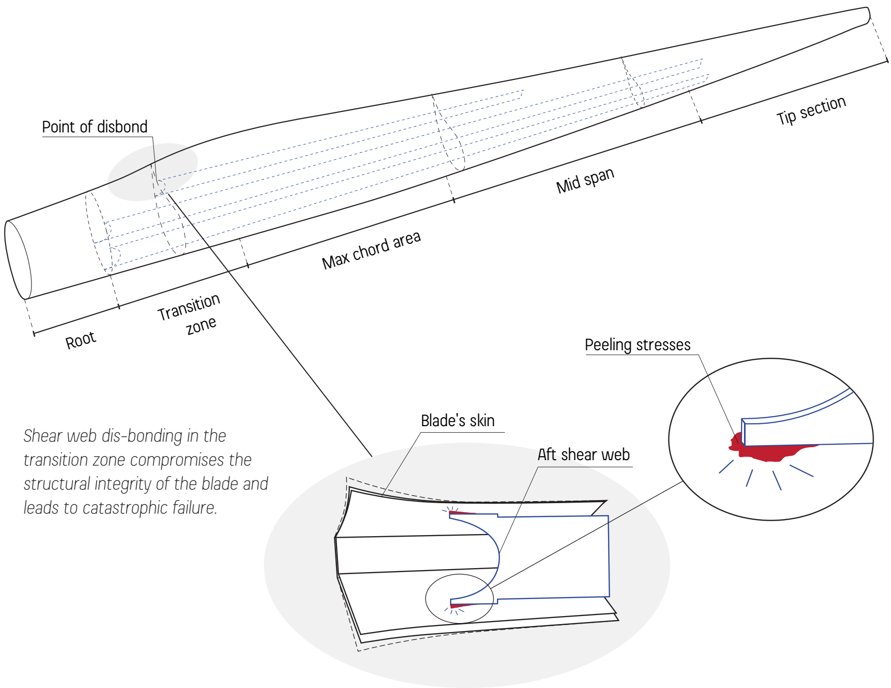
Edgewise vibrations were not relevant for small or medium size blades. This phenomenon is dominated by the eigenfrequencies, which reduce as the blades grow larger.



When resonance occurs, the increased loads due to inertia forces will overload the blade, resulting in total collapse.

I. SHEAR WEB DISBONDING

Shear web disbonding is a bond line failure between the spar cap and the shear web due to out-of-plane deformation (panel breathing) in the root transition zone of the blade.



Shear web dis-bonding in the transition zone compromises the structural integrity of the blade and leads to catastrophic failure.

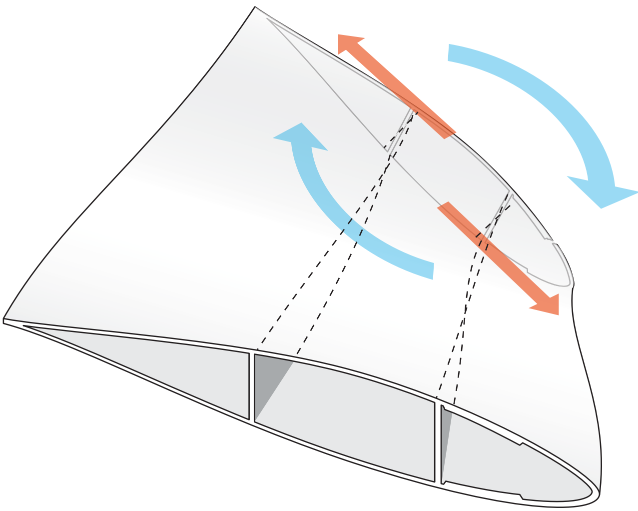
ROOT CAUSE 1
SHEAR DISTORTION

OPERATIONAL FATIGUE

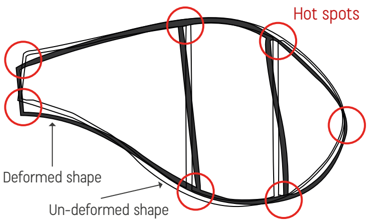
Normal operation

> Cross sectional shear distortion (CSSD)

> Bondlines damage

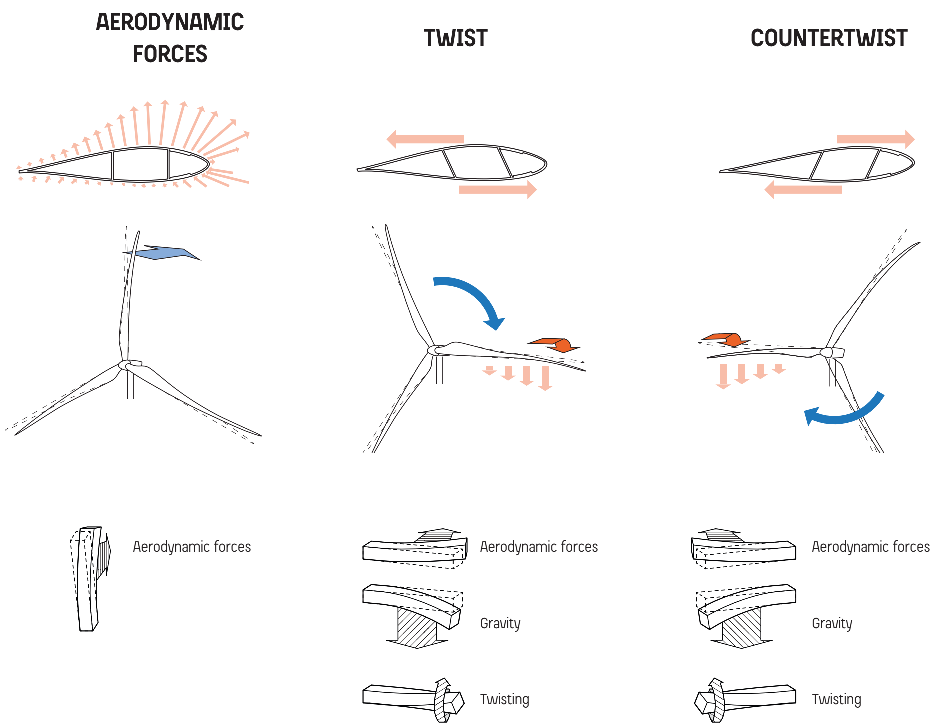


Bondlines damage



Peeling stresses appear in the adhesive bondlines along the blades in certain hot spots

The combination of edgewise loads and aerodynamic forces result in load combinations which could end up into a critical cross sectional shear distortion. This distortion gives a deformation that can lead to bondlines damage.

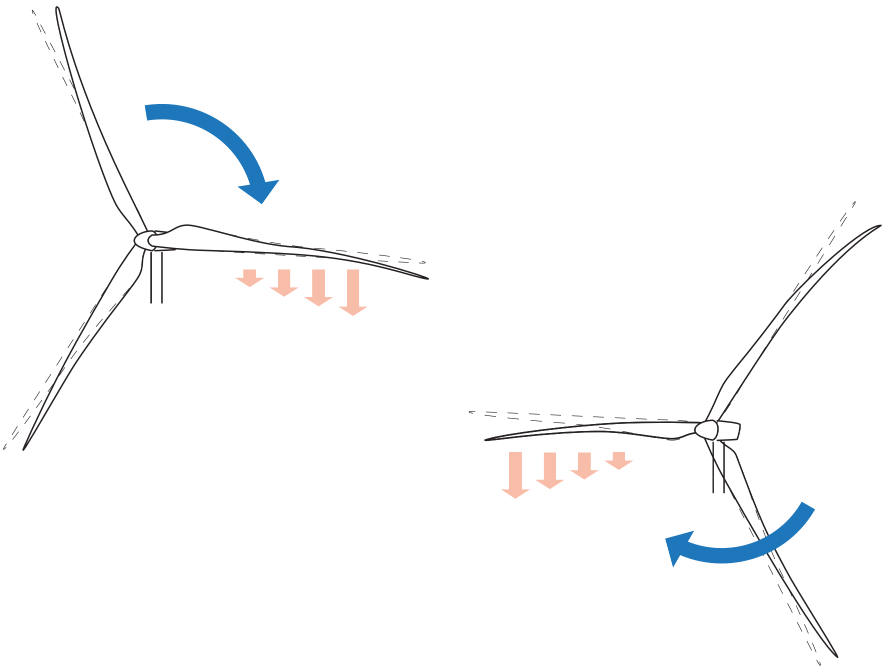


ROOT CAUSE 2
PANEL BREATHING

OPERATIONAL FATIGUE

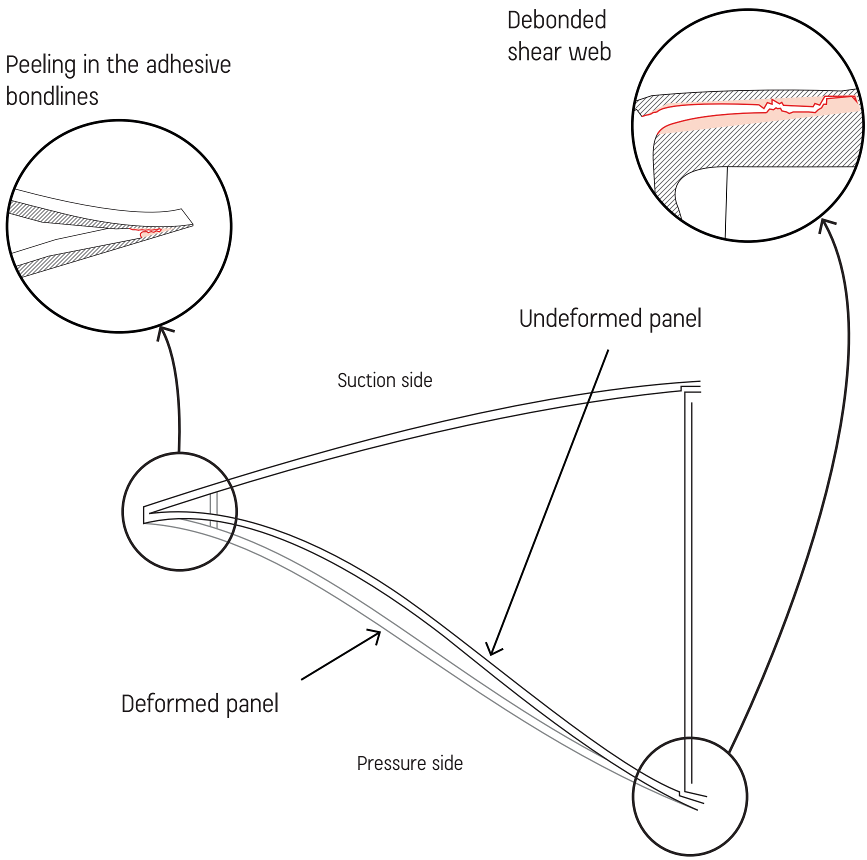
Normal operation
> Panel breathing
> Bondlines damage

Blade panel deformations induced by edgewise gravity induced loads during any operation of any wind turbine makes the panels breath.



BONDLINES DAMAGE

There is a direct connection between the breathing and the peeling stresses in the adhesive bond lines: The higher the magnitude of breathing, the higher the peeling stresses.



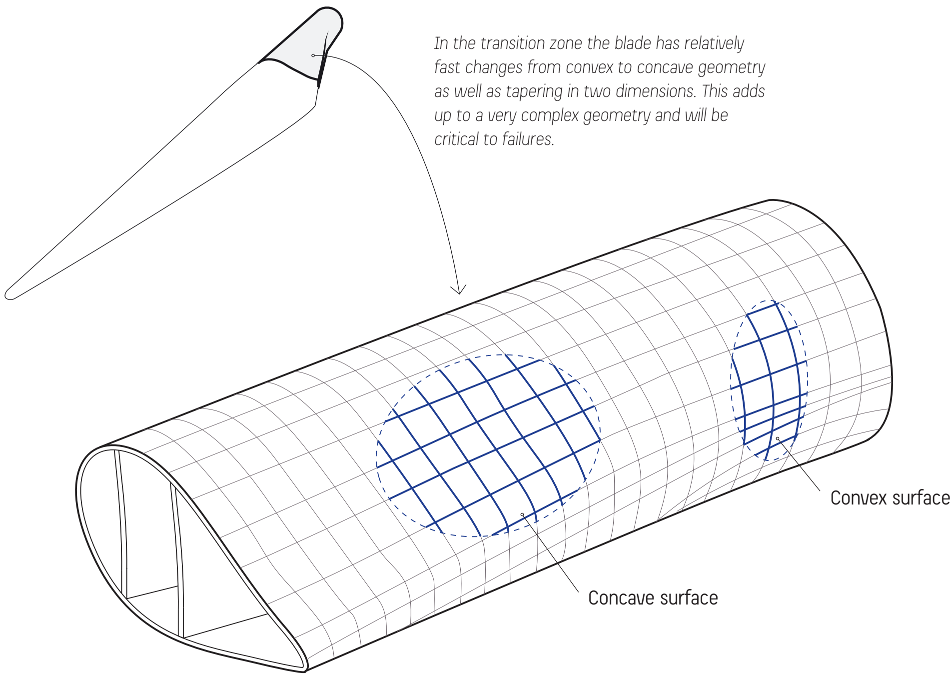
ROOT CAUSE 3
ROOT TRANSITION ZONE

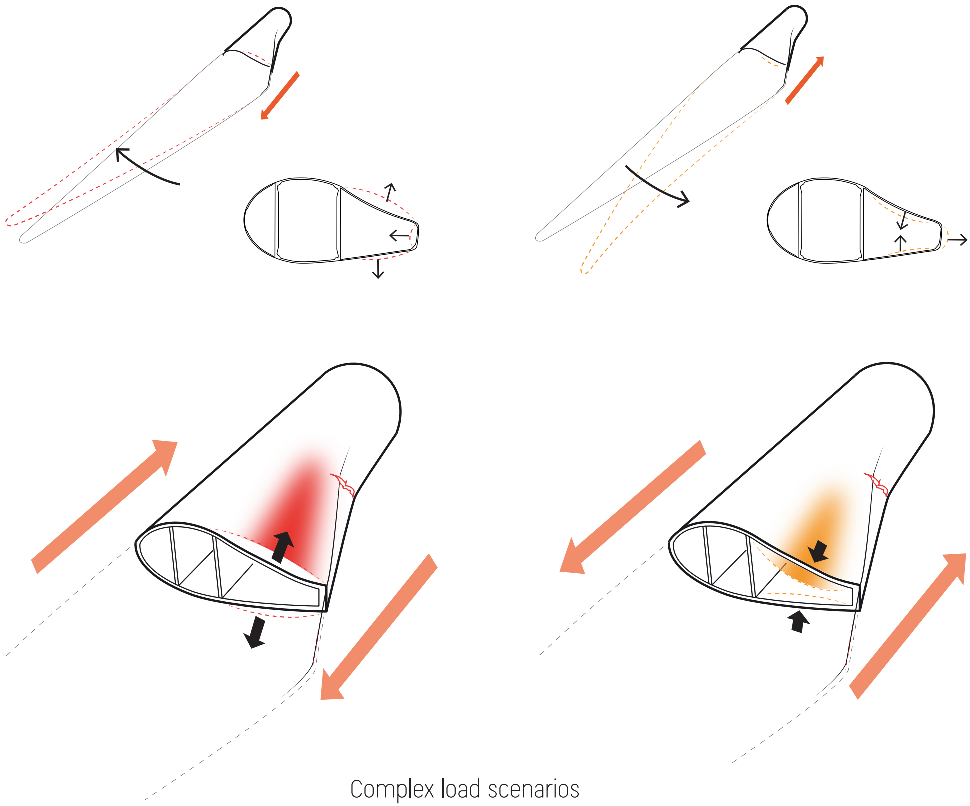
OPERATIONAL FATIGUE

Normal operation

>Panel bending and shear forces

> Root failures





Complex load scenarios

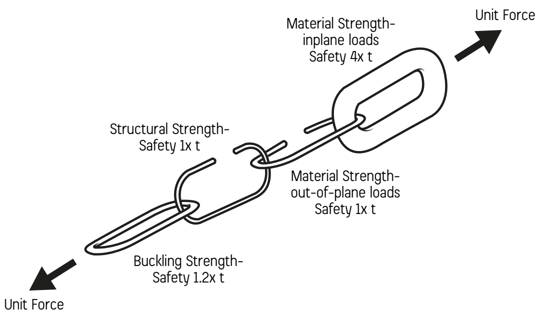
SAFETY MARGINS

Large differences can be found in the safety margins against various types of failure modes, which indicates that current wind turbine blade designs need to be optimized to a higher degree with regards to structural strength.

The chain is only as strong as its weakest link.

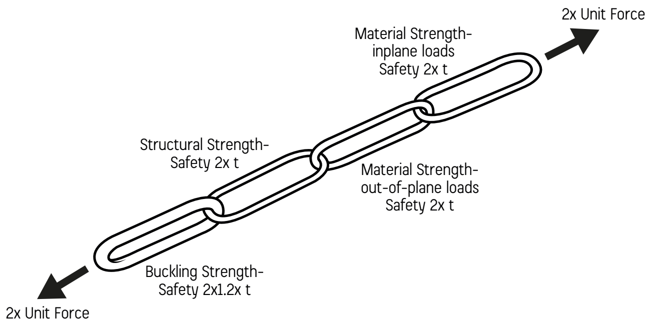
TYPICAL CHAIN OF MARGINS:

Weaknesses are perceived compensated by strengthening other links.



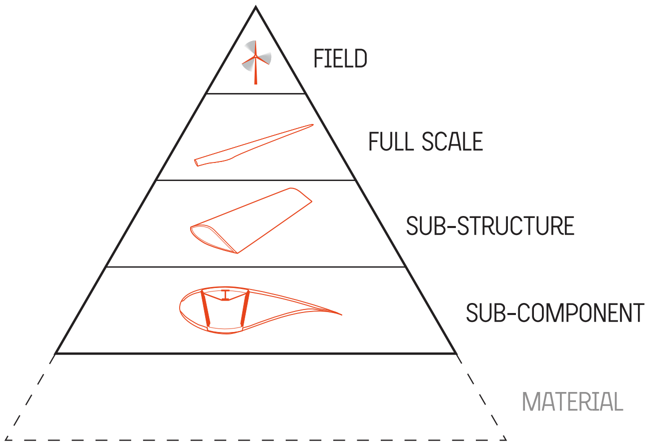
NEW DESIGN PHILOSOPHY:

Strict focus on strengthening the weakest link and optimizing the other links.

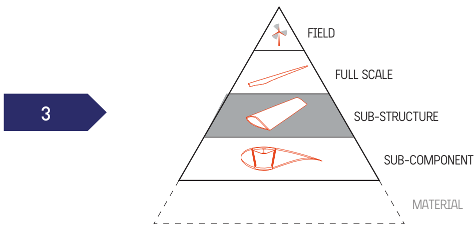


TESTING

LEVELS OF TESTING



Hybrid testing is sub-structure testing

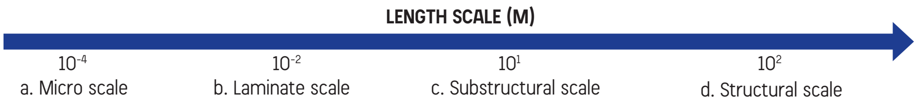


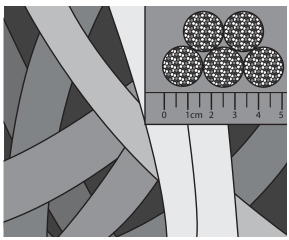
TESTING

There are different levels of testing. Due to the uncertainty in fatigue behaviour of blade materials, it is necessary to test as complementary to blade design. According to standard it is only mandatory to test at material and full-scale level, and at the full-scale level it is only mandatory to test in the pure edgewise and flapwise loading. This loading does not represent the real field loads. Thus, there is a need to include combined loading and other levels of testing that represent failure modes.

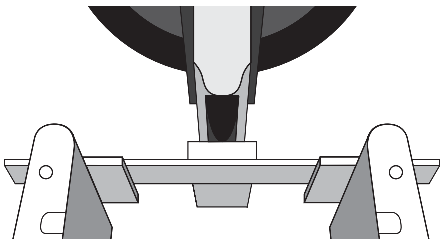
LENGTH SCALE

Testing is defined on a length scale from micro scale to structural scale

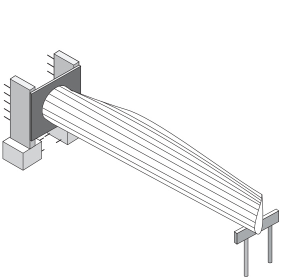




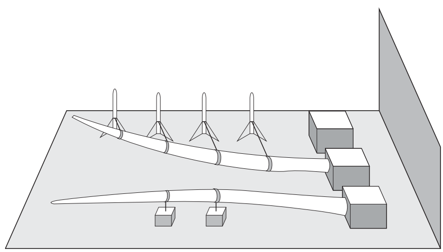
a. Micro scale



b. Laminate scale



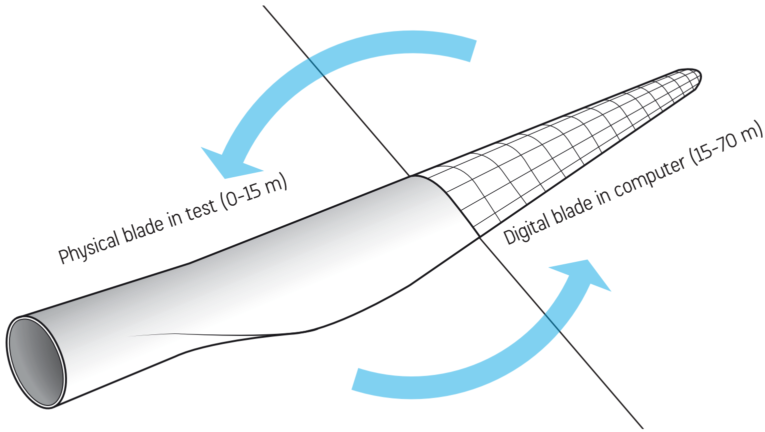
c. Substructural scale



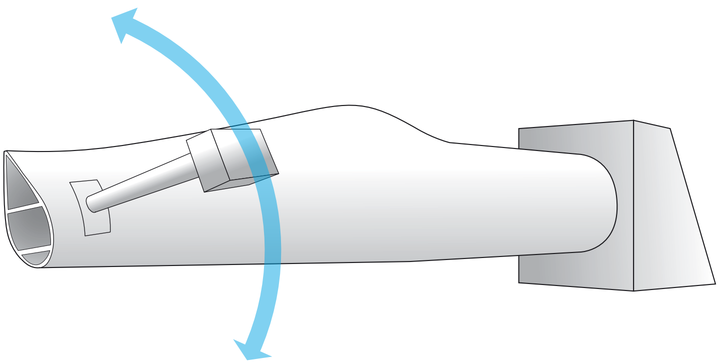
d. Structural scale

HYBRID TESTING/ HYBRID SIMULATION

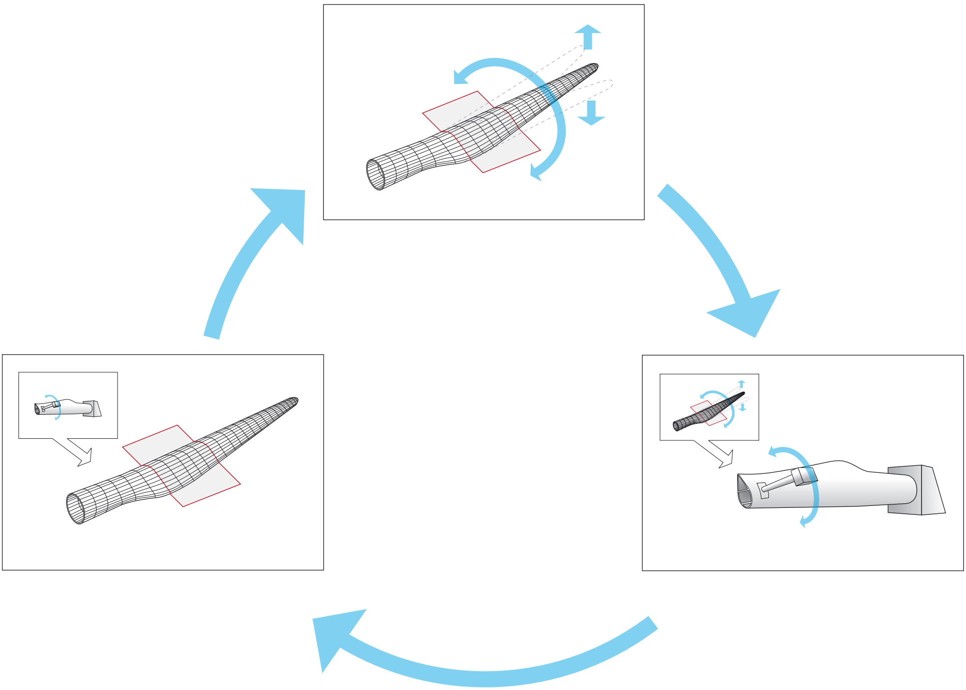
Blade cut (not full-length blade test)



Dynamic testing by adding weight block to blade side



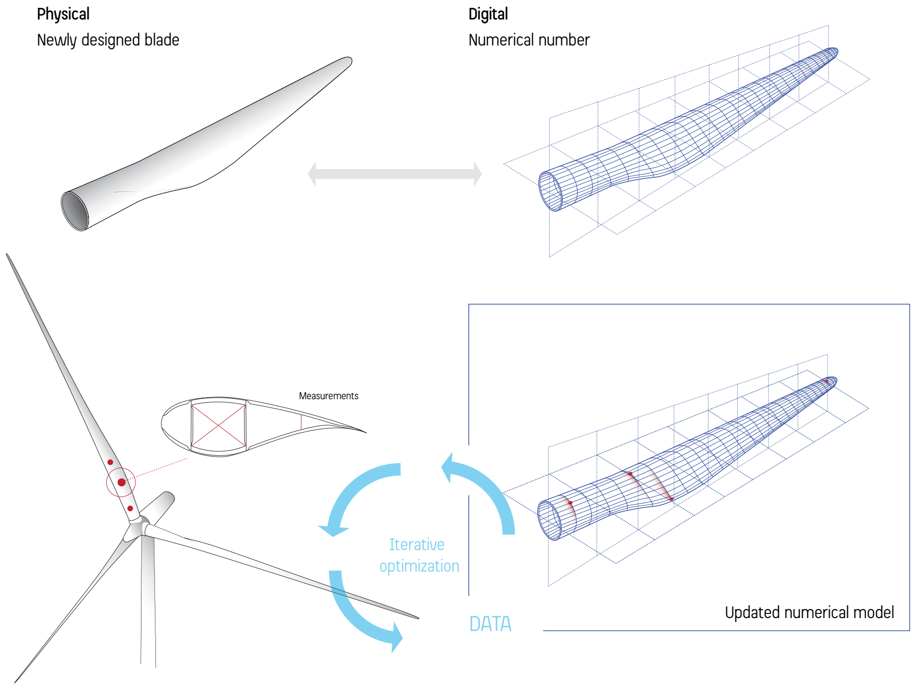
Dialogue between physical and digital blade



Hybrid Simulation is a tool that can be used in substructural testing. Testing at present is performed mainly on laminate and full scale level.

VALIDATION PROCESS

Digital twin is defined as an up-to-date numerical model of a physical asset in operation. It shows the asset's current condition and includes relevant historical data.



Structurally critical measurements on operating wind turbine (Cross-sectional shear distortion, panel breathing)

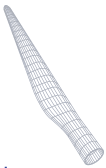
The digital twin will be able to provide the WTOs with information that can assist with the decision-making on areas such as: operation mode, repair strategy, etc. It therefore has the potential to be used as a prognostic health management system, which will be used as a tool to assist in the change in maintenance strategies from fixed schedules and interval towards predictive maintenance.

The validation process for the design phase shown below can be a key input to the numerical model evaluation for the Digital Twin.

OPTIMAL DESIGN AND VALIDATION PROCESS FOR LARGE BLADES (Bladena input to Digital Twin)

STEP 1

FEM numerical model with torsional loads



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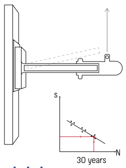
STEP 2

Sub-component test-program initiated to test hotspots



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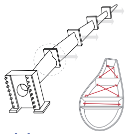
STEP 3

Measurements of critical structural phenomena during static full scale test with torsional loads



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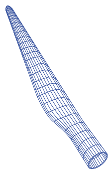
STEP 4

FEM model validation, calibration based on the measurements regarding CSSD and breathing



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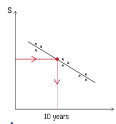
STEP 5

The calibrated FEM model is used to extract new stress levels to re-evaluate lifetime predictions using the S/N curve



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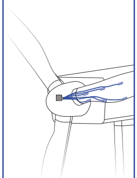
STEP 6

Validate the results through the prototype turbine where the CSSD and breathing measurements are captured



\$\$

Sub-component tests are designed to test hotspots on the blade in order to decide lifetime strength.

Increased number of tests will decrease uncertainties, therefore the risk will also be decreased.

Critical results can be captured before prototype (expensive) turbine testing.

\$: Cost covering additional input, not required by standards

DAMAGE, DEFECT & FAILURE

DEFINITIONS OF TERMS

DAMAGE:
Harm or physical change that impair the normal function of a blade (from an impact, fatigue, wear and tear, etc.).

DEFECT:
A flaw or a weakness in a blade that cause failure.

FAILURE:
The loss of an intended function due to a defect (tensile, shear, compressive etc.).

COLLAPSE:
Complete failure of a blade impossible to repair. Replacement needed.

DAMAGE- / FAILURE- / DEFECT-TYPES (EXAMPLES)

- Defects are faults in the blade that might come from manufacturing.
- Failures are faults in the blade that have occured during the lifetime of the blade, due to outside events (excessive loads, fatigue of materials, etc.)
- A lightning strike which results at the opening of the trailing edge of the blade is considered as *damage* on the blade.
- The failure of the adhesive in a joint due to excessive loading is considered as a *defect* for the blade, but as a *failure* for the adhesive joint.
- The lack of adhesive in a joint is a manufacturing *defect*.
- A failure of a root bolt can lead to a *defect* on the root.

DAMAGE CATEGORY DEFINITION

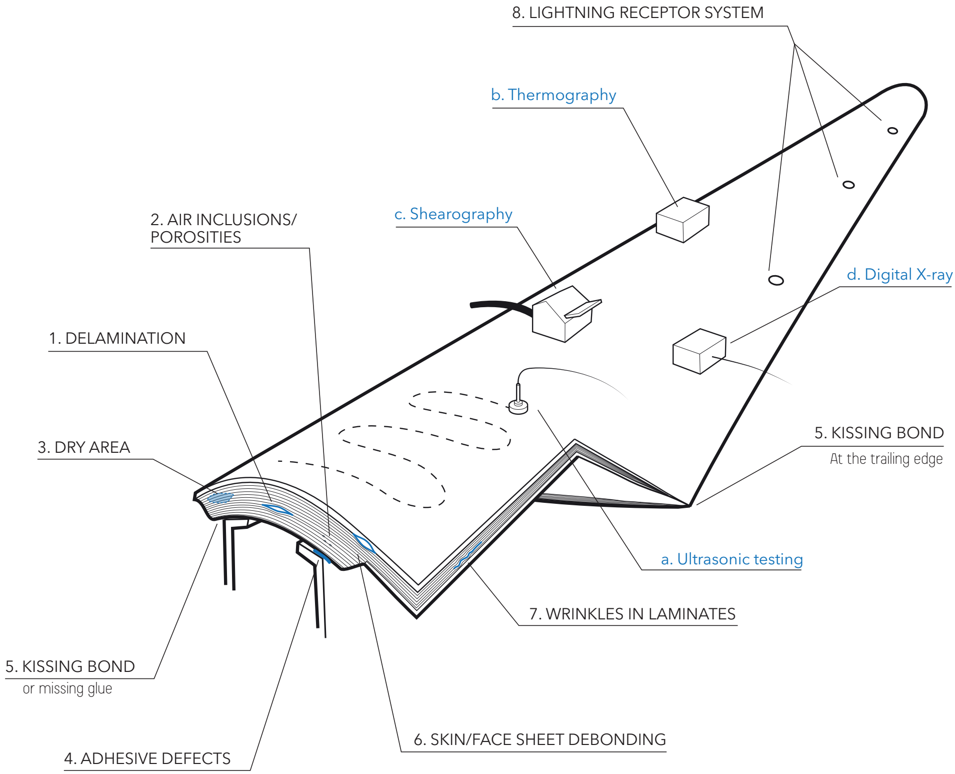
The blade damages can be prioritized when it comes to the impact they have on the wind turbine blade itself. To define the category of the damage, it is important to assess the location, the impact and the time it requires to repair the damage. Below the different categories are described as a guideline to use when inspecting the blades.

CATEGORY	DAMAGE	ACTION	TURBINE
1	Cosmetic Readings of lightning system below 50mΩ	No need for immediate action	**Continue Operation**
2	Damage, below wear and tear	Repair only if other damages are to be repaired	**Continue Operation**
3	Damage, above wear and tear Readings of lightning system above 50mΩ	Repair done within next 6 months	**Continue Operation**
4	Serious damage	Repair performed within next 3 months. Damage monitored	**Continue Operation**
5	Critical damage	Immediate action required to prevent turbine damage. Contact technical support	**STOP Operation** safety is not ensured

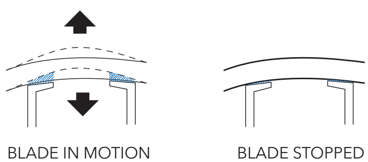
NB! More information about damages and inspections can be found in the NGIR-reports (Next Generation Inspection Reports), please contact Bladena to require these documents.

NDT

DETECTION OF DEFECTS IN WTG BLADES



Potential defects and the different NDT methods

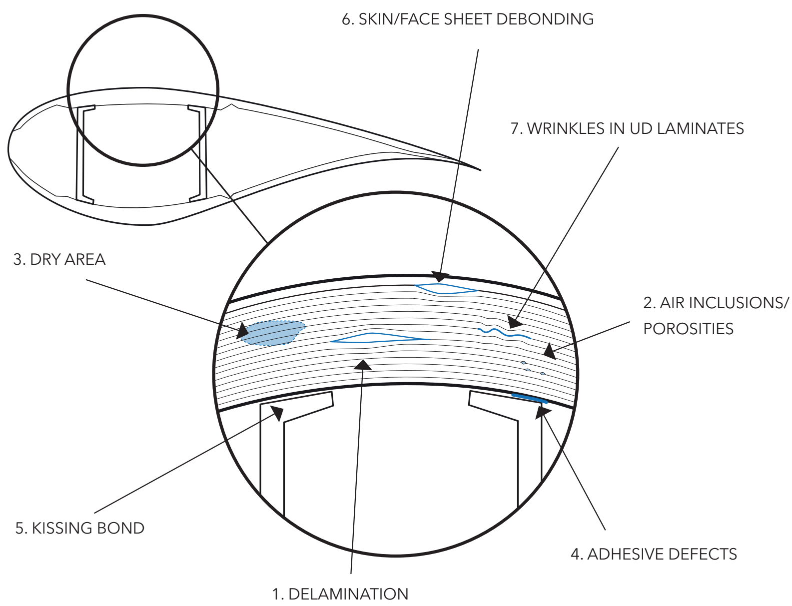


Kissing bond

Can be difficult to detect because there is almost no visual difference when blade is stopped. It is preferable to use automated UT (Ultra-sonic testing) for detection. It enables the possibility to compare adjacent areas.

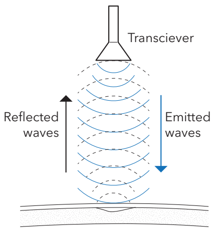
DEFECTS DETECTED WITH NDT

1. Delamination: Lack of fusion between layers/ two fiber laminates which are separated.
2. Air inclusions/Porosities: Small or large air pockets or impurities in material.
3. Dry areas: Lack of resin.
4. Adhesive defects: Adhesive not present, insufficient amount of adhesive or not placed correctly.
5. Kissing bond: Little or no adhesion.
6. Skin/face sheet debonding: The deattachment of the outer or inner skin from the core on a sandwich material.
7. Wrinkles in glass/carbon fiber laminates: Misalignment of fibers before or during curing.
8. Placing and integrity of Lightning Receptor System: Are Receptors and internal connectors intact and placed correctly?



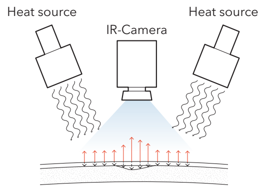
NDT

DETECTION METHODS



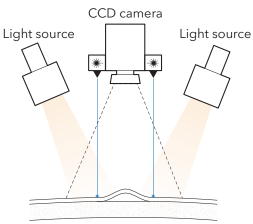
a. ULTRASONIC

Ultrasonic testing (UT) is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested.



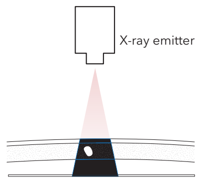
b. THERMOGRAPHIC

Thermographic inspection refers to the non-destructive testing of parts, materials or systems through the imaging of the thermal patterns at the object's surface.



c. SHEAROGRAPHY

Shearography uses coherent light or coherent soundwaves to provide information about the quality of different materials in non-destructive testing and defect detection.

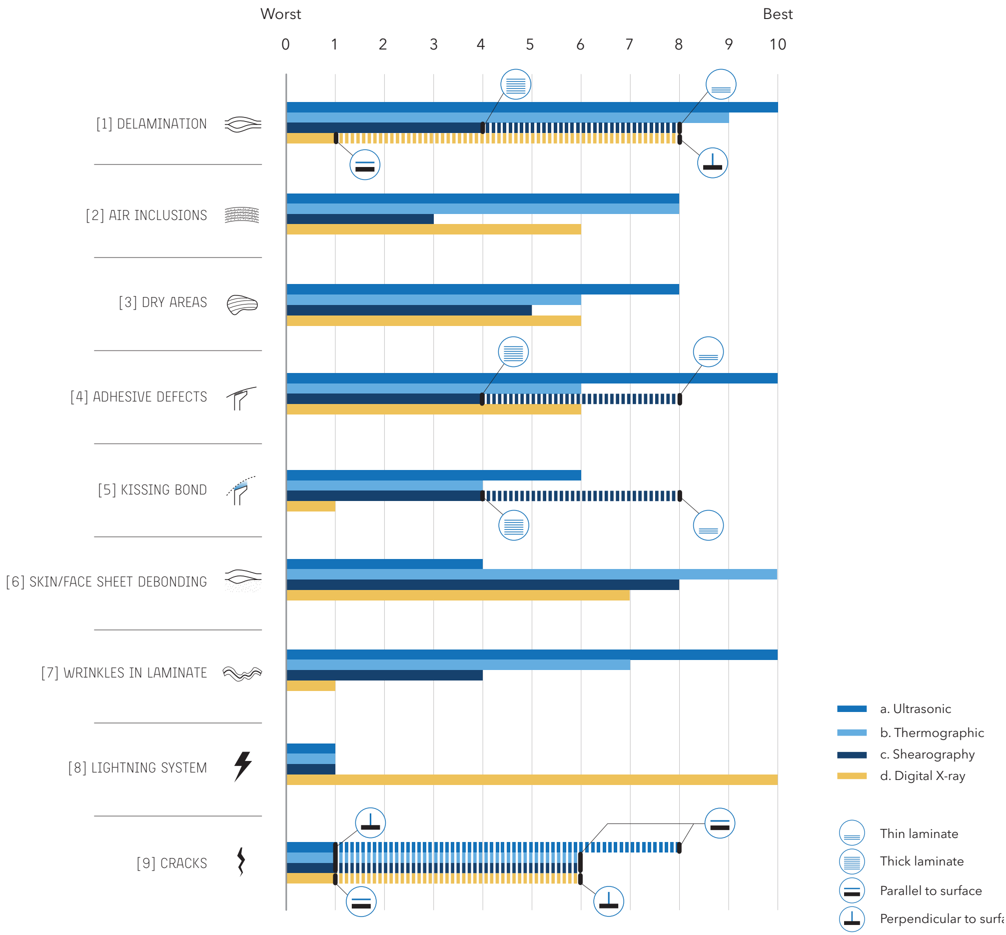


d. DIGITAL X-RAY

Digital radiography is a form of X-ray imaging, where digital X-ray sensors are used instead of traditional photographic film. Advantages include time efficiency through bypassing chemical processing and the ability to digitally transfer and enhance images.

NDT METHODS GRADING SYSTEM

Rating of the NDT detection probability for different defects.



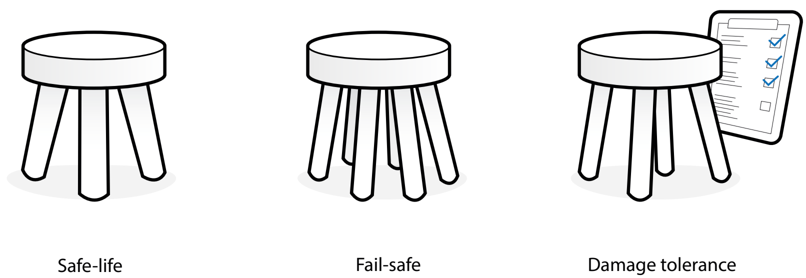
FRACTURE MODES

DEFINITION

A structure can fail via a propagating crack when a concentrated stress exceeds the material's cohesive strength. When a material is subjected to fatigue loading above a certain threshold, microscopic cracks begin to form in areas with stress concentrations (such as the grain boundaries in metals or at the fibre-matrix interface in fibre-reinforced composites). The property which describes the resistance of a material towards the propagation of a crack is called fracture toughness. The field of mechanics concerned with the study of cracks in materials is called fracture mechanics.

In a typical structure with defects, if the cracks are sufficiently small, loads redistribute around cracks with little effect on the global response. Under these conditions, the crack growth rate can be predicted knowing the material properties, the geometry and the applied loads. When flaws are sufficiently large, significant load redistribution may lead to uncontrolled crack propagation, eventually causing the whole structure to fail catastrophically. It is important to know these operational limits, to inspect and treat damages before they reach a critical size.

The capacity of a structure to fulfill its design function (e.g. to support loads and deform as expected) under the presence of cracks, is called Damage Tolerance. This term is also used to describe the design method that takes into account the natural degradation of the materials and the structural damages occurring during its lifetime. The goal is to provide sufficient safety and redundancy in case of predictable and unexpected damage.



Damage tolerance as a design principle.

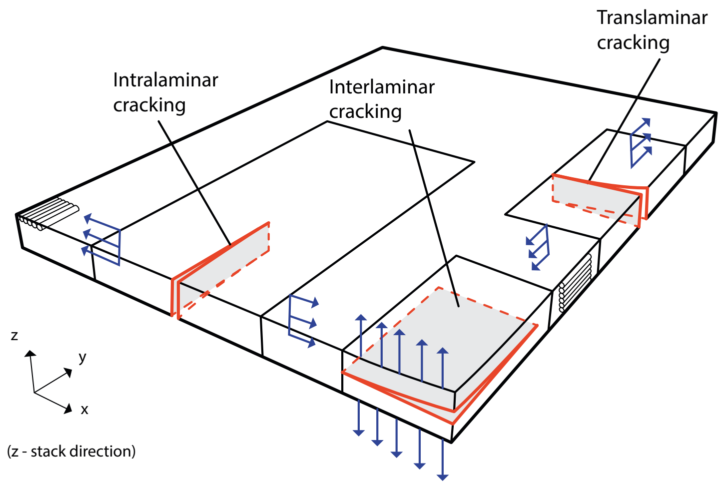
FRACTURE AND DAMAGE MODES IN COMPOSITES

In laminated composites, different modes of fracture can be identified:

Interlaminar cracks, (also known as delaminations) are cracks that grow between two plies. These usually require little energy as they are characterized by low fracture toughness values.

Intralaminar cracks, involve the microscopic debonding between matrix and fibres, and are typically limited in thickness by the two adjacent plies, but can grow under tension and shear through a panel.

Translaminar cracks, similar to the previous, but involve the fracture of the fibre by either traction or compression. Since very high forces are required to fracture fibers, these cracks typically appear later than the other described above, and are an indication of an advanced damage state.



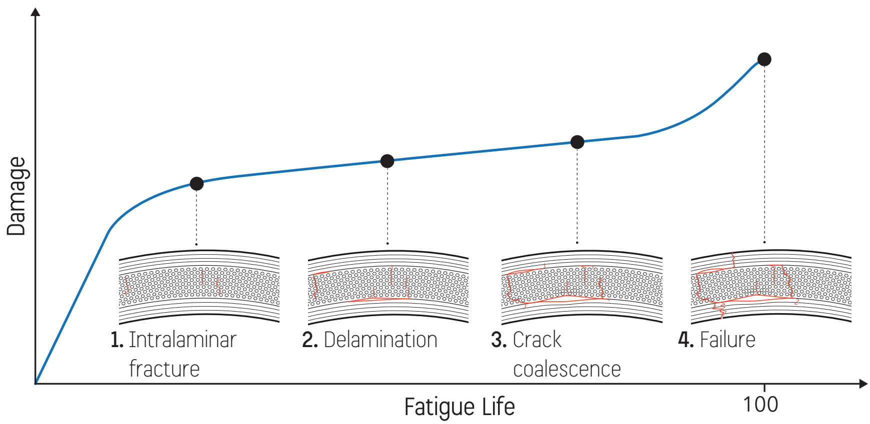
Intralaminar, interlaminar and translaminar cracks.

FRACTURE MODES

FRACTURE AND DAMAGE MODES IN COMPOSITES

Composite materials are made of numerous weaved fibre bundles (the reinforcement) embedded and held together by a resin material (the matrix). In this highly discontinuous structure, it is common to observe multiple microscopic cracks in different locations. Being very small, they are hard to detect with conventional methods, but do not pose any significant risk: It is found that small cracks are present in a composite structure at an early stage, or already after manufacturing, but these are largely unaffected by loads for a great part of its operating life.

For this reason, composites are considered more damage tolerant than metals. Nevertheless, after prolonged loading, these small cracks may eventually coalesce and form a macroscopic fracture. Only at this point, a growing macroscopic crack will start to weaken the structure, eventually leading to failure.

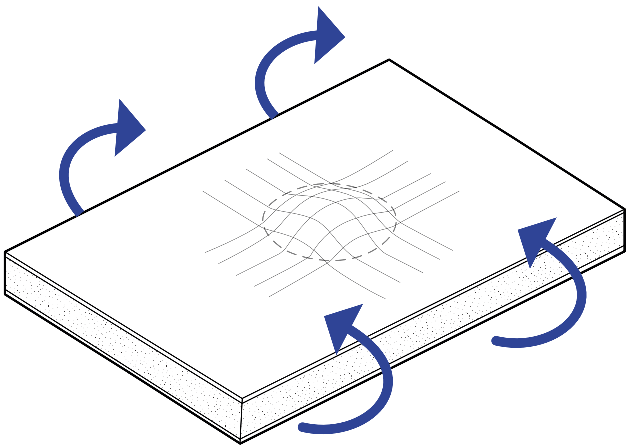


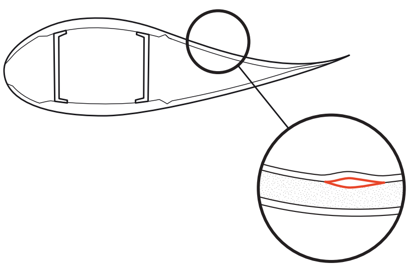
Fatigue life: The development of cracks under applied stress.

FRACTURE MODES IN SANDWICH STRUCTURES

In sandwich panels, in addition to the fracture modes described above, another type of damage exists: This involves the adhesion between the face sheet and the core and takes the name of face-core debonding.

A debonded sandwich panel will not be able to carry the prescribed loads and has much lower bending stiffness.





An example of sandwich debond and loading mode in a WTG blade.

CRACK LOADING

MODES OF CRACK LOADING

There are three types of loading that a crack can experience:

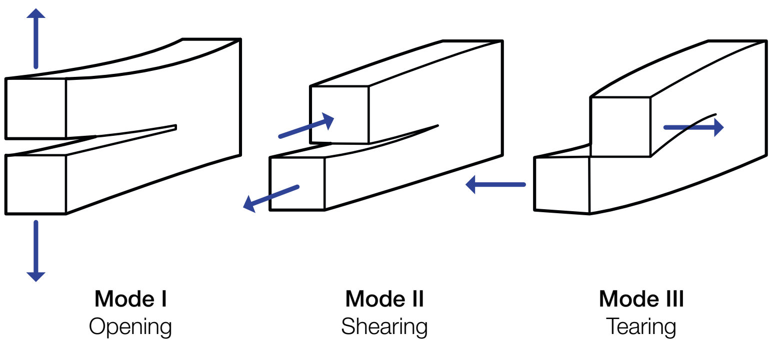
Mode I (opening): The load is opening the two crack faces apart.

Mode II (shearing): The two crack faces slide with respect each other, parallel to the crack propagation direction.

Mode III (tearing): The two crack faces slide with respect to each other in the out-of-plane or transverse direction.

A crack experiences mixed-mode loading when a combination of these three modes is applied. In homogeneous materials, cracks predominantly advance in the most favourable direction, which coincides to pure mode I: under mixed-mode loading the crack will tend to orient itself towards a direction where pure mode I exists.

This is not the case for discontinuous materials such as composites: ply interfaces and fibre alignment act as boundaries which cracks cannot go through. In this case, cracks are forced to propagate under mixed-mode and the growth rate depends on the particular mixed-mode fracture toughness.

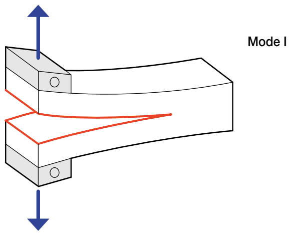


Schematic representations of mode I, mode II and mode III

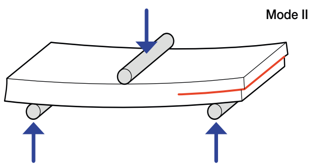
TESTING AND CHARACTERIZATION

Several test methods are available to evaluate the fracture toughness of composite laminates. These tests aim to reproduce the crack deformation shown earlier by applying controlled loads to a specimen. Standard methods are only available for pure mode I, pure mode II and mixed-mode I/II. For mode III the only way to have a stable and measurable crack is by applying a combination of all three modes.

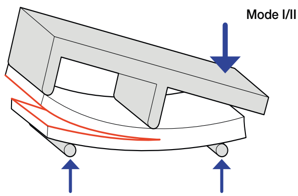
Double Cantilever Beam (DCB) specimen for pure mode I



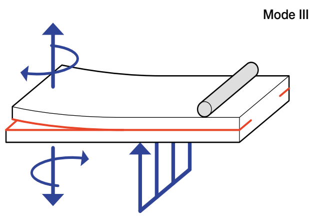
End Notched Flexure (ENF) specimen for pure mode II



Mixed Mode Bending (MMB) specimen for mixed mode I/II



Shear-Torsion-Bending test (STB) specimen for mixed mode I/II/III

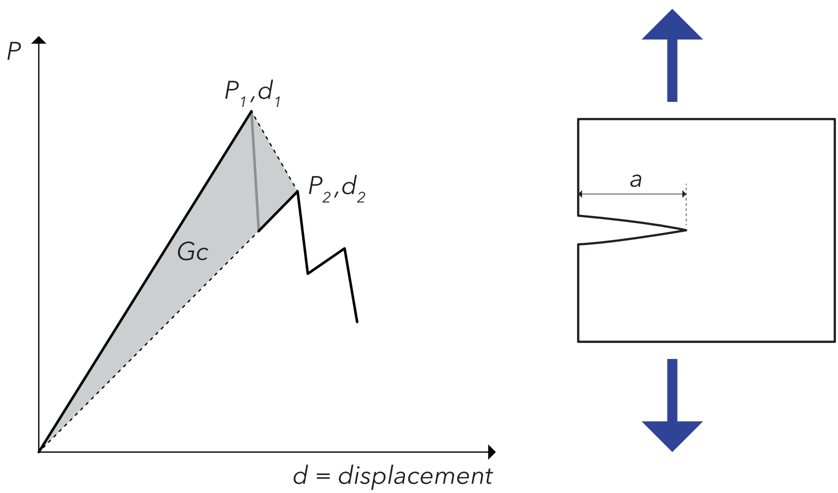


FRACTURE MECHANICS

ENERGY RELEASE DURING CRACK PROPAGATION

A crack in a structure propagates if it has sufficient energy to do so. Several methods are available to measure the amount of energy released during propagation, in basic terms, this can be found simply from the load-displacement curve.

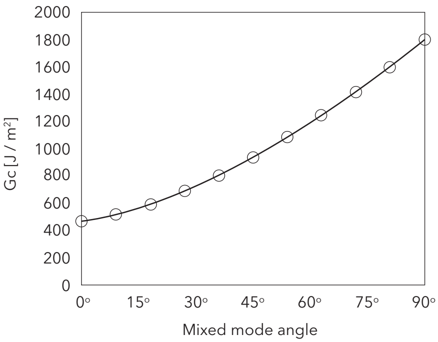
The amount of energy "contained" into a crack is called the energy release rate. When a crack propagates, this quantity reaches a critical value, which takes the name of Fracture Toughness (Gc). It is found that the fracture toughness is independent from the crack length, it is therefore a constant material property. These are the fundamental quantities used in linear elastic fracture mechanics.



Load displacement curve.

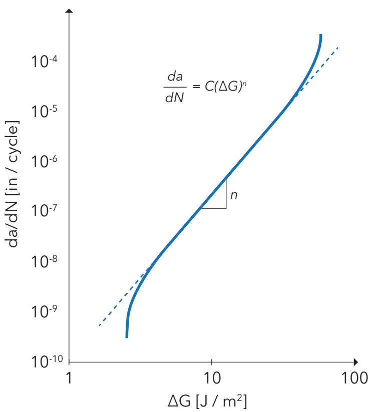
CRACK PROPAGATION RATE

For a generic composite or sandwich material, where cracks can propagate in different modes, the fracture toughness assumes different values. It is then convenient to identify a curve that links this with the mode of crack propagation.



Fracture toughness varies depending on the mode in which the crack propagates. For laminated composites, mode I is 3 to 5 times weaker than mode II..

Ultimately, when applying cyclic loads to a structure, the speed at which a crack grows is also well defined if the loads are expressed using this fundamental material property. The Paris-law curve, indicates that there is a linear correlation between the energy applied to a crack and the speed of propagation.



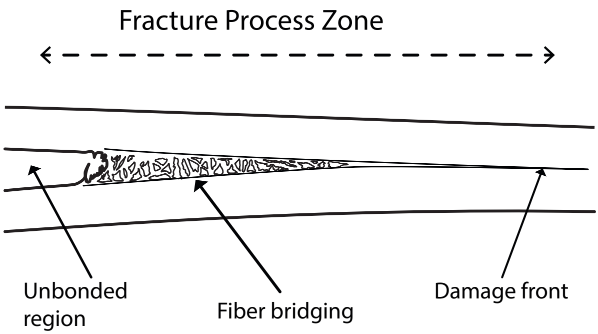
Crack growth rate / crack propagation rate.

Note that the quantity G is not equal to the applied load. A long crack contains a high amount of energy, so it will grow faster than a short crack under the same loads.

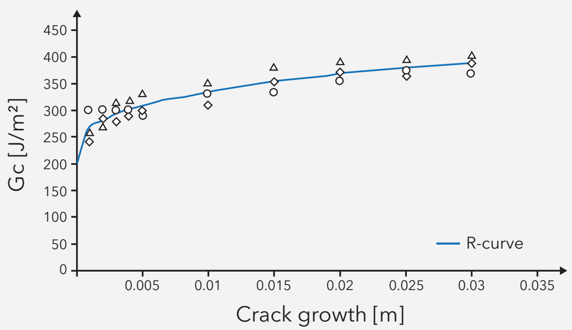
COHESION STRENGTH IN COMPOSITES

FRACTURE PROCESS ZONE

It is possible for interlaminar cracks to be characterised by a long fracture process zone. In this situation, it is not possible to identify a defined crack tip, but there are two distinct regions: A zone where the material is beginning to be damaged and has reduced strength and a second region where intact fibres behind the damage front bridge the crack.



Fracture process zone



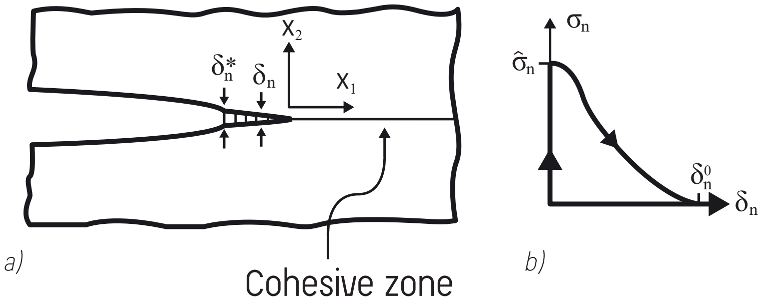
Example of an R-curve

Phenomena like fibre bridging and friction lead to an increased resistance towards fracture as the fracture itself grows (the fracture toughness is not a constant). A graph correlating these two quantities takes the name of R-curve.

COHESIVE ZONE

To accurately characterize such damages, it is convenient to introduce a specialized material model, a cohesive law. This is a simplified relation that links the forces transmitted between the two crack faces and the displacement between them, it is thus called traction-separation relation and is the mathematical representation of the fracture process zone.

Cohesive laws need to be experimentally measured for materials and interfaces. The correct deduction and implementation of these laws enable the accurate prediction of the behaviour of cracked composite structures. These are conveniently introduced in numerical Finite Element tools and used to simulate the propagation of a crack under loads.



Delta(δ) describes the displacement and sigma(σ) describes the stress.

a) Illustration of a cohesive zone, which is specified along the anticipated cracking path

b) Example of the cohesive law describing the relation between the normal stress and the separation

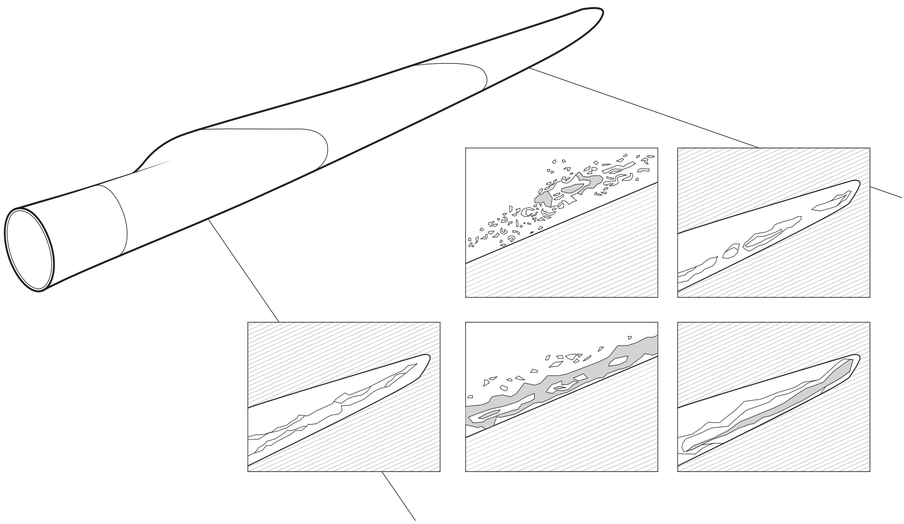
LEADING EDGE EROSION

WHAT IS LEADING EDGE EROSION?

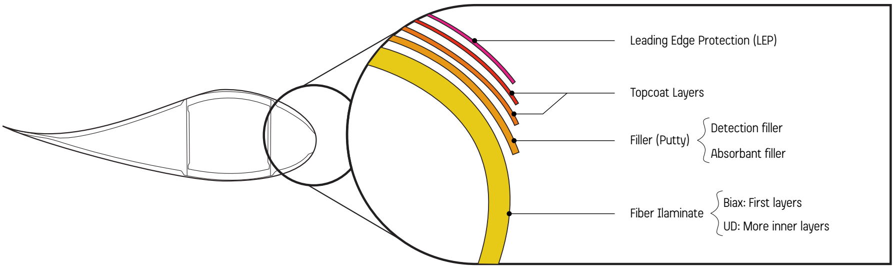
Leading Edge Erosion (LEE) is the degradation of the leading edge due to the interaction of the blade with external factors, such as impacting particles like rain, hail, sand and insects. Other effects like UV radiation, salt mist and alternating temperature can over time degrade the properties of the blade materials.

At the time that the blades have higher tip speeds, leading edge erosion is becoming a more relevant failure mode for the wind energy industry.

Even though there is not a standardized categorization, 5 damage categories are mainly used, related to the area it is covered, combined with the depth of erosion. See image below.



Five types of leading edge erosion

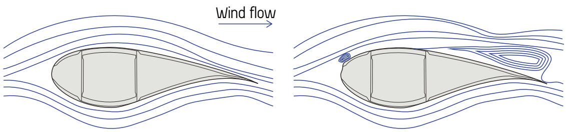


Leading edge surface layers

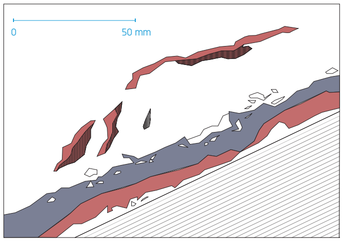
WHY IS LEE IMPORTANT?

Possible consequences:

- Loss of AEP
- Noise emission
- Structural consideration



Normal LE *Damaged LE*

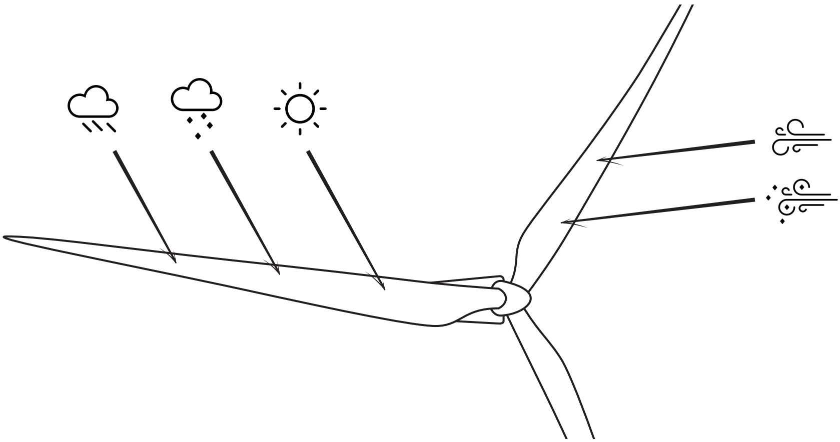


Cracks and surface debonding

LEADING EDGE EROSION

WHY DOES LEE HAPPEN?

The risk of developing LEE mainly depends on wind turbine characteristics (mainly tip speed), leading edge protection, and environmental weather factors. The way each of these weather factors may influence on the risk of developing leading edge erosion will change from site to site according to the specific location and weather characteristics.



	RAIN	HAIL	UV IRRADIATION	SAND	WIND
Severity*	Medium	High	Medium-Low	High	Medium
Occurence*	Medium-High	Medium	High	Low	High
Overall risk**	Medium-High	Medium-Low	Medium	Medium-Low	Medium-High

**It depends on the intensity and on the site characteristics.*

*** The risk can highly change depending on the specific weather conditions. Each site should be studied in detail for a proper risk assessment*

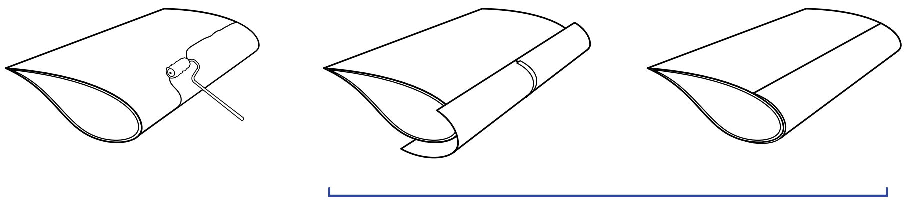
LEADING EDGE PROTECTION (LEP) SOLUTIONS

There are many LEP solutions available in the market that protect the leading edge from being eroded. Most of them are polyurethane based materials that tend to have a good behavior dampening the energy impact.

For an appropriate selection of the LEP, other factors should also be considered, such as:

- *Suceptibility to poor adhesion*
- *Possible aerodynamic issues*
- *Time window and sensitivity of the LEP to weather conditions during installation*
- *Location of the LEP: tip or mid-span section*
- *Main weather factor contributing to LEE*

Most common current LEPs are both erosion shields located at the tip section, and liquid LEP applied on the mid-span.



Liquid solutions: commonly applied in the mid-span area

Erosion shields: commonly applied in the tip section

LIGHTNING

This section presents the lightning induced damages on a wind turbine blade and a typical lightning protection system.

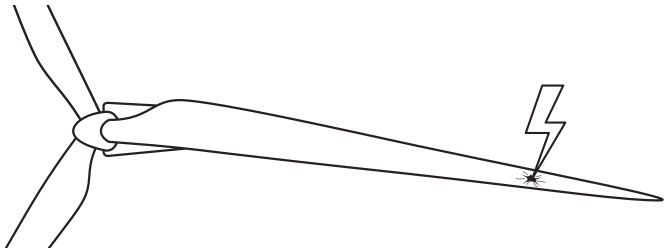
Lightning exposure and potential damages depends on:

- Site characteristics (e.g., lightning activity)
- Blade characteristics (e.g., hub height, blade length, LPS design)

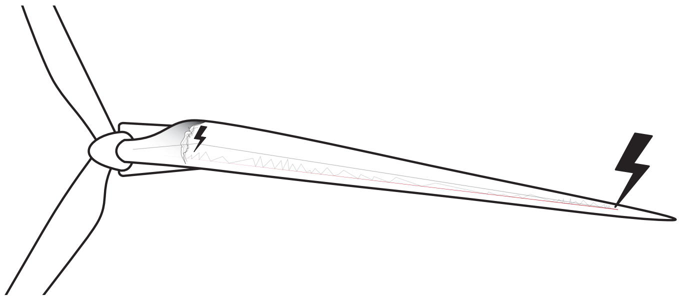
Lightning induced damages can include:

- Wear and erosion of the lightning receptors.

- Pinholes or punctures in the sandwich panel, due to strikes outside the receptors.

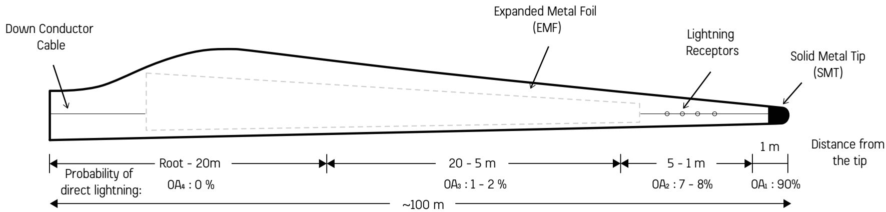


- Side flashes in the structural region that may damage the laminate and compromise the structural integrity.



LIGHTNING PROTECTION SYSTEMS (LPS)

The purpose of the LPS is to attract lightning strikes and to safely transfer the electric current through the designated down conductor to the ground, so that the blade remains unharmed. The blade is normally divided into four different zones as presented in the sketch below (from OA $_1$ to OA $_4$).



Example of generic LPS layout on a blade

1. Solid metal tip (SMT): A strong LPS solution integrated in the blade design. Replace the former discrete tip receptors.

2. Down conductor cable(s): The number of cables, their length, dimensions and routing differs among LPS, according to the designer.

3. Expanded Metal Foil (EMF): The EMF can cover the blade, either partly or completely.

4. Lightning receptors: The number and the position of the receptors vary in LPS designs.

The designer of the LPS is free to define a specific lightning exposure environment for a particular blade design through the principles described in Annex E (IEC 61400-24: 2019). The LPS design must be well coordinated with any conductive elements within the blade, and its performance must be documented by analysis and testing acc. to section 8 and Annex D of IEC 61400-24: 2019.

PART III

11 | SERVICE & INSPECTION

Working conditions
Inspection
Monitoring
Measurements

12 | MARKET

Operation & maintenance
IEC references
Market map
Market & Decision drivers
Decision Making / Operator's Focus

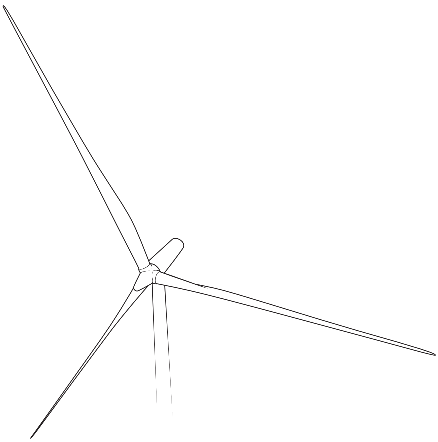
13 | PRODUCT DEVELOPMENT

Design drivers
Technology Readiness Level
Storyboarding

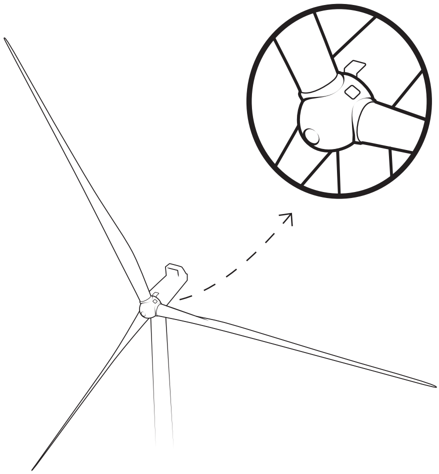
WORKING CONDITIONS

ACCESS

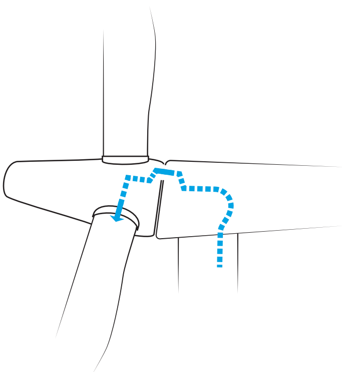
2 types of access - indoor or outdoor access

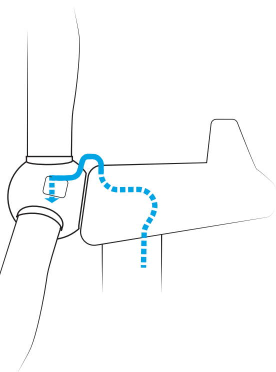


indoor acces



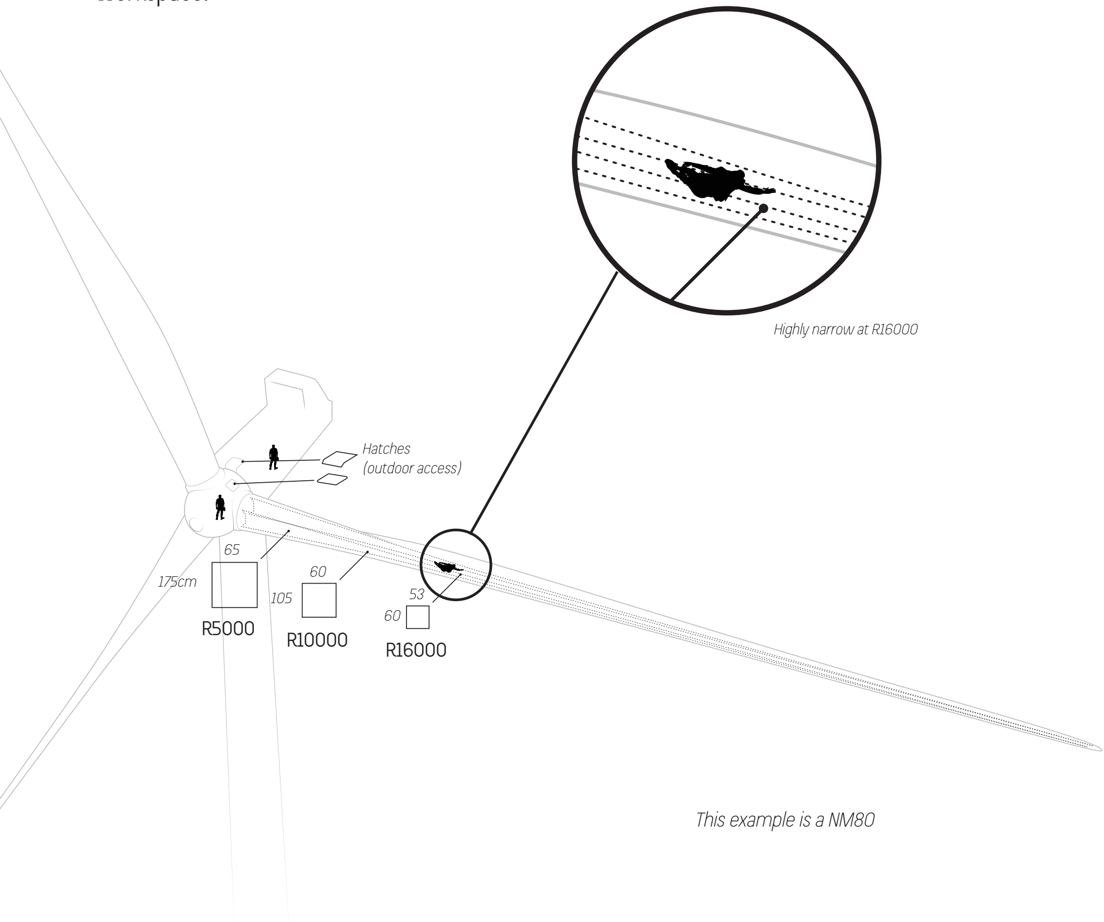
outdoor access





SPACE INSIDE A BLADE

Working conditions are very tight inside a blade and operations need to be planned well in advance before going up in the turbine. More and more companies do not allow confined workspace.



INSPECTION

This chapter provides an overview of Inspection and Monitoring techniques utilized in the industry.

INSPECTION METHODS

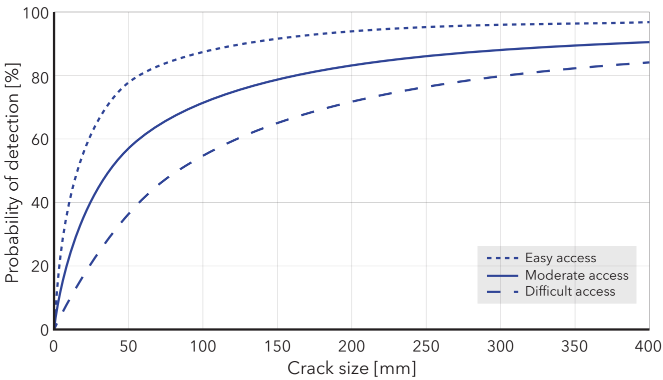
Visual

Ultrasonic
Shearography
Thermography
Digital X-ray

NDT methods (Ultrasonic, Shearography, Thermography, Digital X-ray)

POD (PROBABILITY OF DETECTION)

The probability of detection is used to quantify the ability of a non-destructive testing procedure for detecting a damage with a given size. For wind turbine blades, there are a few non-destructive testing procedures that are usually used.

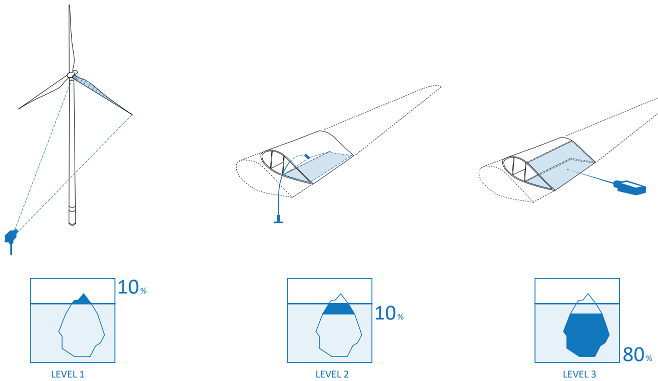


For a specific crack size of a, PoD(a) is the probability that cracks with the size equal to a is detected is PoD(a).

This PoD curve was originally referred to a specific NDT technology used in oil & gas industry. It schematically illustrates the basic idea of PoD. The PoD curves for wind turbine blades may take another form.

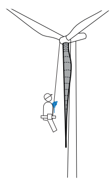
INSPECTION LEVELS

Using both NDT, outside and inside surface inspection you get the full picture of the blade's condition.

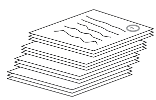


The three inspection levels: Outside, inside and NDT inspection. The outside inspection only sees the tip of the iceberg, by using NDT and inside inspections the whole iceberg can be uncovered.

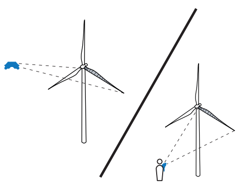
INSPECTION DATA HANDLING



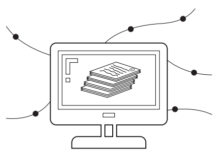
Photos taken directly on each blade



Inspection reports



Photos taken with drones or from ground.

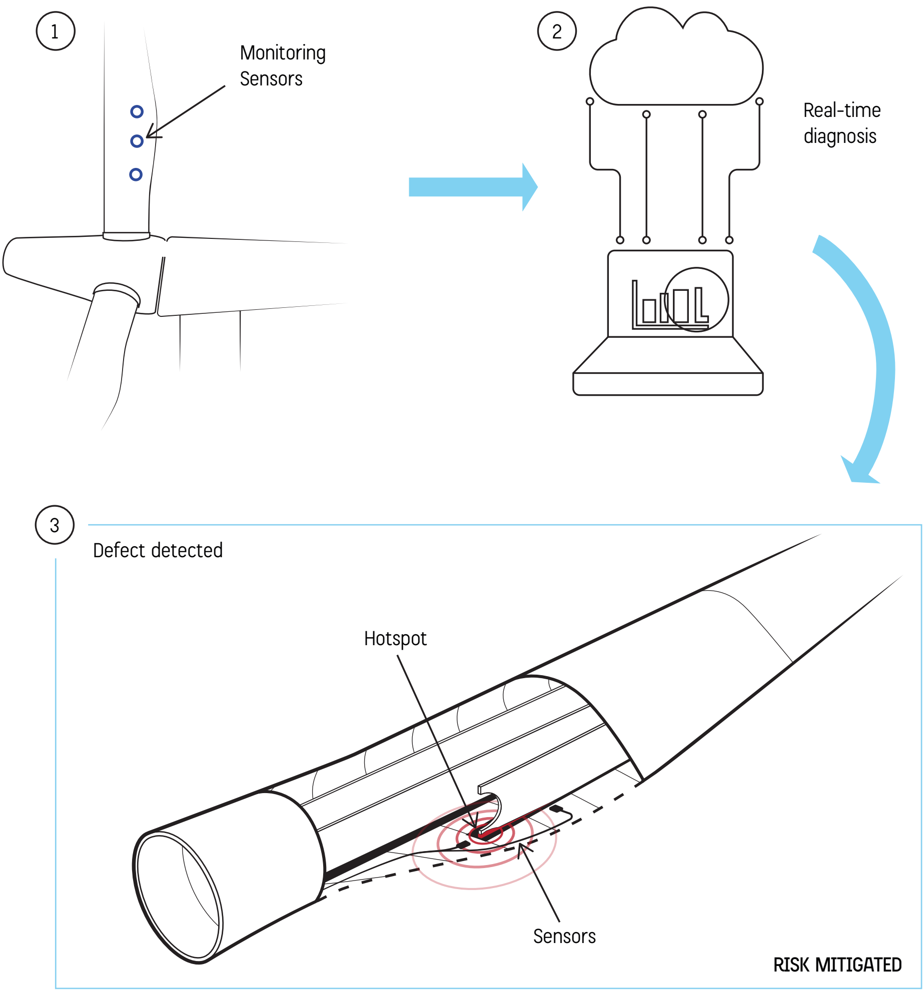


AI handles the majority of the data handling

Individual cases are reviewed by people

MONITORING

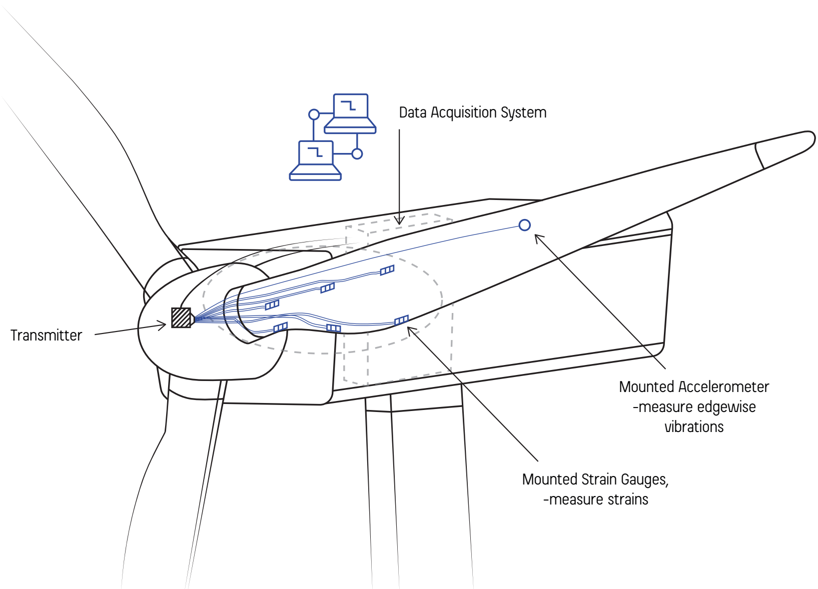
Monitoring can be defined as an automated method for determining damages in a structure and used to de-risk an asset, so the damage is found in time before a catastrophic failure happens. It is a feasible method only if the sensors are monitoring the blade's hotspots. Monitoring techniques can be used as indicators for possible defects in blades, and consequently inspection (visual or NDT) can determine the existence of a damage.



MONITORING TECHNIQUES

VIBRATION-BASED TECHNIQUES

Vibration-based techniques utilize sensors such as accelerometers to measure the eigenfrequencies of the blade. Changes in geometry or stiffness of the blade will modify the blade's eigenfrequencies. The vibrations-based sensors work best for detecting edgewise vibrations and flutter.



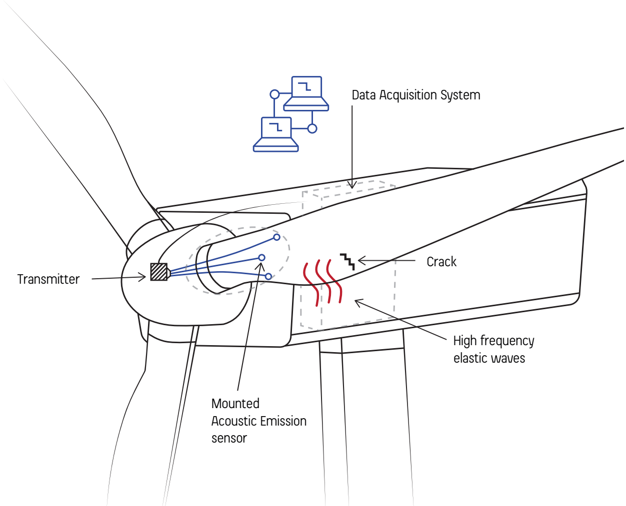
STRAIN GAUGE

Strain gauges can assist with blade monitoring by tracking the relative deflections along the blade. An indication of insufficient stiffness can be obtained, if a given threshold is overpassed by the sensor signal. This stiffness insufficiency might have occurred due to potential damages (e.g., bond line cracks, buckling, etc.).

MONITORING

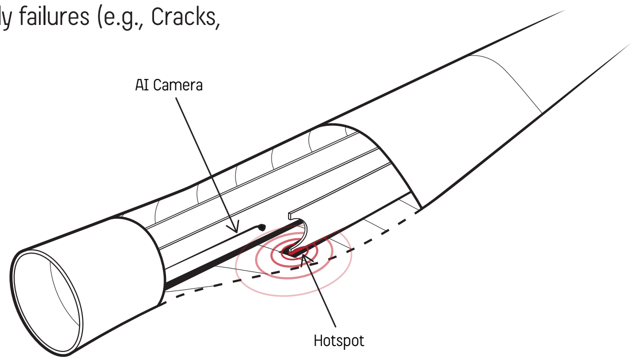
ACOUSTIC EMISSION (AE)

AE utilizes piezoelectric sensors and microphones to detect high-frequency elastic waves generated to be the sudden release of energy due to initiation of damage. The primary focus of the AE is to detect initiation or growth of damages such as cracks or debonding.



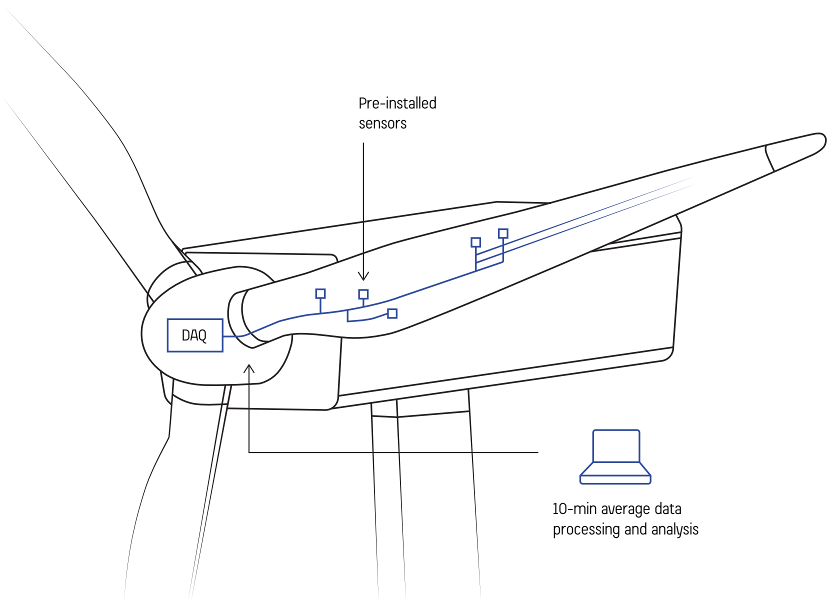
AI CAMERAS

AI cameras are simply cameras utilizing AI programs to detect abnormalities in the photos captured. AI cameras can help identify early failures (e.g., Cracks, Dis-bonding & Delamination).



SCADA - BASED MONITORING

SCADA system records operational and environmental conditions of the wind turbines. Wind speed, wind direction, active power, reactive power, ambient temperature, pitch angle, and rotational speed are the minimum data set provided. SCADA data is to detect performance issues.

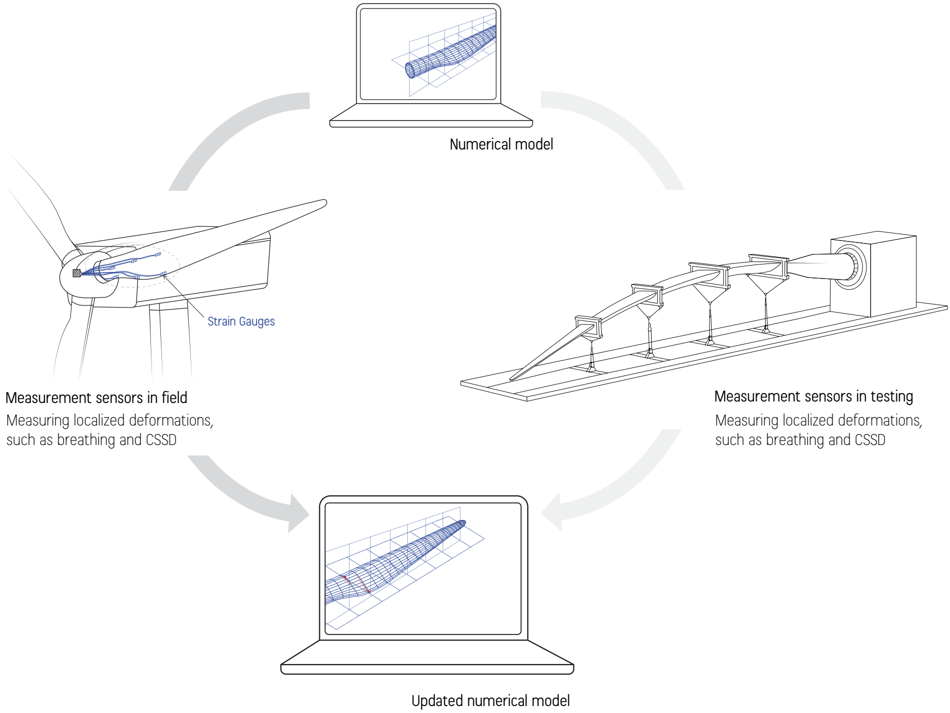


Monitoring techniques are utilized in maintenance strategies for wind turbine blades to detect defect(s) at an early stage and avoid critical damages/blade collapse to de-risk your asset.

MEASUREMENTS

MEASUREMENT

Output from measurement sensors can be used to validate computational models (e.g., FEM models, Aeroelastic tools, Digital twin). Moreover, Boundary conditions for blade testing can be optimized using field measurements.



Measurement sensors that can be used:

STRAIN GAUGES

Sensors installed in the blade to measure strain for post-analysis.

DISPLACEMENT SENSORS

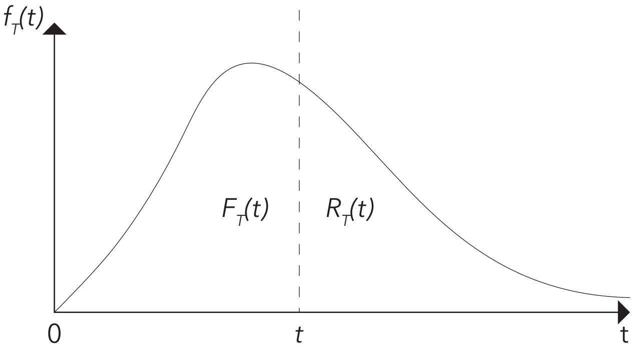
Sensors that measure localized deformations in a blade cross-section (e.g., Panel breathing, CSSD).

LOAD SENSORS

Sensors that measure loads on a blade. Loads sensor can be used for blade load monitoring which could help design cost-effective blades.

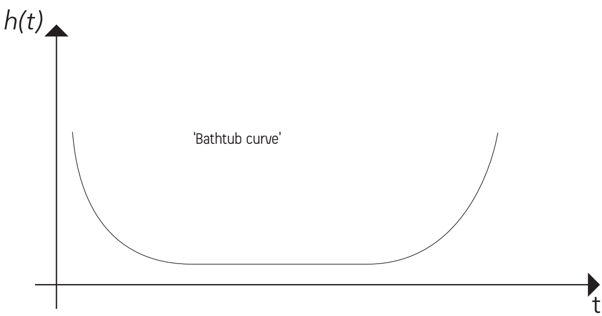
OPERATION & MAINTENANCE

COMPONENTS - CLASSICAL RELIABILITY THEORY



Reliability function $R_T(t)$
= probability that component life > t

Probability of failure $F_F(t)$
$= 1 - RT_T(t)$ = probability of failure of component before time t



Hazard / failure rate
= average number of failures in a given time interval
$[t\,;\,t+\Delta t]$ given survival of the component up to time t

OPERATION & MAINTENANCE OF WIND TURBINES

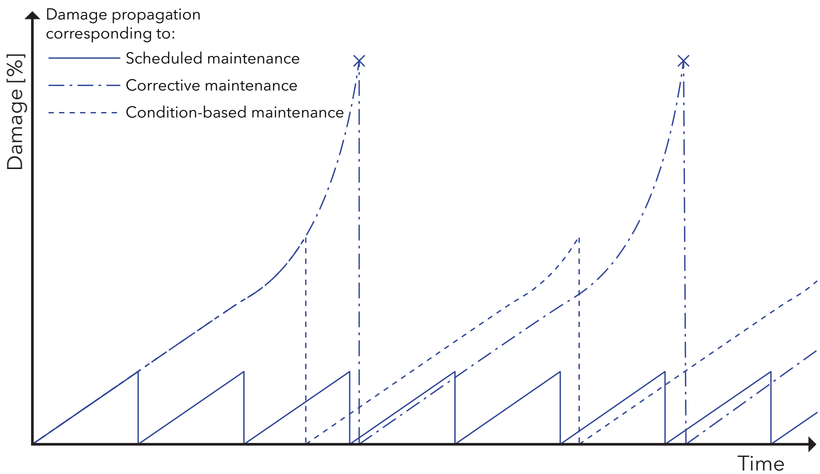
Corrective (unplanned): Exchange / repair of failed components

Preventive (planned): PM is the planned maintenance of plant infrastructure and equipment with the goal of improving equipment life by preventing excess depreciation and impairment. This maintenance includes, but is not limited to, adjustments, cleaning, lubrication, repairs, replacements and the extension of equipment life:

Scheduled: Inspections after predefined scheme.

Condition-based: Monitor condition of system and decide if repair is necessary based on degree of deterioration.

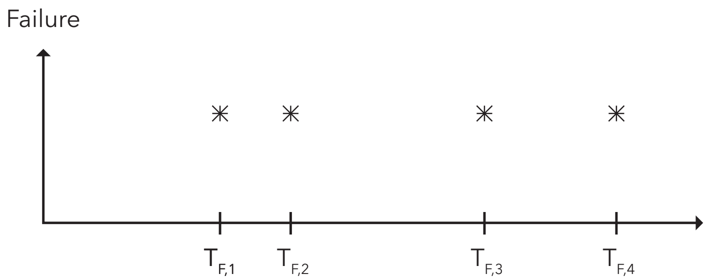
Risk-based: O&M planed based on risk assessment.



OPERATION & MAINTENANCE

CORRECTIVE MAINTENANCE

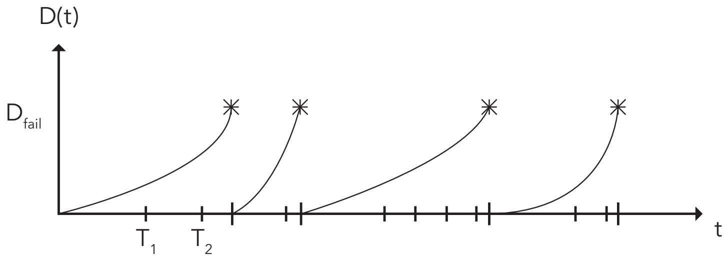
Corrective maintenance is based upon the principle of Run to Failure (RTF). Failures happen at some discrete points as the stars shown in this figure.



Example of corrective maintenance, the turbines run until failure.

CONDITION-BASED MAINTENANCE

Condition-based maintenance is a maintenance strategy that recommends maintenance actions based on the information depicting the current condition of the wind turbine blades. A model (no matter if it is a physics-based or data-driven model) characterizing the deterioration of the wind turbine blades, as the continuous curves shown in this figure, should be defined. Pre-defined decision alternatives (rules) determines the damage thresholds, and the maintenance actions to be done when a damage reaches one specific damage threshold.

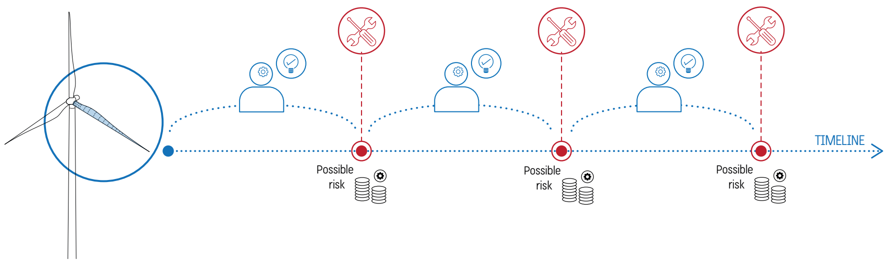


Example of condition-based maintenance. Decision alternatives define the damage thresholds.

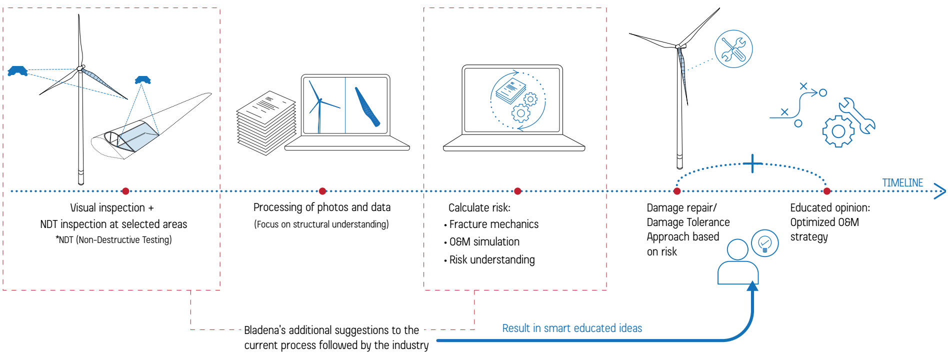
OPERATION & MAINTENANCE

RISK-BASED O&M

A risk-based O&M is a proactive maintenance strategy where decisions are taken based on risk considerations. Risk could be understood as expected cost, combining the consequence of those specific events and the probability of those events taking place.



Risk-based O&M could be perceived as a methodology that transfers technical knowledge on damages, failure modes and uncertainties, into risk and economic indexes, easier to understand, and that can be directly used to take more educated decisions at the time of planning O&M campaigns.



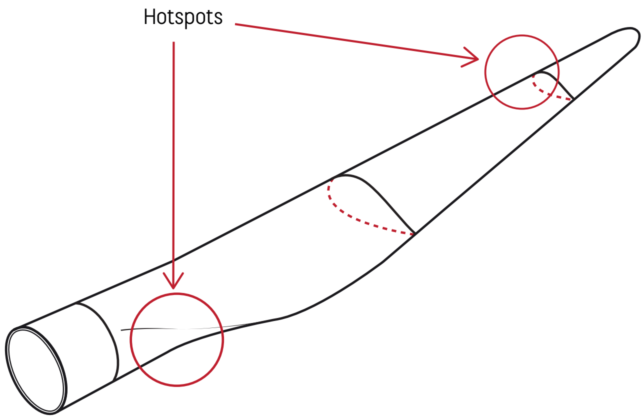
DEVELOPMENT & IMPLEMENTATION OF A RISK-BASED O&M

The implementation of a risk-based O&M requires four different steps:

1. HOTSPOT IDENTIFICATION SCHEME

Identify the damages and the areas with higher risk to know what actions should be prioritized. Each blade section tend to suffer from most severe damages, depending mainly on the blade's structural behavior.

Understanding the most probable damages and consequences, and the most probable areas where these damages may take place, is considered essential to perform an efficient and customized O&M inspection campaign, that reduces the risk of those particular identified failure modes.

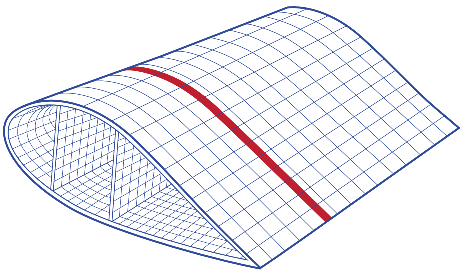


OPERATION & MAINTENANCE

2. CRITICALITY ASSESSMENT

Once the hotspots are identified and inspected, the next step is to evaluate this information focusing on the possible development and possible criticality of those possible damages.

Actions like benchmarking, testing, FMEA, experience under similar conditions, or software tools like FEM, can help to carry out this analysis.



3. MATRIX SELECTION

Once the previous information is gathered, different risk profiles for each asset can be created. The more holistic the analysis has been made, the more accurate and closer to reality the risk profile will be. In this sense, structural understanding should be added to the analysis of other sources of damages like leading edge erosion and lightning.

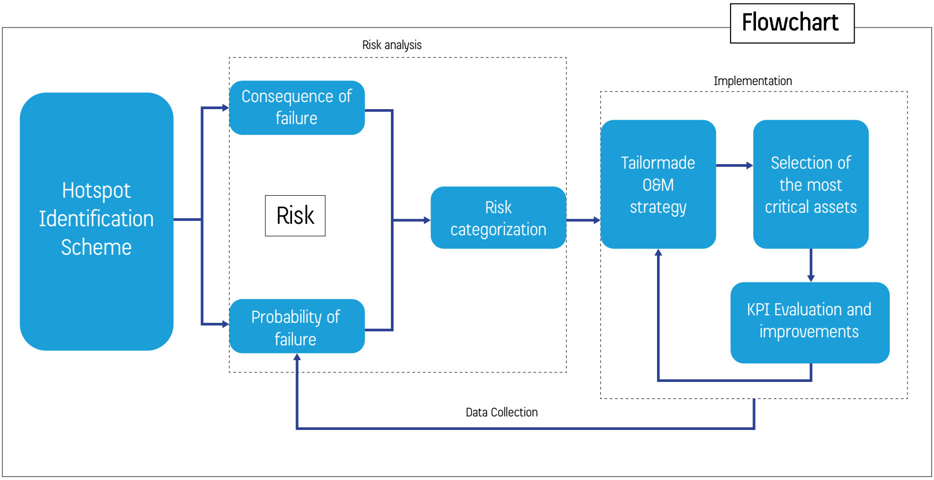
A matrix selection can help to associate each risk profile with a corresponding template or tailored made O&M strategy.

	Site Categorization											
	Low				Medium				High			
Blade size	Blade Risk Level 1	Blade Risk Level 2	Blade Risk Level 3	Blade Risk Level 4	Blade Risk Level 1	Blade Risk Level 2	Blade Risk Level 3	Blade Risk Level 4	Blade Risk Level 1	Blade Risk Level 2	Blade Risk Level 3	Blade Risk Level 4
Small	1	2	4	-	2	2	4	-	-	2	-	-
Medium	-	2	4	8	-	3	5	10	-	-	5	10
Large	-	-	-	9	-	-	6	11	-	-	7	11

Matrix selection

4. TAILORED MADE O&M STRATEGY

Each risk profile should be correlated with a specific tailored made O&M strategy, that helps in relevant decisions and in prioritizing actions.



The customized analysis will provide an educated opinion through individual templates with recommendations in terms of: how often should be the inspection interval, which inspection method should be used for each of the relevant identified potential damages, how it should be the repair criteria, etc., as well as other O&M concerns.

Ideally, the application of these tailored-made O&M strategies should be linked to the specific KPI (Key Performance Indicator) of each wind turbine owner, which could potentially modify the decision-making process.

At the same time, all collected data during the Implementation phase, is aimed to be used for a more accurate future risk analysis in following planning of risk-based maintenance strategies.

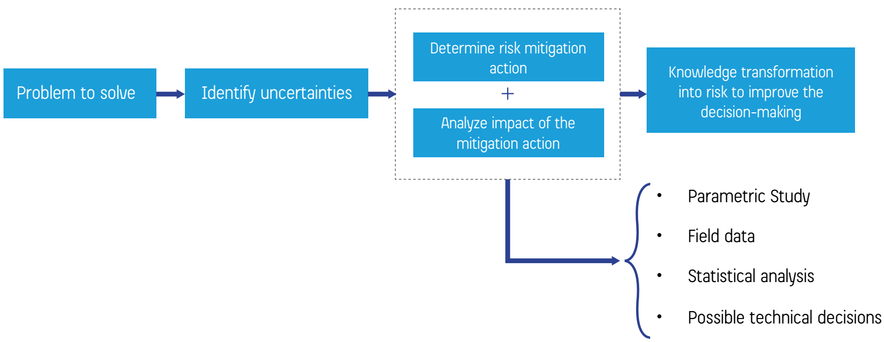
OPERATION & MAINTENANCE

UNCERTAINTIES

A risk-based analysis deals with the probability of that specific scenarios happen. At the time that these scenarios depend on several variables that either cannot be fully controlled, or are random by nature, the reality may differ from the expected scenario considered for the risk analysis. Therefore, it is important to consider all the possible sources of uncertainties that may influence the results.

Sources of uncertainties that should be included in the model	
Physical uncertainties	Wind, loads, fatigue strength, ...
Measurement uncertainties	Probability of detection (POD), accuracy of measurements, ...
Model uncertainties	Shear web growth model, FEM, fracture mechanics
Statistical uncertainties	Limited number of data

To deal with uncertainties, parametric analysis and field data are advised.



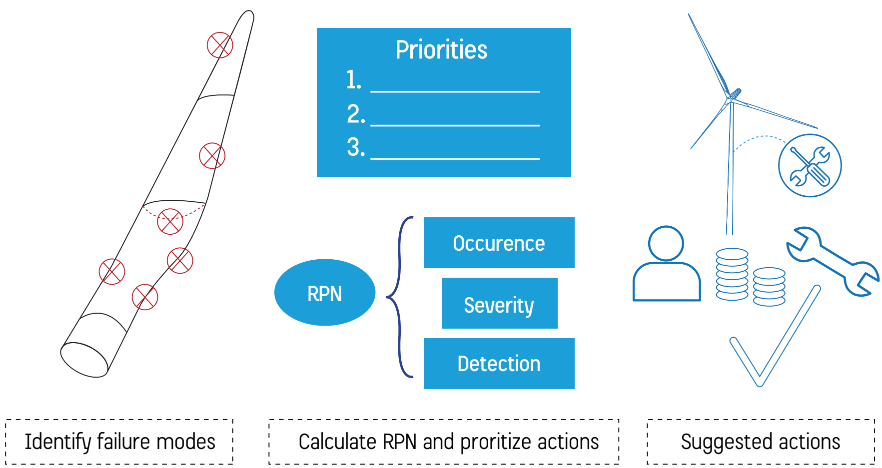
DECISION MAKING

Failure Mode Effect Analysis (FMEA) is a system to measure the risk through a parameter called Risk Priority Numbers (RPN). FMEA can be used to identify failure modes and effects of failures.

An FMEA is often the first step of a system reliability study. It involves reviewing as many components, assemblies, and subsystems as possible, to identify failure modes, and their causes and effects.

The objective is to provide a grading system to the different failure modes in order to determine for which one's actions should be prioritized. The RPN oscillates between 0-1000 and is the result of the multiplication of three variables from 0-10: severity, occurrence, and detection.

An FMEA is often done on an Excel sheet divided in analysis, action, results of mitigated actions.

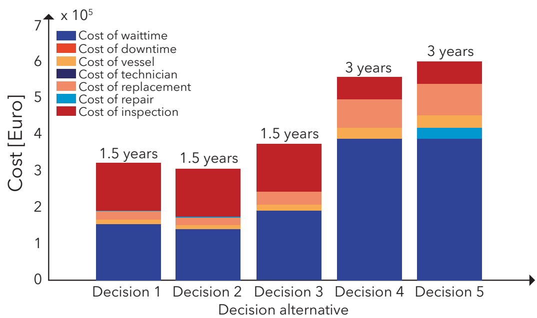


OPERATION & MAINTENANCE

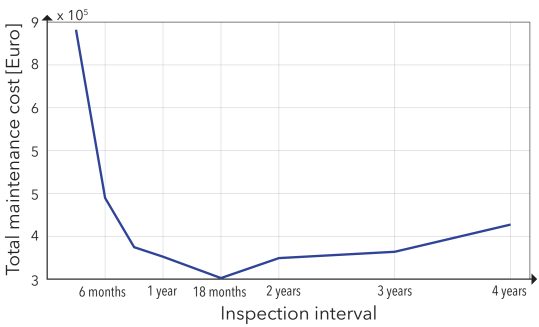
DECISION ALTERNATIVES

Decision alternatives define the actual maintenance actions for a specific damage observed at an inspection, which is closely associated with the total maintenance costs. Based upon the five-level damage category scheme (p. 65), five decision alternatives are defined for illustration and are summarized, see below.

It should be noted that for damage category 5 of offshore wind turbines, a heavy lifting vessel (HLV) should typically be chartered to carry the equipment for major repair or replacement, and a crew transfer vessel (CTV) can often be deployed for the other damage categories.

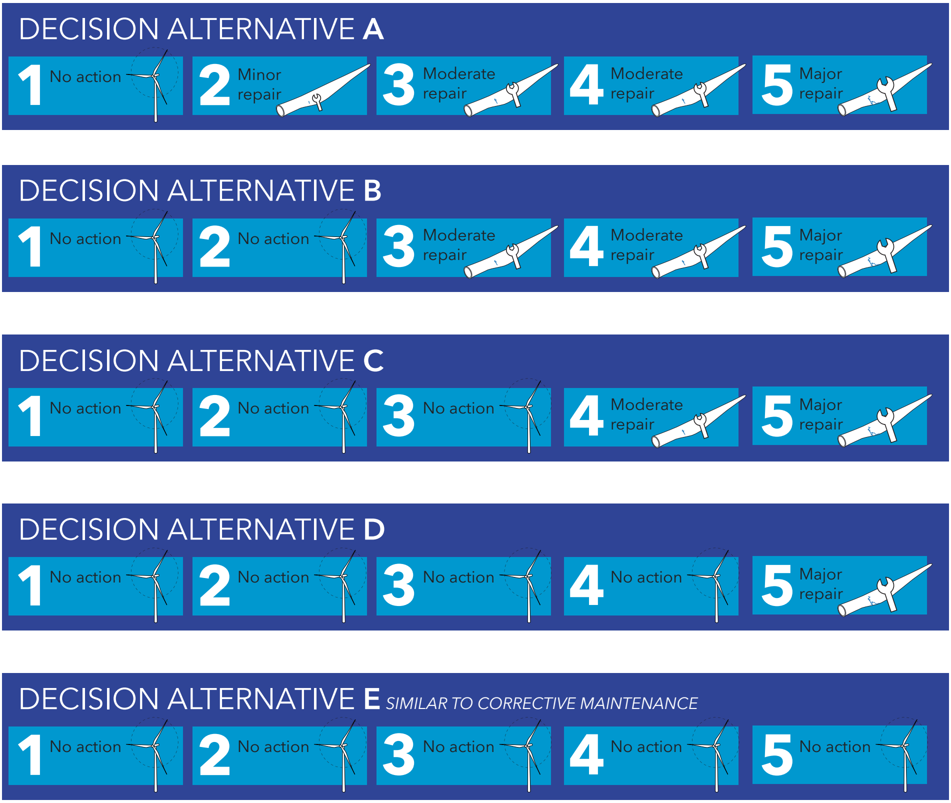


The total maintenance cost for different decision alternatives - Transverse cracks



Cost trend as function of inspection interval - Decision Alternative 2

DECISION ALTERNATIVES - EXAMPLES



A decision alternative implies the action "to repair or not to repair" dependent on the current damage category. Above, five different decision alternatives is shown.

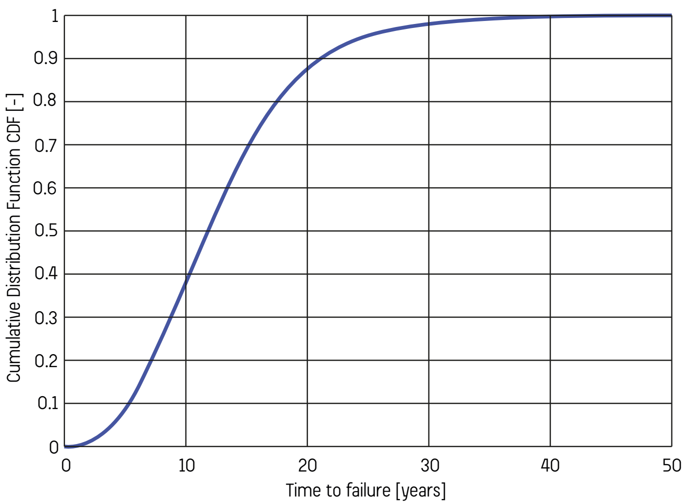
OPERATION & MAINTENANCE

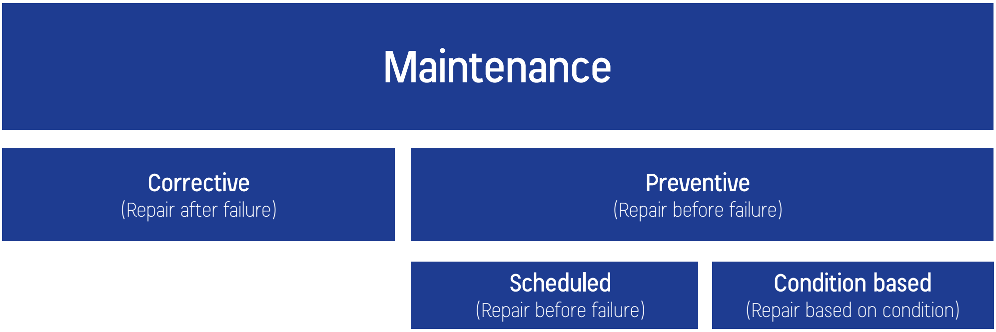
RELIABILITY MODEL - DISCRETE MARKOV CHAIN

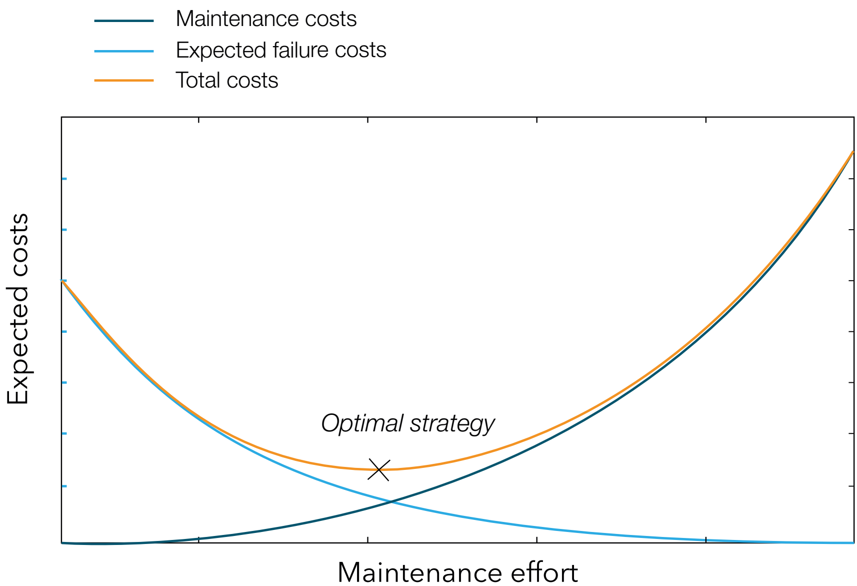
Damages discretized in categories:

Category	Description
1	Cosmetic / no damage
2	Damage below wear and tear
3	Damage above wear and tear
4	Serious damage
5	Critical damage

The Markov model gives the probability of evolution of damage from time step to time step, e.g. the probability that a damage in category 2 develops to category 3 within the next month. The model assumes that predictions for the future development of the damage can be made solely on its present state.
Furtheremore it can be used to estimate e.g. the time to reach a category 5 damage (failure) given it is in category 1 now, represented by a probability distribution function. Example: (expected value: 12.4 years and standard deviation 6.5 years):







The optimal maintenance strategy.

OPERATION & MAINTENANCE

RELIABILITY MODELING

Reliability modeling is the process of predicting or understanding the reliability of a component or system prior to its implementation.

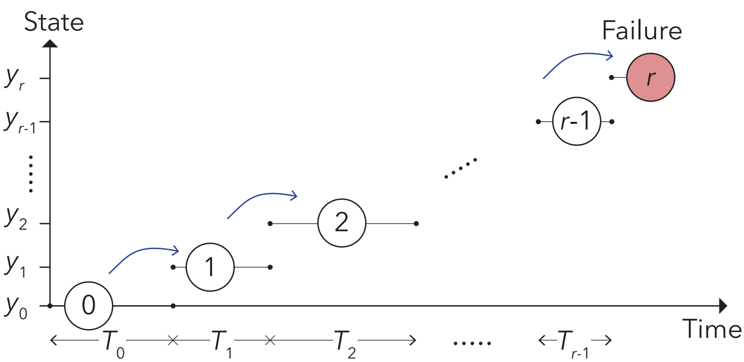
Failure types

a) Failures that can be repaired / maintained

b) Collapse of blade - requiring replacement

A) FAILURE THAT CAN BE REPAIRED/MAINTAINED

Damage categorization model using a discretization of the damage level as shown on page 65. A Discrete Markov Chain model can be used as a probabilistic model



Discrete Markov Chain Model -

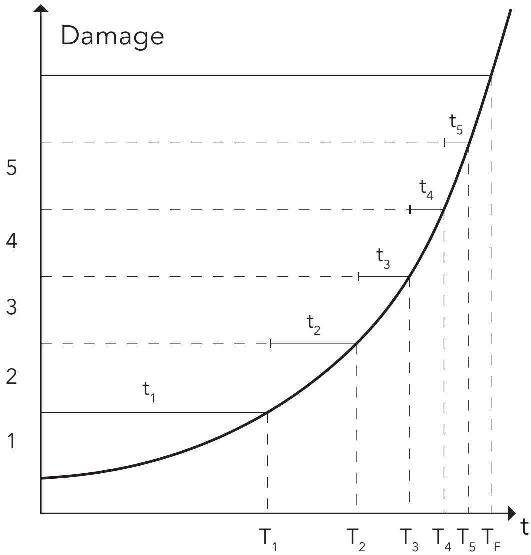
Discretization is the process of replacing a continuum with a finite set of points.

DAMAGE PROPAGATION

Damage is modelled by a continous model

The damage growth rate (increase per time unit) is modelled by the Paris Law:

$$\frac{dq}{dN} = C(\Delta G)^n$$



Continuous damage propagation

IEC REFERENCES

WIND TURBINE STANDARDIZATION IEC

The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees. The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards.

IEC 61400-1	Design requirements
IEC 61400-2	Small wind turbines
IEC 61400-3	Design requirements for offshore wind turbines
IEC 61400-3-2 TS	Design requirements for floating offshore wind turbines
IEC 61400-4	Gears for wind turbines
IEC 61400-5	**Wind Turbine Rotor Blades**
IEC 61400-6	Tower and foundation design
IEC 61400-11	Acoustic noise measurement techniques
IEC 61400-12-1	Power performance measurements of electricity producing wind turbines
IEC 61400-12-2	Power performance of electricity-producing wind turbines based on nacelle annemometry
IEC 61400-12-3	Wind farm power performance testing
IEC 61400-13	Measurement of mechanical loads
IEC 61400-14 TS	Declaration of sound power level and tonality
IEC 61400-15	Assessment of site specific wind conditions for wind power stations
IEC 61400-21	Measurement of power quality characteristics
IEC 61400-22	Conformity Testing and Certification of wind turbines

IEC 61400-23	**Full-scale structural testing of rotor blades**
IEC 61400-24	Lightning protection
IEC 61400-25	Communication
IEC 61400-26 TS	Availability
IEC 61400-27	Electrical simulation models for wind power generation
IEC 61400-28 TS	**Through life management and life extension of wind power assets**

DESIGN LOAD CASES IN IEC 61400-1

- Normal operation - power production (DLC 1)
- Power production plus occurrence of fault (DLC 2)
- Start up (DLC 3)
- Normal shut down (DLC 4)
- Emergency shut Down (DLC 5)
- Parked (standing still or idling) (DLC 6)
- Parked and fault Conditions (DLC 7)
- Transport, assembly, maintenance and Repair (DLC 8)

MARKET MAP

PROJECT DEVELOPMENT

The development of a wind project - from the need is defined till the site is cleaned up after decommissioning - involves several stakeholders each performing various activities as specified below. The lead of the work till commissioning of the project is the Developer. After that, the lead is called the Operator. Developer and Operator can be the same entity, but both

PROJECT DEVELOPMENT - CAPEX

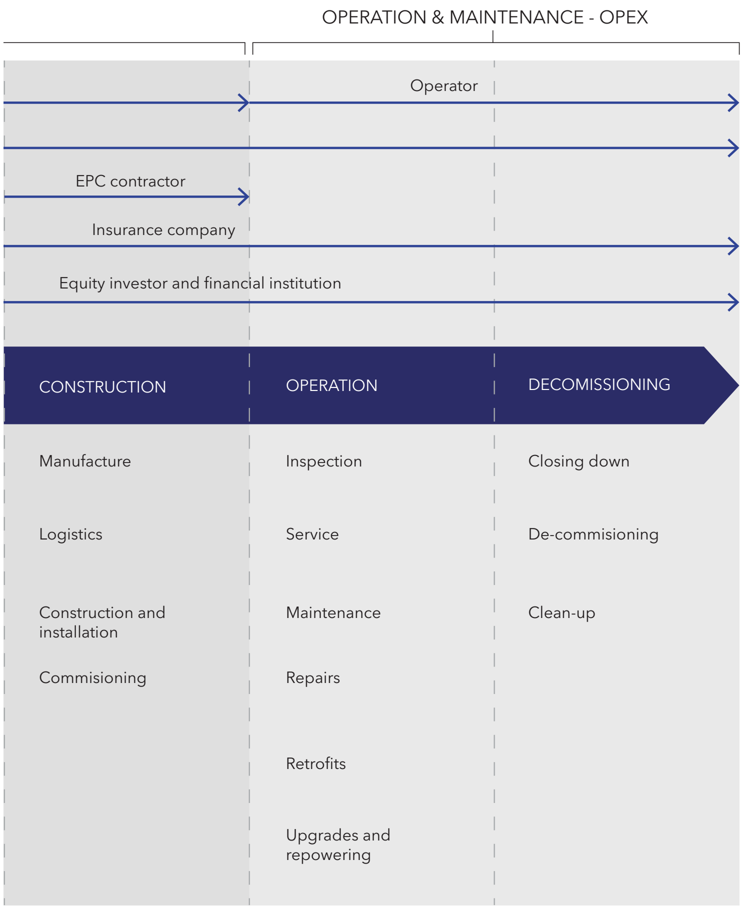
Developer

Owners engineer

Financial advisor

SITING	INFRASTRUCTURE	FINANCING (TENDERING)	PLANNING & PROCUREMENT
Identification and securement of land	Grid connection	Business concept and case	Final micrositing and project layout
Wind ressource assessment	PPA/income model	Equity investor	Procurement of equipment and civil works
Environmental studies	Overall construction plan	Debt financing	Construction plan and permit
Grid connection feasibility and loss analysis	Building permits and required approvals	Construction financing	Insurance covering
List of approved/ accepted turbines	Contractual strategy	Liability coverage plan	
Mico-siting and AEP estimate	Project plan and budget		

will work for the Owner of the project. The current trend is that the Developer develops and owns the project, and also operate for a short period of time after commissioning, and hence is the operator for a while. Then the project is sold of to investors (new owners), but often the Operators continue.



MARKET MAP

WIND TURBINE OPERATION & MAINTENANCE EXECUTION OPTIONS

The current trend among utilities (owners of distribution nets and end-users) with bidding out projects in public tendering covering both financing, construction and operation of a project paid by the developer via procurement of the electricity production to the tendered Feed-In-Tariff(FIT) is effectively an outsourcing of the operation and maintenance to an operator.

OWNER'S/ PROJECT DEVELOPER'S RISK LEVEL	OPERATION IN WARRANTY	OPERATION OUTSIDE WAR-RANTY IN HOUSE	OPERATION OUTSIDE WAR-RANTY OUTSOURCED
1	Turbine OEM		Full outsourcing of both O&M to Operator (could be tendering)
2			Maintenance Contract with Turbine OEM
3		**Fleet wide organisation.** Either with own or sourced service engineers or a combination of those two.	Maintenance Contract with independent service provider
4		**Regional organisation.** Either with own or sourced service engineers or a combination of those two.	
5		Local and autonomous at project level. Either with own or sourced service engineers or a combination of those two.	

WIND PROJECT LIABILITIES AND INSURANCE COVERAGE OPTIONS

CATEGORY	DESCRIPTION	LIABILITY IN WARRANTY	LIABILITY OUTSIDE WARRANTY	WTO INSURANCE OPTIONS
WEAR AND TEAR	Natural and inevitable degradation of the blade due to operation as per the operational procedure.	WTO	WTO	O&M cover, but only to cover unexpected peaks in cost.
OPERATION	Damages due to operation outside operational manual, faulty maintenance/inspections (or lack of), and faulty repairs.	Faulty operation: WTO Other: OEM	WTO	None.
QUALITY	Quality issues in material, workmanship, production methods, transport, storage and installation.	OEM	WTO	Extended Warranty and/or O&M Cover. Business interruption. Serial defects will only be covered until is is realised that they are serial defects. If serial, regress towards OEM.
DESIGN	Either defects due to faulty cotnfiguration/selection of turbine or serial defects.	OEM	OEM	Latent Defects and Business interruption. Regress towards OEM.
ACT OF GOD	Lighting, flooding, extreme weather	WTO	WTO	All risk and business interruption.
ACCIDENT	Any accidental damages to assets.	WTO	WTO	All risk and business interruption.
WILFUL	Theft, vandalism, sabotage, terrorism	WTO	WTO	Operator's risk and business interruption.

Most insurance policies include an element of own risk/deductibles. Hence, regardless of insurance coverage, most events will equal cost for the WTO. Further, there will a coverage limit, both on incident level and annual level.

MARKET MAP

WHAT DRIVES WHO WHEN IN A WIND PROJECT

Although the overall driver for the total project lifetime profitability is the full LCOE with all its components, each stakeholder will sub-optimize on other cost components. As all other projects, the construction, operation and maintenance of a wind project, there are inherent conflicts among the stakeholders as regards to priorities in each specific situation.

STAKEHOLDER	KEY DECISION DRIVER	STAKEHOLDER'S OPERATIONAL FOCUS	CHOICE OF WIND TURBINE OEM
END-USER The ultimate purchaser of the produced electricity.	Cost of Energy	"Operational Profit"	LCOE
UTILITY (OFF-TAKER AND DISTRIBUTOR) Owner of the distribution net, end-users and effectively the off-taker of the produced electricity.	Cost of Energy and Availability	Continuous Business Improvement	LCOE
OPERATOR Operator of either a single project or a portfolio of projects. Income model purely by sell of energy.	Operational Profit	Continuous Business Improvement	AEP and LCOE
OWNER Owner of a project. Typically, a special purpose company and owned by either by an utility or by an operator.	Operational Profit	Continuous Business Improvement	Return on Investment
PROJECT DEVELOPER Developer of a project.	Contract Margin	Risk Management	AEP and Brand
OWNER'S ENGINEER Engineering companies offering engineering services to the Owner, Project Developer or Operator during the lifetime of a project, predominantly during project development.	Contract Margin	Risk Management	AEP, Availability and Brand

STAKEHOLDER	KEY DECISION DRIVER	STAKEHOLDER'S OPERATIONAL FOCUS	CHOICE OF WIND TURBINE OEM
FINANCIAL ADVISOR Company who support the project developer in seeking and finding financing of a project.	Contract Margin	Risk Management	Brand
INVESTOR Investor, Fund, Utility or OEM providing equity for a project.	Return of Investment	Risk Management	Brand and Return of Investment
FINANCIAL INSTITUTION Bank, Fund, Investor or Export Credit Agency providing debt-based financing for a project.	Contract Margin	Risk Management	Brand and Return of Investment
EPC CONTRACTOR Company executing the full EPC contract (Turbines, electrical work and civil work) for a project.	Contract Margin	Risk Management	CAPEX
INSURANCE COMPANY Companies providing insurance coverage of project liabilities.	Contract Margin	Risk Management	Brand
TURBINE OEM Original Equipment Manufacturer deliver the wind turbines for the project.	Contract Margin	Continuous Business Improvement	
IN-HOUSE SERVICE ORGANIZATION Operator's own service organization.	Cost and Availability	Continuous Business Improvement	Maintainability and OPEX
SERVICE CONTRACT HOLDER Service provider (either independent or OEM owned) holding a long-term service contract with operator.	Contract Margin	Continuous Business Improvement	Contract Margin and Company Risk Management (Serial Defects)

MARKET & DECISION DRIVERS

RETURN ON INVESTMENT

In priciple:

$$\frac{\text{Return (benefit)}}{\text{Investment (cost)}} = \text{ROI}$$

However, to include the time factor, most often calculated as Internal Rate of Return, via discounted cash flows:

INTERNAL RATE OF RETURN

n = Number of cash flows

CF_j = Cash flow at period j

IRR = Internal Rate of Return

$$0 = \sum_{j=1}^{k} CF_j \cdot \left[\frac{1 - (1 + IRR)^{-n_j}}{IRR} \right] \cdot \left[(1 + IRR)^{-\sum_{q<j} n_q} \right] + CF_0$$

OPERATIONAL PROFIT AND CONTRACT MARGIN

Company level (given period):

	Operational revenue
–	Total direct cost for delivery of contracts
	Gross margin
–	Sales and general overhead and admin
–	Depreciation and amortization
	Operational profit

Contract level (given period):

	Contract realized revenue
–	Contract realized total cost for delivery
	Contract margin

MARKET & DECISION DRIVERS

LEVELIZED COST OF ENERGY (LCOE)

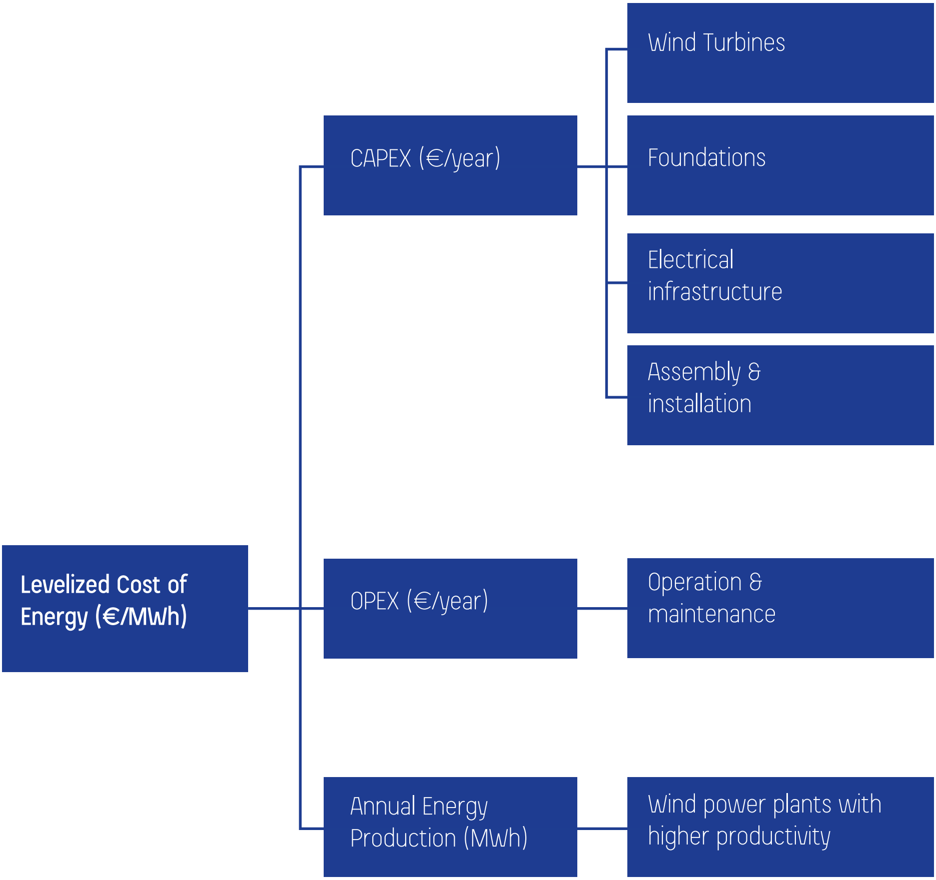
$$LCOE = \frac{CAPEX + OPEX}{AEP}$$

LCOE:	Levelized cost of energy (Euro/Mwh)
CAPEX:	Capital expenditure (Euro)
OPEX:	Operational costs (Euro)
AEP:	Annual energy production (MWh)

or

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}}$$

LCOE:	Levelized cost of energy ($Euro_{2012}$/Mwh)
I_0:	Capital expenditure in Euro
A_t:	Annual operating costs in Euro in year t
M_{el}:	Produced electricity in the corresponding year in MWh
i:	Weighted average cost of capital in %
n:	Operational lifetime (20 years)
t:	Individual year of lifetime (1, 2, ..., n)

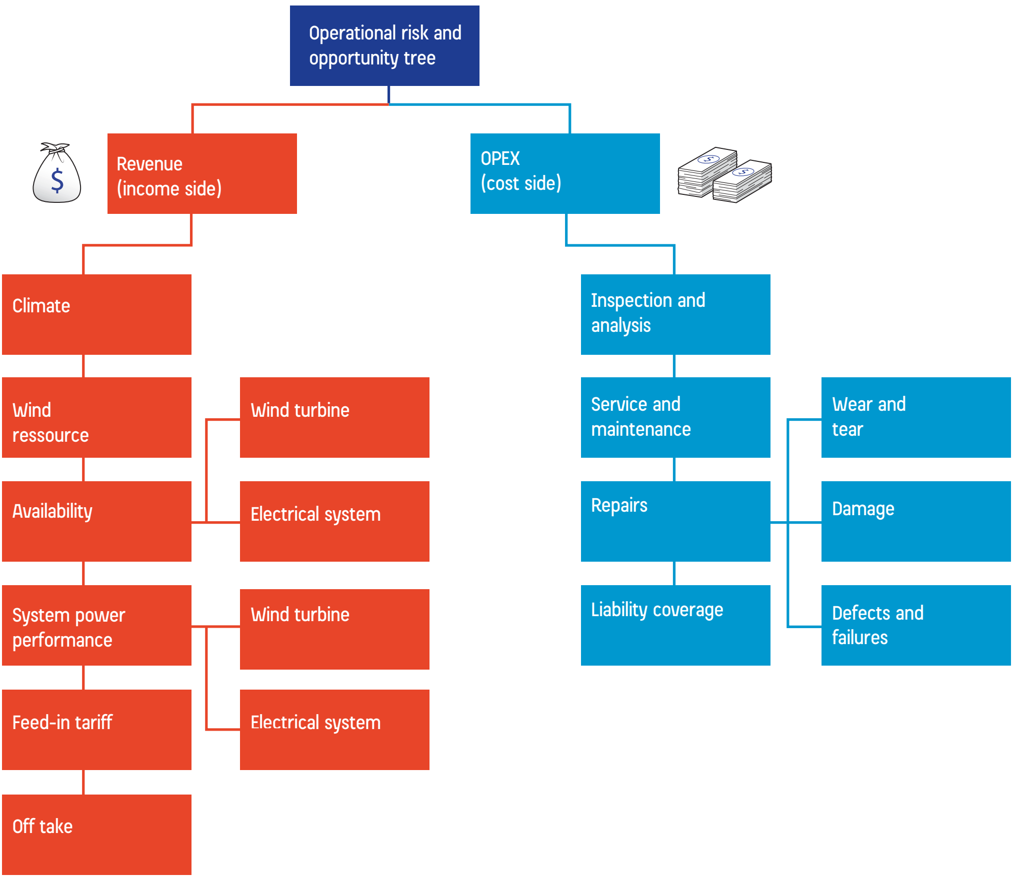


Ref.: MEGAVIND, 2013: THE DANISH WIND POWER HUB - Strategy for Research, Development, and Demonstration

DECISION MAKING / OPERATOR'S FOCUS

OPERATIONAL RISK AND OPPORTUNITY ASSESSMENT

Overview of general elements to review to establish risk and opportunity elements for operational management of a wind turbine project. For each element, the operational management can execute investments to either improve performance, mitigate risk or limit impact for malperformance.



RISK LEVEL VS TIME TO REACT

CONTINUOUS BUSINESS IMPROVEMENT

Continuous business improvement is an ongoing process to improve the products, services or processes of an organization. The improvements sought can be incremental over time or achieved with a breakthrough moment.

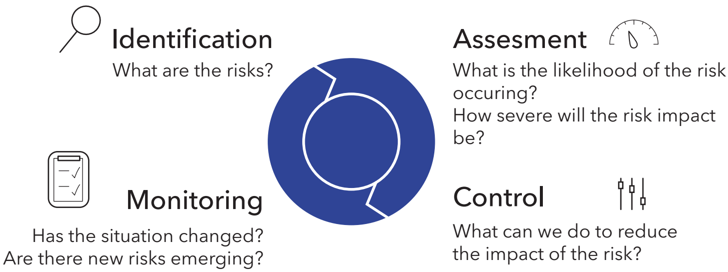
The delivery of those processes is in constant evaluation and change, so further improvements can be developed and applied. The ruler to measure these changes is the efficiency, effectiveness and flexibility of these processes, and the objective is to increase the profitability of the organization.

Continuous business improvement

DECISION MAKING / OPERATOR'S FOCUS

RISK MANAGEMENT

Risk management is the identification, evaluation, and prioritization of risks (defined in ISO 31000 as the effect of uncertainty on objectives) followed by coordinated and economical application of resources to minimize, monitor, and control the probability or impact of unfortunate events or to maximize the realization of opportunities.



DAMAGE CONTROL

Damage control is action that is taken to make the bad results of something as small as possible, when it is impossible to avoid bad results completely.

PRIORITISATION OF INVESTMENT

Each activity to improve operations or reduce impacts will be an investment which will be prioritized among the full portfolio of potential investments. A number of models and parameters are used to prioritize between the portfolio:

Urgency (Continuous business improvement, risk management, damage control)

Cost of no action

Complexity of implementation

Return on Investment

Fit with Constraints:

Resource Constrain: Do we have resources including financial resources to implement?

Liability Constrain: Does implementation increase our liabilities to an unacceptable level?

Contractual Constrain: Will the implementation breach any contracts, either in word or spirit?

Policy Constrain: Does the implementation conflict with any of our internal policies, including maximum payback time or minimum Return of Investment?

Time Constrain: Do we have time to implement?

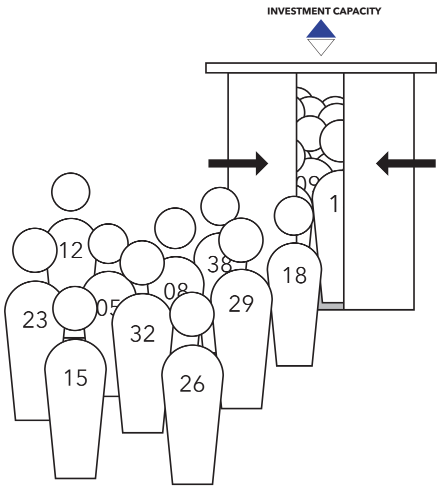
DECISION MAKING / OPERATOR'S FOCUS

PRIORITIZATION OF INVESTMENT

Most organizations will prioritize their investments within their constraints annually in the Annual Operating Plan with an objective to maximize their overall Return on Investment in the following order and to the limit of their budgeted investment capacity:

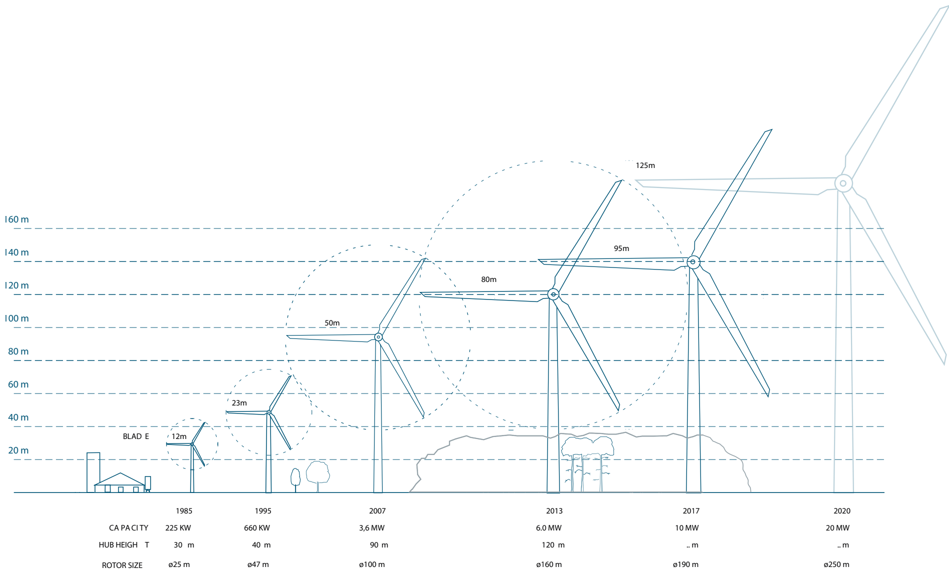
1. Damage Control Investments (must do's) - often prioritized outside budgeting
2. Specific investments supporting overall strategic initiatives
3. Low hanging fruits with high Return on Investment to a given minimum
4. Other investment ranked as per their Return on Investment or other predefined ranking methods to the limit of the budgeted investment capacity.

For an investment request (for blade repairs, blade upgrades or optimization) to be successful, it has to be ranked so high in the priority list that it is within the investment capacity.



SIZE MATTERS

As the blade size increases both the risk and opportunity related to blades and their impact on the overall LCOE increases, and hence blade investments will be ranked relatively higher on the priority list going forward. However, as the operating experience and hence realized operating cost is limited, it is important to monitor and analyse performance of said blade and hence pre-actively and consciously manage risk related to the blades.



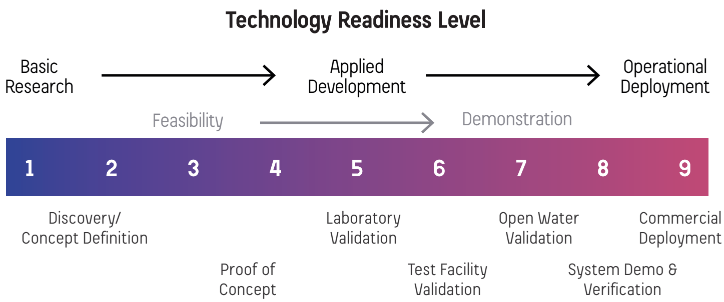
PRODUCT DEVELOPMENT

DESIGN DRIVERS

Key areas cover the entire area of design parameters, which are key for driving the product development forward and minimizing the risk early on in the design process.

TECHNOLOGY READINESS LEVEL (TRL)

TRL is a method of estimating technology maturity of Critical Technology Elements (CTE) of a program during the acquisition process. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRL is based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology. A comprehensive approach and discussion about TRLs has been published by the European Association of Research and Technology Organisations (EARTO).



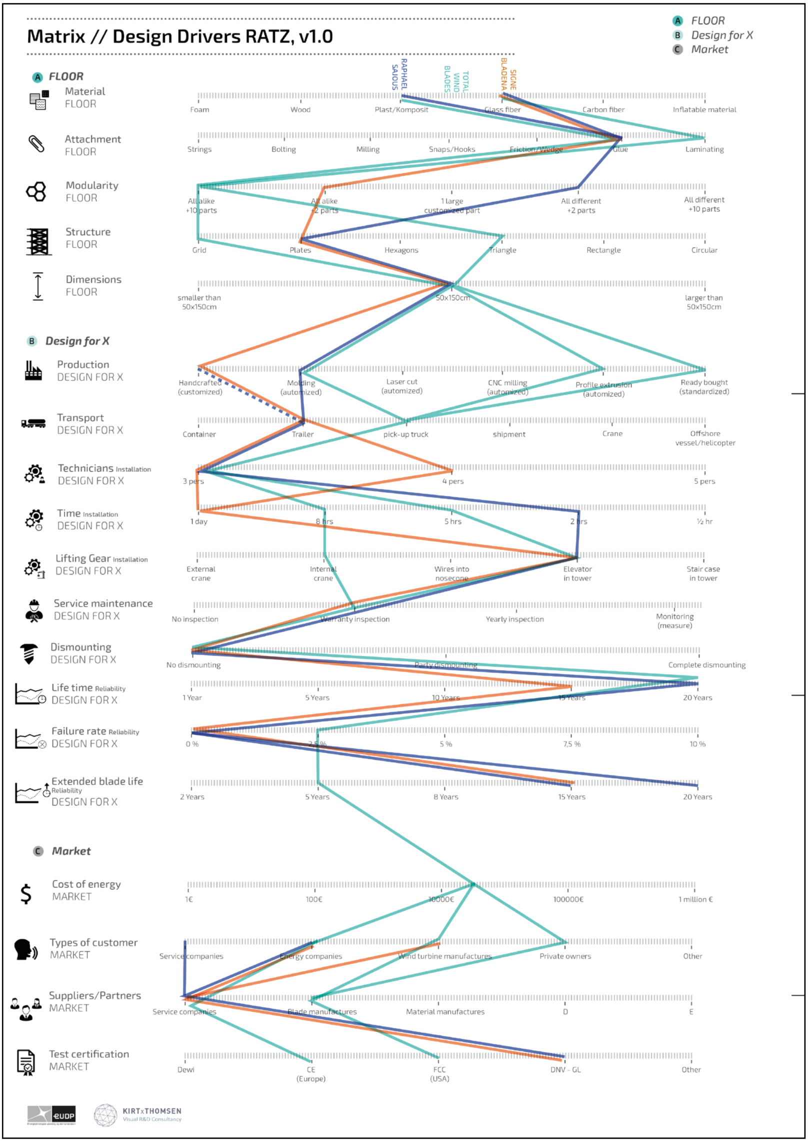
BRAINSTORMING

This process involves generation of a vast number of ideas that can solve or mitigate a specific problem. In the course of brainstorming, there is no assessment of ideas. So, people can speak out their ideas freely without fear of criticism. Even bizarre/strange ideas are accepted with open hands. In fact, the crazier the idea, the better. Taming down is easier than thinking up.

Frequently, ideas are blended to create one good idea as indicated by the slogan "1+1=3." Brainstorming can be done both individually and in groups. The typical brainstorming group includes six to ten people.

MORPHOLOGY MATRIX

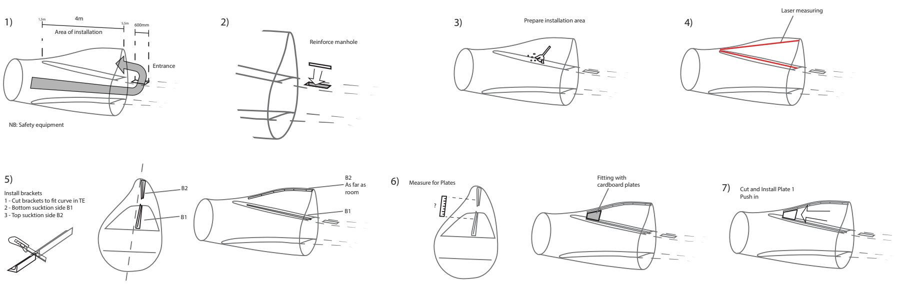
User and stakeholder feedback method to put up options and possibilities in a simple form to gain input, overview and generate alignment among key project participants.



PRODUCT DEVELOPMENT

STORYBOARDING

Storyboarding has to do with developing a visual story to explain or explore. Storyboards can help creative people represent information they gained during research. Pictures, quotes from the user, and other pertinent information are fixed on cork board, or any comparable surface, to stand for a scenario and to assist with comprehending the relationships between various ideas.



PROTOTYPING

A prototype is an early sample, model, or release of a product built to test a concept or process or to act as a thing to be replicated or learned from.
Basic prototype categories.

Prototypes explore different aspects of an intended design:

1. A Proof-of-Principle Prototype serves to verify some key functional aspects of the intended design, but usually does not have all the functionality of the final product.
2. A Working Prototype represents all or nearly all of the functionality of the final product.
3. A Visual Prototype represents the size and appearance, but not the functionality, of the intended design. A Form Study Prototype is a preliminary type of visual prototype in which the geometric features of a design are emphasized, with less concern for color, texture, or other aspects of the final appearance.
4. A User Experience Prototype represents enough of the appearance and function of the product that it can be used for user research.
5. A Functional Prototype captures both function and appearance of the intended design, though it may be created with different techniques and even different scale from final design.
6. A Paper Prototype is a printed or hand-drawn representation of the user interface of a software product. Such prototypes are commonly used for early testing of a software design, and can be part of a software walkthrough to confirm design decisions before more costly levels of design effort are expended.

NOMENCLATURE

ACOUSTIC EMISSION

A family of non-destructive testing (NDT) technique where a sound is monitored using piezoelectric sensors and acoustic emision sensors. The function of acoustic emission is to detect specific damages, origin, serverity and potential growth

ADHESIVE

A material that binds the blade components together by surface attachment. In general, it is used to bind the shear webs to the spar caps and suction side and pressure side shells together in the TE and LE regions (cf. Bondline)

ADHESIVE FAILURE

Adhesive failure indicates that the failure occurs along the interface between bondlines and the laminate. Consequently, the entire adhesive layer will be attached to one of the fracture surfaces, while the other fracture surface is free of adhesive (see also Cohesive failure)

AERODYNAMIC FORCES

Forces caused by the wind flow over wind turbine blades

AEROELASTICITY

The science which studies the interactions among inertial, elastic, and aerodynamic forces

AXIAL DIRECTION

Axial means parallel to the axis of the blade

ANNUAL ENERGY PRODUCTION (AEP)

The amount of energy produced on a yearly basis

BENCHMARK (VALIDATION, COMPARISON)

A standard or point of reference against which things may be compared

BI-DIRECTIONAL FIBERS

Composites in which fibers are aligned in two directions

BLADE LENGTH

Distance from root to tip

BLADE'S RADIUS

The blade's radius is obtained by measuring the distance from the blade root to the region of interest (see also Blade length and Rotor Radius)

BONDLINE

The adhesive layer between different blade components

BOX BAR DESIGN

Load-carrying box (Shear webs and spar caps construction). during manufacturing, the shear webs and spar caps are designed as a box, and the two shells are coupled on the box

BREATHING

Breathing is the relative deformation of panels (in the out-of-plane direction)

BUCKLING

Buckling is a non-linear phenomenon which is the inability of the blade to have a linear response between loads and deformations. A common region for the blade to buckle is mid-span, TE region. Blade in operation are not allowed to buckle, however in static full-scale testing they are allowed to buckle

BUSINESS CASE

In relation to the CAR Tool, business case is the output of the CAR Tool showing the expected commercial benefits of different actions

CAMBER LINE

An aerodynamic reference line with same distance to suction surface and the pressure surface

CAPEX (CAPITAL EXPENDITURES)

The money the company spends acquiring or upgrading its physical assets

CAPACITY FACTOR (CF)

Capacity Factor is the average power generated divided by the peak power

CASH FLOW

The total amount of money that goes into and out of a business

CHORD LENGTH

The distance from LE to TE.

NOMENCLATURE

25% CHORD

The point on a chord line which is 1/4 of the chord length away from the LE. The aerodynamic center of the symmetrical airfoils is located at 25% chord.

CLOSE VISUAL INSPECTION (CVI)

A close examination by visual and/or tactile means of installation, assembly or a specific item to detect damage, failure or irregularity. This level of inspection may require the use of mirrors, magnifying lenses or other aids to provide a means to accomplish a focused inspection. Available lighting is normally supplemented with a direct source of good lighting at an intensity deemed appropriate

COHESIVE FAILURE

The terminology "cohesive failure" is usually used to point out that the failure occurs within a material, e.g. an adhesive layer. It can be recognized from the fracture surfaces in where adhesive will be attached to both surfaces. Failure to take place along the interface between adhesive layer and the substrate material is denoted as "adhesive failure"

COHESIVE ZONE

To accurately represent fracture mechanics, it is convenient to introduce a specialized material model, called a cohesive law. This is a simplified relation that links the tractions (stresses) transmitted between the two crack faces and the displacement between them; thus, it is called traction-separation relation and is the fracture process zone's mathematical representation. Cohesive laws need to be experimentally measured for materials and interfaces. The correct deduction and implementation of these laws enable the accurate prediction of cracked composite structures' behaviour. These are conveniently introduced in numerical Finite Element tools and simulate a crack's propagation in a structure under loads

COLLAPSE

Seperation of the blade from the hub or critical damage to the blade wich cannot be repaired

COMBINED LOADING

A mix of two or more loads. In the wind industry, the mix of edgewise and flapwise loads. It is commonly used as combined loading. Torsional loads are included in this formulation as well

COMPOSITE MATERIAL

A composite material is made by combining two or more materials - often ones that have very different properties. The two materials work together to give the composite unique properties

CONDITION-BASED MAINTENANCE (CBM)

A maintenance strategy that monitors the actual condition of an asset to decide what maintenance needs to be done

CORRECTIVE MAINTENANCE (CM)

Maintenance tasks that are performed in order to repair or restore failures

CORTIR

An EUDP project called "Cost and Risk Tool for Interim and Preventive Repair" headed by Bladena

CRACK

A damage type where material breaks at the crack tip creating a new crack plane (two new fracture surfaces)

CRACK PROPAGATION RATE (CPR)

Change in crack length per load cycle

CRITICAL TECHNOLOGY ELEMENTS (CTE)

The technological elements on which the system depends on to meet the operational requirements

COST OF EQUITY

It is the financial return investors expect to see

COST OF CAPITAL

It is a percentage of return expected by investors who provide capital.

C-WEB

A relatively small shear web installed close to the blade's trailing edge to provide additional stability against buckling and breathing

DAMAGE

Irreversible breakage of materials or interfaces, e.g., the formation of cracks (from manufacturing defects), caused by external loads

NOMENCLATURE

DAMAGE CATEGORY (DC)

Damage category is a term used to quantify the severity of a defect/damage

DEBONDING

Crack growth between the interface of the two different materials (e.g., adhesive/laminate interface)

DECISION RULE (DR)

The decision rule defines the actual maintenance actions for a specific damage observed at an inspection, accordingly to the severity category

DEFECT

A flaw in a wind turbine blade formed during the blade manufacturing (see also Manufacturing flaw)

DELAMINATION

Crack initiation or growth between two layers within laminate

DIGITAL X-RAY

Digital radiography is a form of X-ray imaging, where digital X-ray sensors are used instead of traditional photographic film. Advantages include time efficiency through bypassing chemical processing and the ability to digitally transfer and enhance images

DISCOUNT CASH FLOW (DCF)

Discount cash flow is a analytical method of determining the value of an asset based on its future cash flow (see def. valuation)

DOWNTIME

The time during which a wind turbine is not producing electricity

EDGEWISE LOAD

Loads in the edgewise direction, causing edgewise global deformation

ELASTIC INSTABILITY APPROACH

The method uses the elastic FEM structural simulation tool to identify the impact that certain structural defects/ damage types and sizes have on the blade, from a structural point of view. The method uses a comparative analysis approach when a blade with a defect is compared with one without the defect

EUDP

Energy Technology Development and Demonstration Program. The EUDP supports private companies and universities to develop and demonstrate new technologies.

FAILURE

The loss of an intended function of a component (blades) of a wind turbine and/or a wind turbine due to excess loads

FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

FMEA is a risk assessment tool, that evaluates the severity, occurrence, and detection of risks to prioritize which ones are the most urgent

FAILURE RATE

The average failures of a component during a year

FATIGUE

The process in which damage accumulates under multiple load cycles, resulting in weakening or damaging the material

FIELD CASE STUDY

The field case study is a method of carrying out a detailed examination of information from the field

FINITE ELEMENT METHOD (FEM)

A tool used to simulate the structural behaviour of blades

FLAPWISE LOAD

Loads in the flapwise direction driven by wind causing flapwise bending

FLATBACK

It is the blunt trailing edge of an airfoil. Usually, it is a continuation of the transition zone flatback towards max chord and mid-span in some cases

NOMENCLATURE

FLUTTER

Flutter is an aerodynamic instability of blades which occurs when the torsional and flapwise eigenfrequencies are the same causing resonance

FRACTURE

The process in which damage accumulates under multiple load cycles, resulting in weakening or damaging the material

FRACTURE PROCESS ZONE

Fracture can occur by a sharp crack tip or by a long fracture process zone. In both cases, the zone where the material (or interface) fails is called the fracture process zone. Fracture by a crack tip is called small-scale fracture process zone, while fracture involving a long fracture process zone is called large-scale fracture process zone. For a large-scale fracture process zone, such as delamination crack growth along the layers, it may not possible to identify a defined crack tip, but there are two distinct regions: A zone where the material is beginning to be damaged and has reduced strength and a second region where intact fibres behind the damage front bridge the crack. Typically, fracture involving a small-scale fracture process zone is modelled using linear-elastic fracture mechanics, while fracture involving a large-scale fracture process zone is modelled using cohesive zone modelling

GENERAL VISUAL INSPECTION (GVI)

Quick scanning of the blades using human senses such as vision, touching or any non-specialized equipment. This type of inspection is done from within a touching distance of the wind turbine

GLOBAL DEFORMATION

Deformation seen on blades at blade length-scale level

GUIDE2DEFECT (G2D)

A Danish company (spin-off from Bladena) which has a blade database of failures from the field

IEC

International Electrotechnical Commission (IEC) is an international standards organization that prepares and publishes standards for electrical and related technologies

INTERLAMINAR FRACTURE

Failure mode found in composite laminates. It is the separation of layers within the laminated pile of a composite. This leads to interlaminar stresses which are the cause of the actual failure (see also delamination)

INDEPENDENT SERVICE PROVIDER (ISP)

An independent company specialized in carrying out services related to blades

ISO

International Organization for standardization

KEY PERFORMANCE INDICATOR (KPI)

It is a measurable value that demonstrates how effectively a company is achieving key business objectives or projects

KISSING BOND

Kissing bond is an adhesive bond defect where the two materials are not attached (joined) through the bondline. If only visual inspection is used as inspection technique, a wrong indication can be obtained that there is a bondline between the materials, where in reality there is no adhesion

LEADING EDGE (LE)

The front edge of a wind turbine blade directing towards the incoming wind

LEADING EDGE TOWARDS TRAILING EDGE (LTT)

The term used to define the direction of the load

LEVELIZED COST OF ENERGY (LCOE)

Measures lifetime costs divided by energy production. Calculates the present value of the wind turbine and its operating costs over an assumed lifetime

LOCAL DEFORMATION

Deformation which turbine blade components experience at a much smaller scale compared to global deformation. For example, breathing is a local deformation, and tip deflection is a global deformation

LOCAL PANEL BENDING

To and fro motion of the panel relative to the blade. It is localized out of plane bending of the panel

LOAD-CARRYING SHELLS

Load-carrying shells blade design have spar caps embedded in the aerodynamic shells

NOMENCLATURE

MANUFACTURING FLAWS

Defects in wind turbine blades due to the faulty manufacturing process (see also Defect).

THE MARKOV MODEL

In probability theory, a Markov model is a stochastic model used to model randomly changing systems. It is assumed that future states depend only on the current state, not on the events that occurred before

MATERIAL STRENGTH

It is a measure of a material's ability to withstand an applied load without failure. It is measured as the maximum load per cross-section area

MAX CHORD REGION

The region of the blade with maximum distance between the TE and leading edge. In most cases, this is the region with the largest curvature on the pressure side and is a critical area for TE splits and cracks on TE panels

MEAN DOWN TIME (MDT)

The average amount of hours that AWT does not generate power

MEAN UP TIME (MUT)

The average operational hours of a wind turbine

MEAN WIND SPEED

Average wind speed over a 10 minute time interval

MID-SPAN REGION

The section of the blade between Max Chord Section and 2/3 of the blade length

MODE SHAPE

Specific pattern of vibration executed by a mechanical system at a specific frequency

MTBF

Mean Time Between Failures (MTBF) is an average time between system breakdowns

MTTF

Mean Time to Failures (MTTF) is an average amount of time where a non-repairable asset operates before failing

MVP

Minimal Viable Product is product with enough features to attract customers for validation purpose

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)

A national laboratory in the US. National Renewable Energy Laboratory specializes in research and development and energy sector developing renewable energy and energy efficiency technologies. It is located in Colorado, USA.

NATURAL MODE OF VIBRATION

Each natural frequency has a unique pattern of vibration that occur if the structure is excited at that frequency

NDE (NON-DESTRUCTIVE EVALUATION)

A group of quantitative methods to describe material abnormalities or material properties without causing any damage. For example, the location, size, shape and orientation of a flaw or elastic property of a material.
NDE methods are often characterized by:

- *A reference block with artificially made "flaws" to calibrate the method*
- *An automated scanner or robot to move a sensor*
- *Signal processing of the recorded data (E.g. Phased array, Fast Fourier Transform, Hilbert transform)*
- *Evaluation of data using rule-based methods (i.e. artificial network, Machine Learning)*

The most common NDE methods are Vision systems, Automated ultrasonic testing (AUT), Computed tomography (CT) and Active dynamic thermography (ADT)
Synonyms: QNDE (Quantitative Non-Destructive Evaluation)

NDT (NON-DESTRUCTIVE TESTING)

A group of qualitative methods to identify abnormalities in a material without causing any damage. The most common NDT methods for blade testing are, manual ultrasonic testing (UT), shearography, radiographic testing (RT) and thermographic testing (TT)
Synonyms: NDI (Non-Destructive Inspection)

O&M

Operation and Maintenance

NOMENCLATURE

OEM

Original equipment manufacturer

OPEX (OPERATIONAL EXPENDITURES)

The money the company spends on day-to-day basis in order to run a business (wind turbine/wind farm)

OUT-OF-PLANE DEFORMATION

Out-of-plane deformations are deformation occurring on the perpendicular to the panel direction

OWNERS REQUIREMENT

Additional specifications added to the existing certification requirements found in standards today requested by wind turbine owners

PARAMETER (ALL TYPE OF CAR TOOL INPUT ARE "PARAMETERS" - NO "VARIABLE")

Parameter is a numerical input which defines the operating conditions of a system or a software.

PARAMETRIC STUDY (SENSITIVITY STUDY)

A parameter study relates to a situation where one value depends on several parameters, and the dependency of parameters is explored systematically by varying one parameter at a time while keeping the others fixed

PARIS ERDOGAN LAW

The Paris-Erdogan law is an empirical relationship that is used to describe cyclic crack growth. The crack growth rate is expressed through the stress intensity range via parameters fitted to experimental data

PEELING STRESS

Peeling stresses are stresses ahead of a crack tip acting in the direction normal to the crack plane

POST-PROCESSING (OF RESULTS)

Analysis of results from models or experiments with the purpose of generating more knowledge (interpretation of data)

POWER PURCHASE AGREEMENT (PPA)

A contract between a company willing to sell electricity and the one which is looking to buy electricity

POWER TAX CREDIT (PTC)

It is a tax credit for electricity generated using qualified energy resources

PPA

Power purchase agreement

PRESSURE SIDE (PS)

Side of the blade which has high pressure. Usually, it is the more curved side of the blades. Synonym: Windward side

PREVENTIVE MAINTENANCE (PM)

A regularly performed maintenance to decrease the chance of failure of a component of wind turbine

PROBABILITY OF DETECTION (PoD)

A statistical method utilized to evaluate how well an inspection method detects a defect/damage. The figure below shows a PoD curve. The figure shows the probability of detection increases as a damage size increases

PTC

Power tax credit

RE-ENGINEERING

In wind turbine industry, re-engineering is a term used to describe the process of examining and understanding a blade to see the important structural parameters in order to enhance or duplicate the blade when the information about the original drawings and/or manufacturing process is not available

RELATIVE THICKNESS

Thickness of a cross-section of a blade as percenatge of the chord

RETURN ON INVESTMENT (ROI)

Return on investment is a ratio between net profit and cost of investment. A high ROI means the investment's gains compare favorably to its cost.

RISK

Risk is a consequence of a decision taken in spite of uncertainty. Uncertainty is a potential uncontrollable outcome

NOMENCLATURE

ROOT

Circular part of the blade connected to the hub using bolts. Typically, a thick laminate to accommodate the bolts

ROTOR RADIUS

Distance from the rotor to the tip of one blade in the axial direction

SANDWICH PANEL

A panel that is made of three layers: outer skin, a core and inner skin. Each of the skins can be made of multiple layers

SHEAROGRAPHY

Shearography is a non-destructive technique which uses coherent light or coherent soundwaves to provide information about the location of the damage

SHEAR WEB

Supporting beams connecting the load carrying shells (spar caps) which increases the flapwise stiffness

SHELLS

The Suction Side (SS) and Pressure Side (PS) shells are large aerodynamic panels designed to transfer aerodynamic forces that define the blade capacity to extract energy from the wind

SIMULATION

The use of a (numerical) model to predict behavior of a structure or a component under loads. Synonym: Modelling

SKIN DEBONDING

Skin debonding refers to the detachment of the skin from the core material. Synonym: Face sheet debonding

STRATEGY

An approach towards success. In relation to CAR tool, strategy refers to the maintenance strategy, a set of rules describing when to inspect, repair etc.

STANDSTILL OR PARKED POSTION

Wind turbine position in which the rotor is not rotating

SUB-COMPONENT TEST

Test procedure where part of the blade is subjected to loads in a control environment

SUCTION SIDE (SS)

Suction side is a low-pressure side of the wind turbine blade. It is the side facing tower during operation. Synonym: Down wind side and leeward side.

SPAR CAPS

Part of the blade with the primary function being to keep the blade's global shape in the flapwise direction. The PS cap works in tension and SS cap works in compression.

TECHNOLOGY READINESS LEVEL

It is used to assess the development level of a product

THERMOGRAPHY

Thermographic inspection refers to the non-destructive testing of parts, materials, or systems by imaging the thermal patterns (temperature field) at the object's surface after having been subjected to controlled heating. Thermography can also be used to detect damages in a blade subjected to cyclic loading since damages typically generate local heating due to irreversible damage during cyclic loading

THICKNESS

Thickness is a general term used to define the distance through object, as distinct from width or height. In aerodynamics, thickness is the distance between the outer surfaces of the suction side and the pressure side. In material science, it is used to define the width of laminates, bondlines and core.

TIP REGION

Part of the blade close to the tip, depending on the blade size different lengths can be considered.

TORSIONAL OPERATIONAL LOADS

Torsion is generated when the blade is rotating due to the aerodynamic forces. Any kind of rotation (of the rotor/ blade) driven by wind (aerodynamic forces) will introduce torsion on blades. Magnitude varies depending on the wind velocity. Max torsion is obtained at around rated wind speed. Turbulence, wind shear, tower shadows add variation to the torsion (which is bad for the blade-it adds fatigue driven damages). The resultant of the aerodynamic forces (pressure distribution) is the force(s) that the blade is subjected to in the aerodynamic centre (along the blade)

NOMENCLATURE

TRAILING EDGE (TE)

Thin edge of the blade directing opposite the direction of the incoming wind

TRAILING EDGE TOWARDS LEADING EDGE (TTL)

Abbreviation/term used to describe the direction of loads

TRANSITION ZONE (TZ)

Region of the blade where the geometry of the blade changes from circular to an aerodynamical shape

TRANSVERSE STRAINS

Normal strains in the transverse direction of a blade

TRI DIRECTIONAL FIBERS (TRIAX)

Composites in which fibers are aligned in three directions.

TURBULENCE (WIND)

Atmospheric turbulence is the set of apparently random and continuously changing air motions that are superimposed on the wind's average motion

TWISTING (AERODYNAMIC)

The difference in angle between a chord line of a blade's cross-section and a reference cross-section's chord line

TWISTING (STRUCTURAL)

A deformation mode which is typically used for beam-like specimens. The cross-section is rotated around the beam's longitudinal axis (see also twist)

ULTRASONIC

Ultrasonic testing (UT) is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested

UPFRONT INVESTMENT

An initial investment

UUNDIRECTIONAL (UD) LAYERS

In composite material, Undirirectional layers mean that the fibers are aligned in primarily one direction

VALUE CHAIN

A value chain is a concept describing the full chain of a business's activities in the creation or improvement of a product or service. In the wind industry, the value chain consists of WTOs, OEMs, ISPs, and insurance companies.

VALUE PROPOSITION

A value proposition is a promise of value to be delivered, communicated, and acknowledged to customers, should they choose to buy a product.

VALUATION

Valuation is a analytical process of determining the current (or projected) worth of an asset or company

WIND FARM (WF)

A group of wind turbines installed in the same area to produce electricity

WIND TURBINE (WT)

Energy generating machine which converts kinetic energy (wind) to electrical energy

WRINKLES

Wrinkles is a defect type in which a thick layer buckles locally during manufacturing, so that the fibers are oriented off the intended plane, usually due to local shear stresses or compressive stresses developed during the handling of the layer during manufacturing. After consolidation, wrinkles in a laminate can lead to the development of a damage.

WTO

Wind Turbine Owner

BLADE HANDBOOK

Visual dictionary for R&D

This Blade Handbook is aimed at helping all parties involved in R&D of wind turbine blades to get a common understanding of words, process, levels and concepts.

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