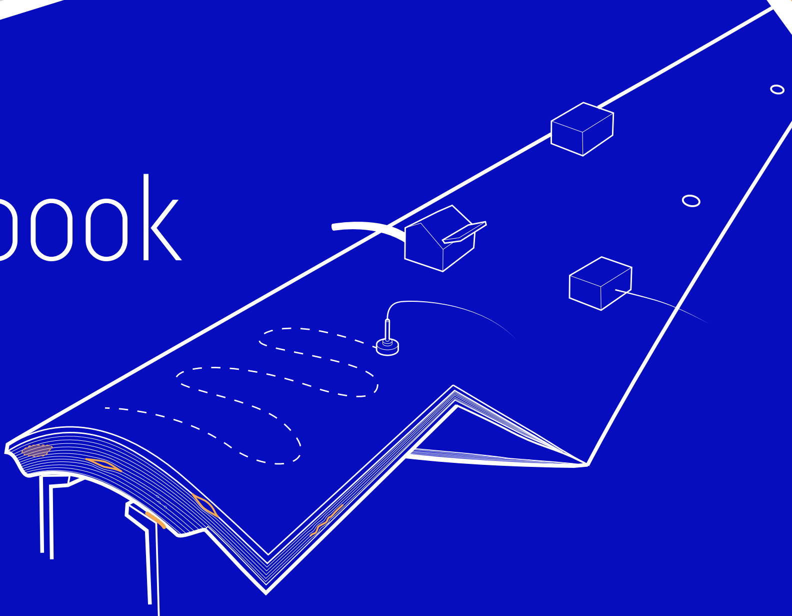
WIND TURBINE BLADES

Handbook

Edition 2019 CORTIR



KIRTxTHOMSEN

Bladena
BLADE ENABLER

Concept & Design

Communication design, illustration and graphic design

KIRTxTHOMSEN
Visual R&D Consultancy

Editor & contributor

Bladena
BLADE ENABLER

Contributors

AALBORG UNIVERSITET

FORCE TECHNOLOGY

DIS

DTU Mechanical Engineering
Department of Mechanical Engineering

GLOBALWINDSERVICE

DTU Wind Energy
Department of Wind Energy

G2D GUIDE2DEFECT

Partners

e·on, VATTENFALL, ENGIE, innogy, enel, EWII, Ørsted, equinor, acciona, HOFOR, ARISE, FALCK RENEWABLES, Statkraft, CODAN, NORDEX, LM WIND POWER

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 projects mainly funded by EUDP (Energy Technology Development and Demonstration Programme)

Input by Find Mølholt Jensen & Co (Bladena), Rune Kirt & Co (KIRT x THOMSEN), Søren Horn Petersen & Co (Guide2Defect), Jan Vig Andersen & Co (FORCE Technology), John Dalsgaard Sørensen & Co (AAU), Lars Damkilde & Co (AAU), Christian Berggreen & Co (DTU Mek), Torben J. Larsen & Co (DTU Wind) Peder Jacobsen & Co (Global Wind Service), Mads Lübbert & Co (DIS)

Handbook conceptualized and produced by KIRT x THOMSEN

NORDIC SWAN ECOLABEL

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THE BLADE
HANDBOOK™

A shared lingo for the future of wind

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WHY A HANDBOOK

During the three EUDP projects LEX, RATZ and CORTIR partners from all segments of the wind industry value chain has 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

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Blade & cross section
Surface
Inside
Root
Load cases

2 | STRUCTURAL

Strain & Stress
Materials
Beam structure
Bending & Torsion
Local effects

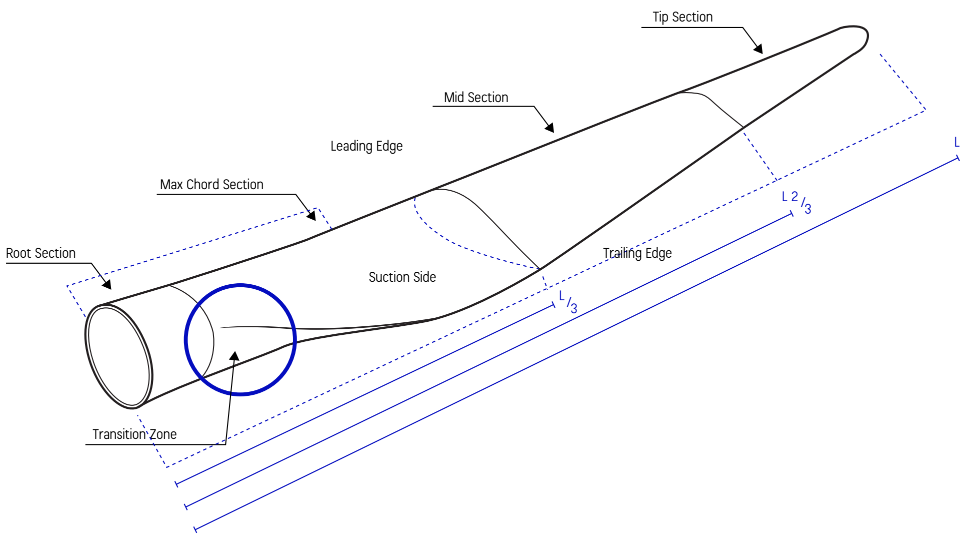
3 | LOADS

Wind conditions
Turbulence
Aerodynamics
Structural dynamics

ANATOMY OF A BLADE

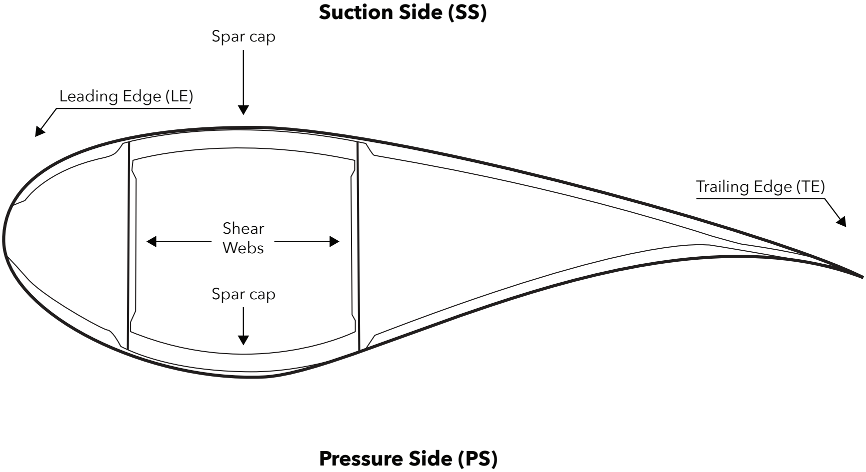
BLADE SECTIONS

A wind turbine blade is divided into different sections as shown

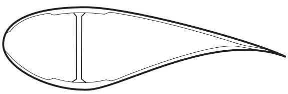


CROSS SECTION

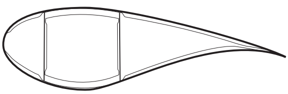
Blade cross section indicating main construction elements



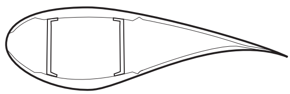
Types of cross sections



Closed shell



Box spar



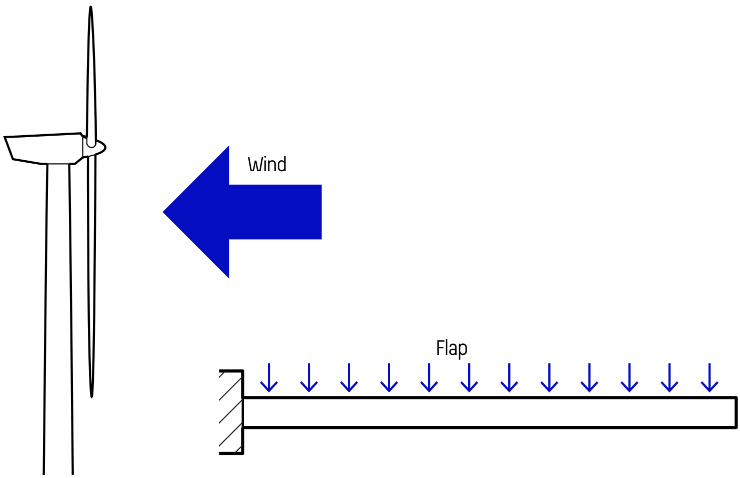
Load carrying shell

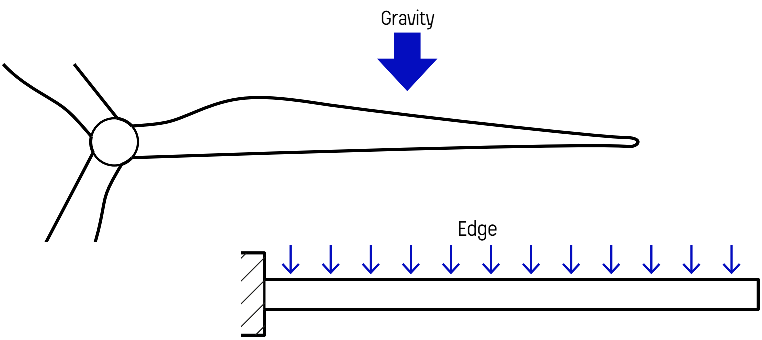
ANATOMY OF A BLADE

FUNCTION

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

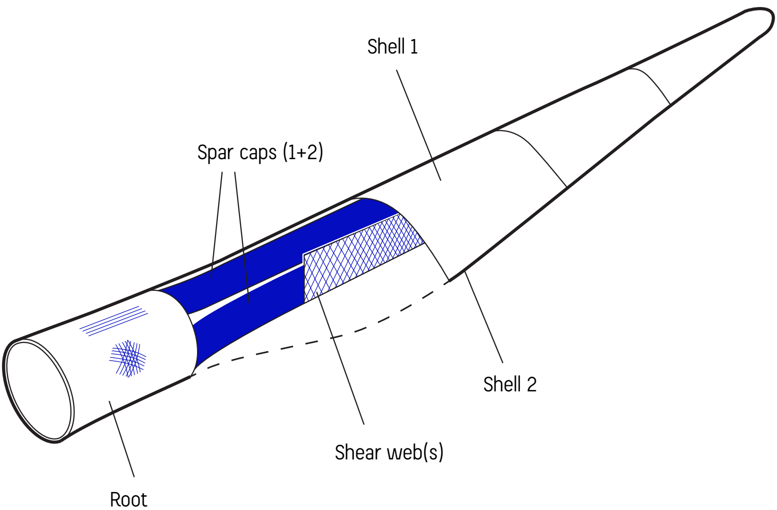
A blade can be regarded as a large cantilever beam





CONSTRUCTION

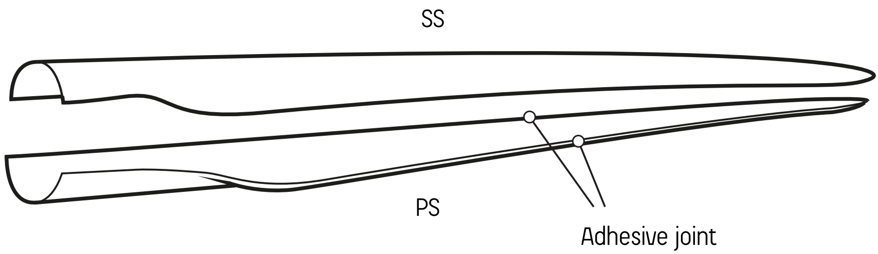
A blade can be segmented into 4 main parts, each parts fulfilling a specific function (shell, caps, shear webs, root).



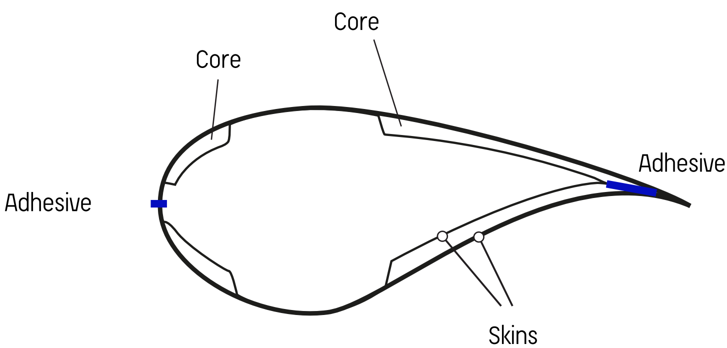
SURFACE

SHELLS

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



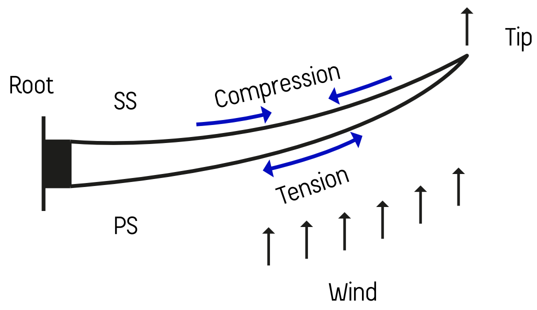
They are typically moulded in two blade shell tools (SS and PS moulds), and adhesively bonded to each other along their leading and trailing edge, and to the SS and PS spar caps in the middle. The shell skins are lightweight glass fiber skins (often 2 to 54 layers of triax material at 0, +45 and -45Deg), 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.

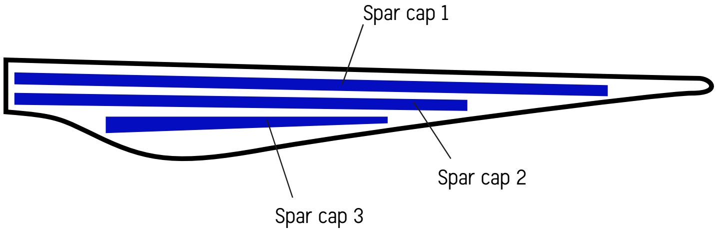


SPAR CAPS

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.



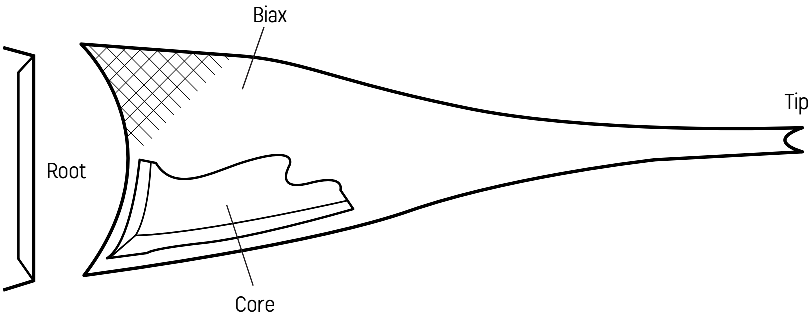


Several spar caps are found in large blades.

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.



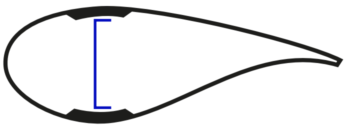
They only carry shear loads, and the challenge from a design point of view is to stop them crushing and/or buckling.

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

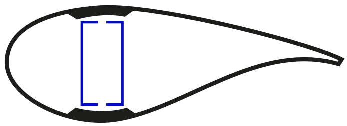
SPAR CAPS

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

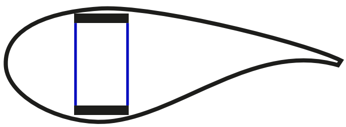
They sometime include feets or flanges, a transition where the skins join each others to facilitate the load transfer to the shells or spar caps.



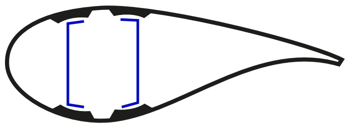
1 web, 2 caps



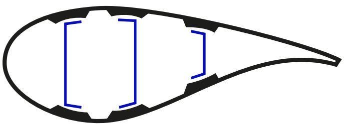
2 webs, 2 caps



Box spar



2 webs, 4 caps



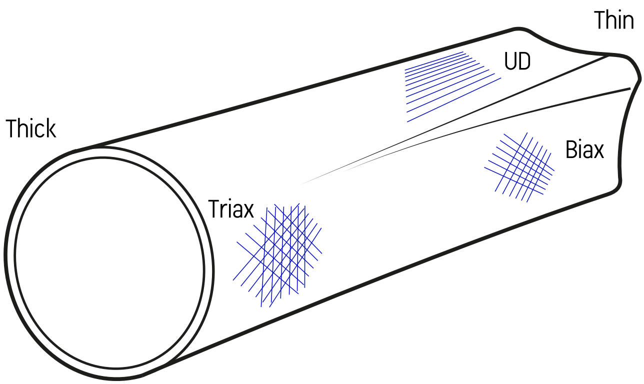
3 webs, 6 caps

ROOT

SHEAR WEBS

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°.

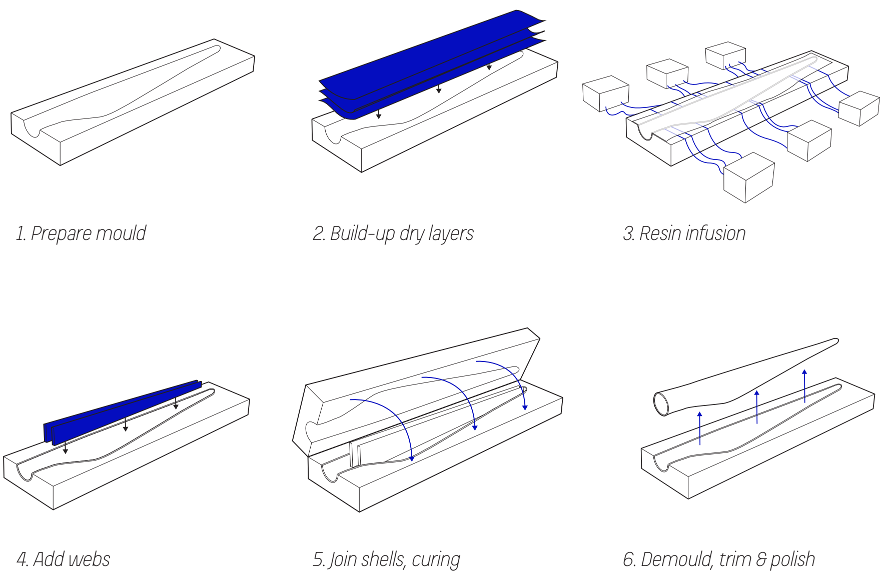
The thickness is needed to accommodate the root bolts, that create weakness in the laminate.

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 variaions, 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.



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

FLAPWISE DIRECTION

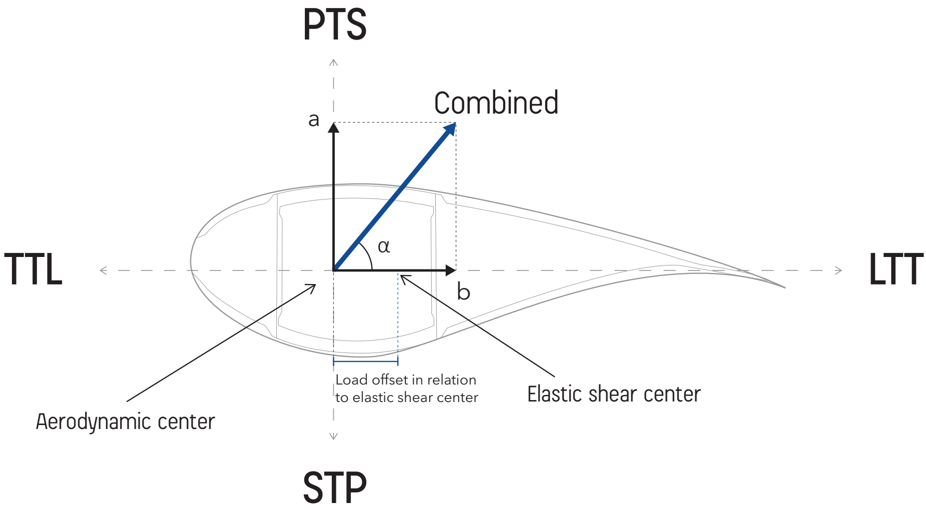
- TTL - trailing edge towards leading edge
- LTT - leading edge towards trailing edge

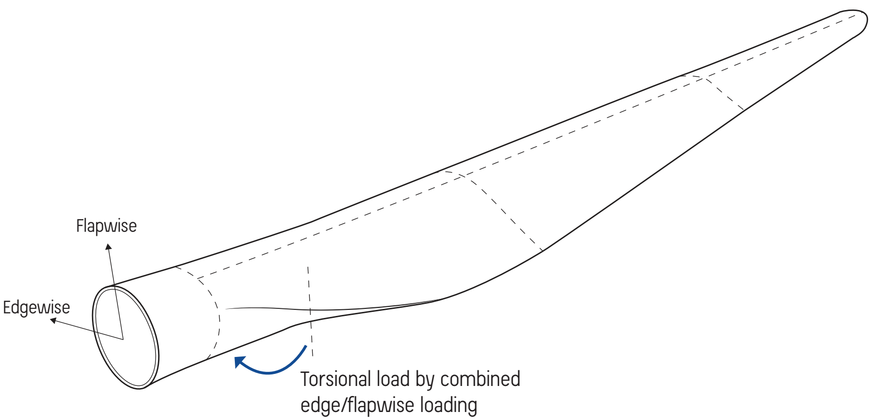
COMBINED LOADING

- Combination of flapwise direction with edgewise direction.

TORSIONAL LOAD (COMPONENT)

- Torsional load component generated by the combination of flapwise and edgewise loads. The transition zone and max chord regions are subjected to this load.


PTS
Combined
a
α
TTL
LTT
b
Load offset in relation
to elastic shear center
Elastic shear center
Aerodynamic center
STP


Flapwise
Edgewise
Torsional load by combined
edge/flapwise loading

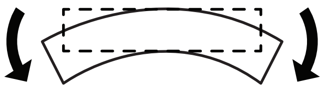
STRAIN & STRESS

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.

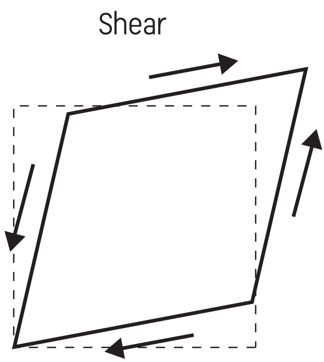
a) Axial strain due to axial load.



b) Axial strain due to bending.

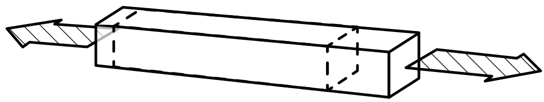
SHEAR STRAIN

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

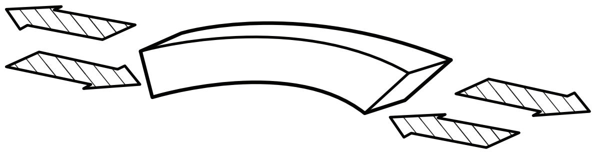


AXIAL STRESS

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.



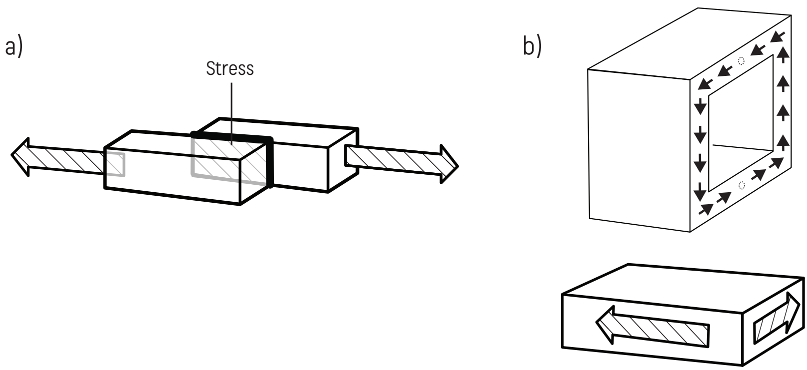
a) Axial stresses due to stretching a rod



b) Axial stresses du 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).

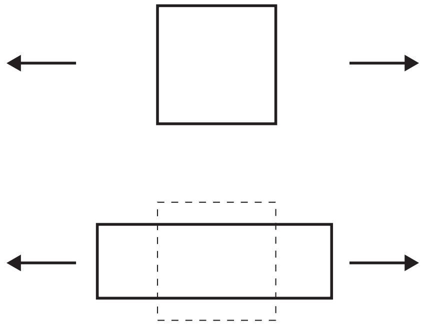


MATERIALS

ELASTIC BEHAVIOR

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

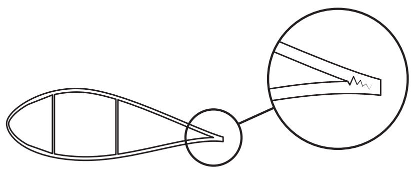
An isotropic material has equal properties in all directions. The properties are described by the Modulus of Elasticity (E) which defines the stress for a strain increment in a given direction and the Poisson ratio (ν) which defines the deformation perpendicular to the stress direction.



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, and due to bending in the panels, which will over time cause skin-debonding. Bending in the laminate can also introduce interlaminar failure.

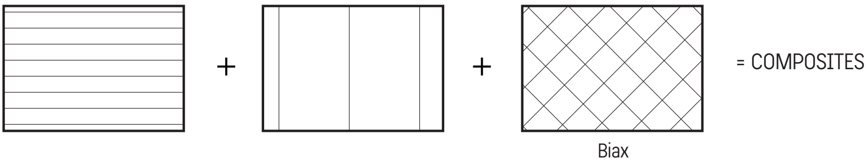
a) Load cycles induces fatigue over time.

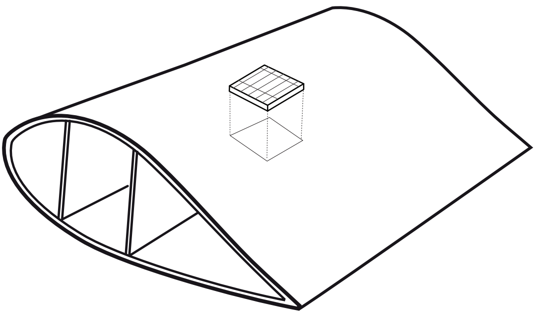


b) Example of fatigue cracks in the trailing edge due to peeling stresses.

COMPOSITES

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



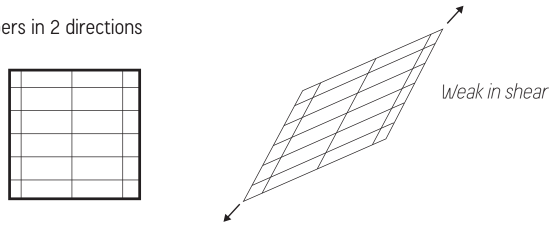


In composite materials the fibers can be arranged in many different ways, so that the strength and stiffness will depend on the direction in the material.

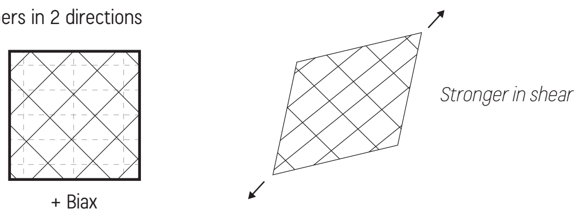
In a wind turbine blade there will be more fibers in the longitudinal blade direction in order to handle the bending of the blade. There will be fewer fibers in the transverse direction.

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



Fibers in 2 directions

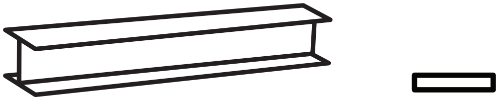


+ Biax

BEAM STRUCTURE

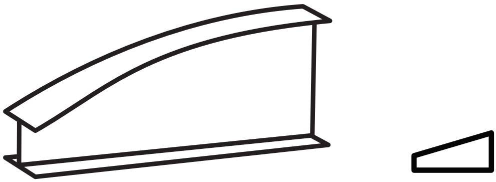
Wind turbine blades acts as a beam i.e. say a structure with a dominant length direction. Beams used in e.g. building design normally have constant cross-sections. For various design reasons the beam can also be tapered or twisted.

A



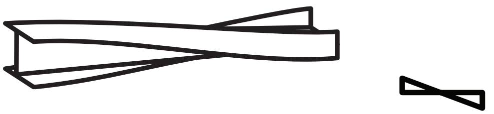
Constant

B



Tapered

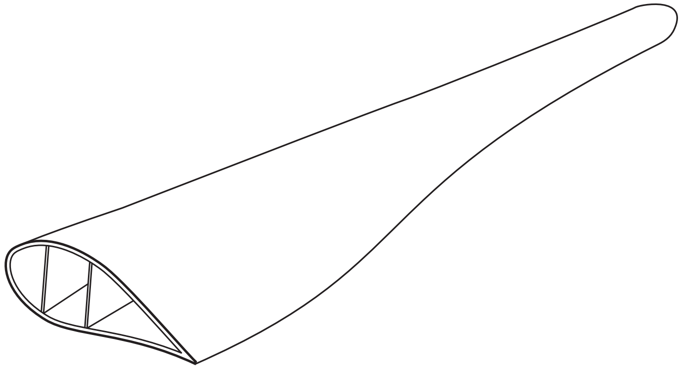
C

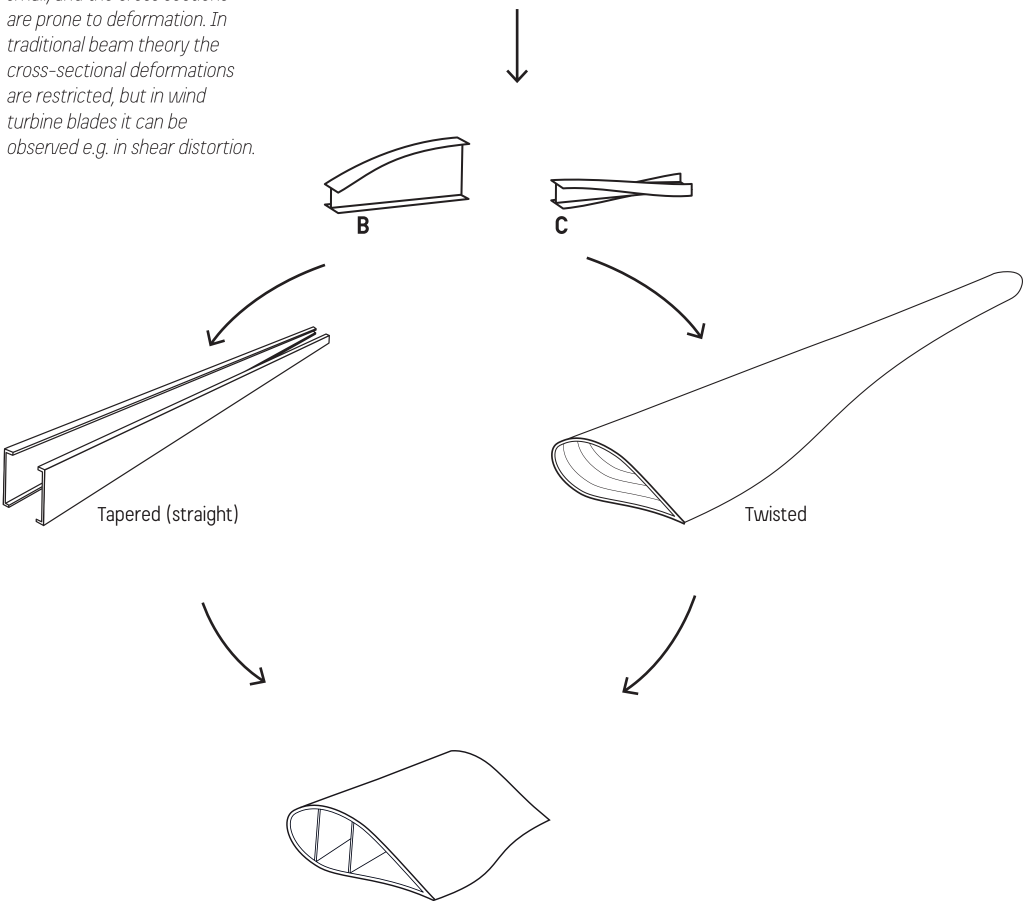


Twisted

IN A BLADE

A typical wind turbine blade will be both tapered and twisted. Furthermore, the material thicknesses will be relatively small, and the cross sections are prone to deformation. In traditional beam theory the cross-sectional deformations are restricted, but in wind turbine blades it can be observed e.g. in shear distortion.





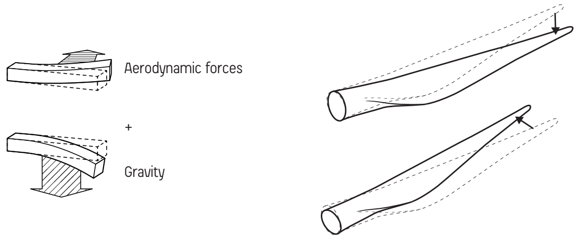
Together that is a PRE-TWISTED STRUCTURE
(eg. similar to a helicopter blade)

BENDING & TORSION

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

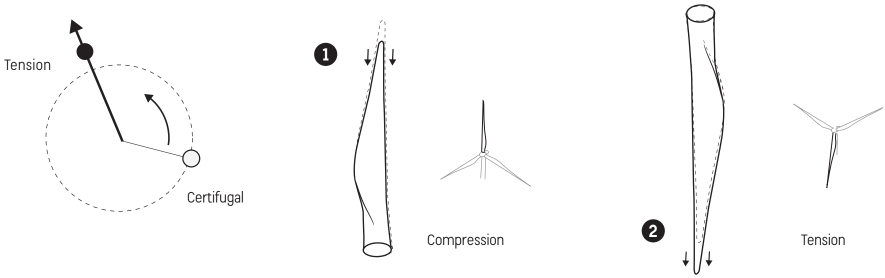
A. BENDING

The primary way of carrying the loads are through bending.



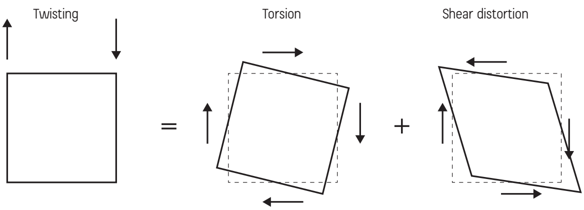
B. AXIAL FORCE

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



C. TWISTING

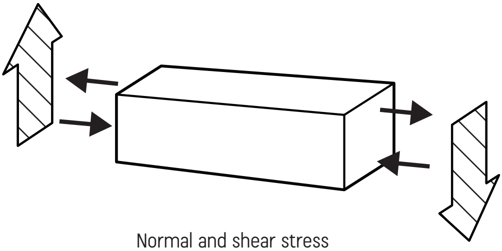
Wind loads act excentrical and creates twisting in the blade.



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**

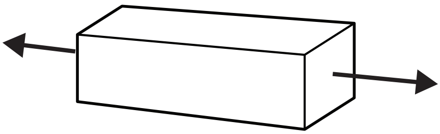
The bending moments create normal and shear stresses



Normal and shear stress

AXIAL FORCE → **NORMAL STRESS**

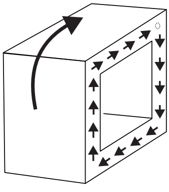
The axial force creates normal stresses

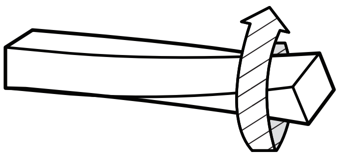


Normal stress

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

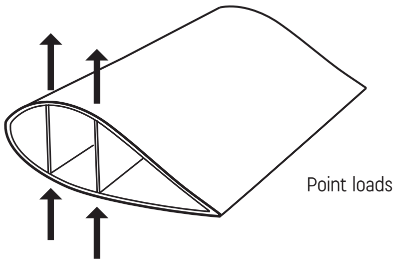
LOCAL EFFECTS

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.

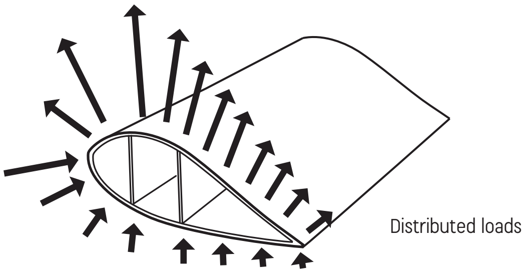
BLADE TESTS TODAY VS REAL LIFE

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..

TODAY'S PRACTICE



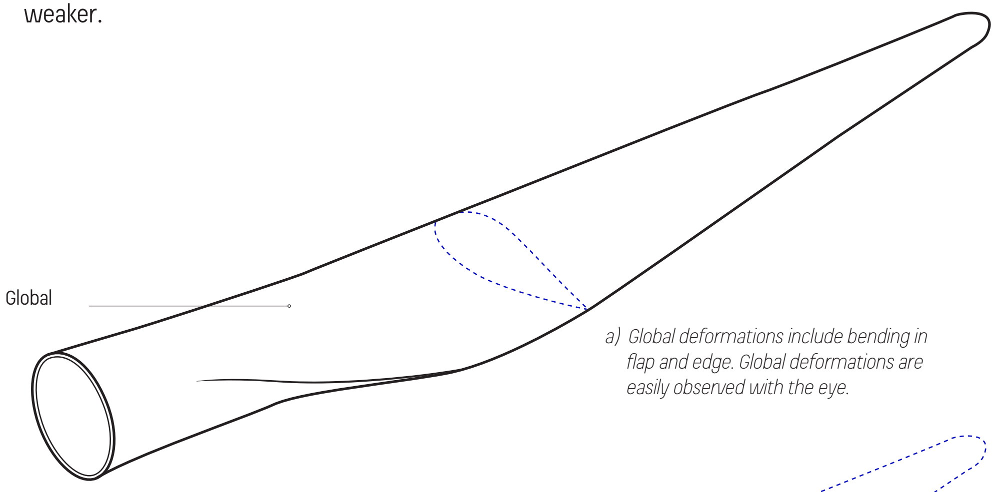
REAL LIFE



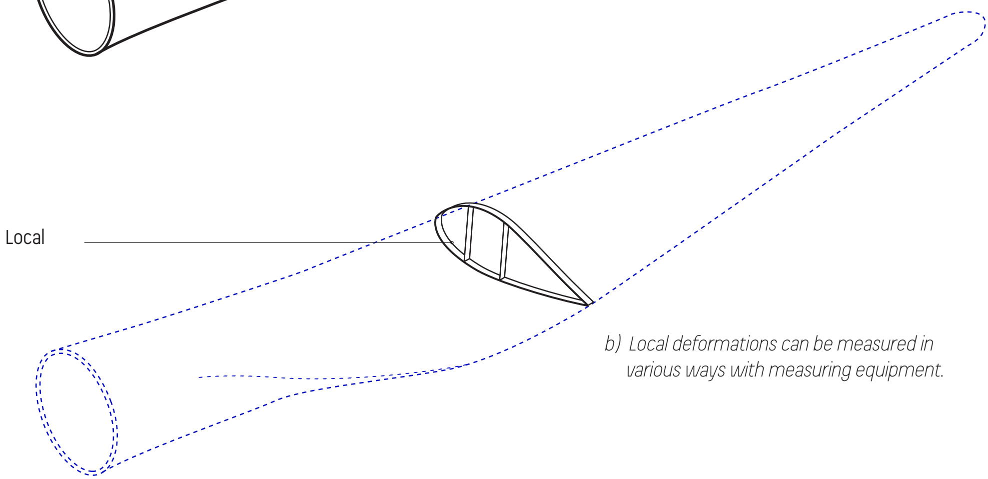
GLOBAL VS LOCAL

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. 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 very large impact on composite structures, where the main strength direction is the longitudinal and the transverse strength typically is weaker.



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

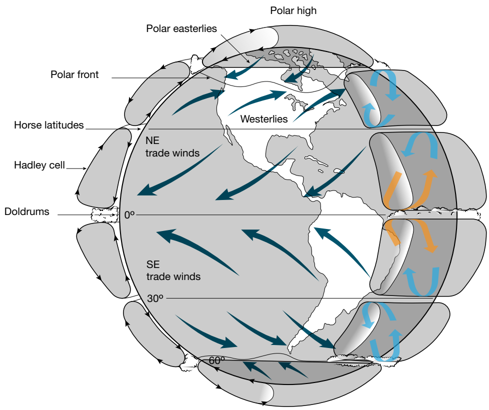


b) Local deformations can be measured in various ways with measuring equipment.

WIND CONDITIONS

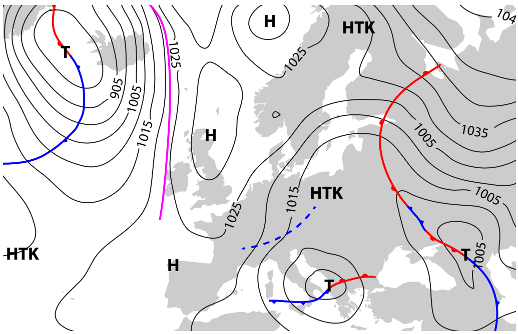
GLOBAL

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.



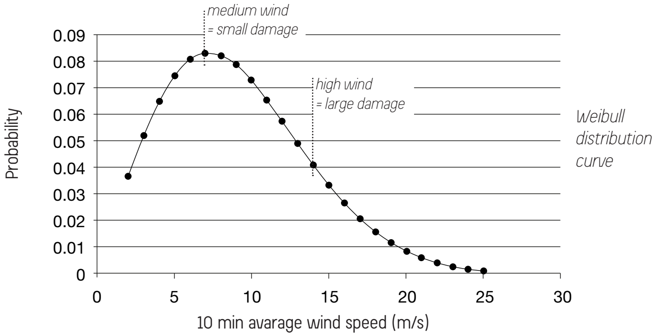
REGIONAL

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.



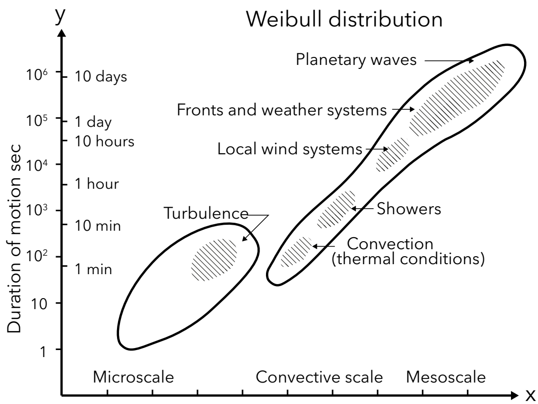
PROBABILITY

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).

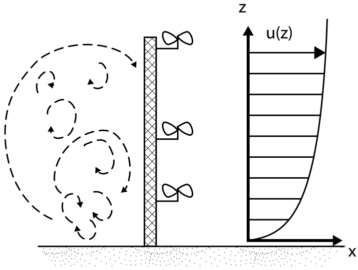


Courtesy Courtney, M, Troen, I. (1990). Wind Spectrum for one year of continuous 8Hz measurements. Pp 301-304, 9th symposium on Turbulence and diffusion.

TURBULENCE

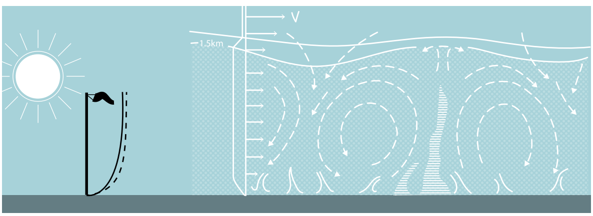
HEIGHTS

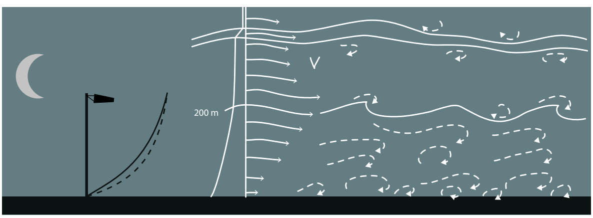
The type of terrain near the turbine has a friction level on the wind - also denoted a terrain roughness. The roughness causes a near surface boundary layer with increasing wind speed for increasing height. The roughness also creates turbulent vortices with length scales increasing with height.



DAY VS NIGHT

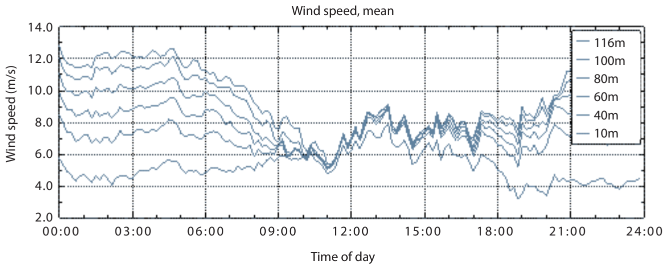
Temperature effects in the boundary layer has a direct impact on the turbulent flow. The mixing of warm and cold air near the surface causes unstable conditions yielding increased turbulent mixing - with a large shear in the mean wind speed.





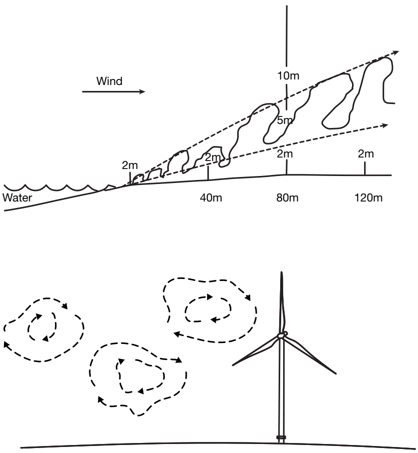
HEIGHT & TIME

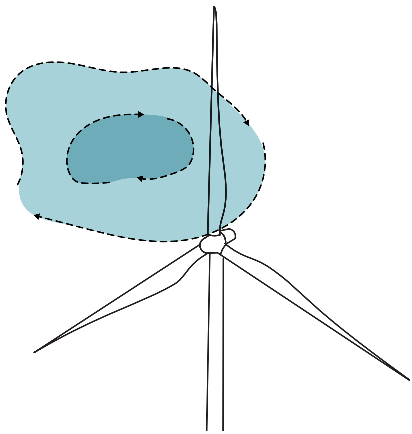
Measured wind speed in different heights at the Høvsøre test site. Cold temperature at night causes very stable conditions where the heating from the sun causes unstable conditions with a significant turbulent mixing.



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.

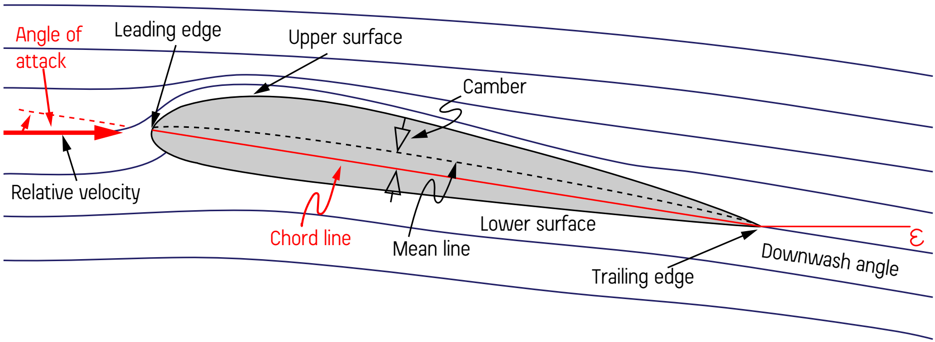




AERODYNAMICS

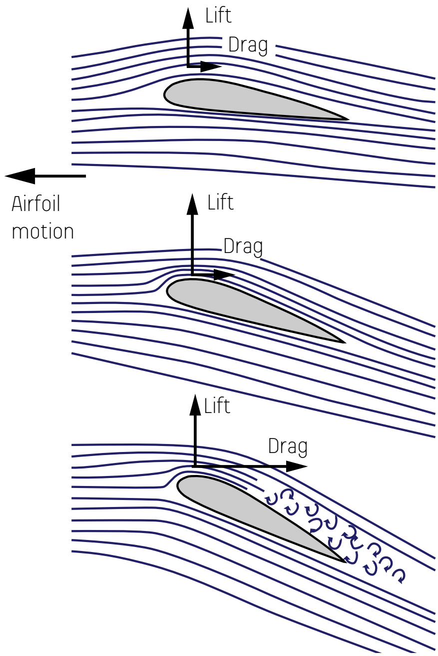
AIRFOIL TERMINOLOGY

2D airfoil terminology



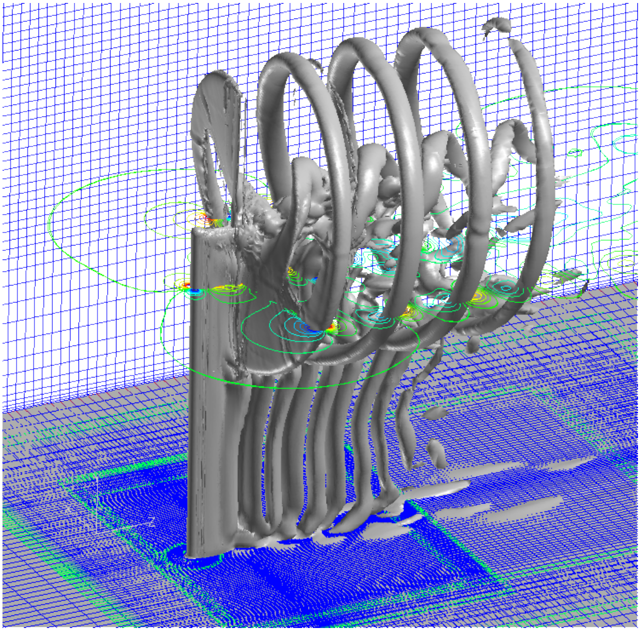
LIFT & DRAG

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

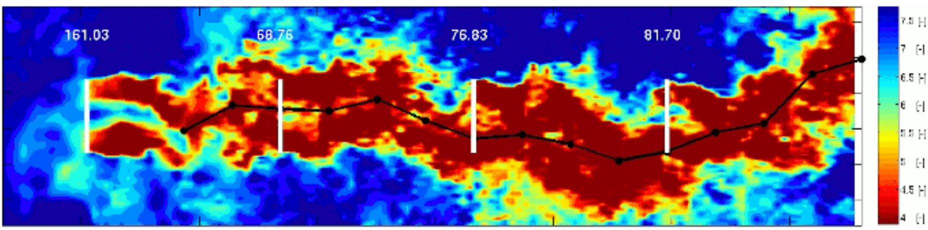
Detailed vortex system behind a turbine. (In this particular case a two-bladed downwind turbine). The tip and root vortex system can be seen as well as the tower shadow. Details of the aerodynamic rotor/tower interaction are seen on the right.



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



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

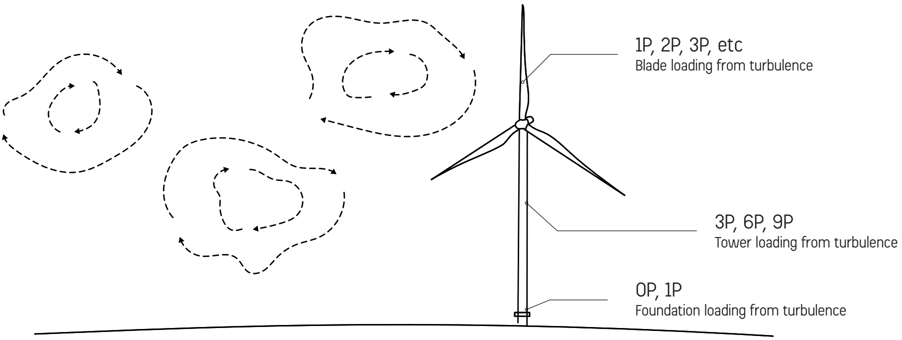
4x wind turbines

Wake pattern from a row of 4 turbines behind each other. The wind speed reduction seen with red colors "waves" in a pattern caused by the large scale structures in the incoming free wind field. This has a direct negative impact on the production and also causes increased load levels on the downwind turbines.

STRUCTURAL DYNAMICS

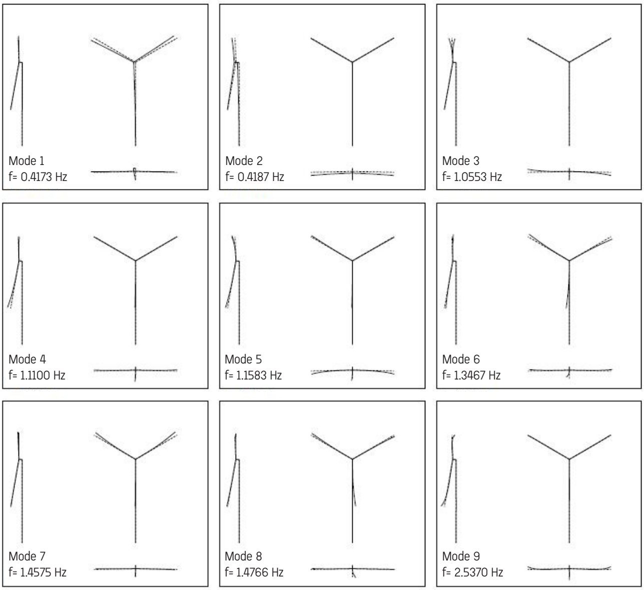
OPERATIONAL FREQUENCY

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.



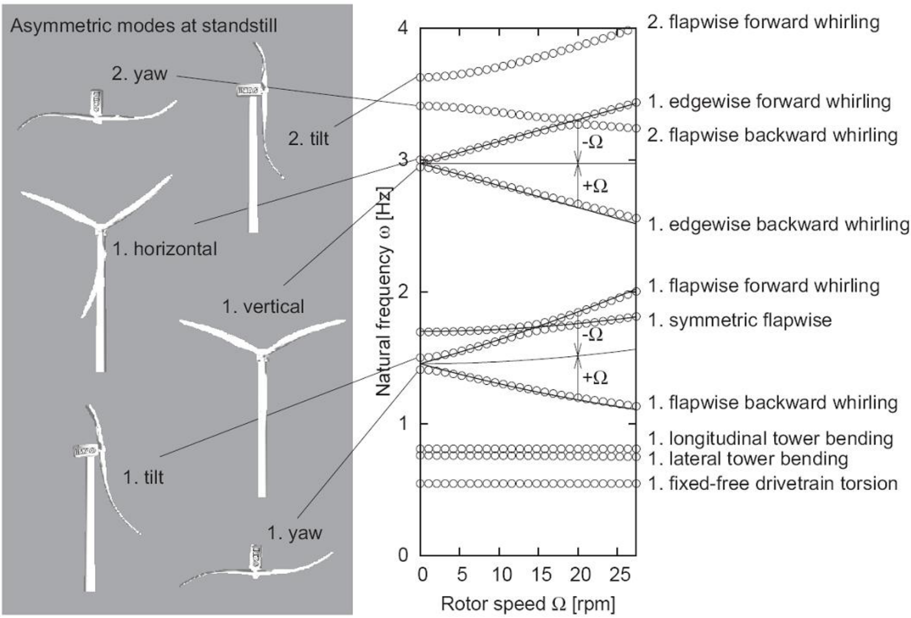
MODE SHAPES

Natural frequencies and modeshapes of a turbine in standstill with the rotor shaft locked. 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 normally not contribute to dynamic loads on the structure.



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

PART II

4 | VIBRATIONS

Aeroelastic instability

5 | FAILURES

Failure modes
Root causes
Safety margins

6 | TESTING

Hybrid testing/hybrid simulation

7 | DAMAGE

Damage, defect & failure
NDT

8 | FRACTURE MECH.

Fracture modes
Crack loading
Cohesion strength in composites

VIBRATIONS

NATURAL FREQUENCY

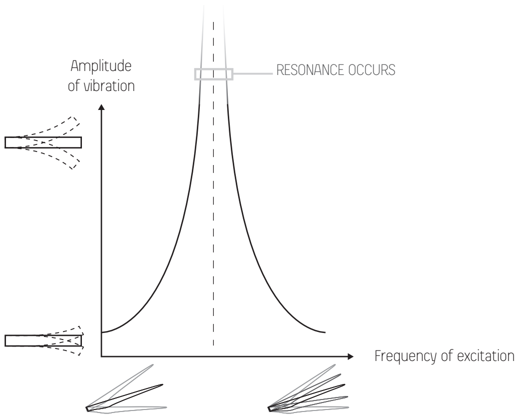
Blades have different natural frequencies depending on the direction of vibration i.e. flapwise, edgewise and twisting/torsion. Natural frequencies are the inherent frequencies which a blade will adopt its free vibrations when set in motion by a single impact or a momentarily displacement from its rest 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

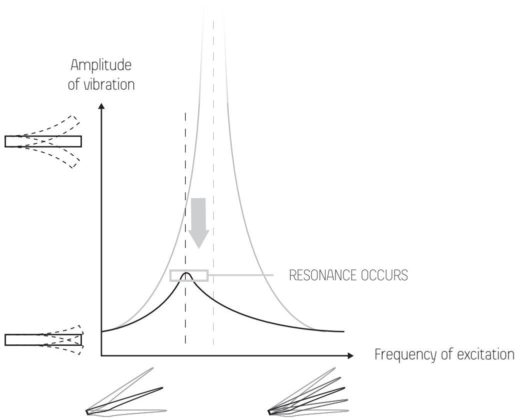
Resonance can occur when a blade is excited by external periodic forces at a frequency close to one of its natural frequencies. Small periodic forces at a resonant frequency can build up to produce large and violent oscillations of the structure. If the resonance occurs, the structure could in the worst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

DAMPING

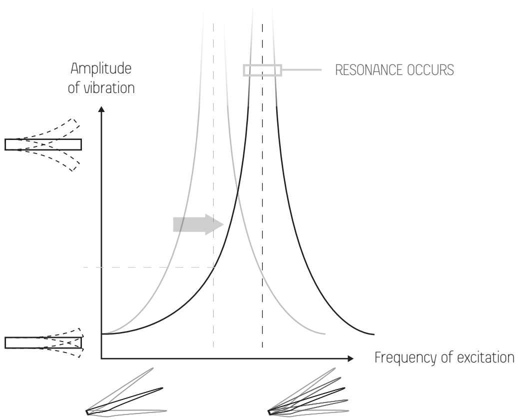
Damping reduces the amplitude of vibrations in a structure by dissipation energy from the system. Energy can be dissipated in the structure due to friction and generation of heat or by means of mechanical devices i.e. a viscous damper (dashpot).



NO DAMPING



WITH DAMPING



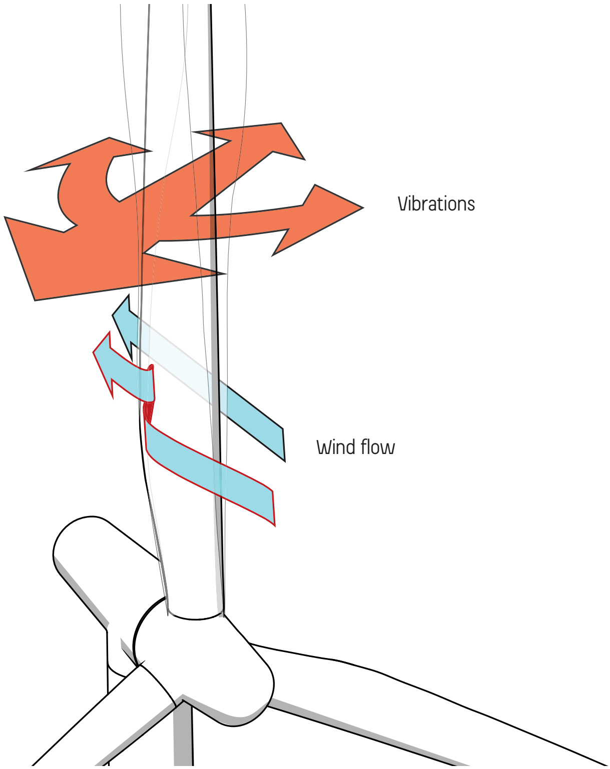
INCREASED
STIFFNESS

AEROELASTIC INSTABILITY

TWO PHENOMENAS

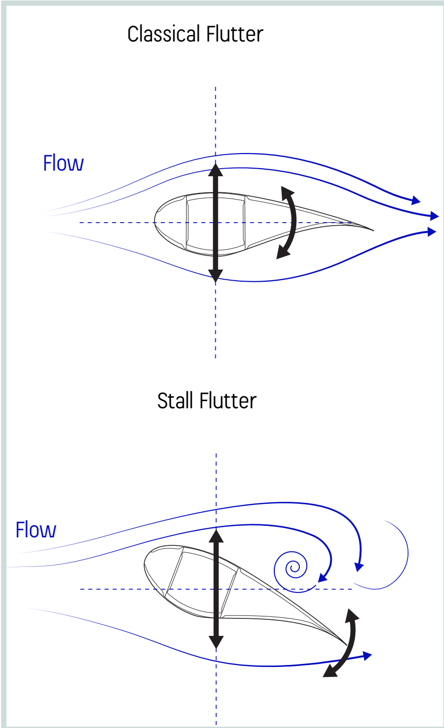
The phenomenon of aeroelastic instability, also called flutter, can can occur due to the structural flexibility of wind turbines. Structural deformations induce changes in aerodynamic forces, i.e. operation above rated speed or during standstill or parked position. The additional aerodynamic forces cause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

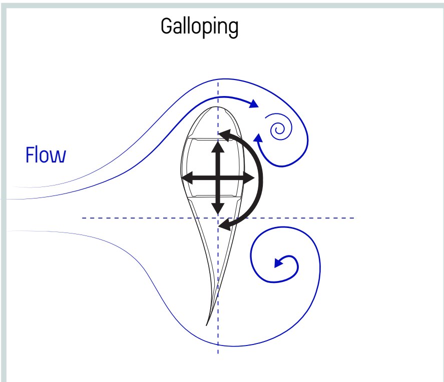


CLASSICAL FLUTTER involves the coupling between torsional- and flapwise-vibration.

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



GALLOPING involves only separated flow over bluff structures.



FAILURE MODES (1)

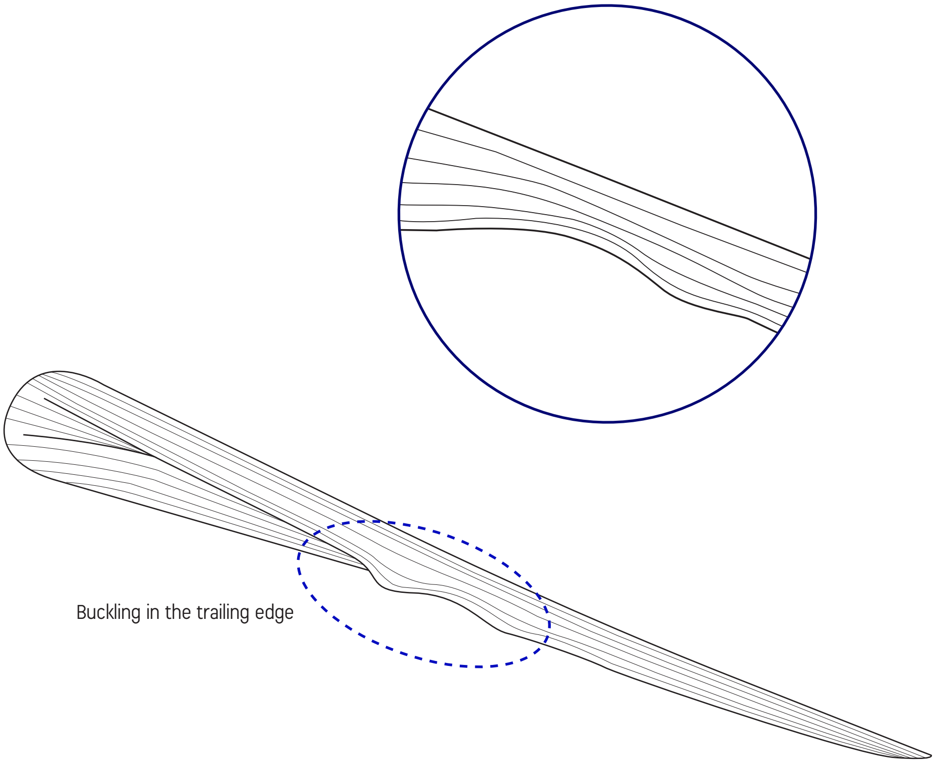
FIVE MODES OF FAILURE

Failures are catagorized in 5 defined failure modes:

	Failure Mode	Recommended	Used in industry	Required	Mentioned
1	Buckling (non-linear approach)	YES	YES	NO	YES
2	Bondlines (Peeling test)	YES	(YES)	NO	YES
3	Skin debonding from core (Test)	YES	(NO)	NO	NO
4	Interlaminar failure (Bending test)	YES	(NO)	NO	NO
5	Strain based (failure criteria)	NO	YES	YES	YES

BUCKLING (FAILURE MODE 1)

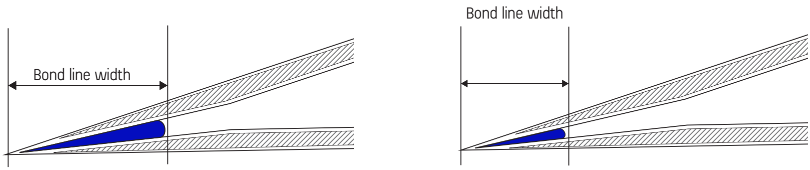
Buckling is a non-linear in-plane stability phenomena. It can be predicted by non-linear FEM. Using a combined loading load case for both numerical simulations and testing will capture the phenomenon.
Premises for failure: The bending of the blade due to aerodynamic forces and reduced buckling capacity of the blade in mid span and mid span towards the tip creates premises for failure.



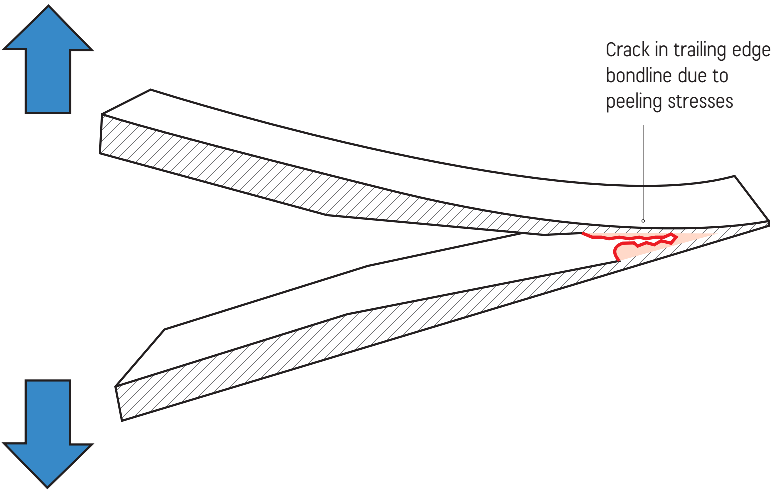
FAILURE MODES (2-3)

BONDLINES, TE (FAILURE MODE 2)

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.

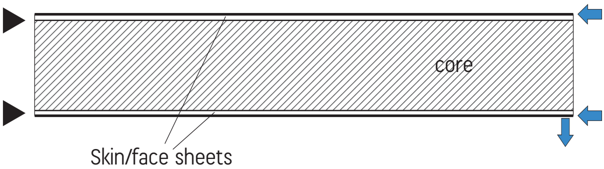


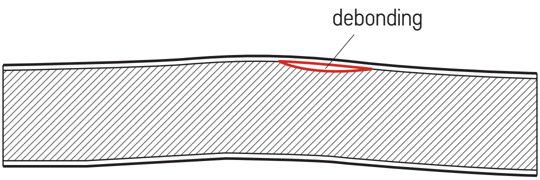
Different lengths of the bond line



SKIN DEBONDING (FAILURE MODE 3)

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.

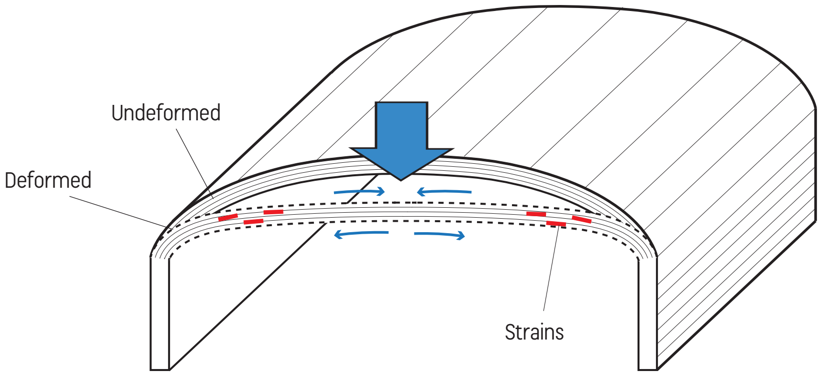




FAILURE MODES (4-5)

INTERLAMINAR FAILURE (FAILURE MODE 4)

Bending of the laminate causes interlaminar failure



STRAIN BASED FAILURE (FAILURE MODE 5)

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).

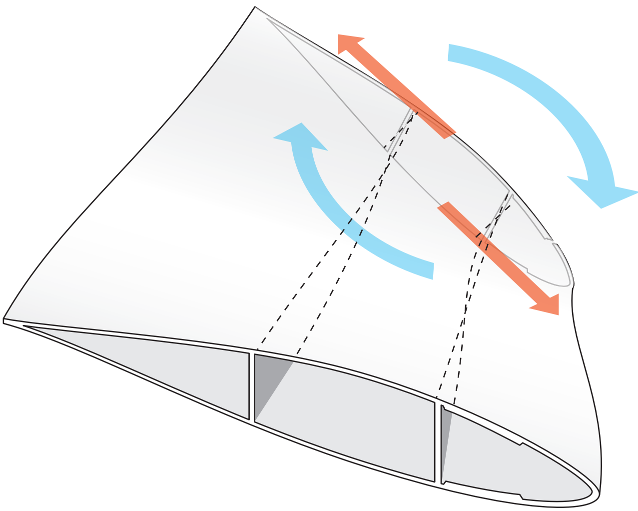
ROOT CAUSE 1
SHEAR DISTORTION

OPERATIONAL FATIGUE

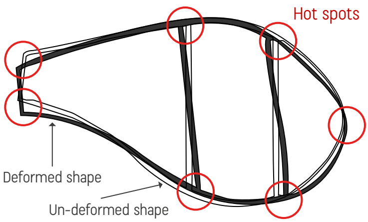
Normal operation

> Cross sectional shear distortion (CSSD)

> Bondlines damage

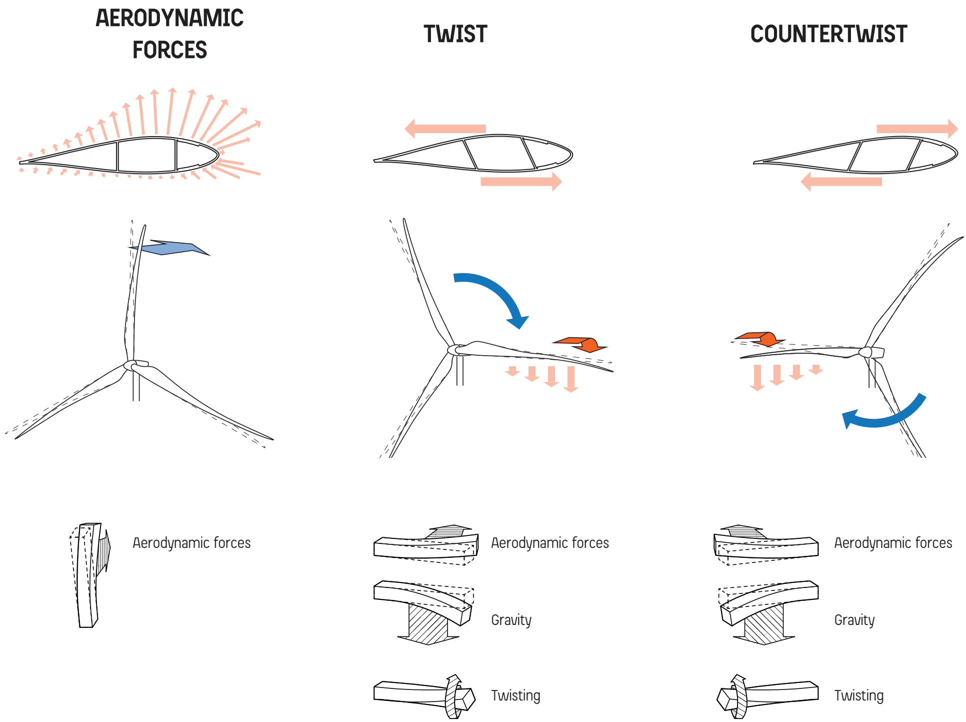


Bondlines damage



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.

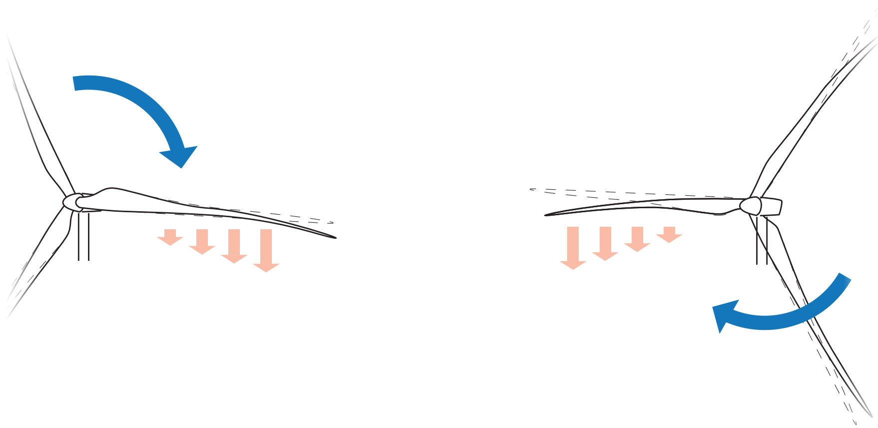


ROOT CAUSE 2
PANEL BREATHING

OPERATIONAL FATIGUE

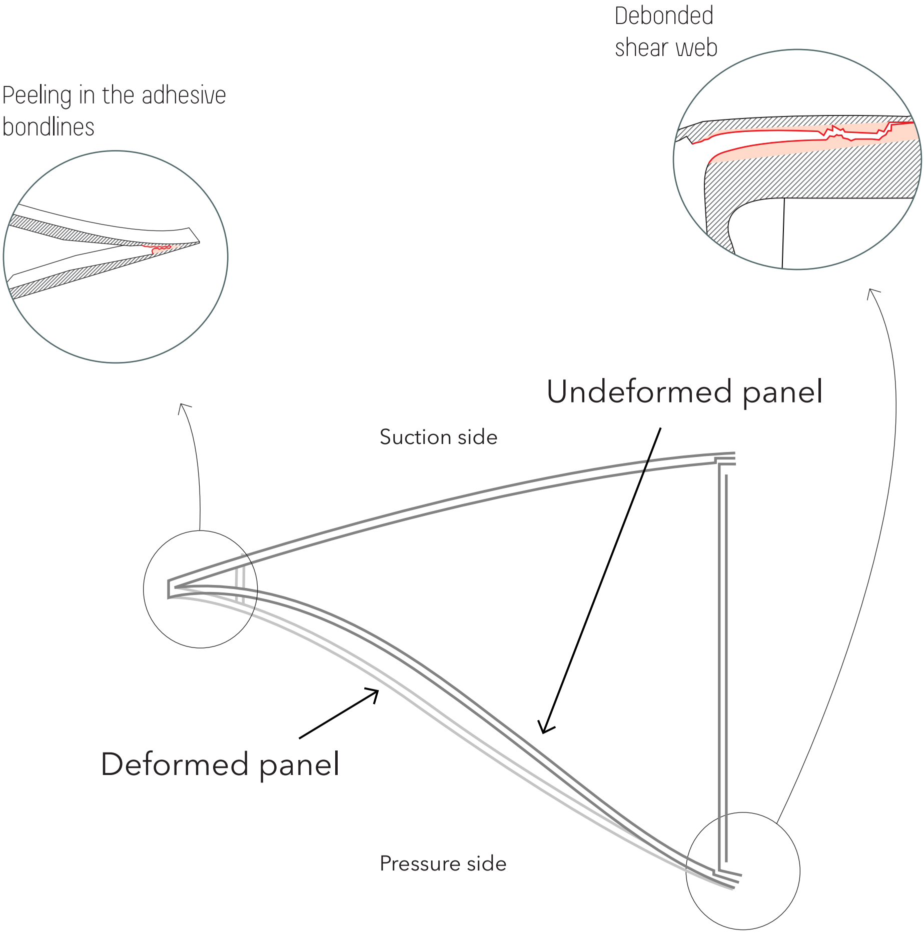
Normal operation
> Panel breathing
> Bondlines damage

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.



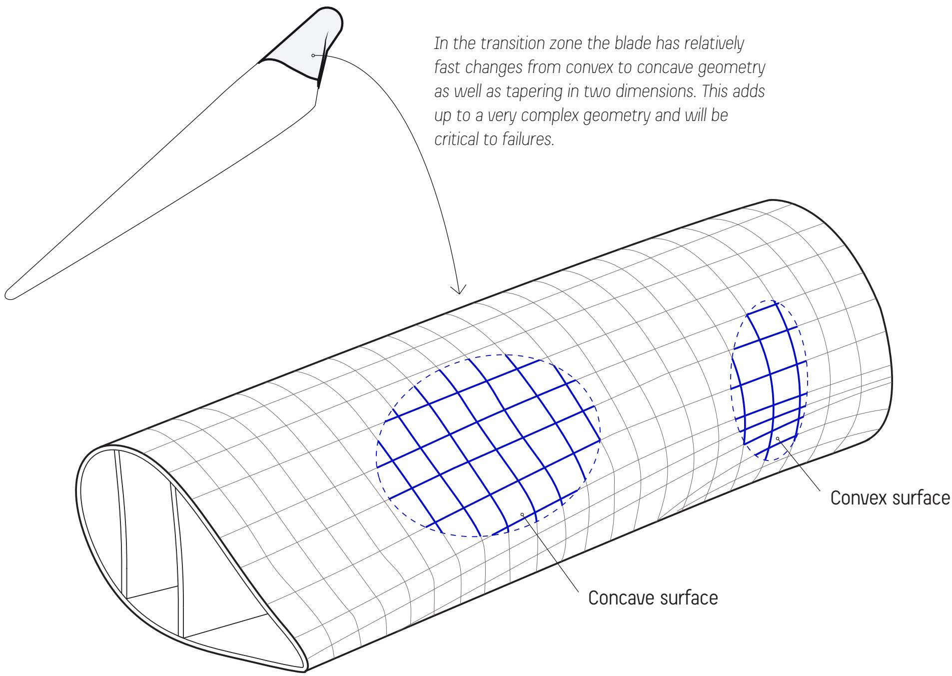
ROOT CAUSE 3
ROOT TRANSITION ZONE

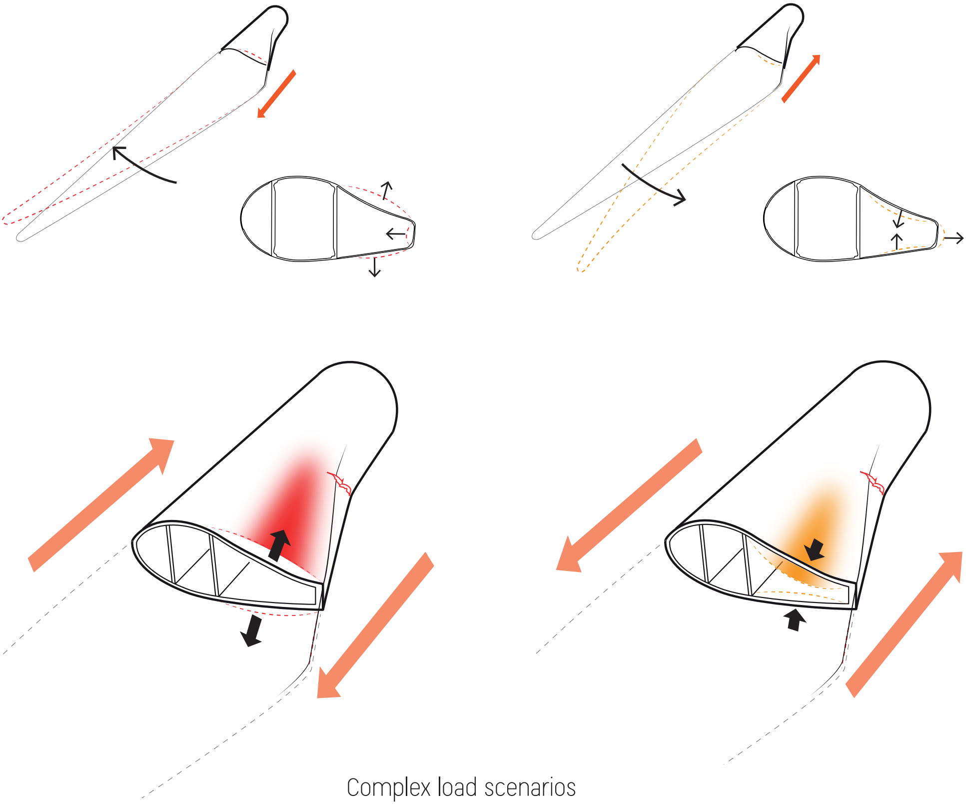
OPERATIONAL FATIGUE

Normal operation

>Panel bending and shear forces

> Root failures





Complex load scenarios

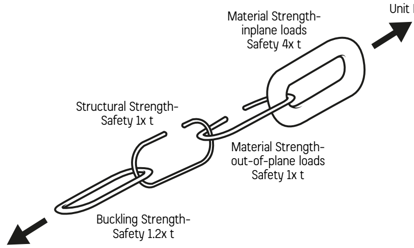
SAFETY MARGINS

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.

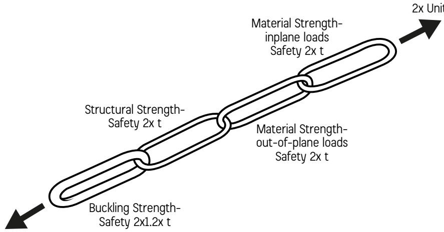
TYPICAL CHAIN OF MARGINS:

Weaknesses are perceived compensated by strengthening other links.



NEW DESIGN PHILOSOPHY:

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

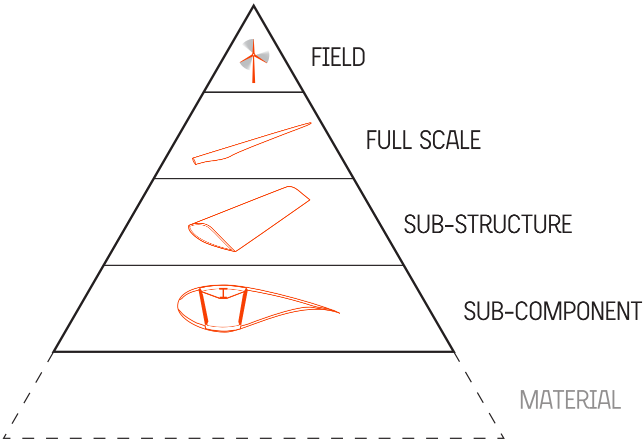


FMEA

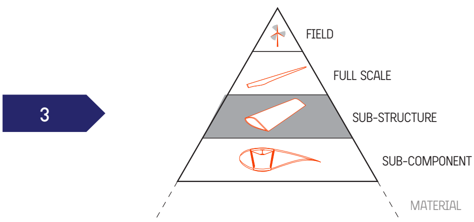
Failure Mode and Effects Analysis (FMEA)—also "failure modes", plural, in many publications—was one of the first highly structured, systematic techniques for failure analysis. It was developed by reliability engineers in the late 1950s to study problems that might arise from malfunctions of military systems. 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. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. There are numerous variations of such worksheets.

TESTING

LEVELS OF TESTING [SIZE]



Hybrid testing is sub-structure testing

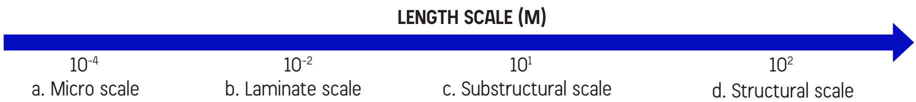


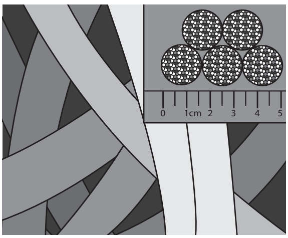
TESTING

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. 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.

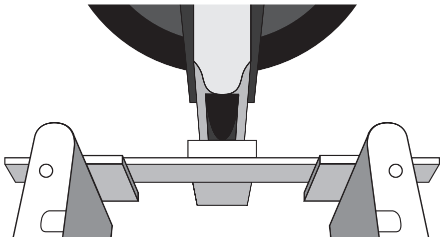
LENGTH SCALE

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

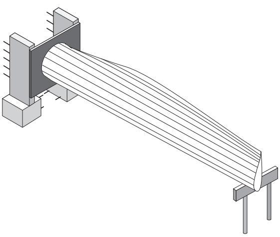




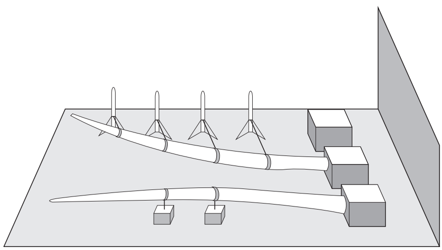
a. Micro scale



b. Laminate scale



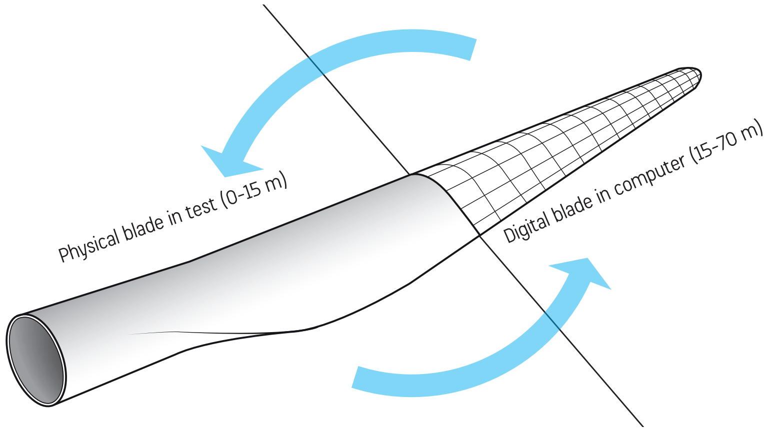
c. Substructural scale



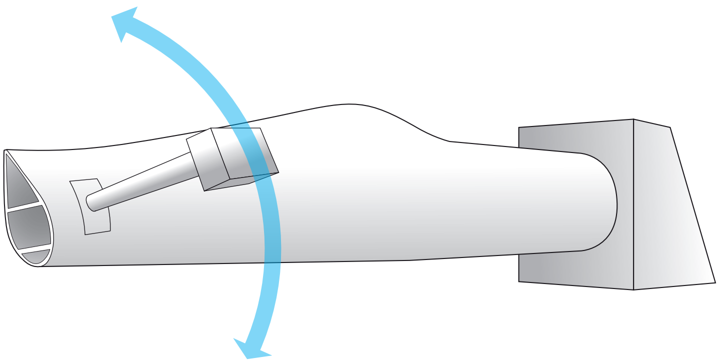
d. Structural scale

HYBRID TESTING/ HYBRID SIMULATION

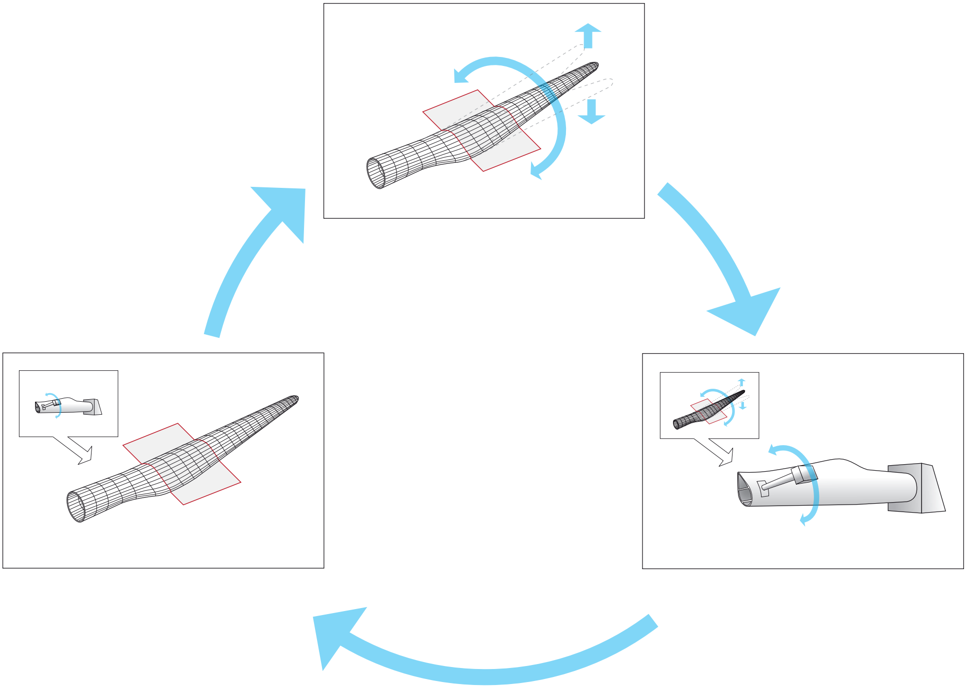
Blade cut (not full-length blade test)



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.

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

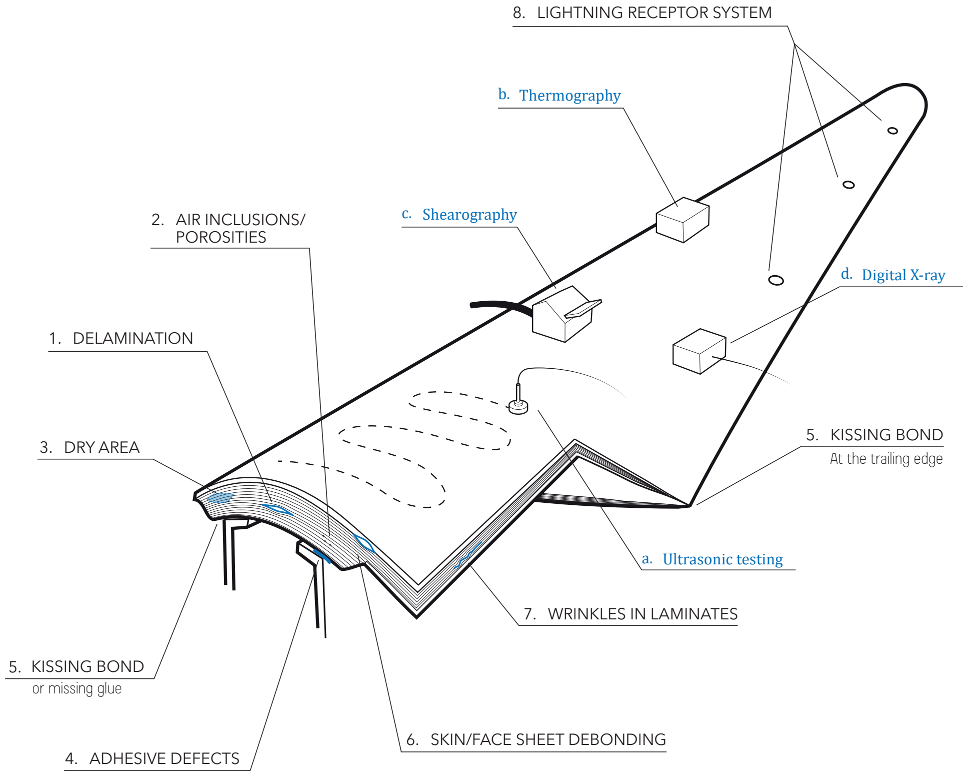
The blade damages can be prioritized when it comes to the impact they have on the wind turbine blade itself. To define the category of the damage, it is important to assess the location, the impact and the time it requires to repair the damage. Below the different categories are described as a guideline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

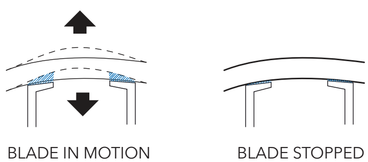
NB! More information about damages and inspections can be found in the NGIR-reports (Next Generation Inspection Reports), please contact Bladena to require these documents.

NDT

DETECTION OF DEFECTS IN WTG BLADES



Potential defects and the different NDT methods

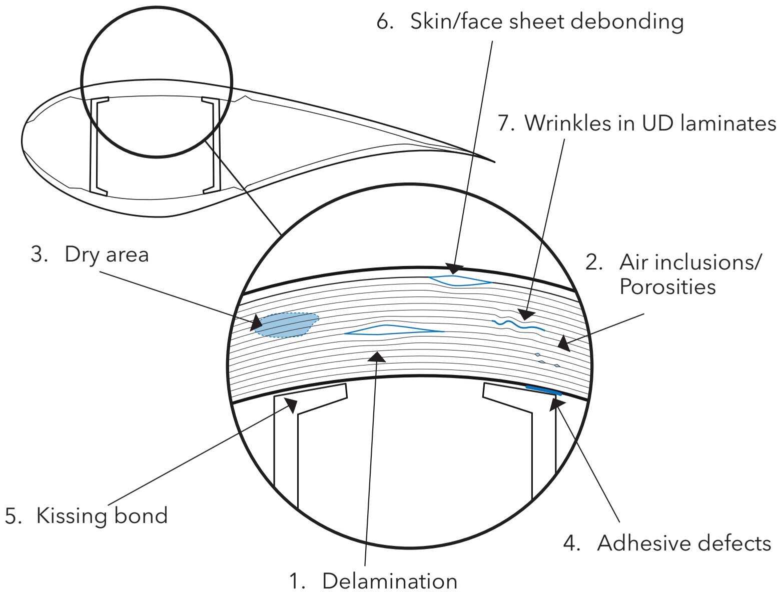


Kissing bond

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.

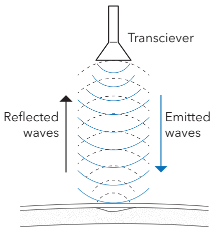
DEFECTS DETECTED WITH NDT

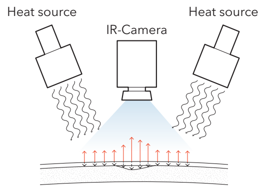
1. Delamination: Lack of fusion between layers/ two fiber laminates which are separated.
2. Air inclusions/Porosities: Small or large air pockets or impurities in material.
3. Dry areas: Lack of resin.
4. Adhesive defects: Adhesive not present, insufficient amount of adhesive or not placed correctly.
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

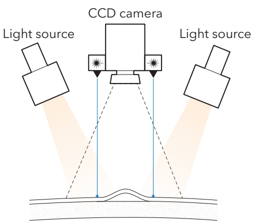
DETECTION METHODS

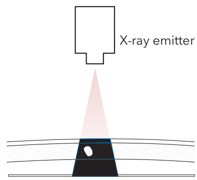




a. ULTRASONIC
Ultrasonic testing (UT) is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested.

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.



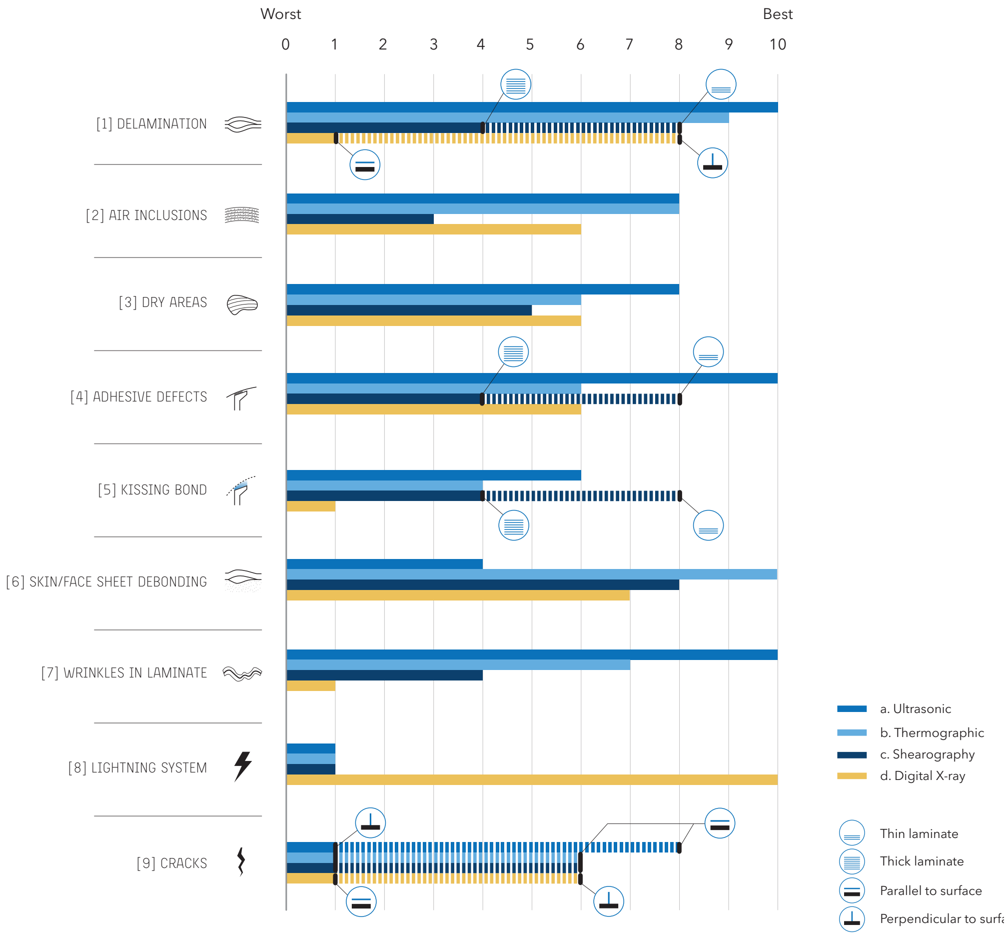


c. SHEAROGRAPHY
Shearography uses coherent light or coherent soundwaves to provide information about the quality of different materials in non-destructive testing and defect detection.

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.



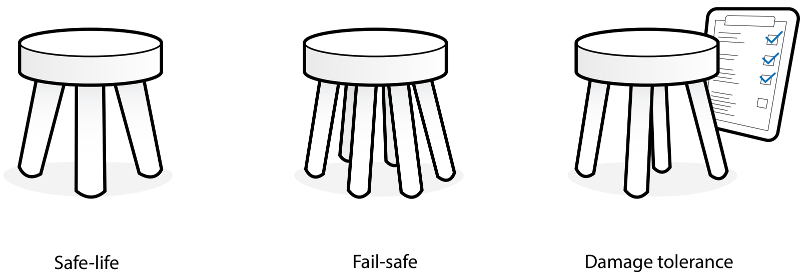
FRACTURE MODES

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.

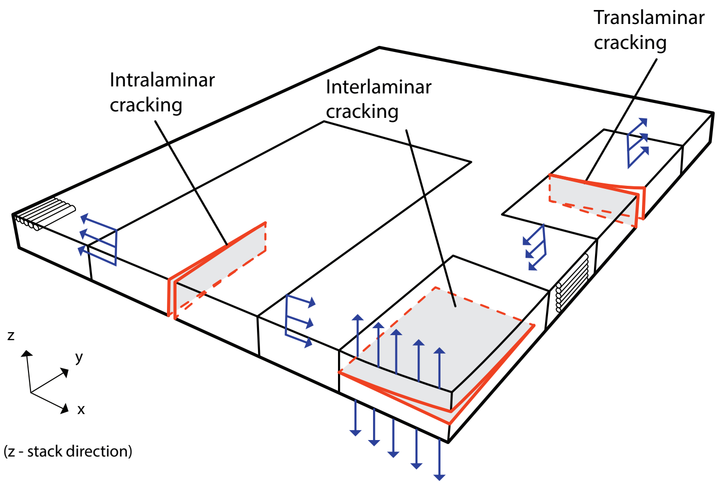
FRACTURE AND DAMAGE MODES IN COMPOSITES

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.



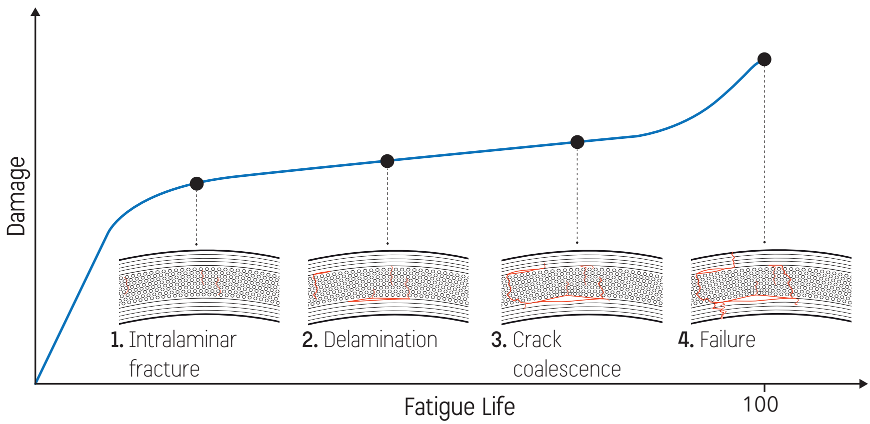
Intralaminar, interlaminar and translaminar cracks.

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.

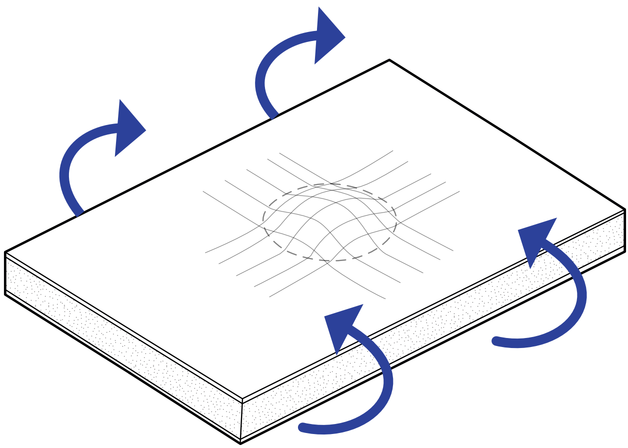


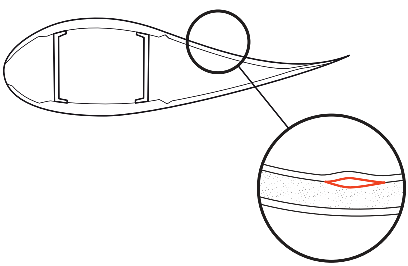
Fatigue life: The development of cracks under applied stress.

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:

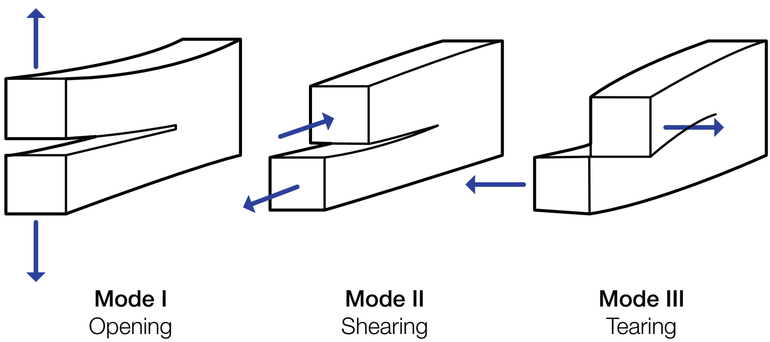
Mode I (tearing): The load is opening the two crack faces apart.

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

Mode III (shearing): 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.

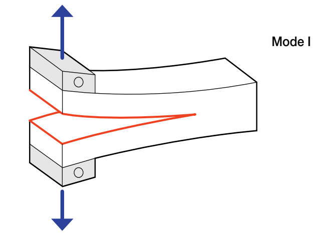


Schematic representations of mode I, mode II and mode III

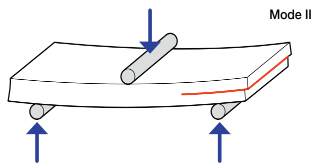
TESTING AND CHARACTERIZATION

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.

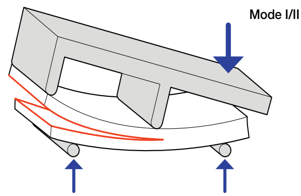
Double Cantilever Beam (DCB) specimen for pure mode I



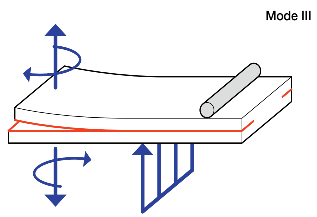
End Notched Flexure (ENF) specimen for pure mode II



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



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

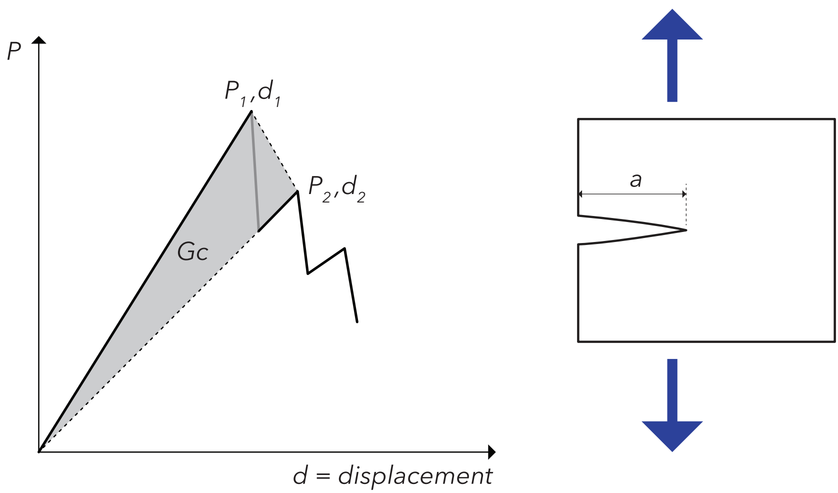


FRACTURE MECHANICS

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.

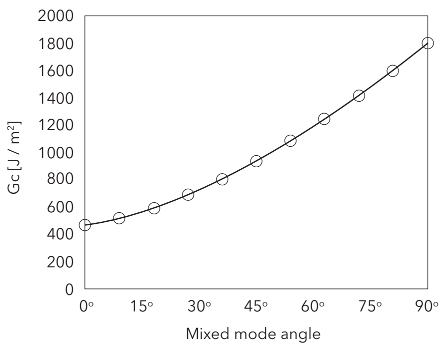
The amount of energy "contained" into a crack is called the energy release rate. When a crack propagates, this quantity reaches a critical value, which takes the name of Fracture Toughness (Gc). It is found that the fracture toughness is independent from the crack length, it is therefore a constant material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



Load displacement curve.

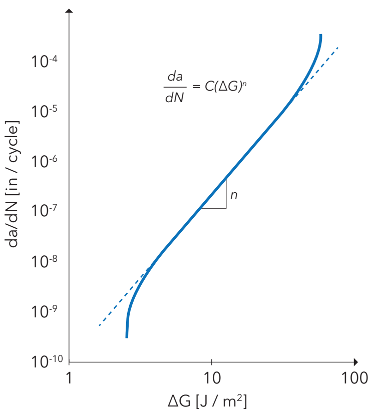
CRACK PROPAGATION RATE

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.



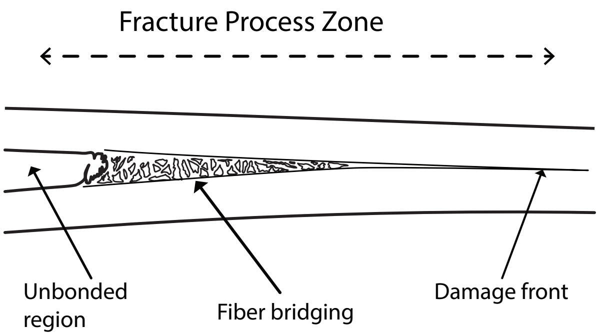
Crack growth rate / crack propagation rate.

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.

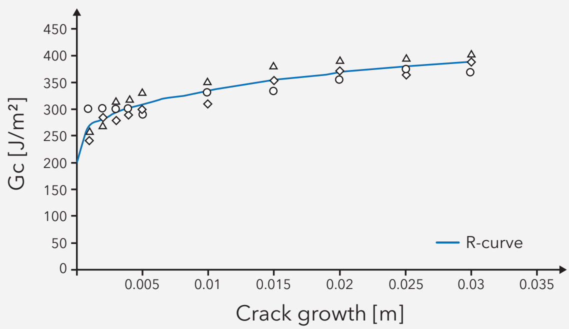
COHESION STRENGTH IN COMPOSITES

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



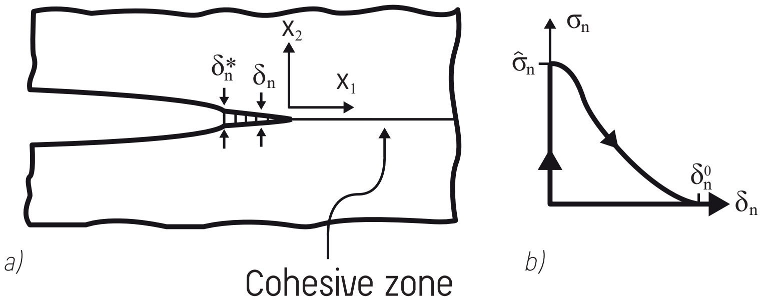
Example of an R-curve

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

PART III

9 | SERVICE & INSPECTION

Working conditions
Inspection

10 | MARKET

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

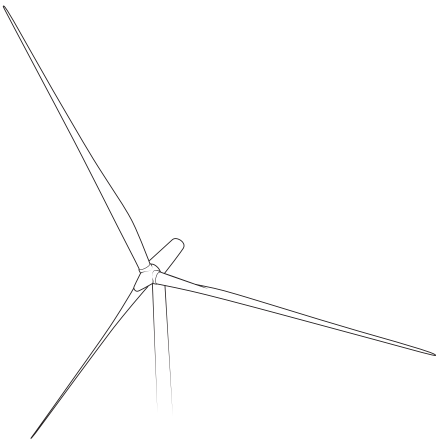
11 | PRODUCT DEVELOPMENT

Design drivers
Technology Readiness Level
Storyboarding

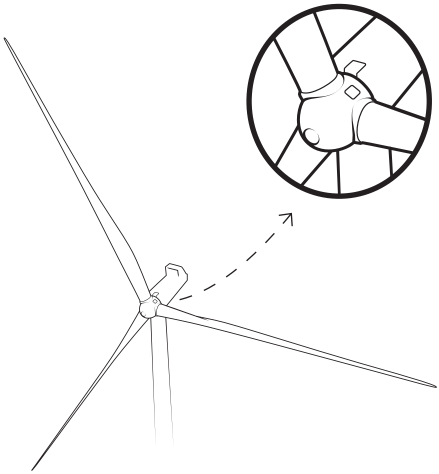
WORKING CONDITIONS

ACCESS

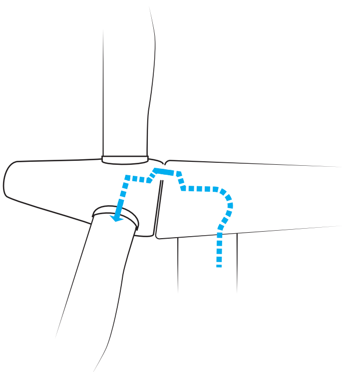
2 types of access - indoor or outdoor access

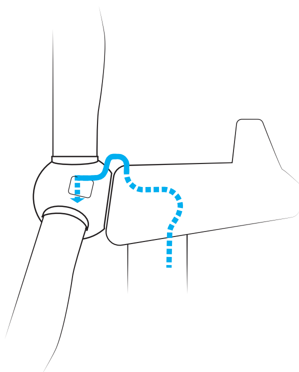


indoor acces



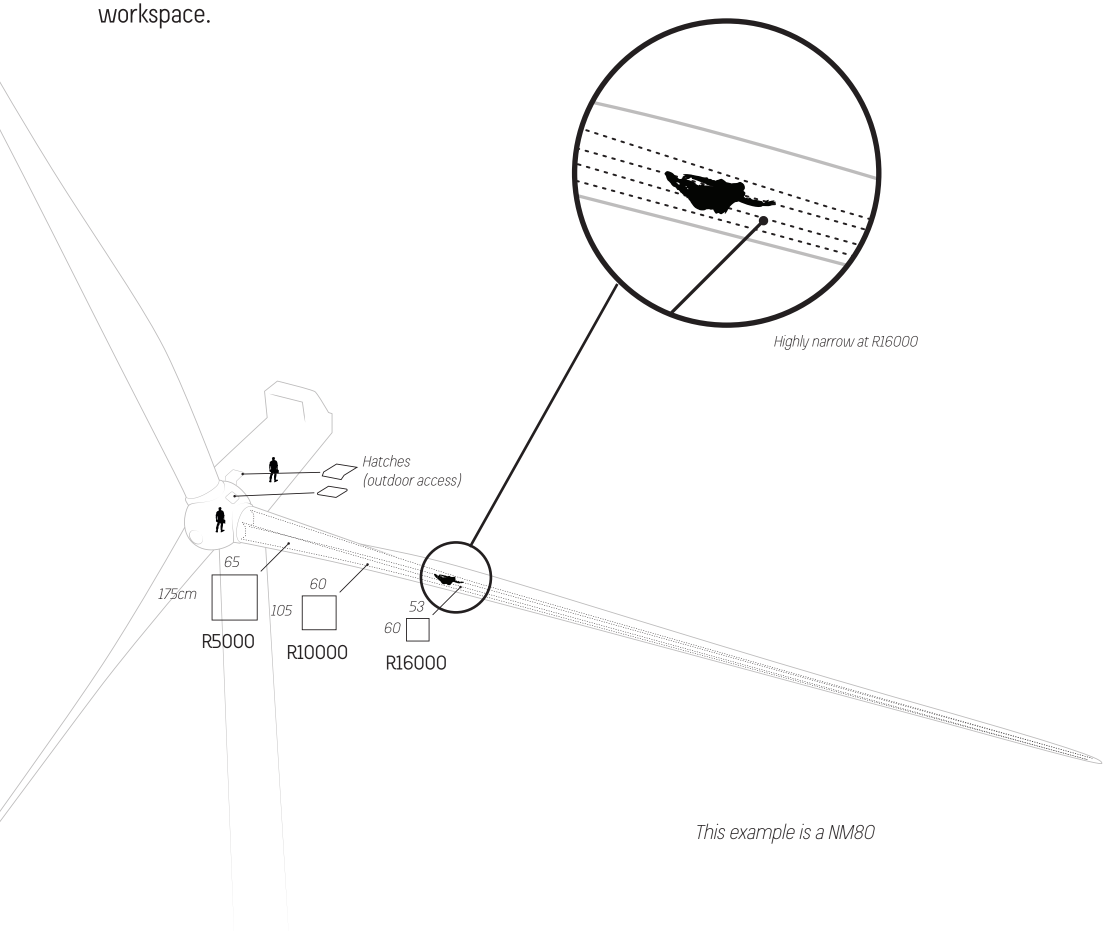
outdoor access





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.



This example is a NM80

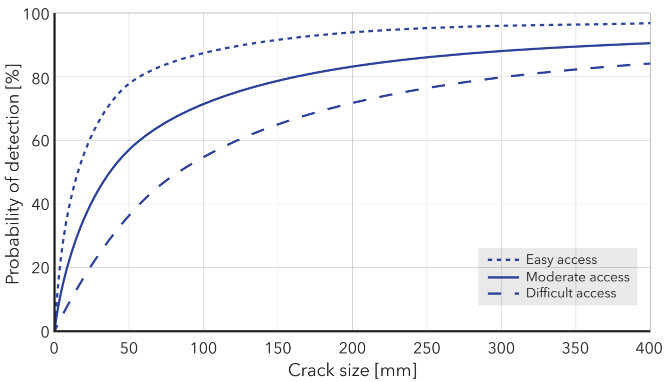
INSPECTION

INSPECTION METHODS

Visual inspection
Acoustic emission
Ultrasonic testing
Shearography
Thermography
Digital X-ray

POD (PROBABILITY OF DETECTION)

The probability of detection is used to quantify the ability of an 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.

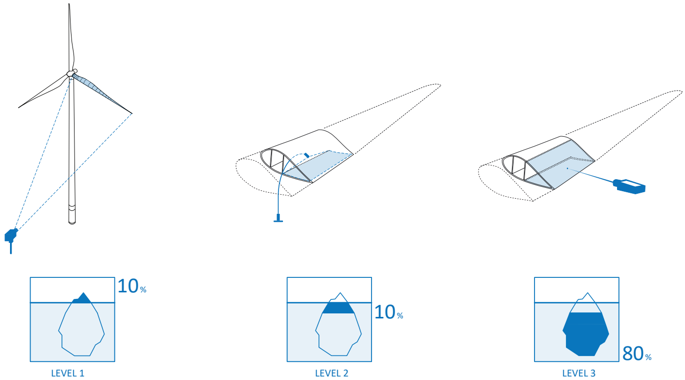


For a specific crack size of a, PoD(a) is the probability that cracks with the size equal to a is detected is PoD(a).

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.

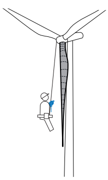
INSPECTION LEVELS

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

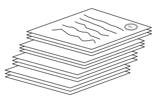


The three inspection levels: Outside, inside and NDT inspection. The outside inspection only sees the tip of the iceberg, by using NDT and inside inspections the whole iceberg can be uncovered.

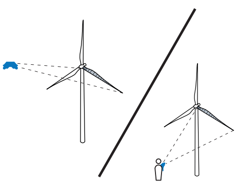
INSPECTION DATA HANDLING



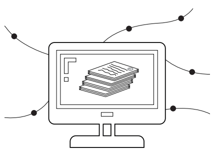
Photos taken directly on each blade



Inspection reports



Photos taken with drones or from ground.

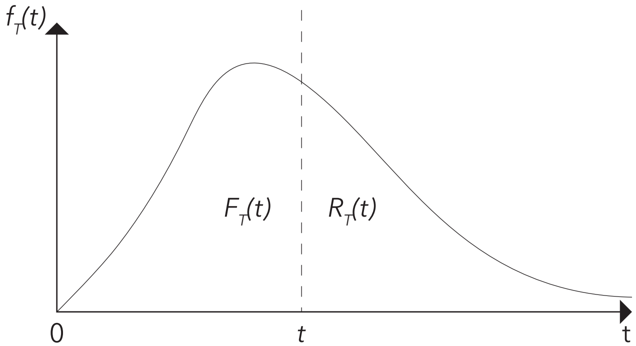


AI handles the majority of the data handling

Individual cases are reviewed by people

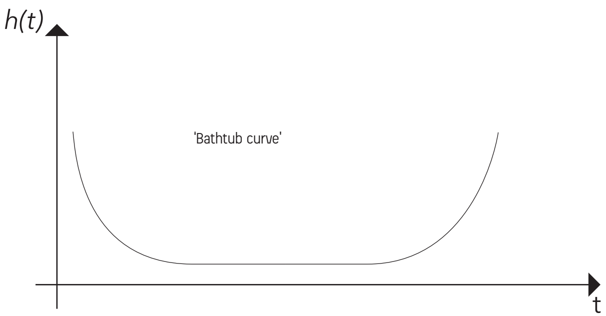
OPERATION & MAINTENANCE

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

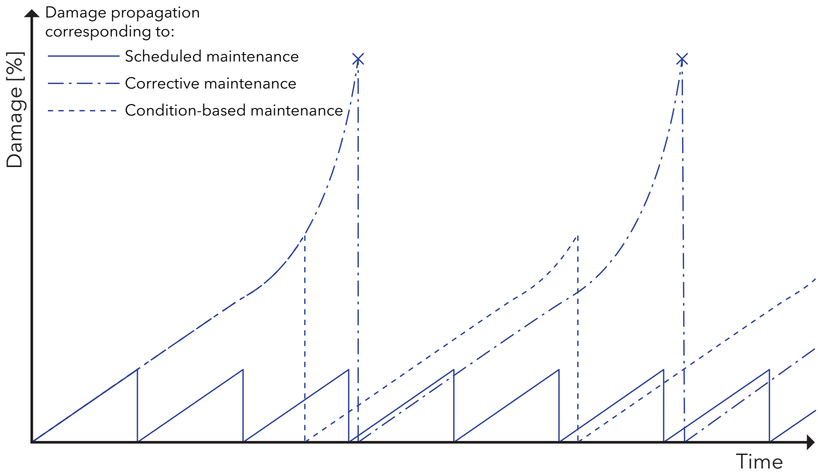
Corrective (unplanned): Exchange / repair of failed components

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.

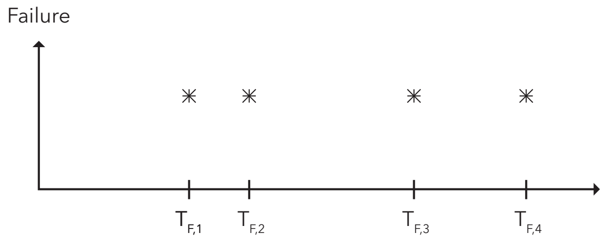
Risk-based: O&M planed based on risk assessment.



OPERATION & MAINTENANCE

CORRECTIVE MAINTENANCE

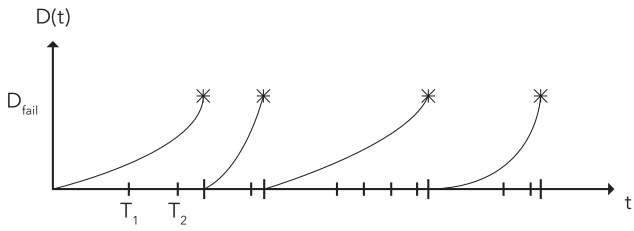
Corrective maintenance is based upon the principle of Run to Failure (RTF). Failures happen at some discrete points as the stars shown in this figure.



Example of corrective maintenance, the turbines run until failure.

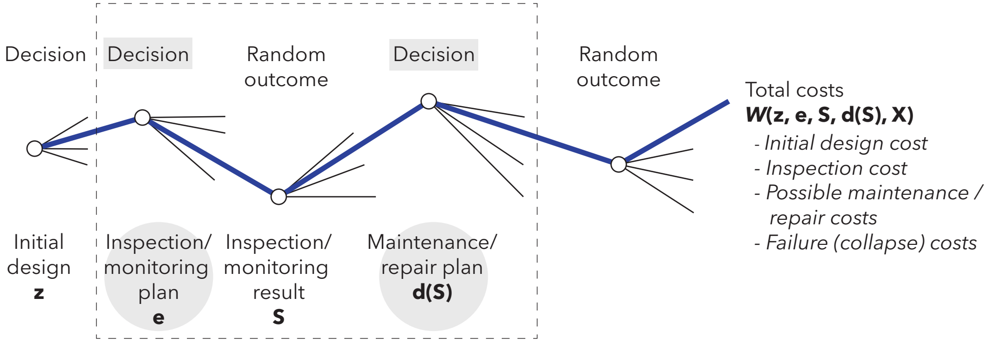
CONDITION-BASED MAINTENANCE

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.

RISK-BASED OPERATION & MAINTENANCE



Optimal decision: Minimum total expected costs in remaining lifetime.

DECISION MAKING

Minimize the total expected total costs (in the remaining lifetime)
or
Minimize the Levelized Cost of Energy (LCOE)

Decision alternatives / parameters:

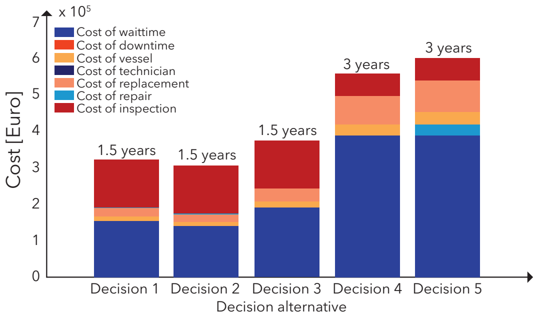
- When and how to inspect?
- When and how much to repair / exchange?
- Which decision rule to apply for choosing between repair alternatives?
- Lifetime extension, e.g. 4 years

OPERATION & MAINTENANCE

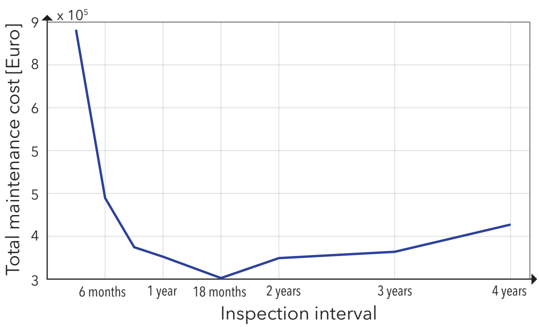
DECISION ALTERNATIVES

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.

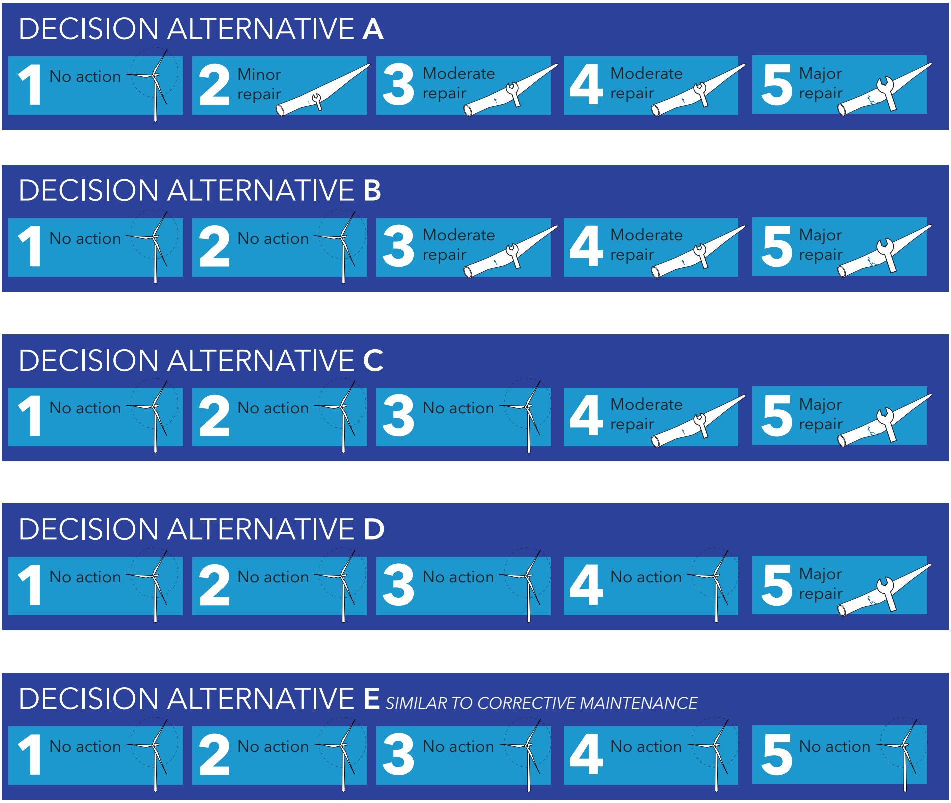


The total maintenance cost for different decision alternatives - Transverse cracks



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.

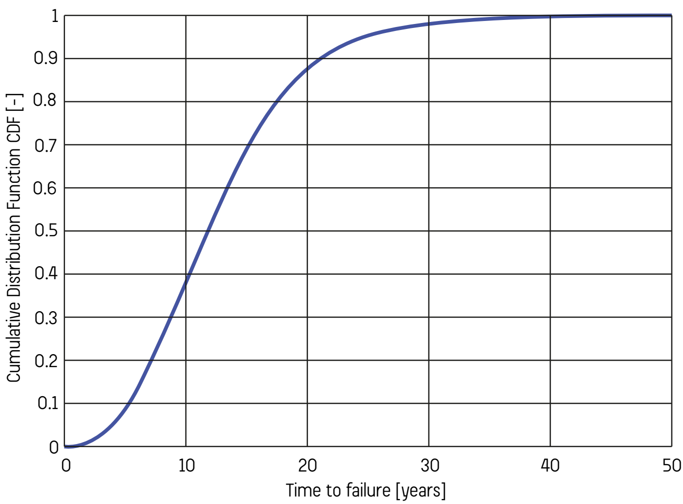
OPERATION & MAINTENANCE

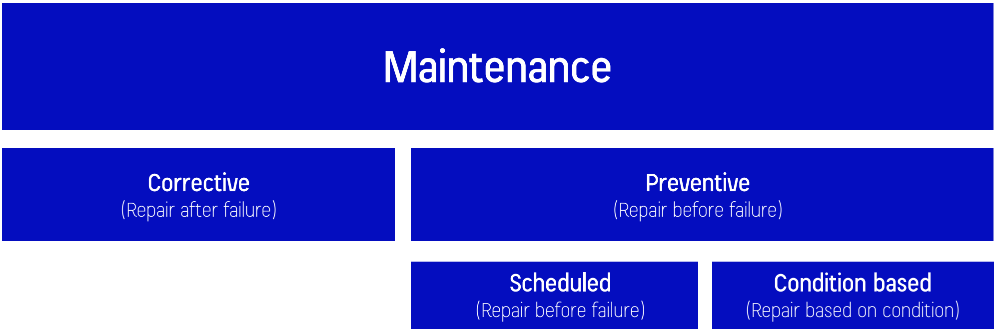
RELIABILITY MODEL - DISCRETE MARKOV CHAIN

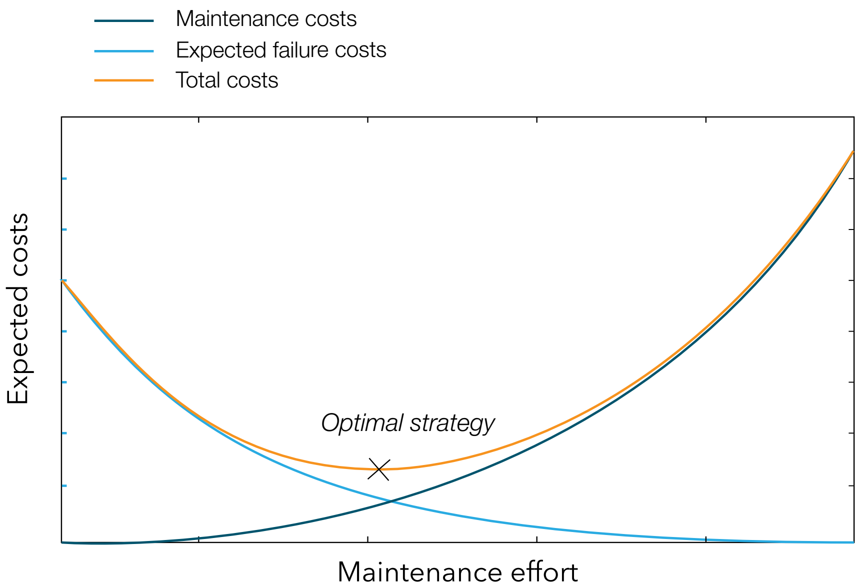
Damages discretized in categories:

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.

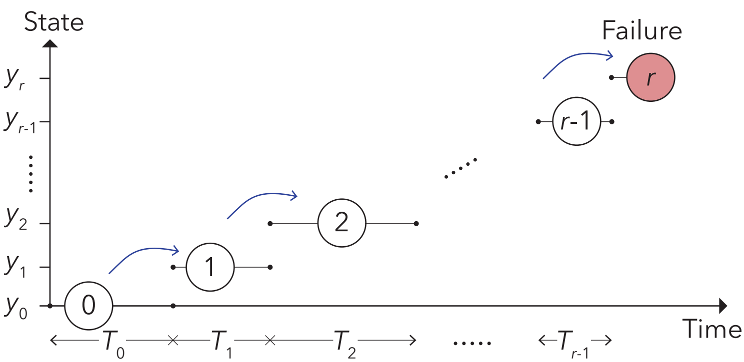
Failure types

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 -

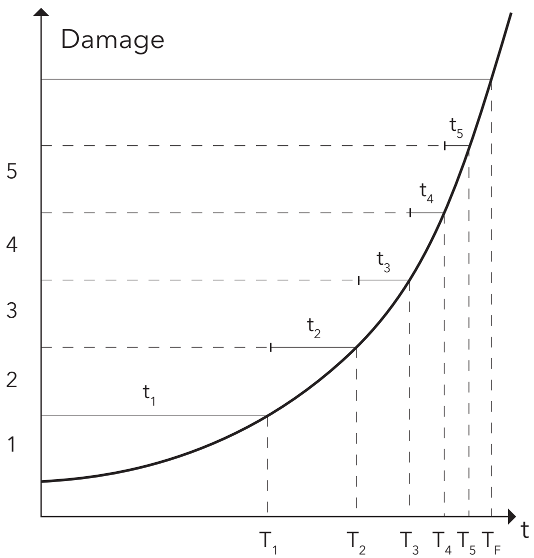
Discretization is the process of replacing a continuum with a finite set of points.

DAMAGE PROPAGATION

Damage is modelled by a continous model

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

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



Continuos 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

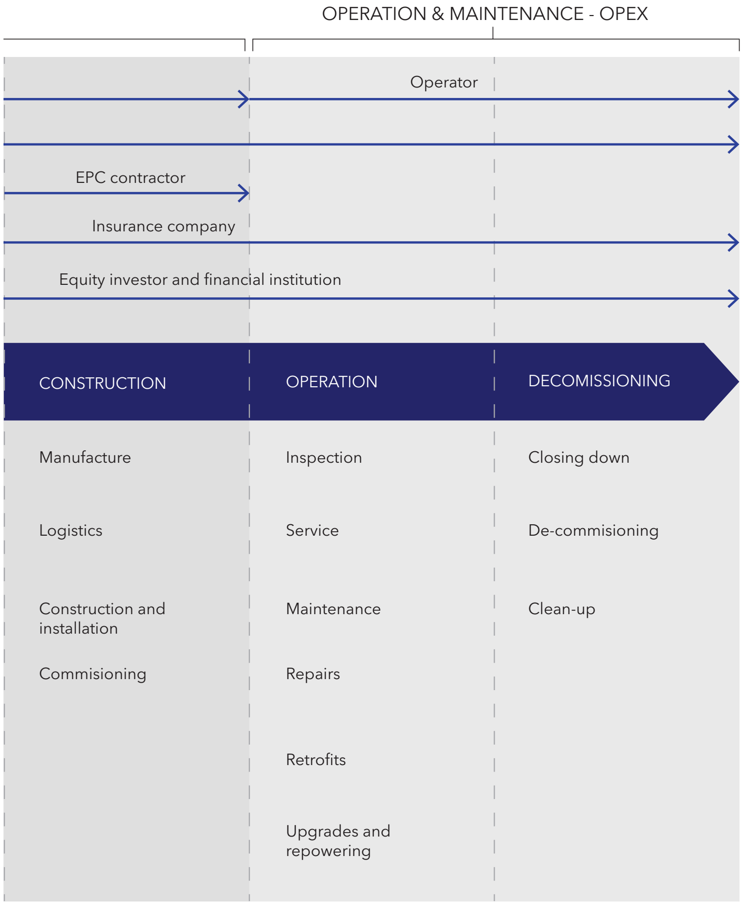
Developer

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 Fit-in-Tariff 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)

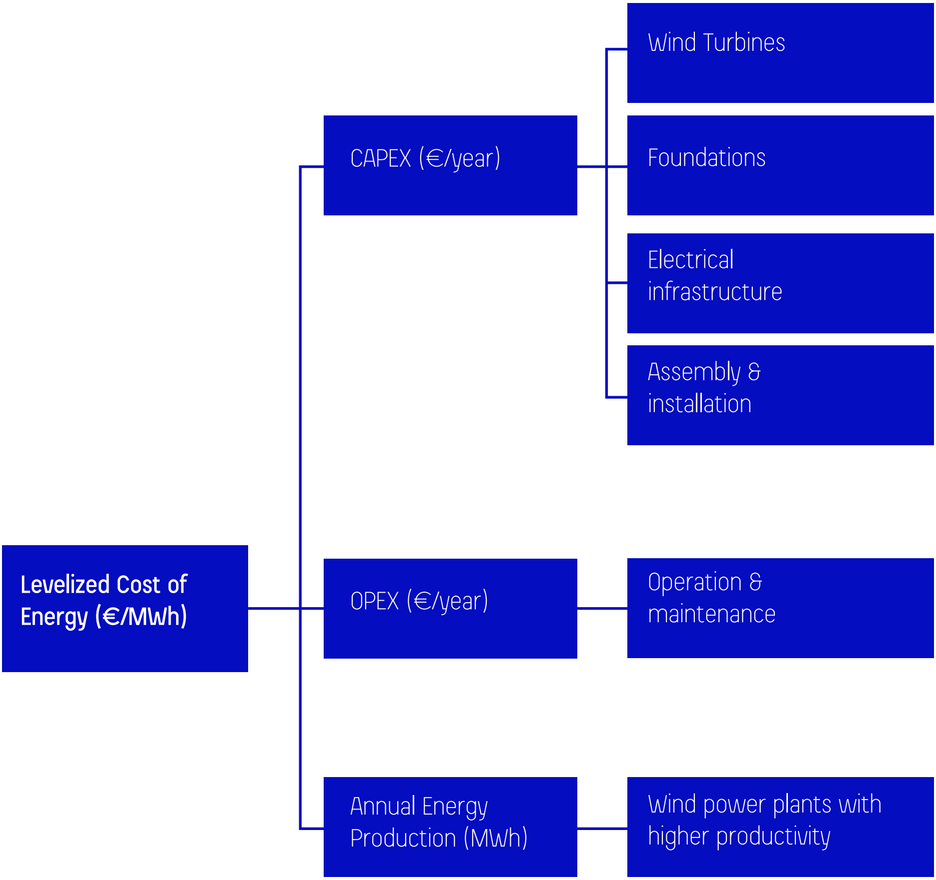
$$LCOE = \frac{CAPEX + OPEX}{AEP}$$

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)

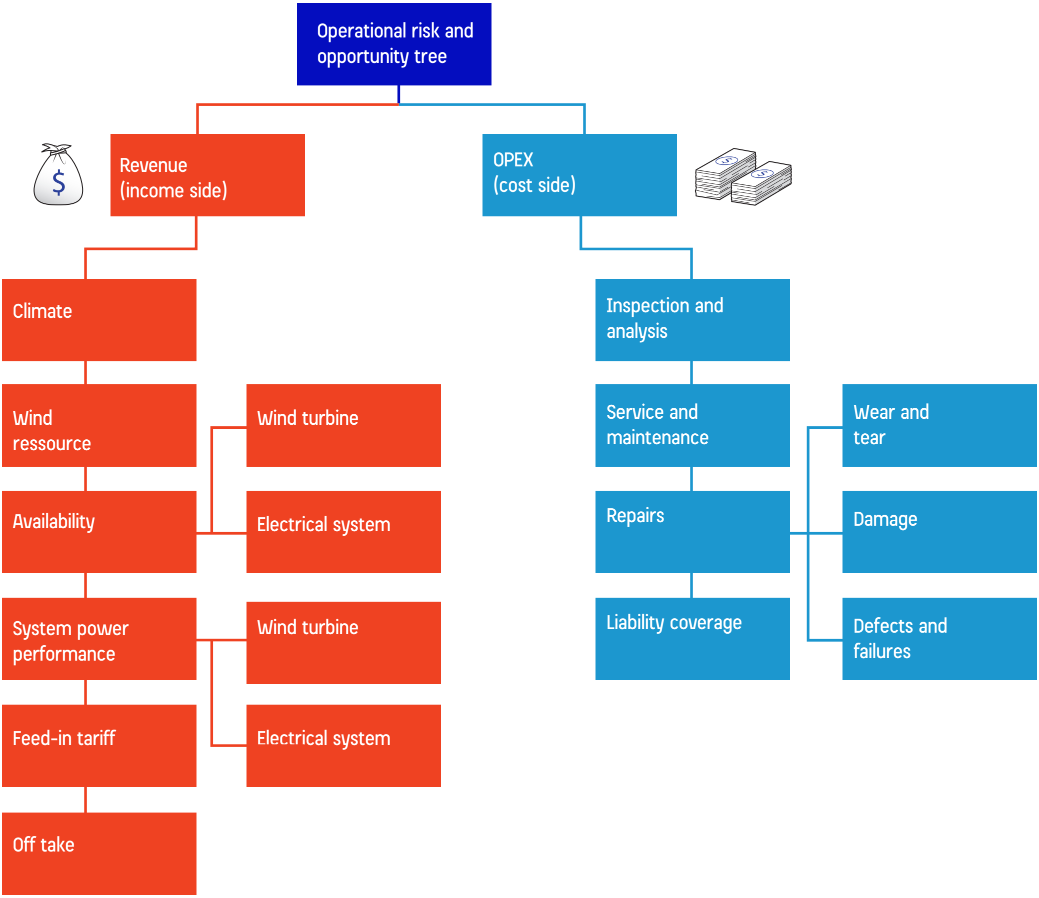


Ref.: MEGAVIND, 2013: THE DANISH WIND POWER HUB - Strategy for Research, Development, and Demonstration

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.

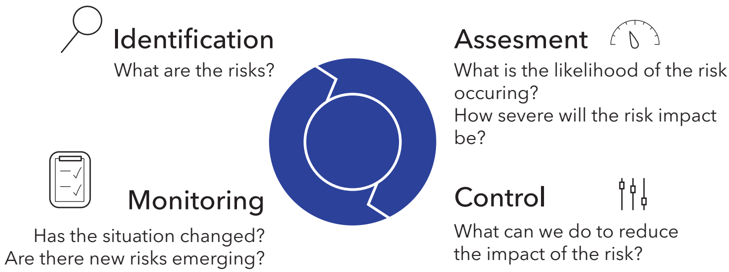
The delivery of those processes is in constant evaluation and change, so further improvements can be developed and applied. The ruler to measure these changes is the efficiency, effectiveness and flexibility of these processes, and the objective is to increase the profitability of the organization.

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?

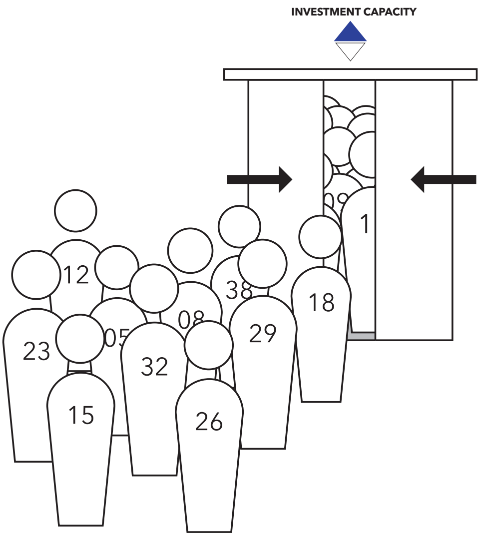
DECISION MAKING / OPERATOR'S FOCUS

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:

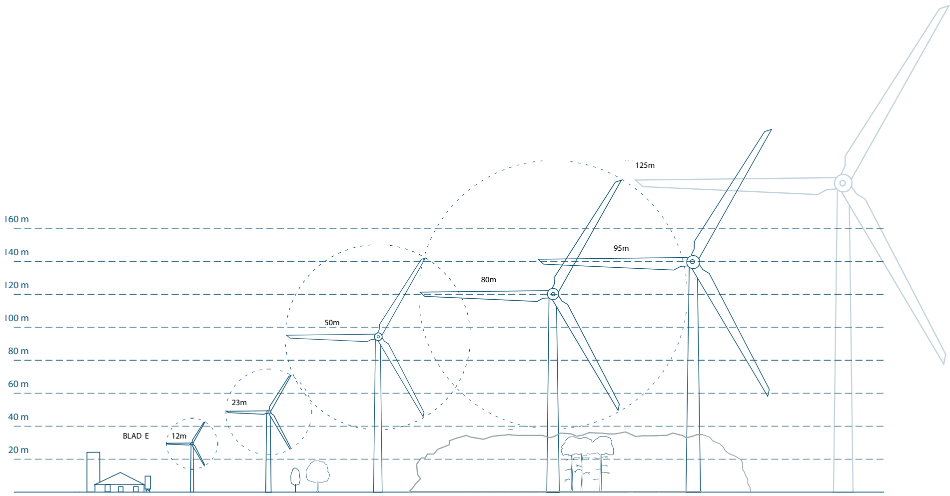
1. Damage Control Investments (must do's) - often prioritized outside budgeting
2. Specific investments supporting overall strategic initiatives
3. Low hanging fruits with high Return on Investment to a given minimum
4. Other investment ranked as per their Return on Investment or other predefined ranking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



	1985	1995	2007	2013	2017	2020
CA PA CI TY	225 KW	660 KW	3,6 MW	6.0 MW	10 MW	20 MW
HUB HEIGH T	30 m	40 m	90 m	120 m	.. m	.. m
ROTOR SIZE	ø25 m	ø47 m	ø100 m	ø160 m	ø190 m	ø250 m

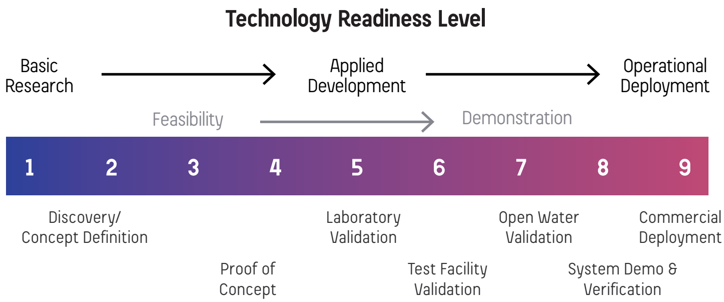
PRODUCT DEVELOPMENT

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).

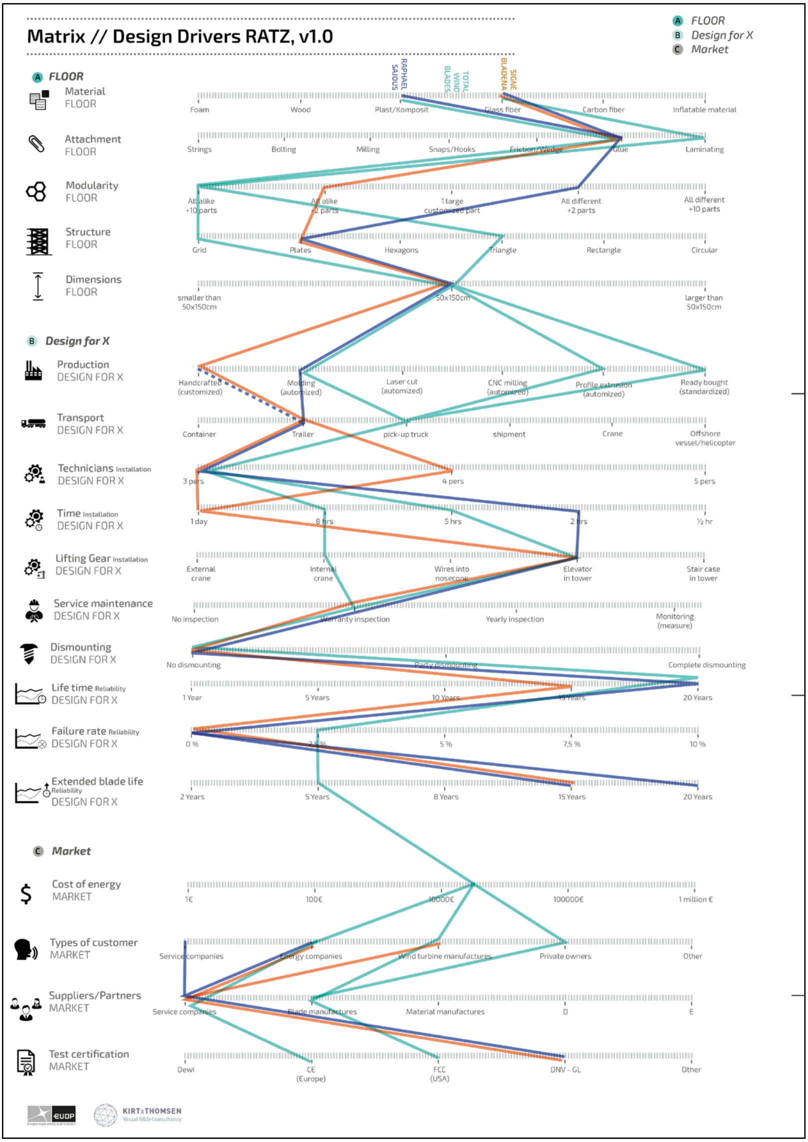


BRAINSTORMING

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

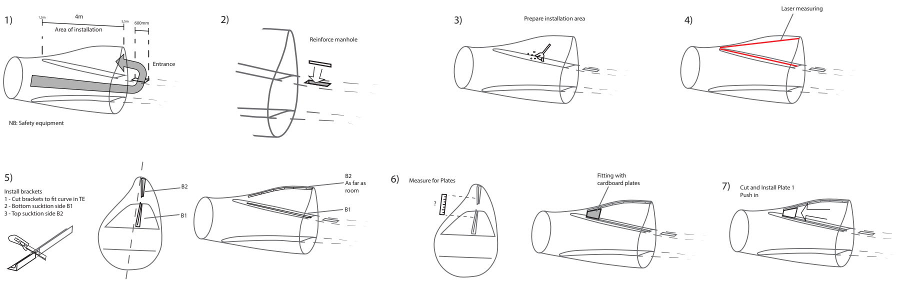
User and stakeholder feedback method to put up options and possibilities in a simple form to gain input, overview and generate alignment among key project participants.



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

AEROELASTICITY

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

AERODYNAMIC FORCES

Forces caused by the wind flow over structures.

ANNUAL ENERGY PRODUCTION (AEP)

The amount of energy produced by a yearly basis.

CAPEX

Capital Expense. The money the company spends to acquire or upgrade its physical assets.

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.

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.

COMBINED LOADING

A mix of two or more loads. I.e. the mix of gravitational load and flapwise load.

CONDITION-BASED MAINTENANCE (CBM)

A maintenance strategy that recommends maintenance actions based on the information on the current damage severity.

CORRECTIVE MAINTENANCE (CM)

A maintenance strategy based upon the Run to Failure principle

CORTIR

Cost and Risk Tool for Interim and Preventive Repair. The title of an EUDP Project headed by Bladena.

CRACK PROPAGATION RATE (CPR)

The rate that the transverse crack grows with.

CRITICAL TECHNOLOGY ELEMENTS (CTE)

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

DAMAGE CATEGORY (DC)

Wind turbine position i Damage category is used to quantitatively characterize a damage by its size, which is called damage grade in the Guide2Defect database.

DECISION ALTERNATIVE/RULE

The decision alternative/rule defines the actual maintenance actions for a specific damage observed at an inspection.

DOWNTIME

The time which the wind turbine is not producing electricity.

NOMENCLATURE

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.

FATIGUE

The process in which damage accumulates due to application of loads reversals whose magnitude are typically much lower than the strength of the material.

GENERAL VISUAL INSPECTION (GVI)

A general examination by visual means of an interior or exterior area, installation, assembly or a specific item to detect obvious damage, failure or irregularity.
This level of inspection is made from within touching distance unless otherwise specified. While maintaining this level of inspection, use of a mirror or other visual aids may be necessary to allow visual access to exposed surfaces in the inspection area. This level of inspection is made under normally available lighting conditions such as daylight, hangar lighting, flashlight or drop-light.

GUIDE2DEFECT (G2D)

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

ISP

Independent Service Provider.

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.

MATERIAL STRENGTH

Ability to withstand an applied load without failure.

MEAN WIND SPEED

Average wind speed over a 10 minute time interval.

MODE SHAPE

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

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)

A national laboratory in the US.

NATURAL MODE OF VIBRATION

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

NDT (NON-DESTRUCTIVE TESTING)

Non-destructive testing is commonly used to localize and size defects in structures. The detection ability for the NDT method is defined as a function of a defect size, through probability of detection curves.

O&M

Operation and Maintenance.

OEM

Original equipment manufacturer.

OPEX

Operational Expenses. The money the company spends on an ongoing, day-to-day basis in order to run a business (the wind turbine).

OWNERS REQUIREMENT

Additional specifications added to the existing certification requirements found in standards today.

NOMENCLATURE

PPA

Power purchase agreement.

PROBABILITY OF DETECTION (PoD)

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.

PREVENTIVE MAINTENANCE (PM)

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.

PTC

Power tax credit.

RETURN ON INVESTMENT (ROI)

Measures the efficiency of an investment.

RISK

The probability that the investment will lose value.

STANDSTILL OR PARKED POSTION

Wind turbine position in which the rotor is not rotating.

TECHNOLOGY READINESS LEVEL (TRL)

TRL is a method of estimating technology maturity of Critical Technology Elements (CTE) of a program during the acquisition process.

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.

TURBULENCE (WIND)

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

VALUE CHAIN

The Value Chain in the Wind Industry consists of three parties: Wind Turbine Manufacturers (OEMs), Wind Turbine Owners (WTOs) and Insurance Companies.

WTG

Wind Turbine Generator.

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.

Developed in 2012-2019 with input from some of industry's leading experts and universities within this field.

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