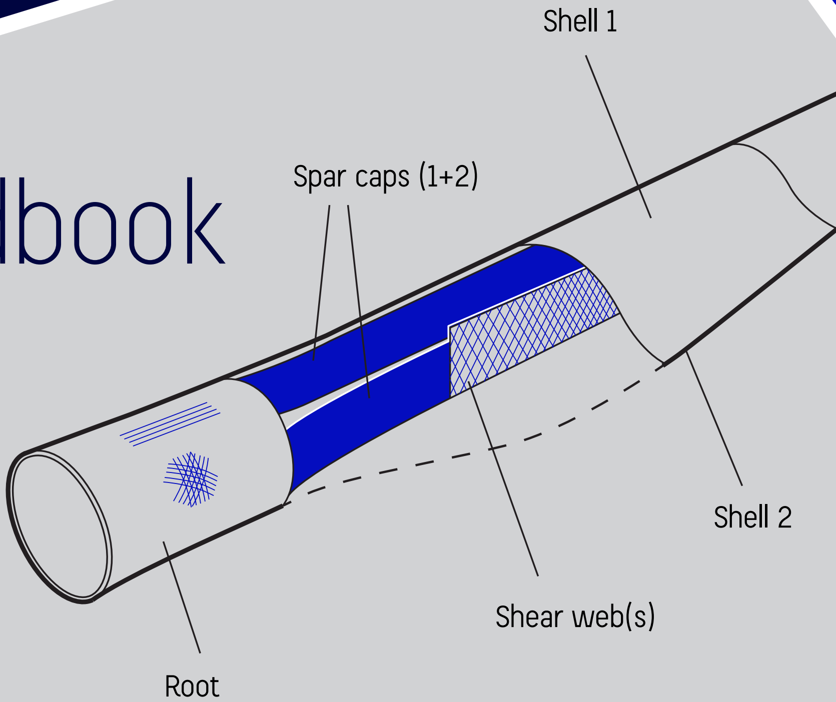
WIND TURBINE
BLADES

Handbook



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Total Wind Blades

DIS

VATTENFALL

e·on

DONG energy

Blade Handbook | Visual Dictionary of terms and definitions for wind turbine blades

Input by Lars Damkilde (AAU), Torben J. Larsen (DTU Wind), Jaocb Walbjørn (DTU Mek), John Dalsgaard Sørensen (AAU), Engineering (Bladena), Rune Kirt (KIRT x THOMSEN), Johnny Plauborg (Total Wind Blades), Mads Lübbert (DIS), Vasileios Karatzas (DTU Mek)

Handbook conceptualized and produced by KIRT x THOMSEN

INDEX

WHY A HANDBOOK

During the two EUDP projects LEX and RATZ 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 business to get and overview. The present Blade Handbook is a direct further development of the LEX Handbook.

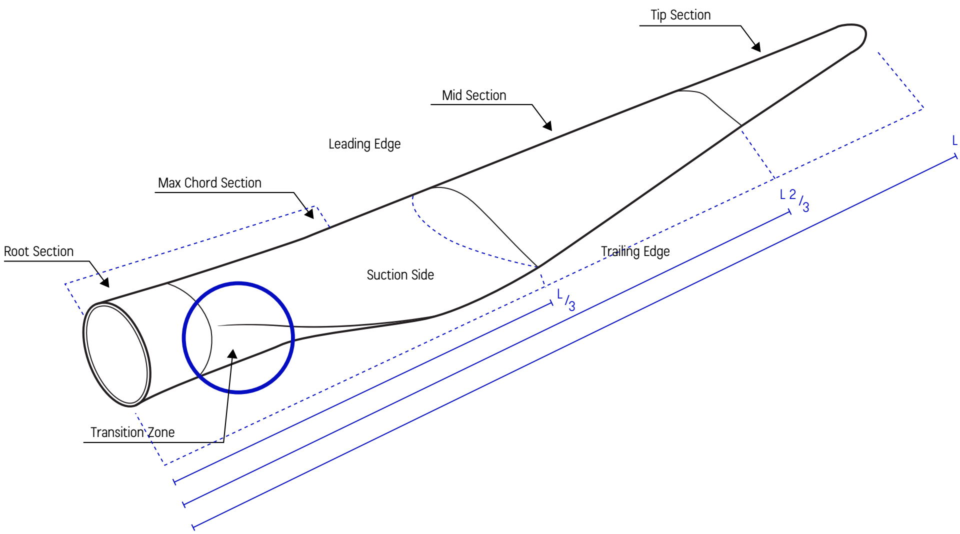
Thus, this Blade Handbook is aimed at helping all parties involved in R&D of wind turbine blades to get a common understanding of words, process, levels and concepts.

✖ *Terms marked with X are elaborated and/or translated in the Nomenclature section*

ANATOMY OF A BLADE

BLADE SECTIONS

A wind turbine blade is divided into different sections as shown

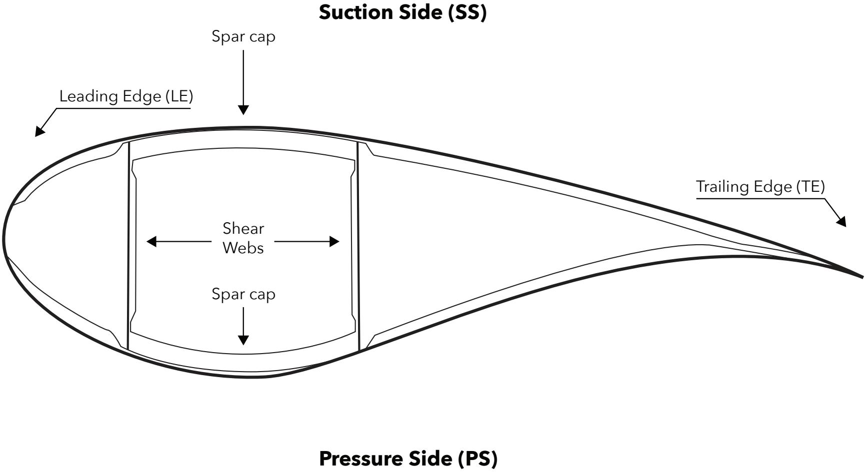


Wind turbine blade model: **SSP 34**

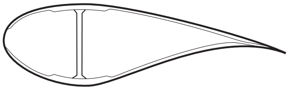
34m blade manufactured by SSP-Tecnology A/S

CROSS SECTION

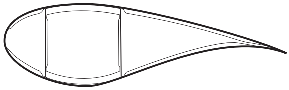
Blade cross section indicating main construction elements



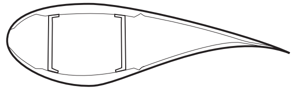
Types of cross sections



Closed shell



Box spar



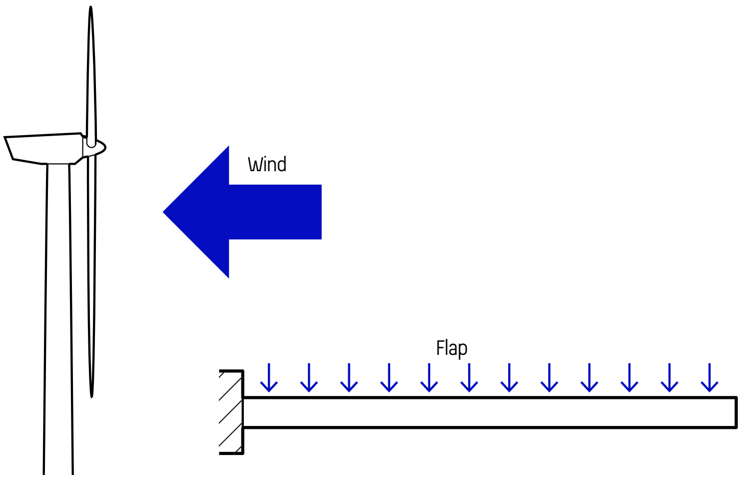
Load carrying shell

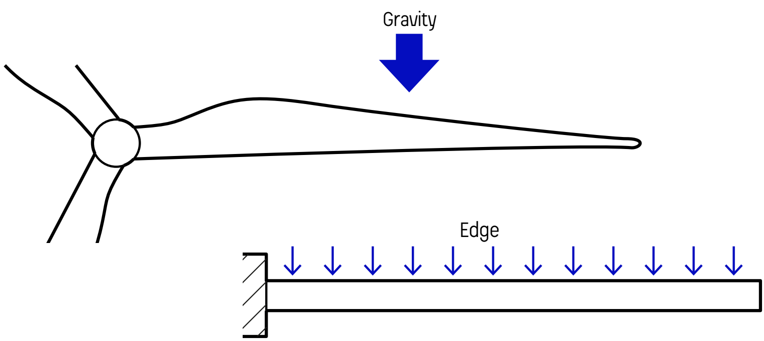
ANATOMY OF A BLADE

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.

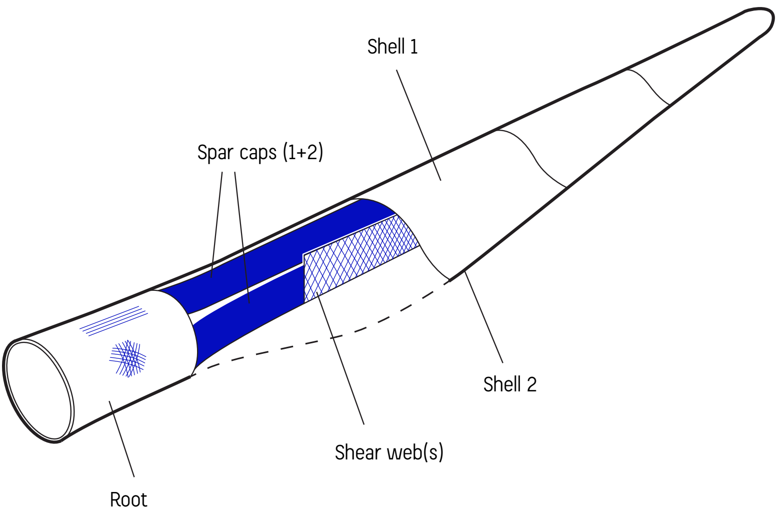
A blade is a large cantilever beam.





CONSTRUCTION

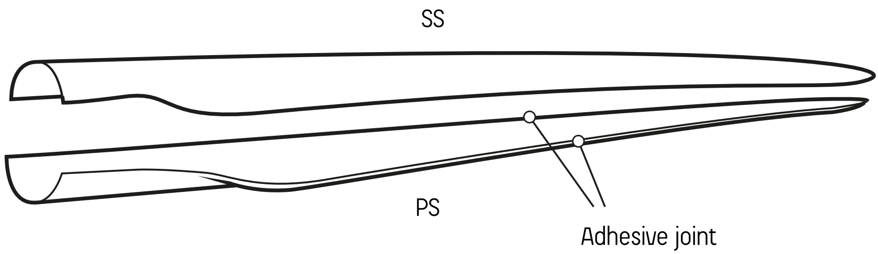
A blade can be segmented into 4 main parts, each parts fulfilling a specific function (shell, caps, shear webs, root).



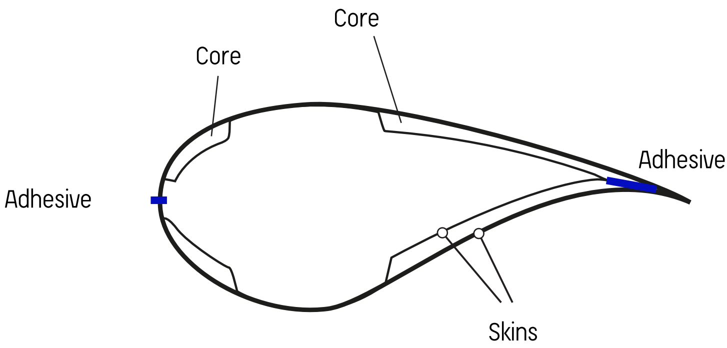
SURFACE

SHELLS

The SS and PS shells are large aerodynamic panels designed to "catch the wind" and transfer the loads to the spar caps.



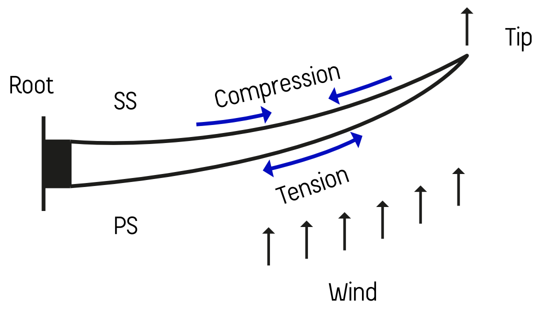
They are typically moulded in two "blade shell" tools (SS and PS moulds), and adhesively bonded to each other along their leading and trailing edge, and to the SS and PS spar caps in the middle. Shell skins are lightweight glass fiber skins (often 2 to 54 layers of "triax" material at 0, +45 and -45Deg), 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 not be able to keep their required profile.

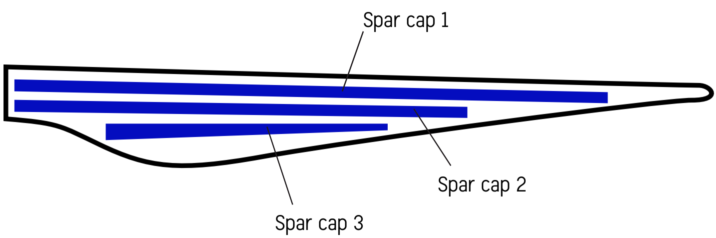


SPAR CAPS

Primary function: 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.

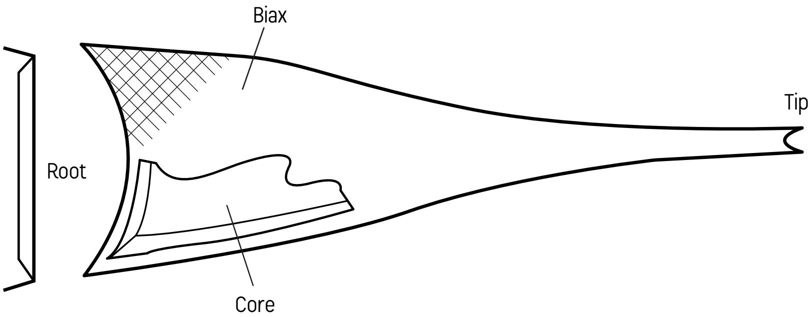




INSIDE

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.



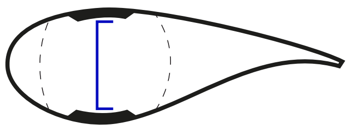
They only carry shear loads, and the challenge from a design point of view is to stop them crushing and/or buckling.

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

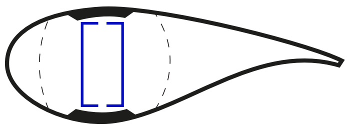
SPAR CAPS

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

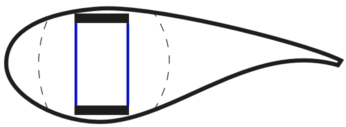
They sometime include "feets" or "flanges", a transition where the skins join each others to facilitate the load transfer to the shells or spar caps.



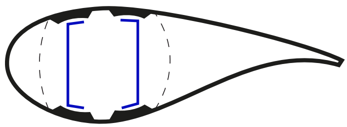
1 web, 2 caps



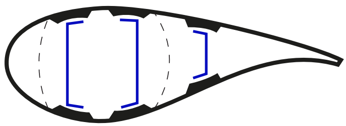
2 webs, 2 caps



Box spar



2 webs, 4 caps



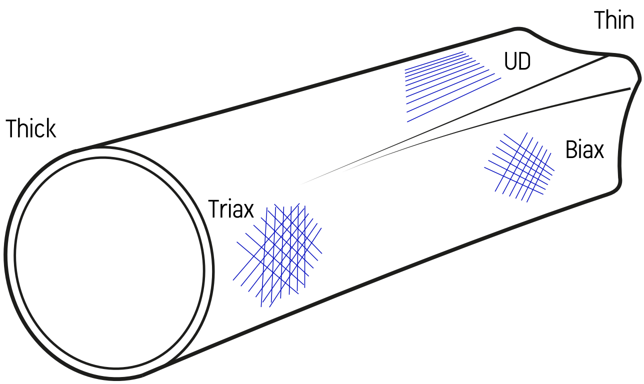
3 webs, 6 caps

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)

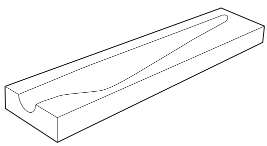
The root is typically a thick laminate, with a limited amount of fibers at 0° and most fibers at +/- 45°.

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

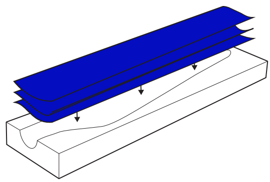
MANUFACTURING

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

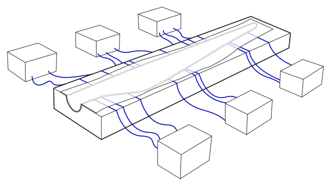
Blade manufacturing procedures can introduce conditions in the composite which strongly influence fatigue life and potential failures. These conditions include local resin content variations, local fiber curvature, and local residual stress. Such conditions are variables in all composite manufacturing processes and should be considered in design.



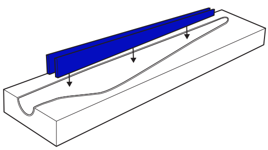
1. Prepare mould



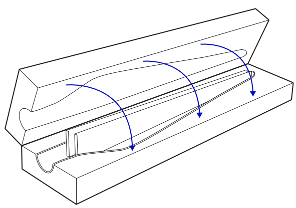
2. Build-up dry layers



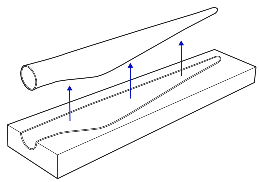
3. Resin infusion



4. Add webs



5. Join shells, Curring



6. Demould, trim & polish

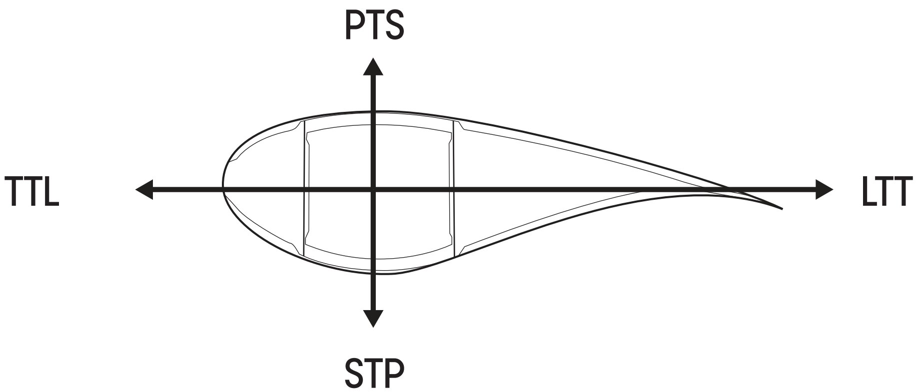
Generic steps of composite blade production

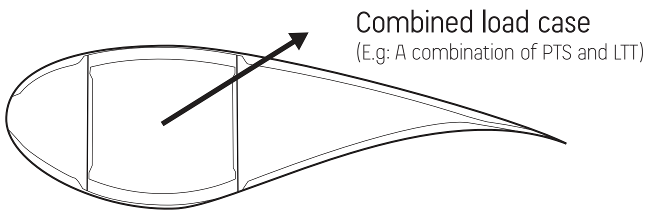
LOAD CASES

TYPES OF LOAD CASES

LOAD CASES IN FULL-SCALE TEST

- PTS - pressure side towards suction side
- STP - suction side towards pressure side
- TTL - trailing edge towards leading edge
- LTT - leading edge towards trailing edge
- Combined load case - a combination of flap and edge load
  - Twisting


PTS
TTL
LTT
STP


Combined load case
(E.g: A combination of PTS and LTT)

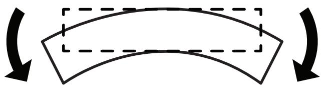
STRAIN & STRESS

Strains and stresses are both responses to loading a structure. 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.

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..

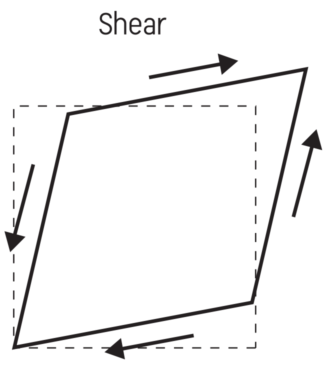
a) Axial strain due to axial load.



b) Axial strain due to bending.

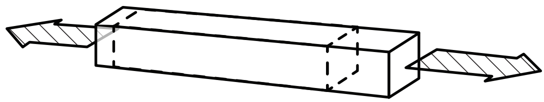
SHEAR STRAIN

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

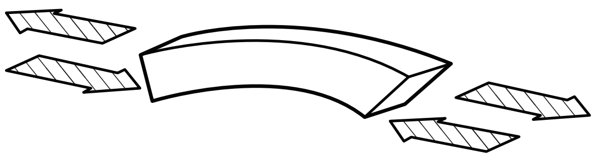


STRESS

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

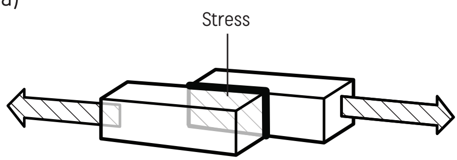


b) Axial stresses du to bending.

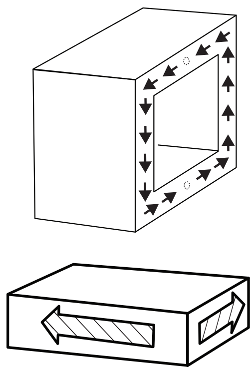
SHEAR STRESS

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

a)



b)

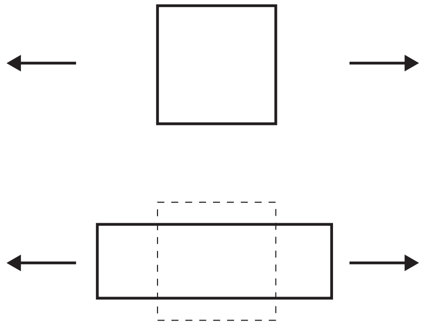


MATERIALS

ELASTIC

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

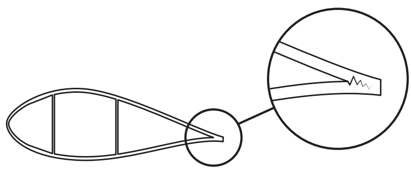
An isotropic material has equal properties in all directions. The properties are described by the Modulus of Elasticity (E) which defines the stress for a strain increment in a given direction and the Poisson ratio (ν) which defines the deformation perpendicular to the stress direction.



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.

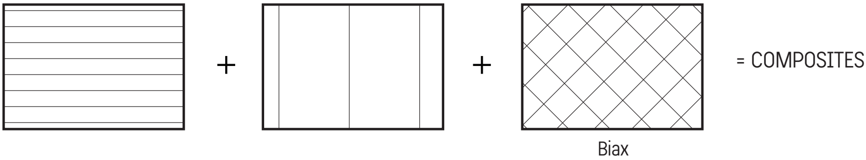
a) Load cycles induces fatigue over time.

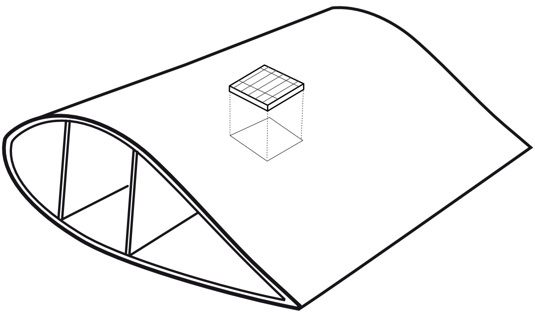


b) Example of fatigue cracks in the trailing edge due to peeling stresses.

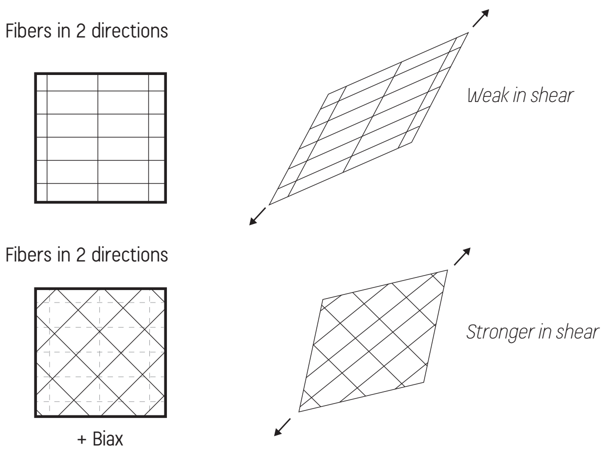
COMPOSITES

Composites are a number of layers glued together in different directions.





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.



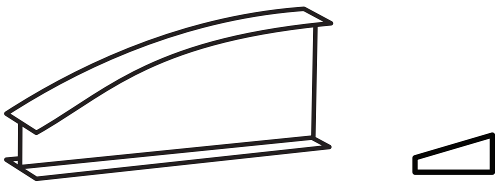
BEAM STRUCTURE

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

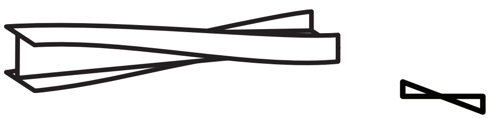
Constant

B



Tapered

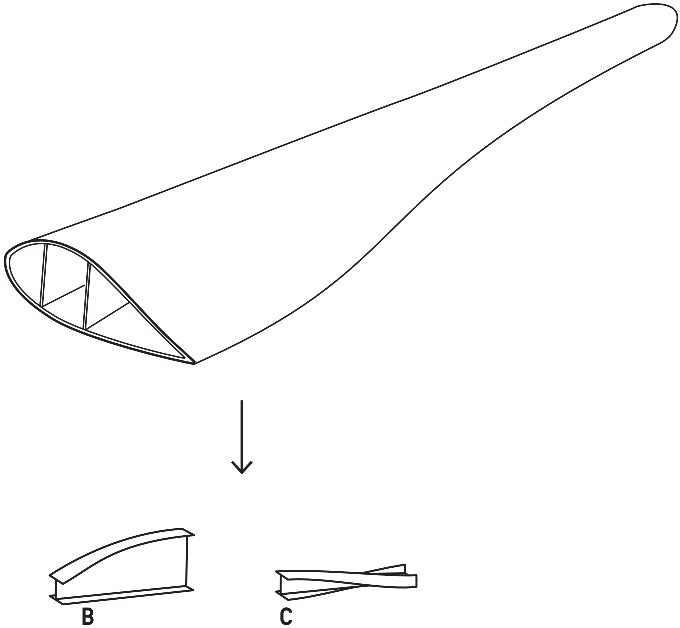
C

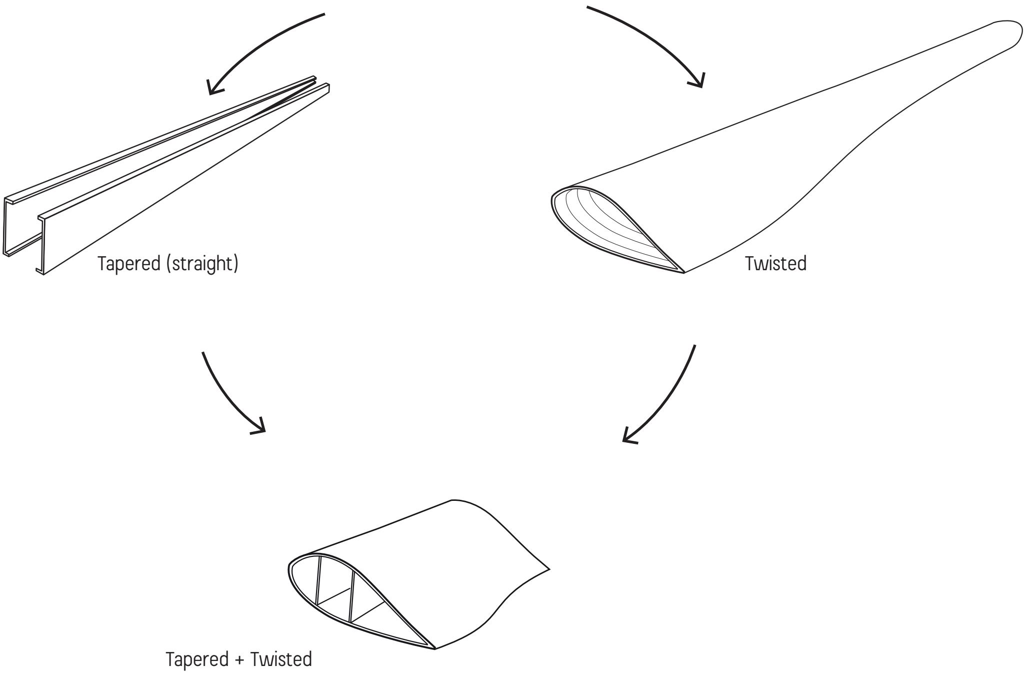


Twisted

IN A BLADE

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





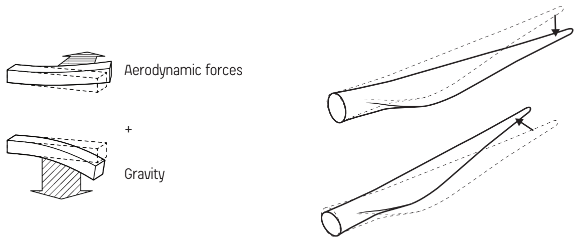
Together that is a PRE-TWISTED STRUCTURE
(eg. similar to a helicopter blade)

BENDING & TORSION

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

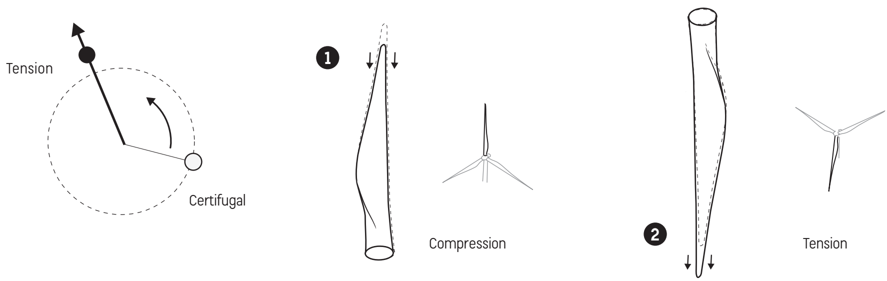
A. BENDING

The primary way of carrying the loads are through bending.



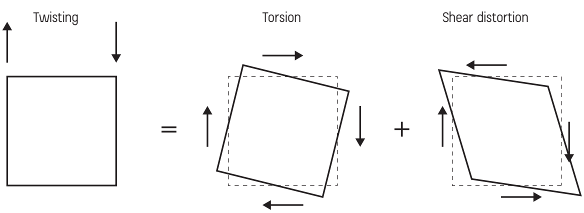
B. AXIAL FORCE

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



C. TWISTING

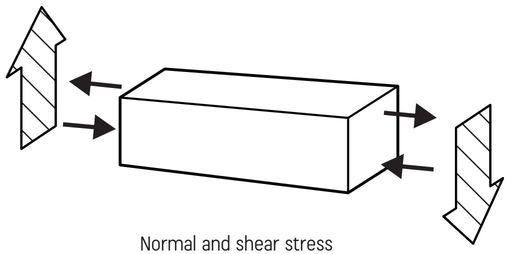
Wind loads act excentrical and creates twisting in the blade.



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**

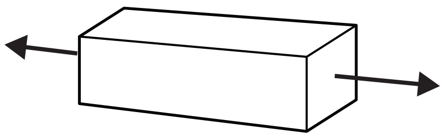
The bending moments create normal and shear stresses



Normal and shear stress

AXIAL FORCE → **NORMAL STRESS**

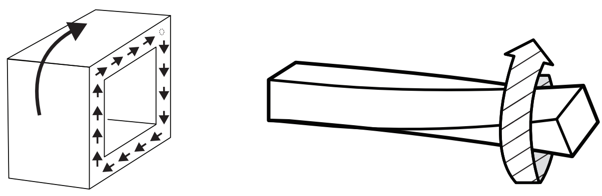
The axial force creates normal stresses



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.



Shear stress

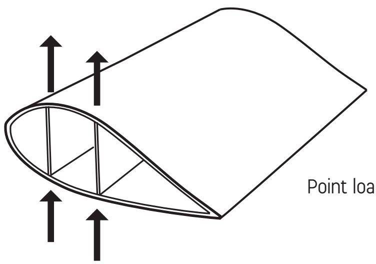
LOCAL EFFECTS

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

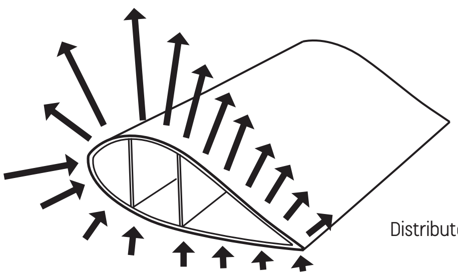
Wind loads are today referred directly to the stiff part of the structure, when load calculations and FEM analysis are being done, and this is not on the conservative side compared to a distributed pressure load closer resembling the actual load..

TODAY'S PRACTICE



Point loads

REAL LIFE

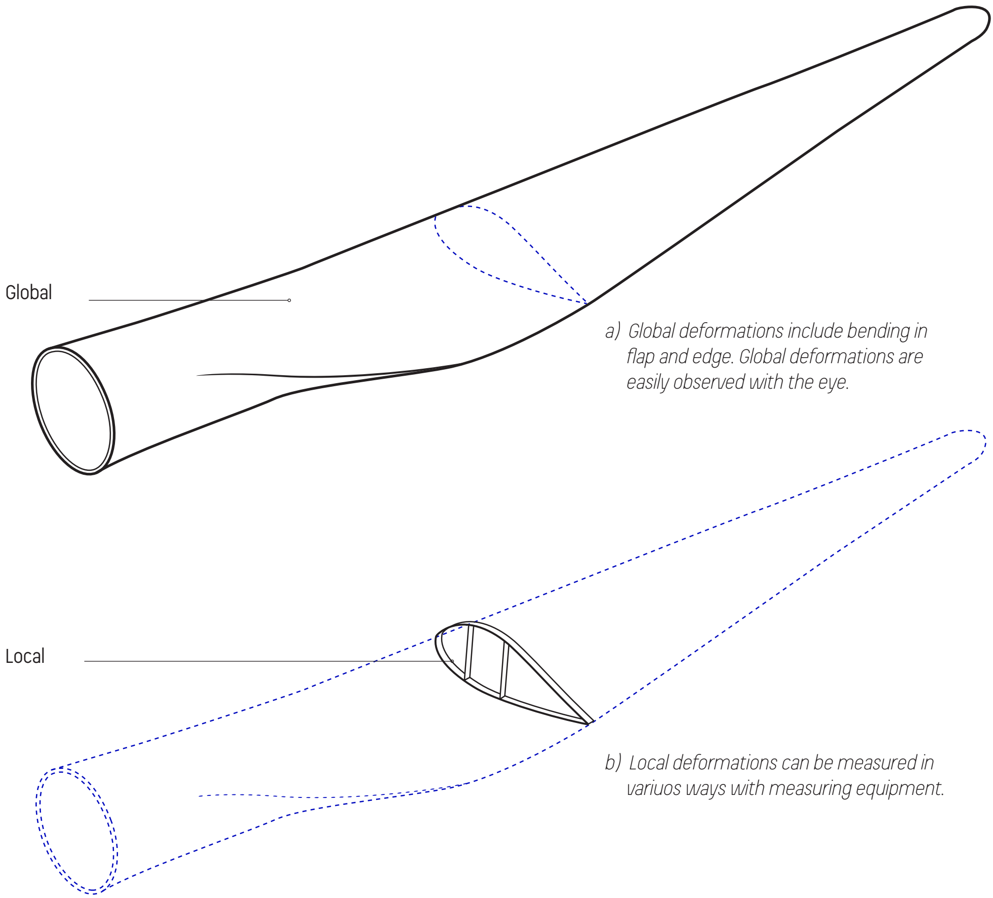


Distributed loads

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.



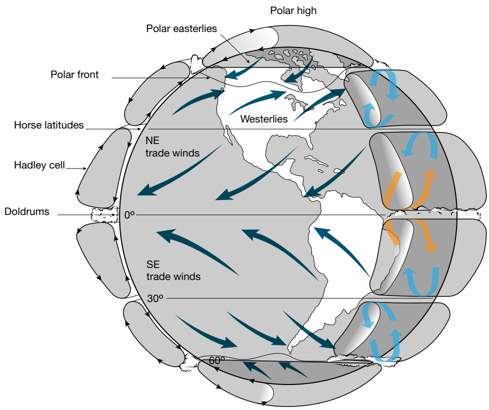
a) Global deformations include bending in flap and edge. Global deformations are easily observed with the eye.

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

WIND CONDITIONS

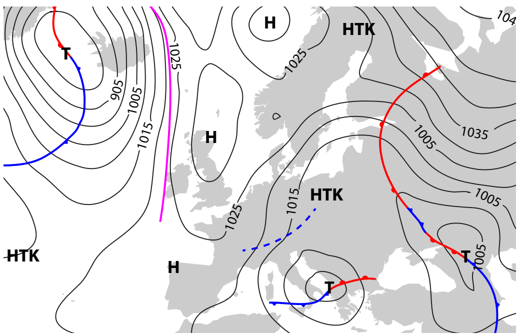
GLOBAL

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.



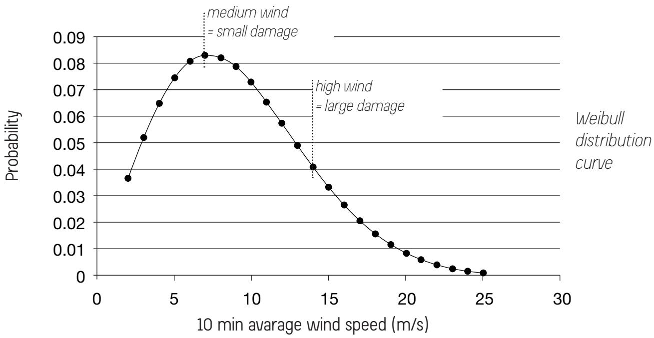
REGIONAL

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



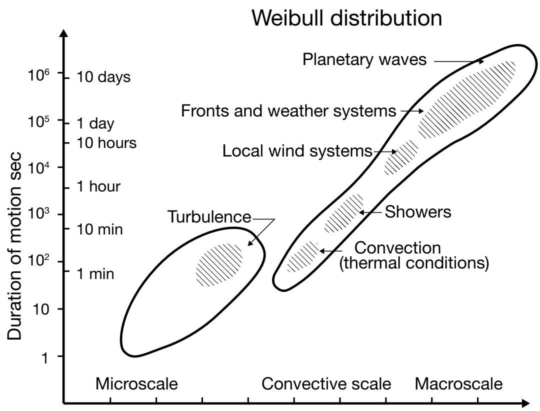
PROBABILITY

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 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).

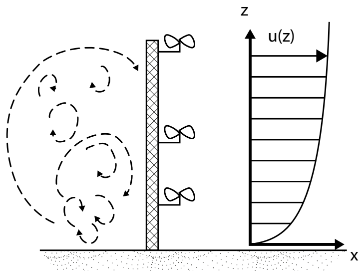


Courtesy Courtney, M, Troen, I. (1990). Wind Spectrum for one year of continuous 8Hz measurements. Pp 301-304, 9th symposium on Turbulence and diffusion.

TURBULENCE

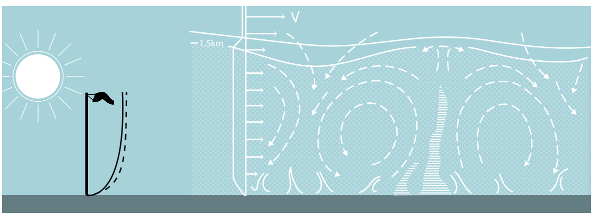
HEIGHTS

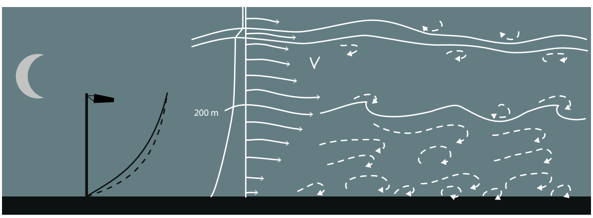
The type of terrain near the turbine has a friction level on the wind - also denoted a terrain roughness. The roughness causes a near surface boundary layer with increasing wind speed for increasing height. The roughness also creates turbulent vortices with length scales increasing with height.



TIME. DAY VS NIGHT

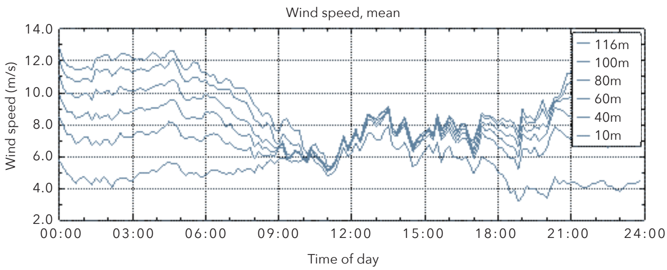
Temperature effects in the boundary layer has a direct impact on the turbulent flow. Warm air near the surface causes unstable conditions creating an increased turbulent mixing whereas cold air near the ground caused more low turbulent laminar flow - but with a large shear in the mean wind speed.





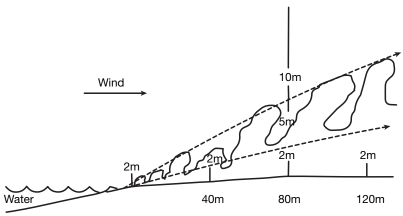
HEIGHT & TIME

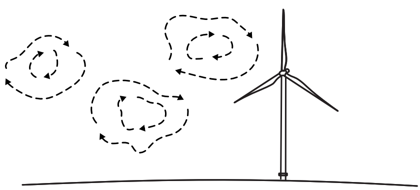
Measured wind speed in different heights at the Høvsøre test site. Cold temperature at night causes very stable conditions where the heating from the sun causes unstable conditions with a significant turbulent mixing.

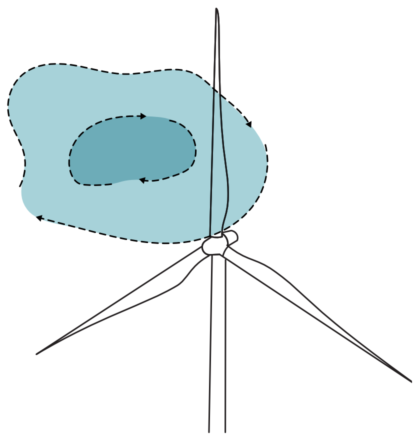


TERRAIN

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.



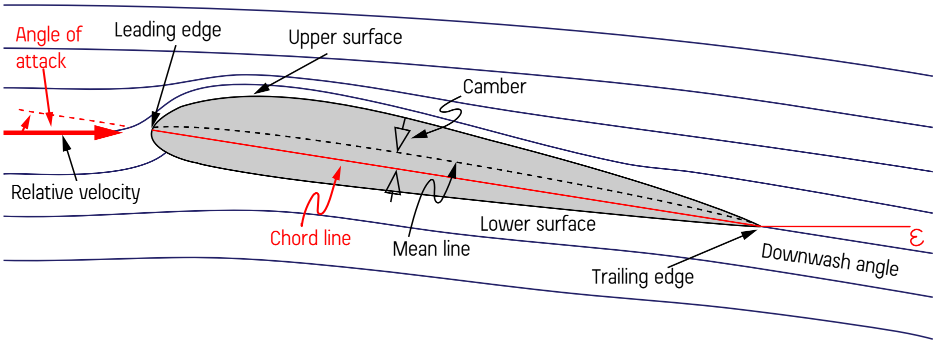




AERODYNAMICS

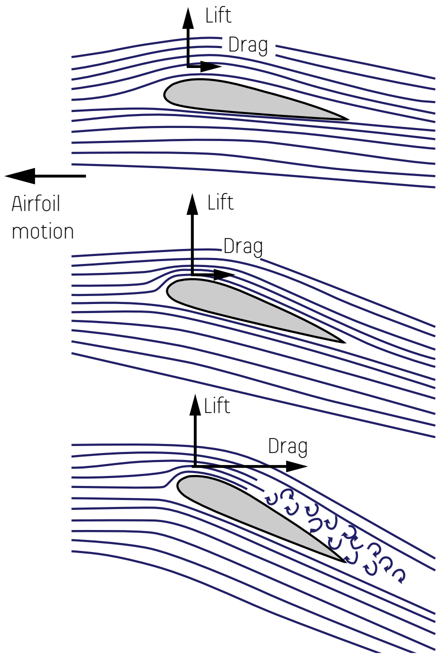
AIRFOIL TERMINOLOGY

2D airfoil terminology



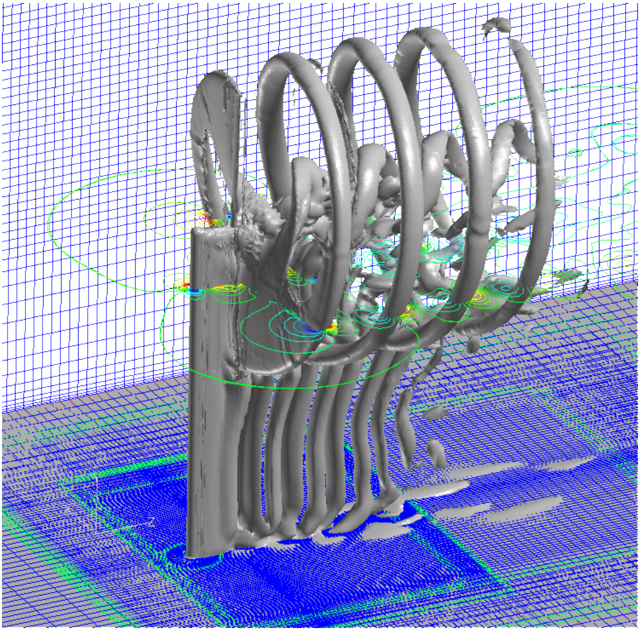
LIFT & DRAG

The presence of an airfoil in a flow will cause a bending of the air flow lines. As the air particles are forced downwards due to the airfoil, there will be an opposite equal sized 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 stall separation occurs which lowers the lift and increase the drag force.



VORTEX

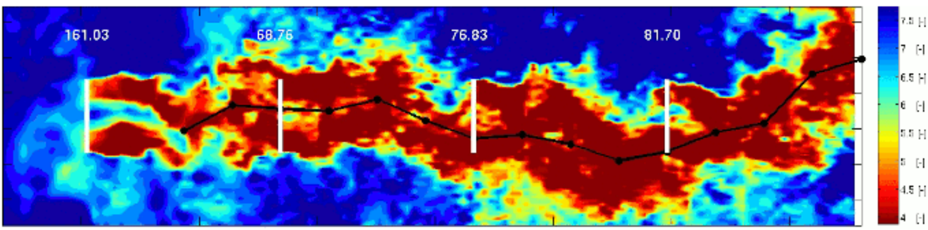
Detailed vortex system behind a turbine. (In this particular case a two-bladed downwind turbine). The tip and root vortex system can be seen as well as the tower shadow. Details of the aerodynamic rotor/tower interaction are seen on the right.



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)).

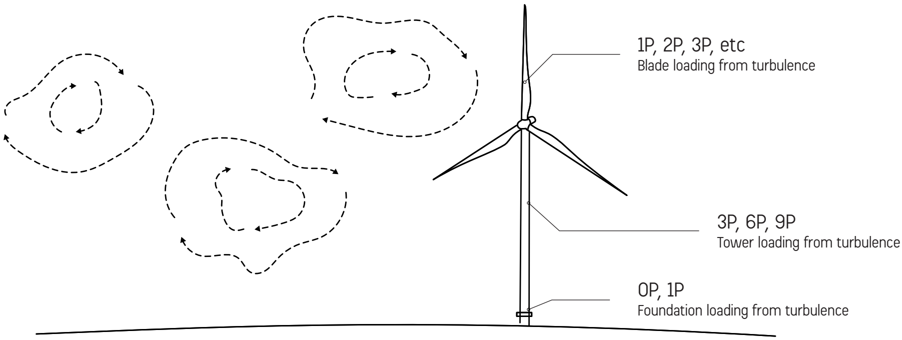
4x wind turbines

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

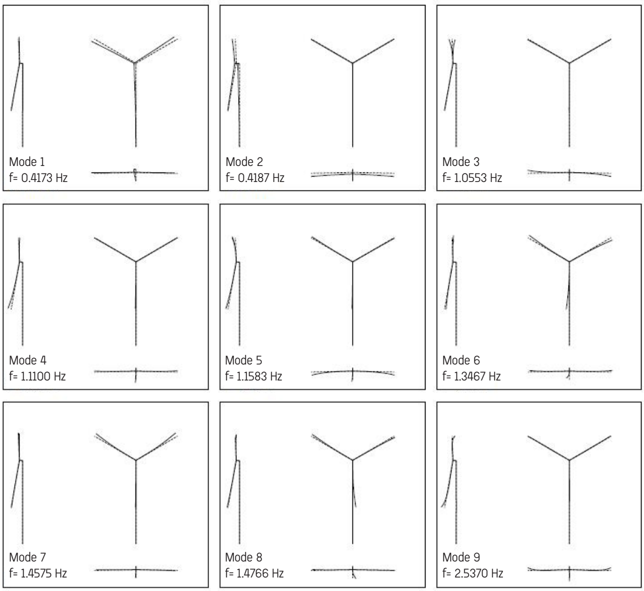
OPERATIONAL FREQUENCY

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.



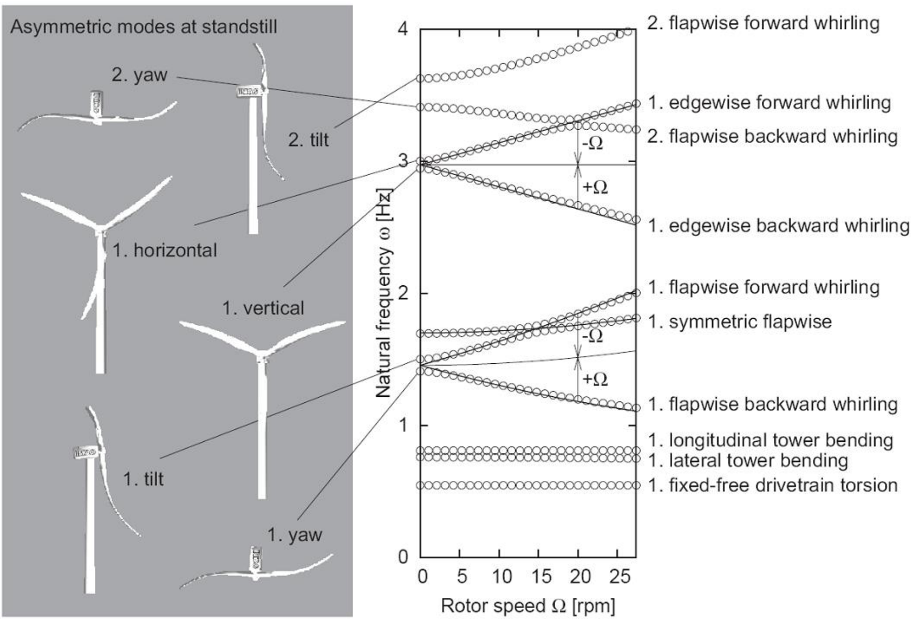
MODE SHAPES

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 decreases for larger turbines. The first two modes mainly consist of tower motion (lateral and logitudianal), 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 does 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 states. The modes split up with +/- 1P seen from a fixed frame of reference (eg. the tower system). In a rotating coordinates system (following the blade) the blade frequencies remain the same as a standstill - but may be increased slightly due to centrifugal stiffening. The frequencies therefore appear differently depending on which component that is observed.



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

VIBRATIONS

NATURAL FREQUENCY

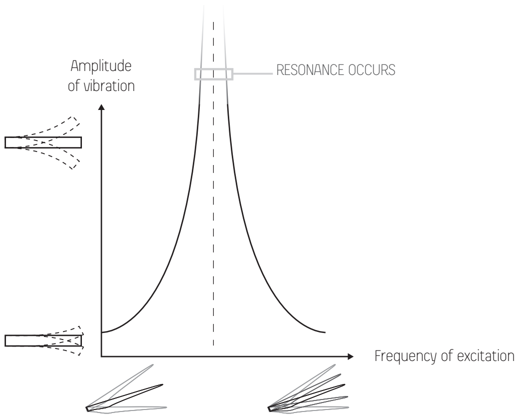
Blades have different natural frequencies depending on the direction of vibration i.e. flapwise, edgewise and twisting/ torsion. Natural frequency are the inherent frequencies which a blade will adopt its free vibrations when set in motion by a single impact or a momentarily displacement from its rest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

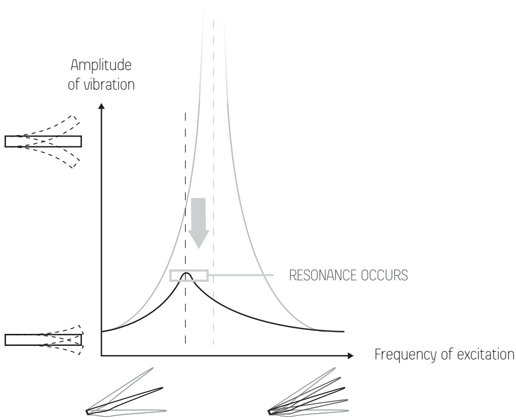
Resonance can occur when a blade is excited by external periodic forces at a frequency close to one of its natural frequencies. Small periodic forces at a resonant frequency can build up to produce large and violent oscillations of the structure.

DAMPING

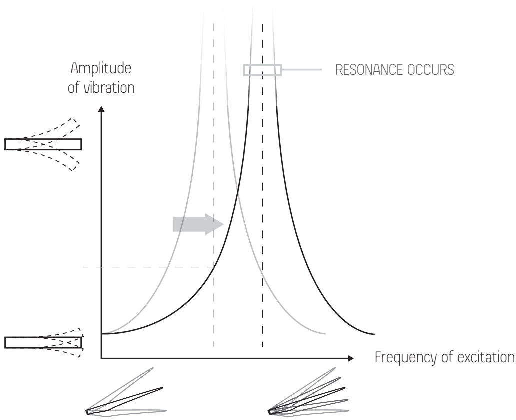
Damping reduces the amplitude of vibrations in a structure by dissipation energy from the system. Energy can be dissipated in the structure due to friction and generation of heat or by means of mechanical devices i.e. a viscous damper (dashpot).



NO DAMPING



WITH DAMPING



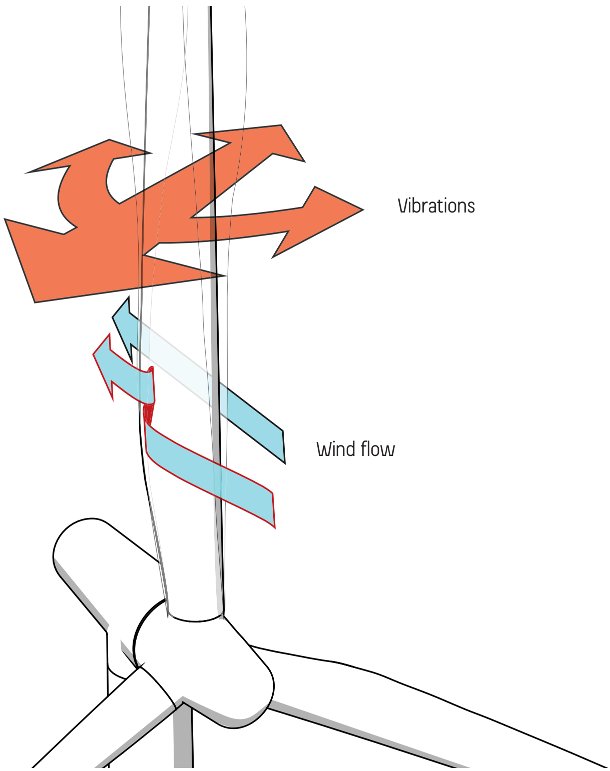
INCREASED
STIFFNESS

AEROELASTIC* INSTABILITY

TWO PHENOMENAS

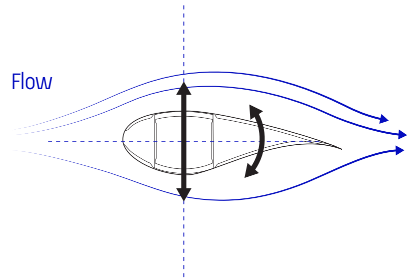
The phenomena of aeroelastic instability, also called flutter, can can occur due to the structural flexibility of wind turbines. Structural deformations induce changes in aerodynamic forces, i.e. operation above rated speed or during standstill or parked position. The additional aerodynamic forces cause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



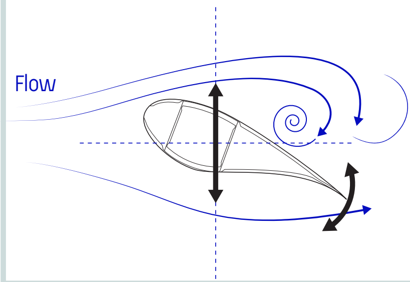
CLASSICAL FLUTTER involves the coupling between torsional- and flapwise-vibration.

Classical Flutter



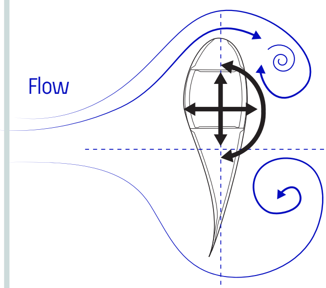
STALL FLUTTER involves the coupling between separated and attached flow to the surface of the blade in a cyclic manner.

Stall Flutter



GALLOPING involves only separated flow over bluff structures.

Galloping



FAILURE MODES (1)

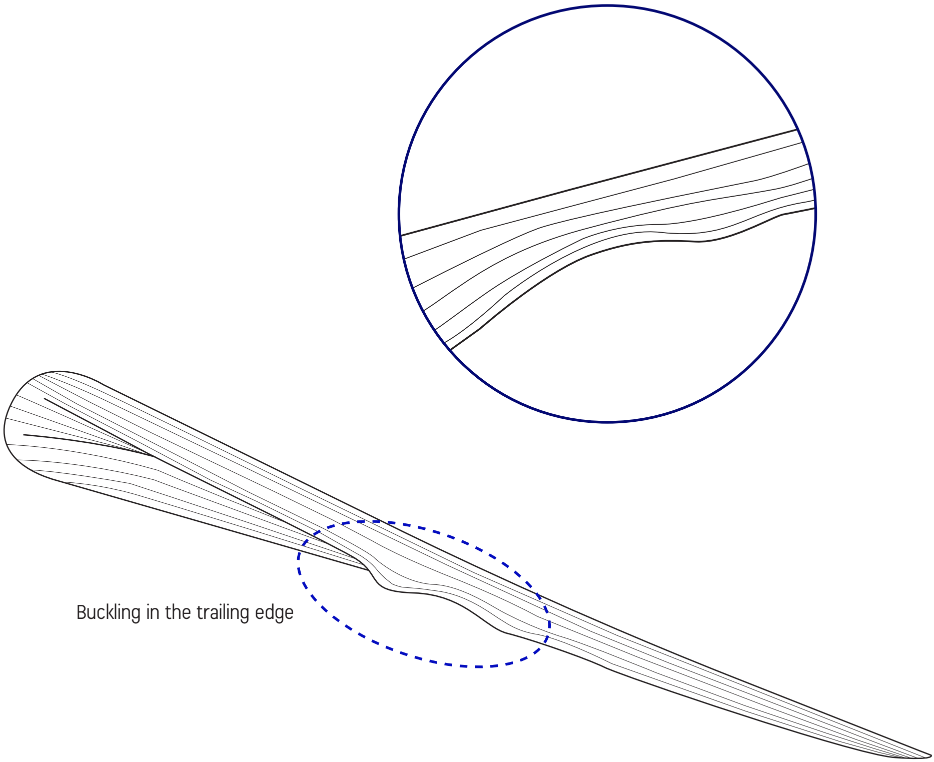
FIVE MODES OF FAILURE

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)

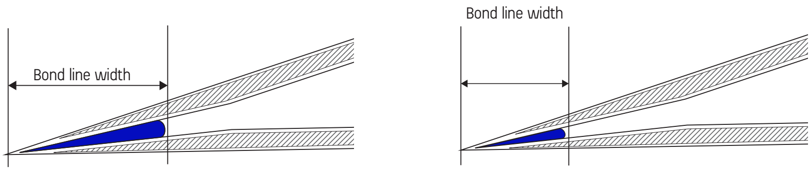
Buckling is a non-linear in-plane stability phenomena. It can be predicted by non-linear FEM. Using a combined loading load case for both numerical simulations and testing will capture the phenomenon.
Premises for failure: The bending of the blade due to aerodynamic forces and reduced buckling capacity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



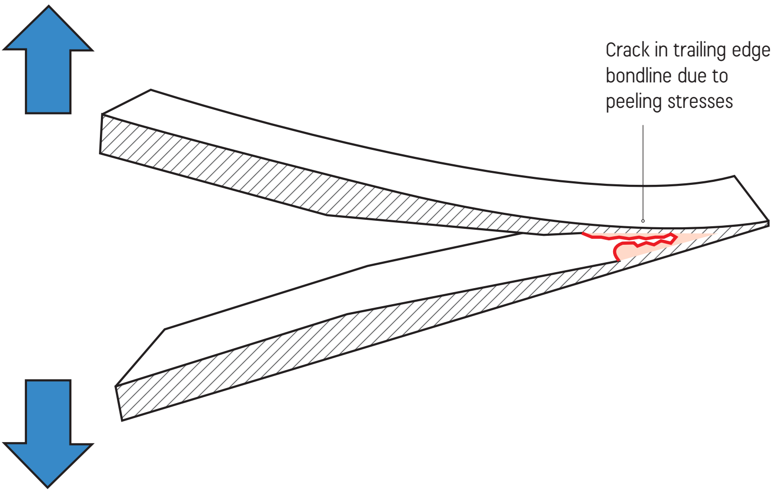
FAILURE MODES (2-3)

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.

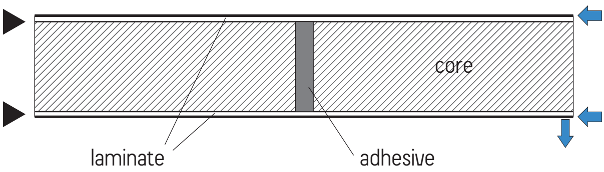


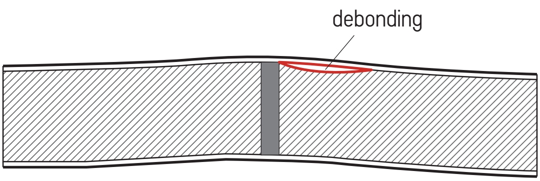
Different lengths of the bond line

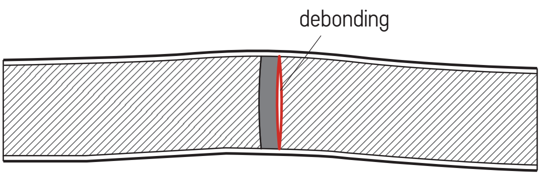


SKIN DEBONDING (FAILURE MODE 3)

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.



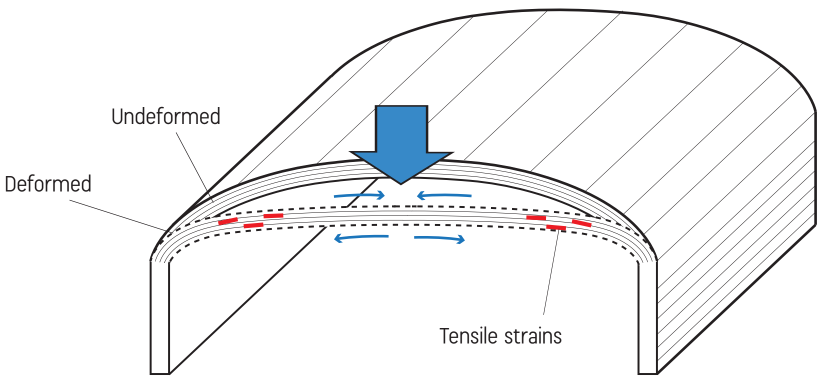




FAILURE MODES (4-5)

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 delamination. 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

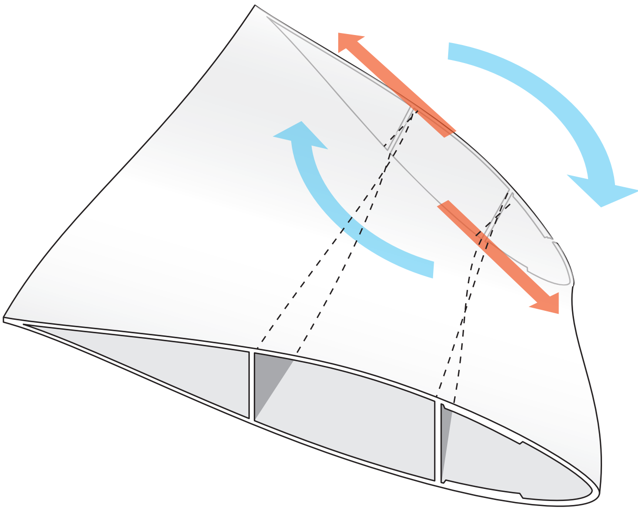
SHEAR DISTORTION

OPERATIONAL FATIGUE

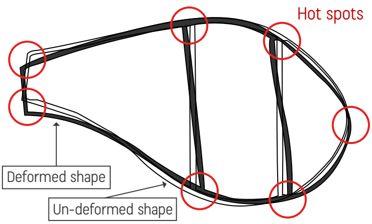
Normal operation

> Cross sectional shear distortion (CSSD)

> Bondlines damage

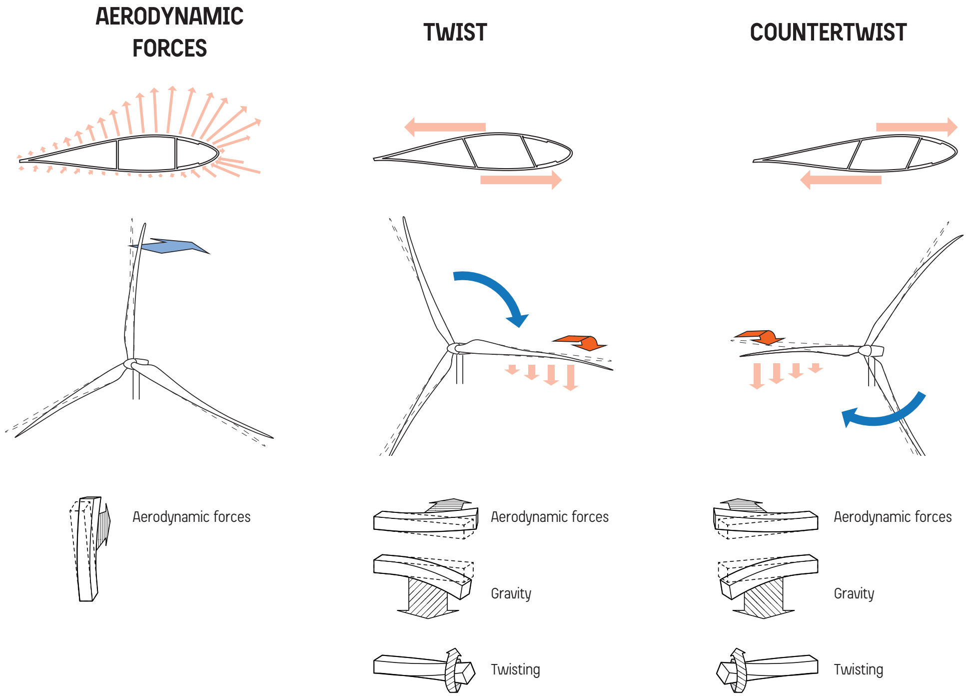


Bondlines damage



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.



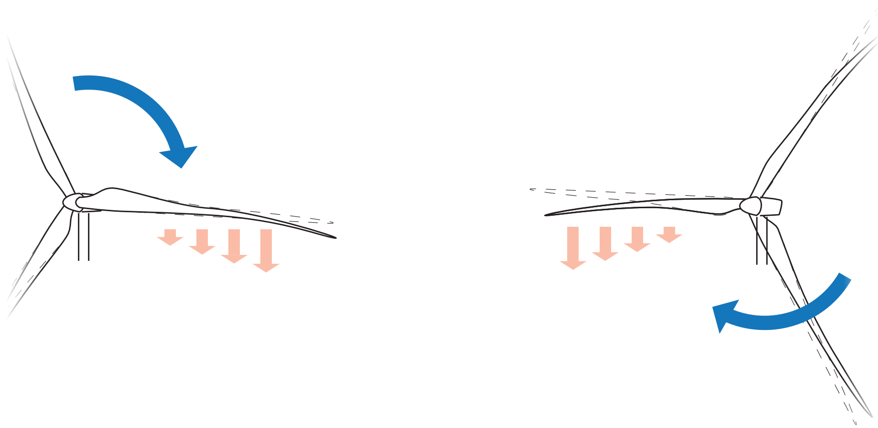
ROOT CAUSE 2

PANEL BREATHING

OPERATIONAL FATIGUE

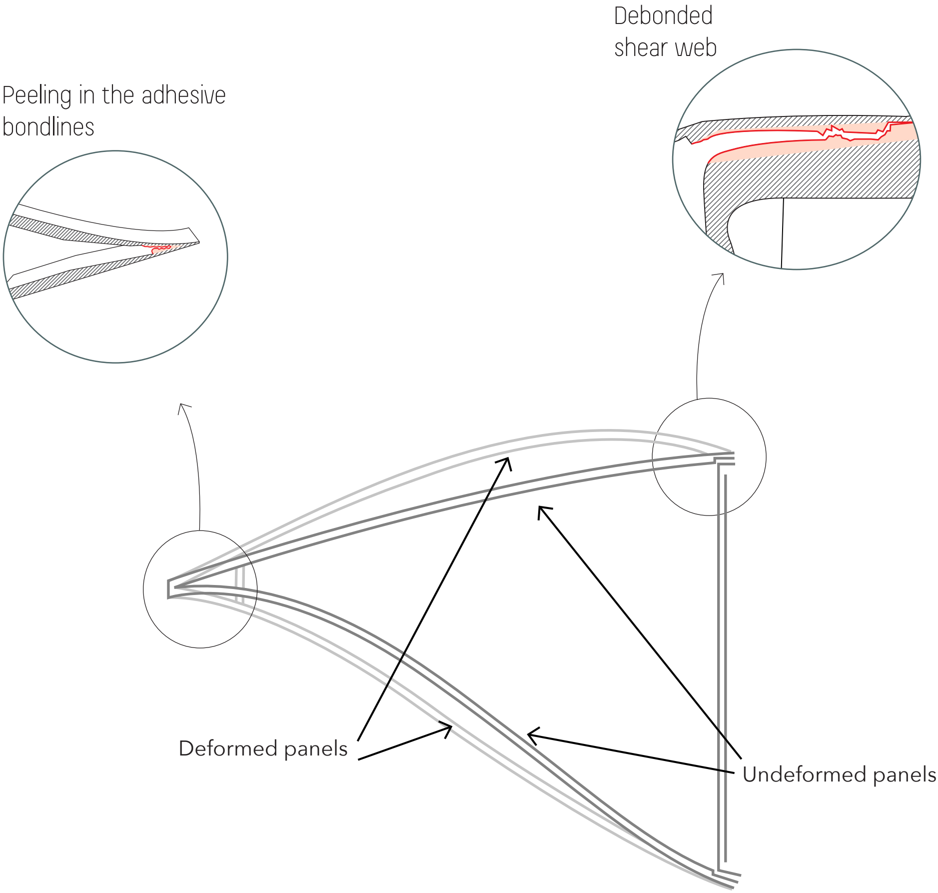
Normal operation
> Panel breathing
> Bondlines damage

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

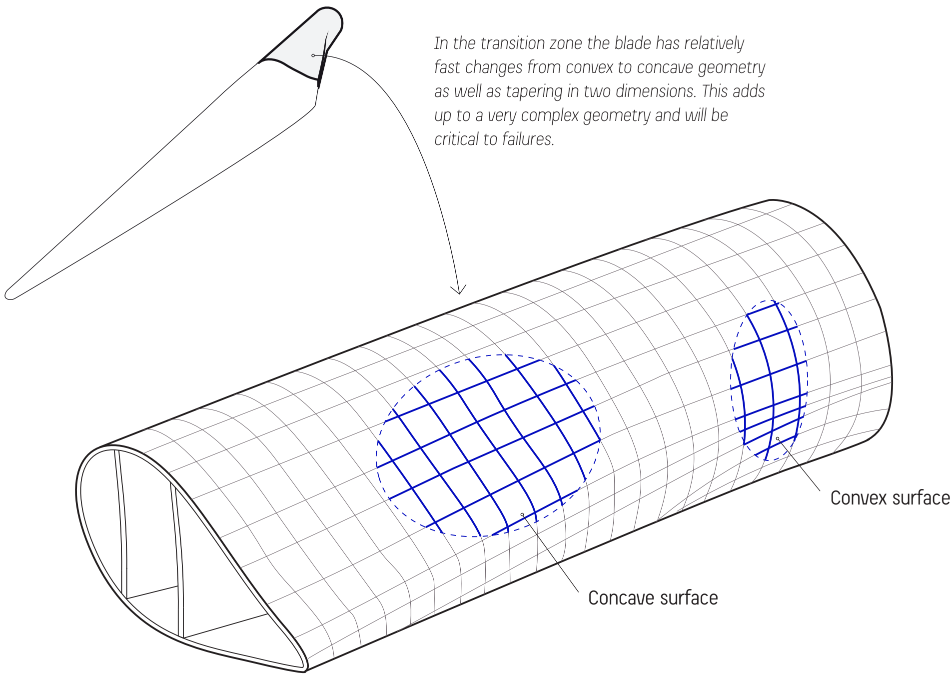
ROOT TRANSITION ZONE

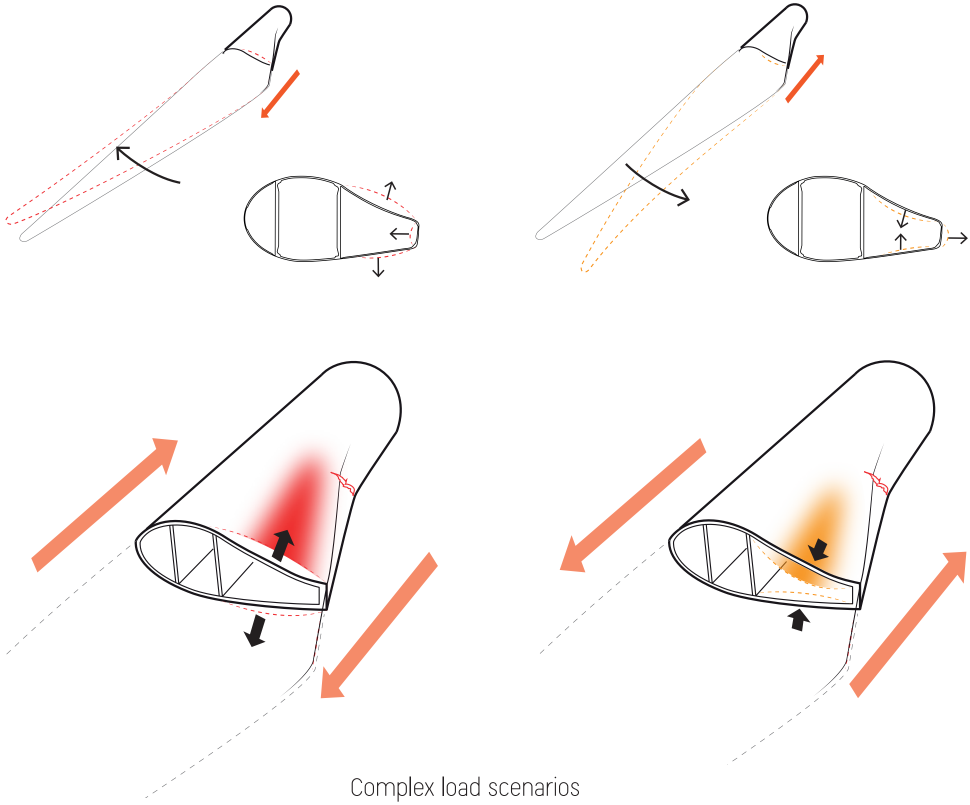
OPERATIONAL FATIGUE

Normal operation

>Panel bending and shear forces

> Root failures

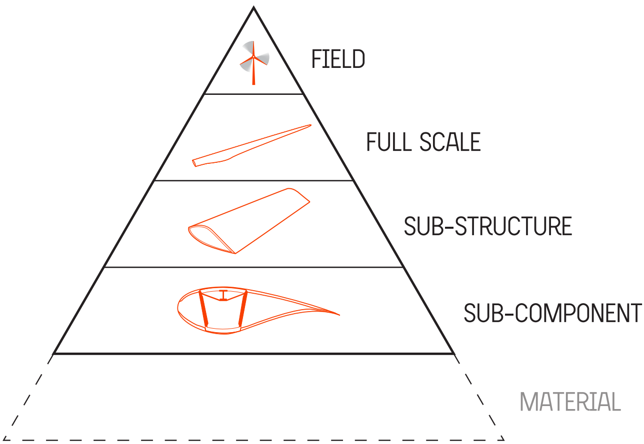




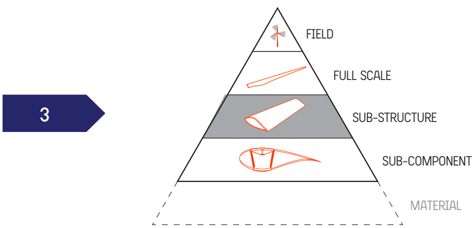
Complex load scenarios

TESTING

LEVELS OF TESTING [SIZE]



Hybrid testing is sub-structure testing



TESTING

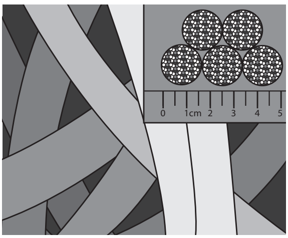
There are different levels of testing. Due to the uncertainty in fatigue behaviour of blade materials it is necessary to test as complementary to blade design. According to standard it is only mandatory to test at material and full-scale level. At the full-scale level it is only mandatory to test in 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

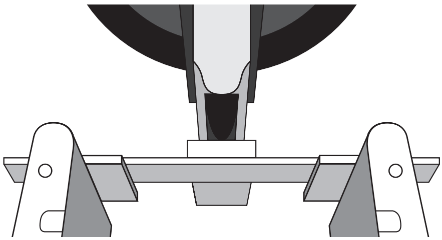
Testing is defined on a length scale from micro scale to structural scale

LENGTH SCALE (M)

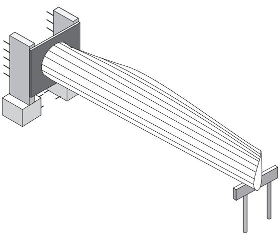
10^{-4}	10^{-2}	10^{1}	10^{2}
a. Micro scale	b. Laminate scale	c. Substructural scale	d. Structural scale



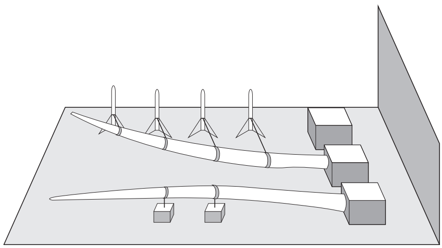
a. Micro scale



b. Laminate scale



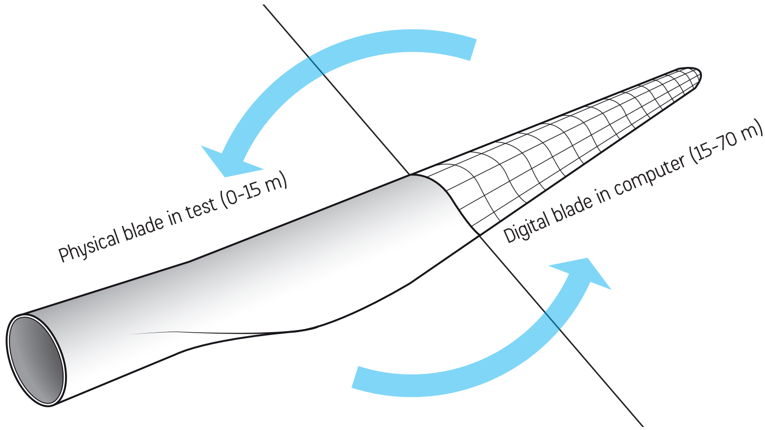
c. Substructural scale



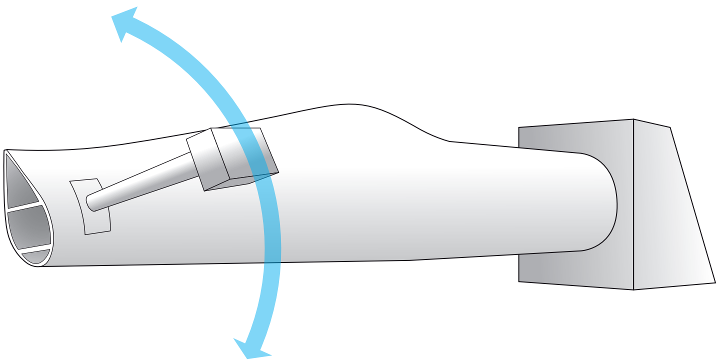
d. Structural scale

HYBRID TESTING/ HYBRID SIMULATION

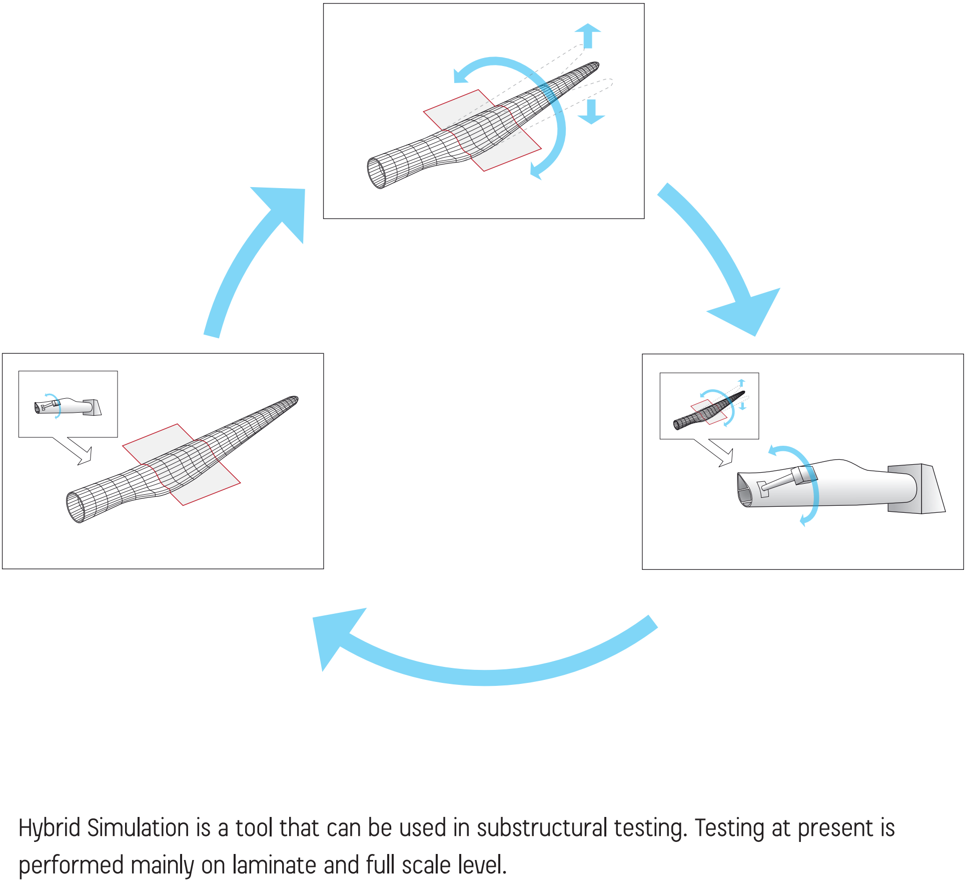
Blade cut (not full-length blade test)



Dynamic testing by adding weight block to blade side



Dialogue between physical and digital blade

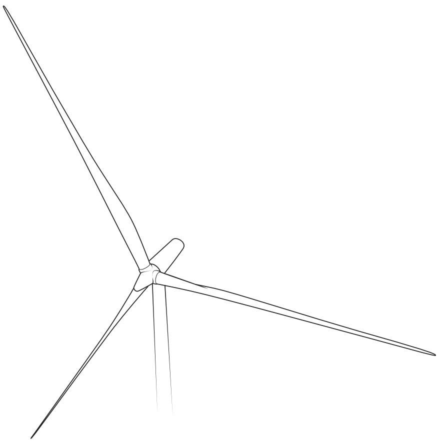


Hybrid Simulation is a tool that can be used in substructural testing. Testing at present is performed mainly on laminate and full scale level.

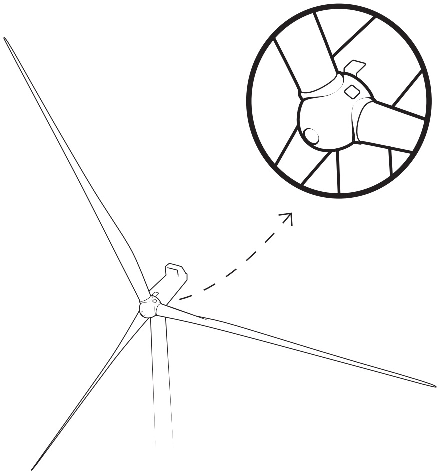
WORKING CONDITIONS

ACCESS

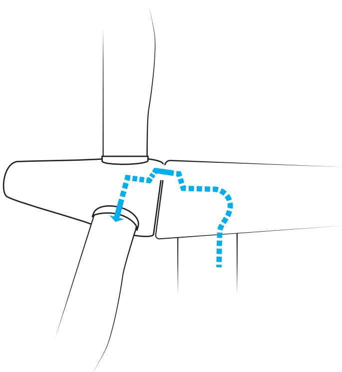
Basical 2 types of access - indoor or outdoor access

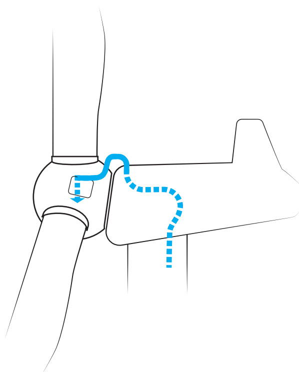


indoor acces



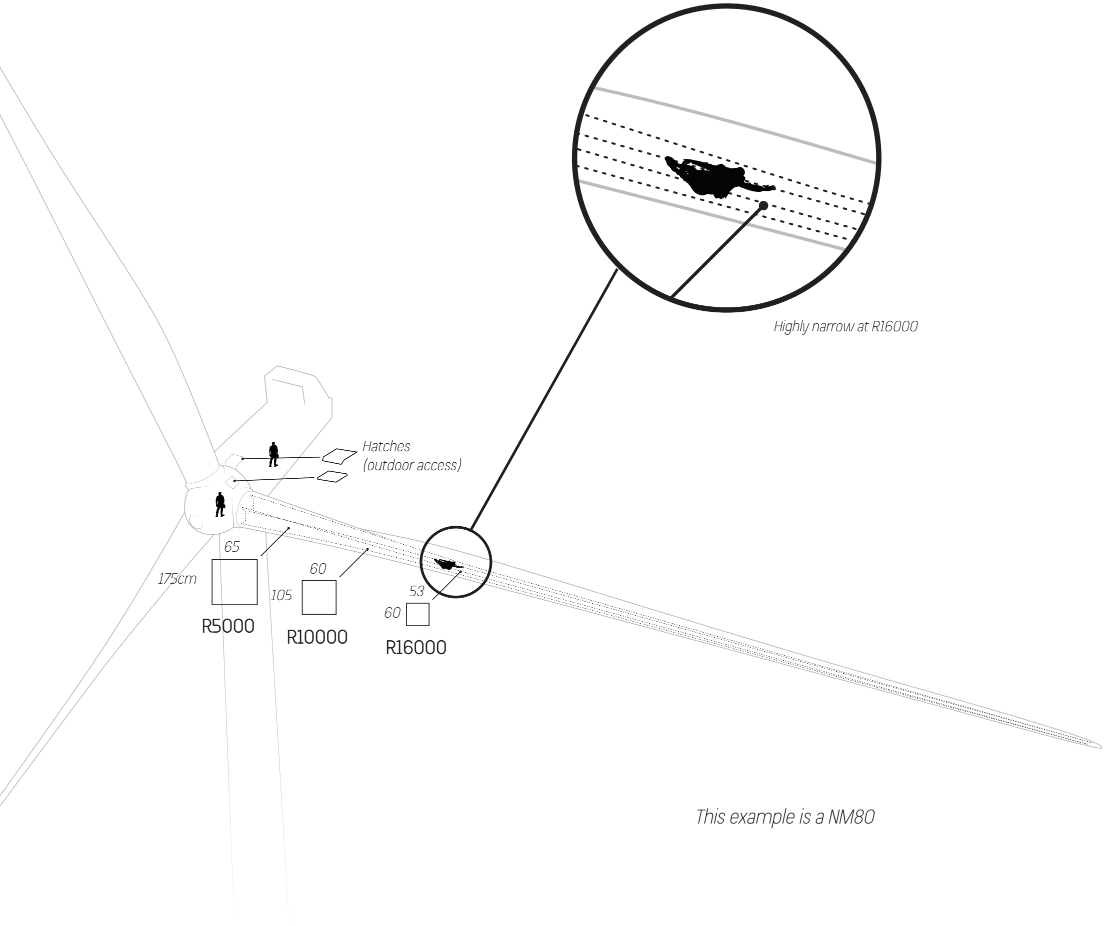
outdoor access





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.



This example is a NM80

COST OF ENERGY

LEVELIZED COST OF ENERGY (LCOE)

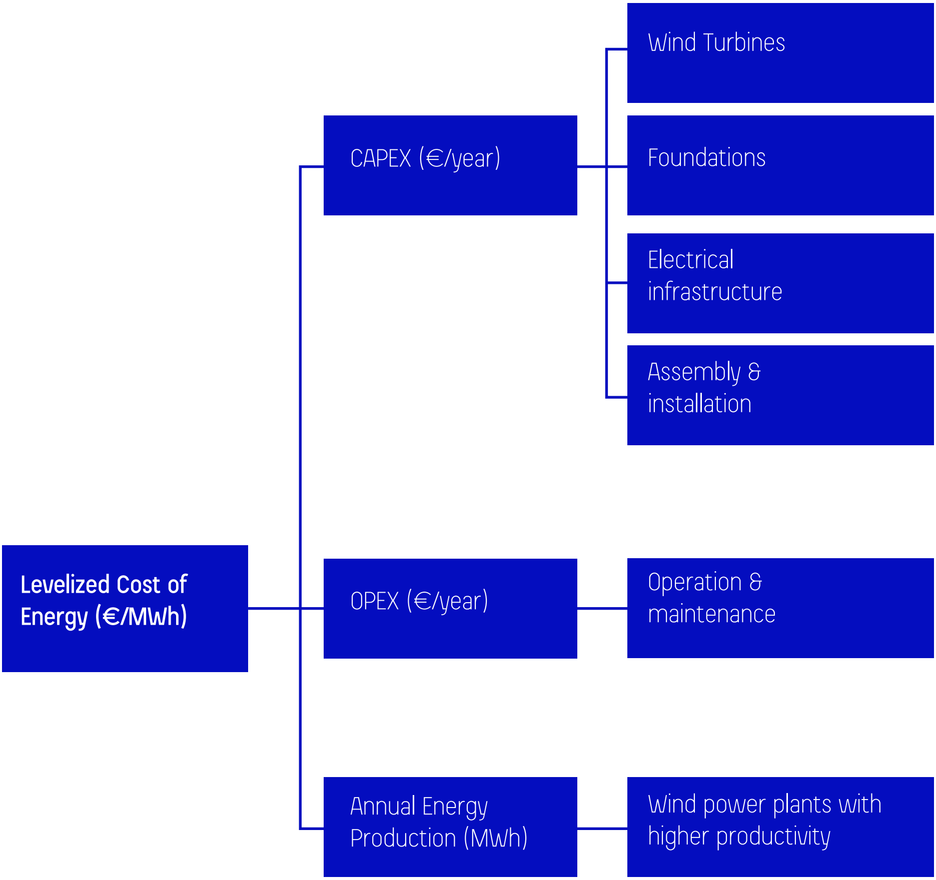
$$LCOE = \frac{CAPEX + OPEX}{AEP}$$

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

or

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

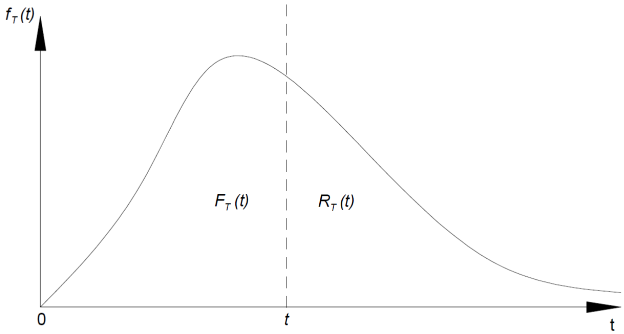
LCOE:	Levelized cost of energy ($Euro_{2012}$/Mwh)
I_0:	Capital expenditure in Euro
A_t:	Annual operating costs in Euro in year t
M_{el}:	Produced electricity in the corresponding year in MWh
i:	Weighted average cost of capital in %
n:	Operational lifetime (20 years)
t:	Individual year of lifetime (1,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



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

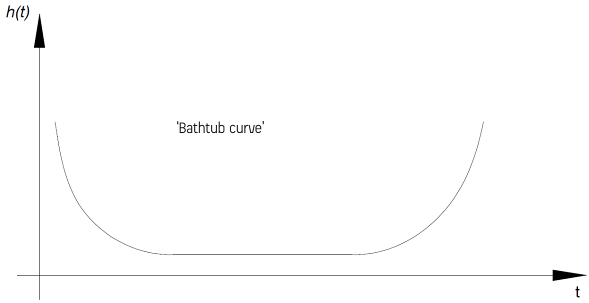
OPERATION & MAINTENANCE

COMPONENTS - CLASSICAL RELIABILITY THEORY



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

Probability of failure $F_F(t)$
$= 1 - RT(t)$ = 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

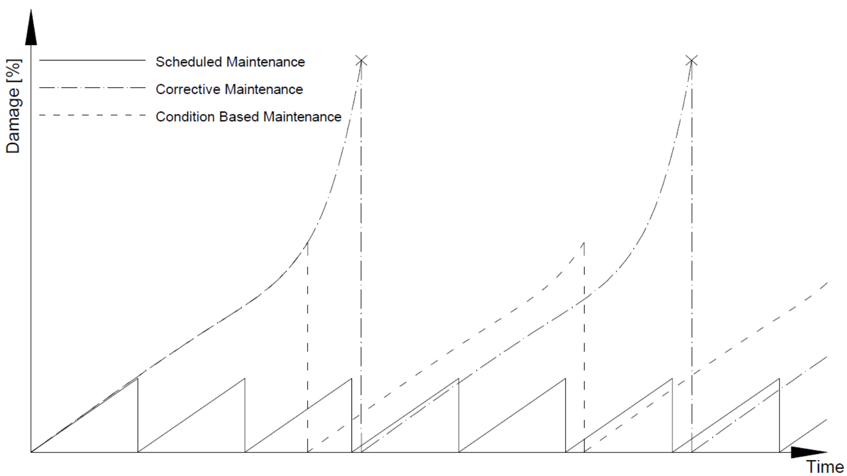
OPERATION & MAINTENANCE OF WIND TURBINES

Corrective (unplanned): exchange / repair of failed components

Preventive (planned):
Scheduled: inspections after predefined scheme

Condition-based: monitor condition of system and decide next on evt. repair based on degree of deterioration

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



OPERATION & MAINTENANCE

MARKOV RELIABILITY MODEL

Damages discretized in categories:

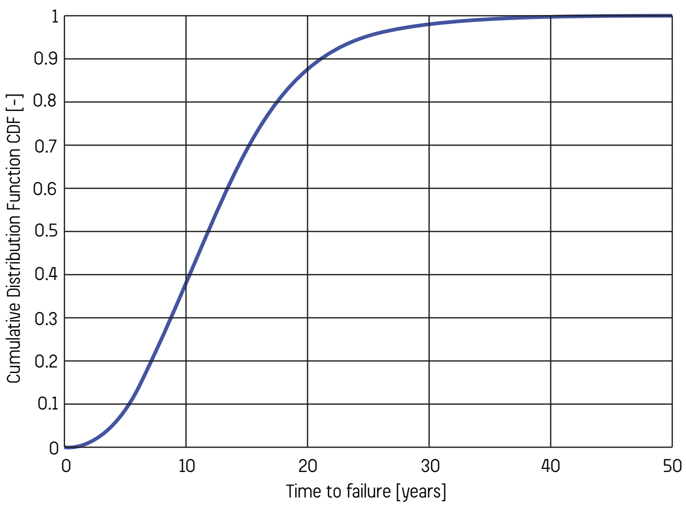
Category	Description
1	Cosmetic / no damage
2	Damage below wear and tear
3	Damage above wear and tear
4	Serious damage
5	Critical damage

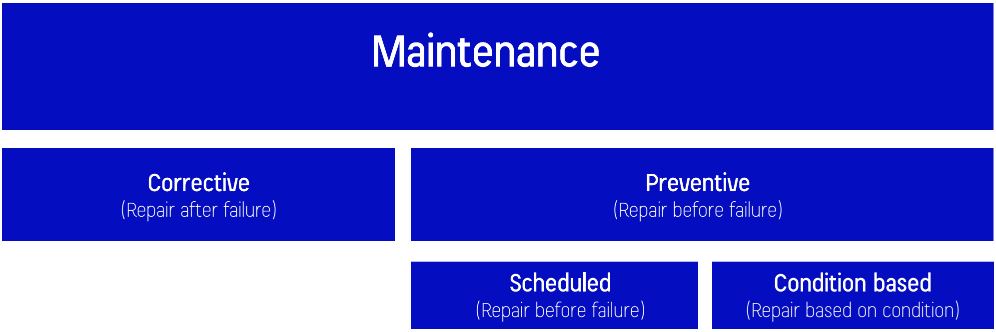
The Markov probability model gives the probability of evolution of damage from time step to time step, e.g. the probability that a damage in category 2 develops to category 3 within the next month.

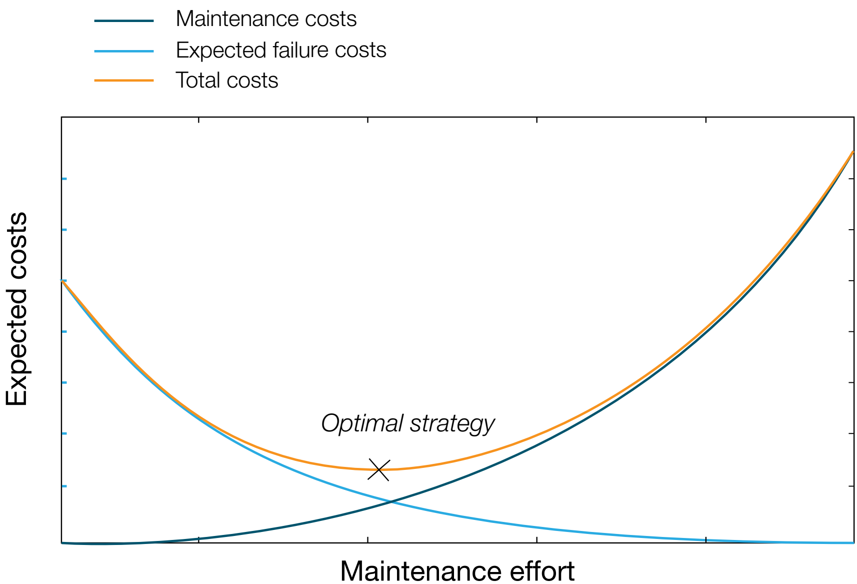
The Markov model assumes that predictions for the future development of the damage can be made solely on its present state.

The Markov model 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):




Maintenance
Corrective
(Repair after failure)
Preventive
(Repair before failure)
Scheduled
(Repair before failure)
Condition based
(Repair based on condition)


Maintenance costs
Expected failure costs
Total costs
Expected costs
Optimal strategy
Maintenance effort

IEC REFERENCES

WIND TURBINE STANDARDIZATION IEC

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

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)

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...)

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...)
- The failure of a root bolt creates a defect in the root (where we look from)
- The lack of adhesive joint is a manufacturing defect.
- The failure of an adhesive in a joint due to an excessive load is a defect in a blade, and a failure of the adhesive joint.

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

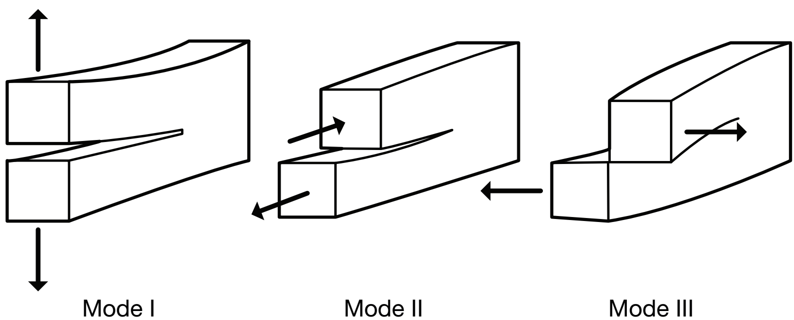
OBS! More information about damages and inspections can be found in the NGIR-reports (Next Generation Inspection Reports), please contact Bladena to require these documents.

FRACTURE MECHANICS

WHAT IS..

A material 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 stress concentration areas (such as the grain interfaces in metals or at the interface between the fibres and the matrix in fibre reinforced composites). A crack will eventually grow until a critical size is reached after which it propagates suddenly and fracture occurs. The property which describes the ability of a material containing a crack to resist fracture is called fracture toughness. The field of mechanics concerned with the study of cracks in materials is called fracture mechanics.

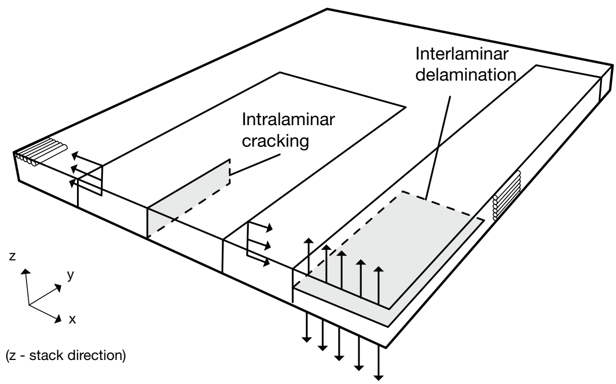
There are three types of loading that a crack can experience (Figure 1), namely: Mode I loading, where the principal load is opening the crack. Mode II corresponds to tend to slide one crack face with respect to the other in-plane. Mode III refers to out-of-plane shear. A cracked body can be loaded in any one of these modes, or in a combination of two or three modes (referred to as mixed mode loading). In homogeneous materials cracks will predominantly advance under pure mode I conditions and under mixed mode loading the crack will try to kink in a path where pure mode I exists. This is not necessarily the case in inhomogeneous materials. Consequently the fracture toughness depends on the mode mixity for such materials.



Schematic representations of Mode I, mode II and mode III

INTRALAMINAR CRACKS

Cracks in composites might advance either between two adjacent plies, referred to as interlaminar delaminations, or they may form and advance within one or multiple plies (intralaminar cracks) see Figure 2). Quite frequently, delaminations and intralaminar cracks arise concurrently within a composite structure.

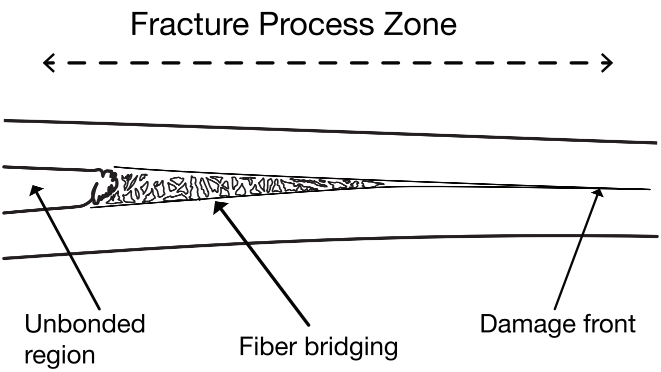


Intralaminar versus interlaminar cracks

FRACTURE MECHANICS

FRACTURE PROCESS ZONE

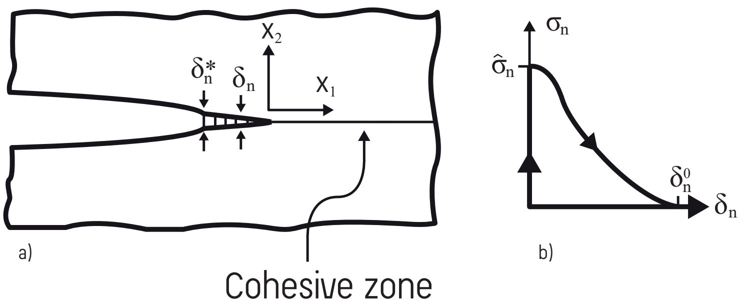
Cracks in composites are typically characterised by lengthy fracture process zone, i.e. the zone near a crack tip where the material develops damage. Fracture process zone may include two distinct phenomena in two distinct regions, the first one being the zone near a crack tip where the material strength is locally reduced, and the second one being the zone where intact fibres behind the damage front bridge the crack (Figure 3).



Fracture process zone

COHESIVE ZONE

To accurately characterise such damages, a specialised material model, a cohesive law, should be determined. A cohesive law is a traction-separation relation that represents the stress transmitted between the crack faces in a cohesive zone, which is the mathematical representation of the fracture process zone figure 4. 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.



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

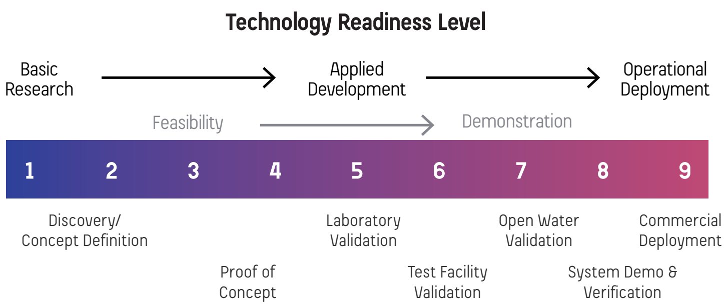
PRODUCT DEVELOPMENT

DESIGN DRIVERS

Key areas to cover the entire area of design parameterswhich are key for driven the product development and minimize risk early in the process.

TECHNOLOGY READINESS LEVEL (TRL)

TRL are 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 are 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 Organizations (EARTO).

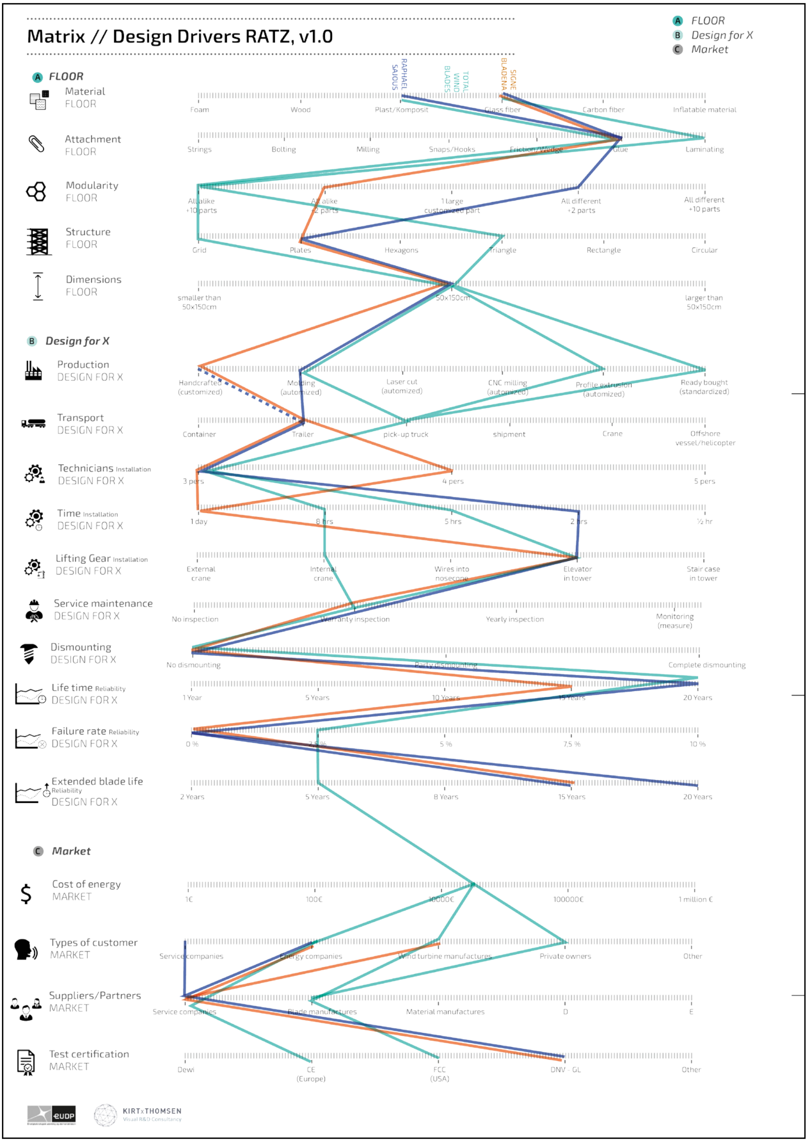


BRAINSTORMING

This process involves engendering a huge number of solutions for a specific problem with emphasis being on the number of ideas. 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.

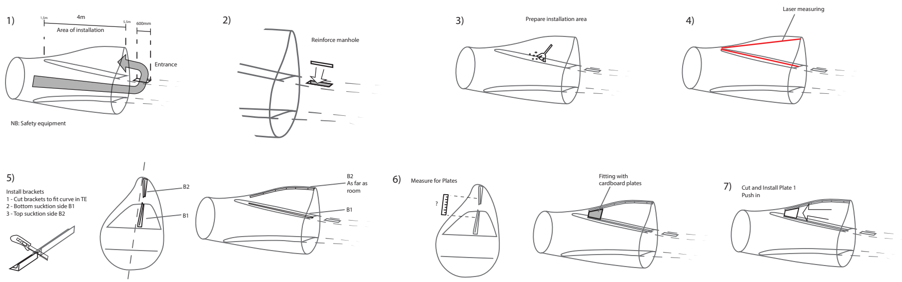
MORPHOLOGY MATRIX

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.



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.



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.

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.
1. A Working Prototype represents all or nearly all of the functionality of the final product.
1. 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.
1. A User Experience Prototype represents enough of the appearance and function of the product that it can be used for user research.
1. 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.
1. 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.

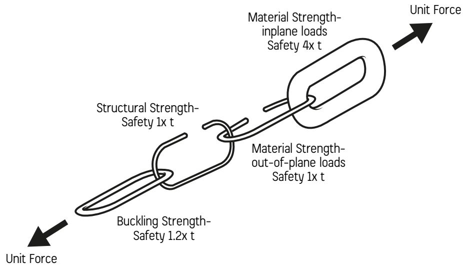
SAFETY MARGINS

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

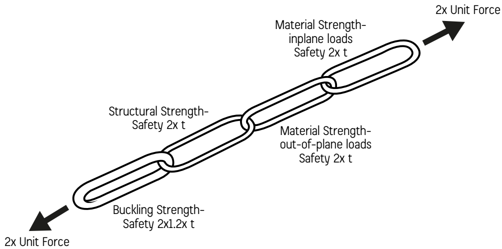
TYPICAL CHAIN OF MARGINS:

Weaknesses are perceived compensated by strengthening other links.



NEW DESIGN PHILOSOPHY:

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



NOMENCLATURE

AEROELASTICITY

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

AERODYNAMIC FORCES

Forces caused by the wind flow over structures.

WIND TURBINE RATED SPEED

Rotational speed of the wind turbine on which is has been designed for.

STANDSTILL OR PARKED POSTION

Wind turbine position in which the rotor is not rotating.

NATURAL MODE OF VIBRATION

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

OEM

Original equipment manufacturer.

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.

MATERIAL STRENGTH

Ability to withstand an applied load without failure or plastic deformation.

MODE SHAPE

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

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.

LEVELIZED COST OF ENERGY (LCOE)

The total cost of installing and operating a project per kilowatt-hour of electricity generated by the system over its life.

TURBULENCE (WIND)

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

WTG

Wind Turbine Generator.

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 2012-2017 with input from some of industry's leading experts and universities within this felt.

Energiteknologisk udvikling og demonstration

Developed by

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