Technical University of Denmark

LEX Project. Handbook - terms and definitions v. 4

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Total Wind Blades

Focus group

VATTENFALL

e·on

DONG energy

LEX PROJECT

Handbook - Terms and Definitions v.4

December 2015

eUDP
Energiteknologisk udvikling og demonstration

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EUDP | **LEX Project** | Stiffening of wind turbine blades - mitigating leading edge damages

Input by Lars Damkilde (AAU), Torben J. Larsen (DTU Wind), Jaocb Walbjørn (DTU Mek), John Dalsgaard Sørensen (AAU), Andrei Buliga (Bladena), Johnny Plauborg (Total Wind Blades)

Handbook concept & design by KIRT x THOMSEN

INDEX

DEFINITIONS

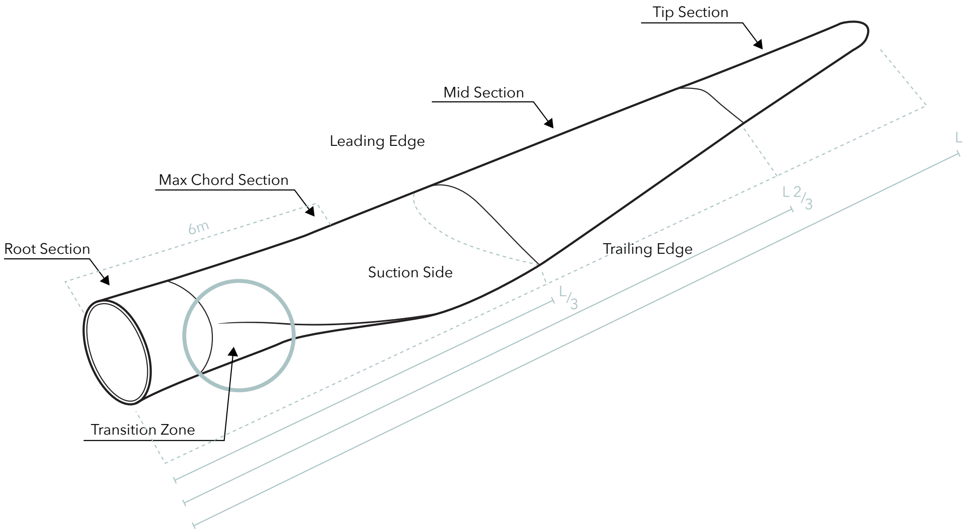
This document is aimed at helping all parties involved in the LEX project to get a common understanding of words, process, levels and the overall concept.

✖ *Terms marked with X are elaborated and/or translated in the Nomenclature* *(page 44)*

ANATOMY OF A BLADE

BLADE SECTIONS

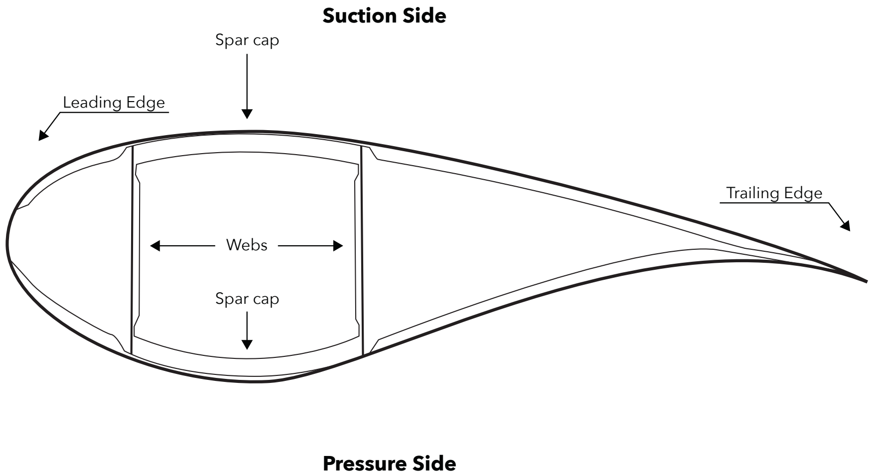
Figure 1: A wind turbine blade is divided into different sections as shown



Full scale test: **SSP 34**
34m blade manufactured be SSP-Tecnology A/S

CROSS SECTION

Figure 2: Blade cross section indicating main construction elements



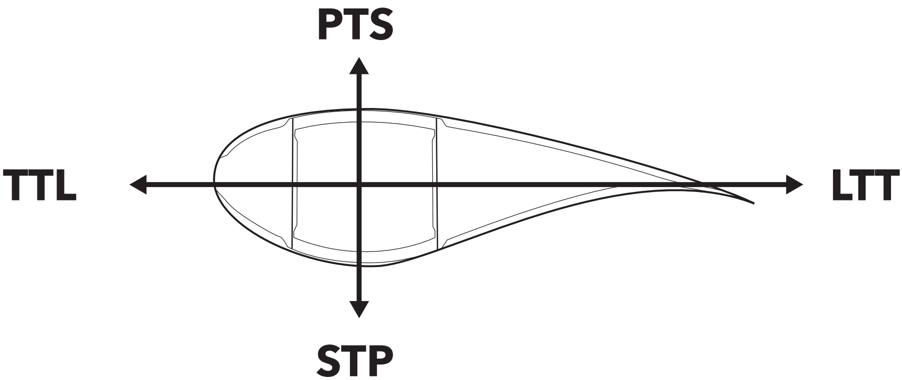
- Leading edge, LE
- Trailing edge, TE
- Pressure side, PS
- Suction side, SS
- Spar caps
- Shear webs
- Trailing edge bondline - the adhesive joint at the trailing edge

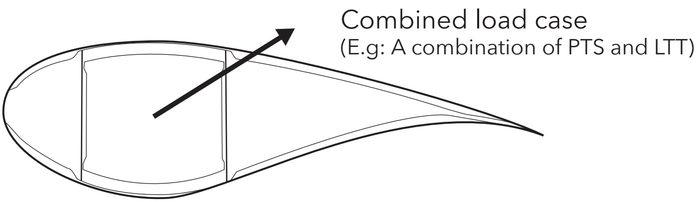
LOAD CASES

TYPES OF LOAD CASES

LOAD CASE 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
  - · Twisting


PTS
TTL
LTT
STP

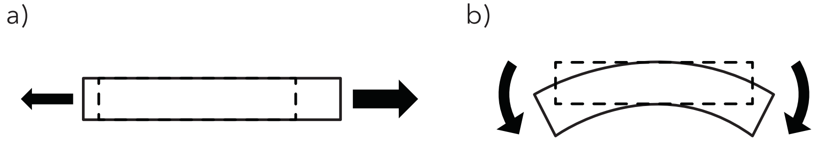

Combined load case
(E.g: A combination of PTS and LTT)

STRAIN & STRESS

Strains and stresses are both responses to loading a structure. The strains are relative changes in length, and define the deformation of the structure. The stresses are the response of the material to the strains, and the stresses should be in equilibrium with the loads. The strain and stresses are coupled via the material model e.g. Hookes law.

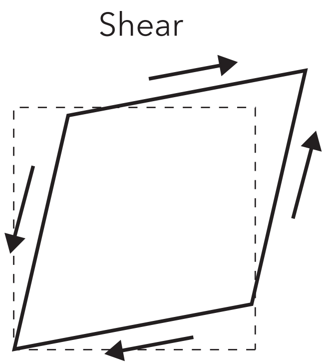
STRAIN

Figure 1: The strains are divided into axial strains i.e. elongation of the individual fibers.



SHEAR STRAIN

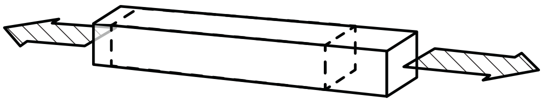
Figure 2 : The other type of strains is shear strains that changes the angles between fibers.



STRESS

Figure 3: 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)



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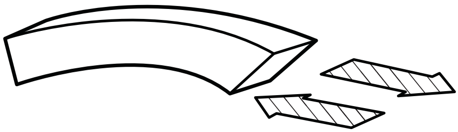
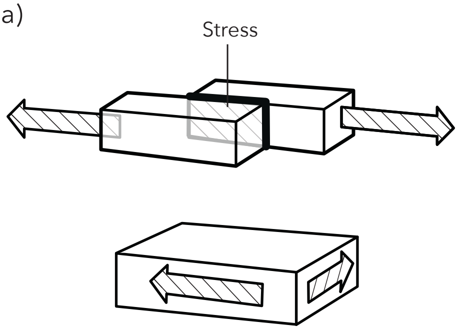


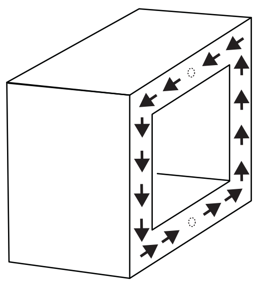
SHEAR STRESS

Figure 4: The other type of stresses are shear stresses and will be directed along the surfaces of the fibers. Shear stresses can be seen in overlap joints or in torsion of a cross-section.

a)



b)

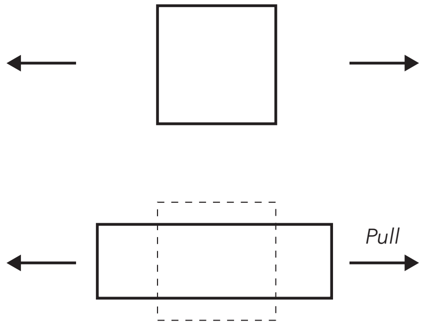


MATERIALS

ELASTIC

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

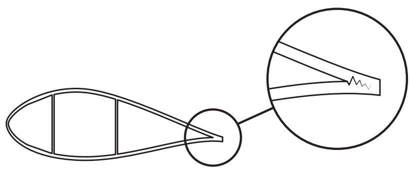
Figure 1. For isotropic material i.e. materials equal in all directions the material behavior is described by the Modulus of Elasticity E, which defines the axial stress for a strain increment. The Poisson ratio defines the deformation perpendicular to the stress direction. For tension in one direction the material will be smaller in the two perpendicular directions.

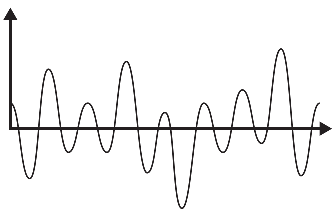


Deformation of

STATIC (FATIGUE STRENGTH)

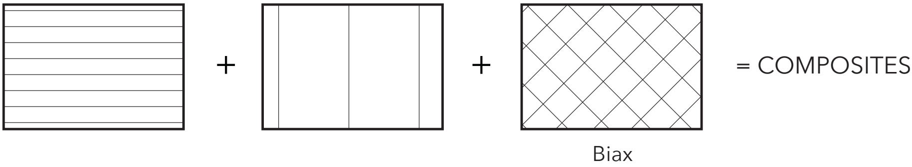
Figure 1. Materials subjected to repeated loads may fail. The number of load cycles in a wind turbine blade is very large. The fatigue problems will often exist in joints i.e. place where different fiber directions are merged. Fatigue problems in the transverse direction e.g. leading and trailing damages will be due to secondary stresses.

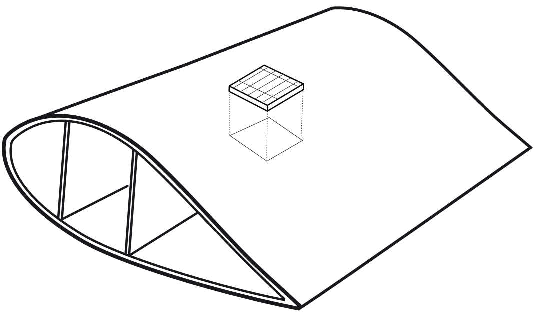




COMPOSITES

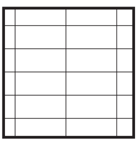
Composites are a number of layers glued together in different directions.

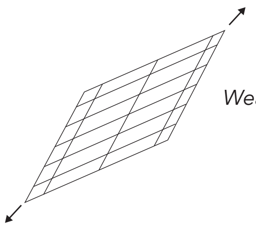




In composites material the fibers can be arranged in many different ways, so that the strength and stiffness will depend on the direction in the material. In wind turbine blade there will be more fibers in the blade direction in order to handle the bending of the blade. There will be fewer fibers in the transverse direction. The directional differences makes the analysis more complicated as the secondary direction (the transverse) has a small impact from the loads but also a low strength due to fewer fibers.

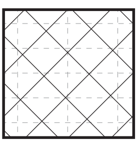
Fibers in 2 directions



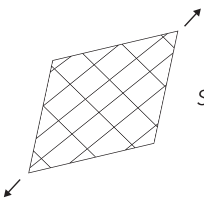


Weak in shear

Fibers in 2 directions



+ Biax



Stronger in shear

2 | STRUCTURE

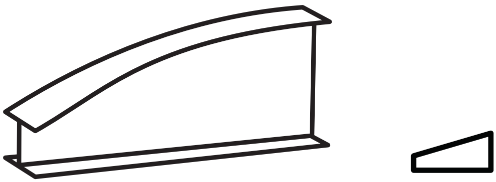
BEAM STRUCTURE

Wind turbine blades acts as a beam i.e. say a structure with a length direction. Beams used in e.g. building design is normally with constant cross-sections. In order to have a more optimal design the beam can be tapered and also twisted.

A

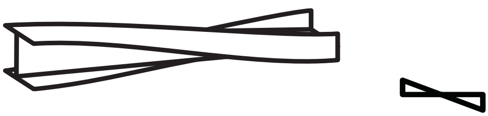
Constant

B



Tapered

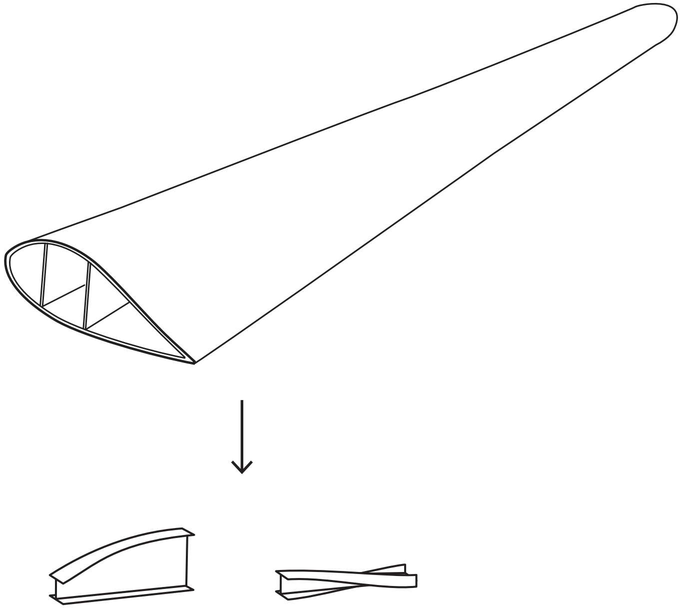
C

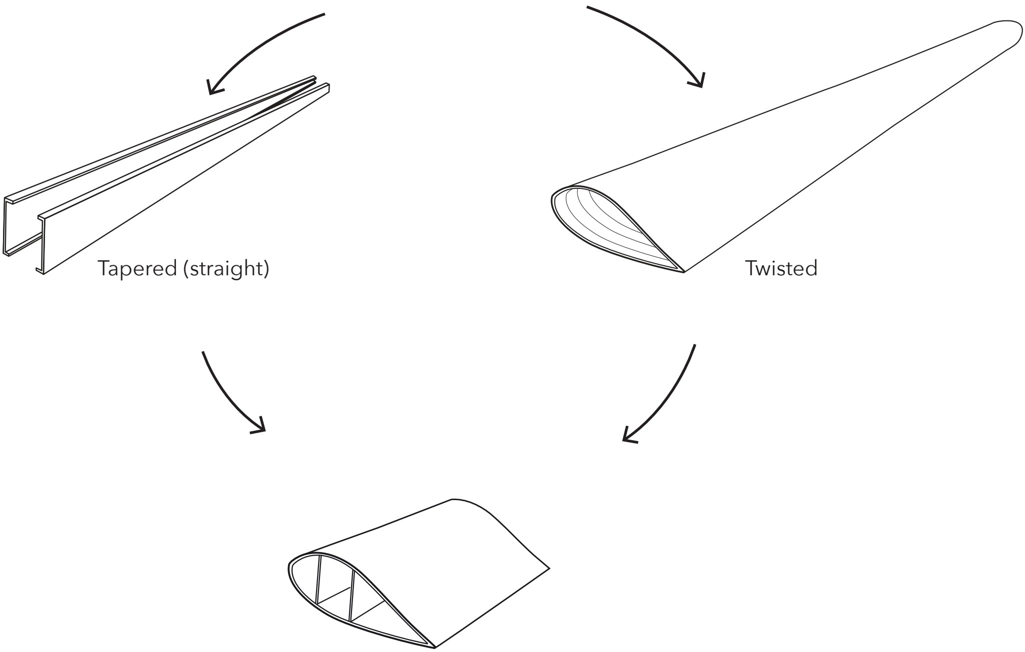


Twisted

IN A BLADE

A typical wind turbine blade will be tapered and twisted. Furthermore the thicknesses will be relative small, which may give deformation in the cross-section. In traditional beam theory the cross-sectional deformations is not possible, 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)

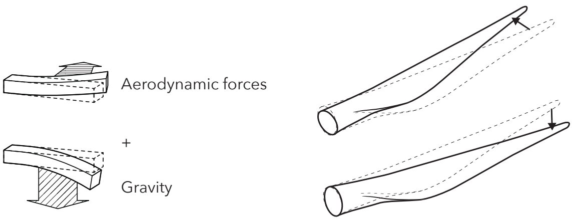
2 | STRUCTURE

BENDING & TORSION

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

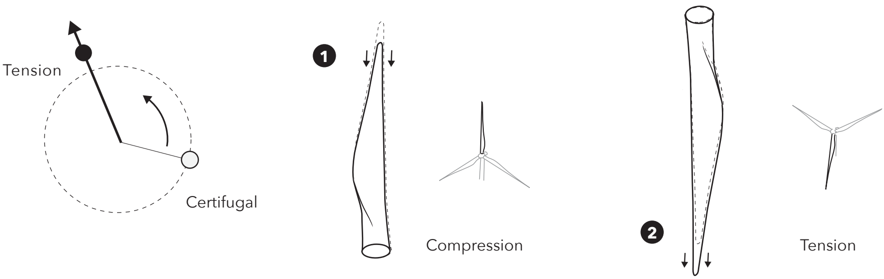
A. BENDING

The primary way of carrying the loads are through bending.



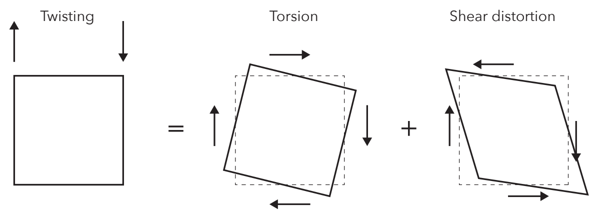
B. AXIAL FORCE

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



C. TORSION

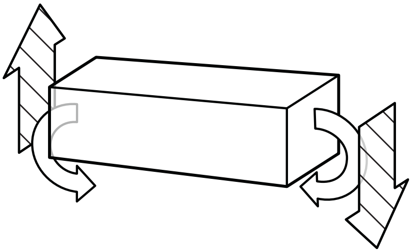
Wind loads act excentrical and creates twisting in the blade.



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 slender wind turbine blades. The contribution is not covered be traditional beam theory, but will be seen in a Finite Element analysis.

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

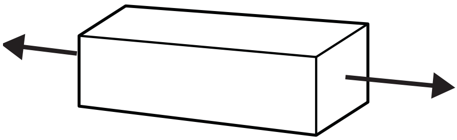
The bending moments create normal and shear stresses



Normal and shear stress

AXIAL FORCE → **NORMAL STRESS**

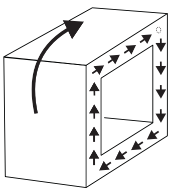
The axial force creates normal stresses

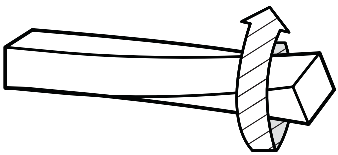


Normal stress

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.





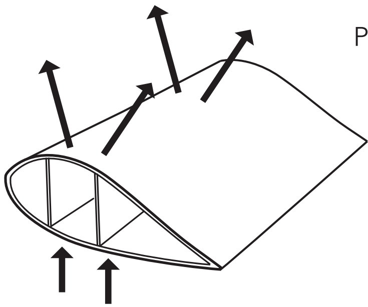
Shear stress

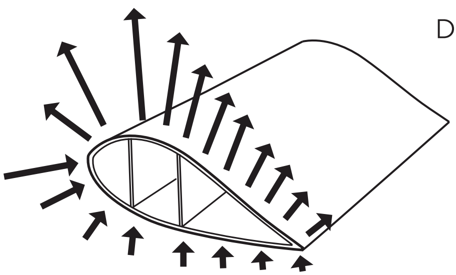
LOCAL EFFECTS

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, and they are more distinct in slender blades.

TESTS TODAY & REAL LIFE

Figure 1: Wind loads are today referred directly to the stiff part of the structure, and this is not on the safe side compared to a distributed pressure load.

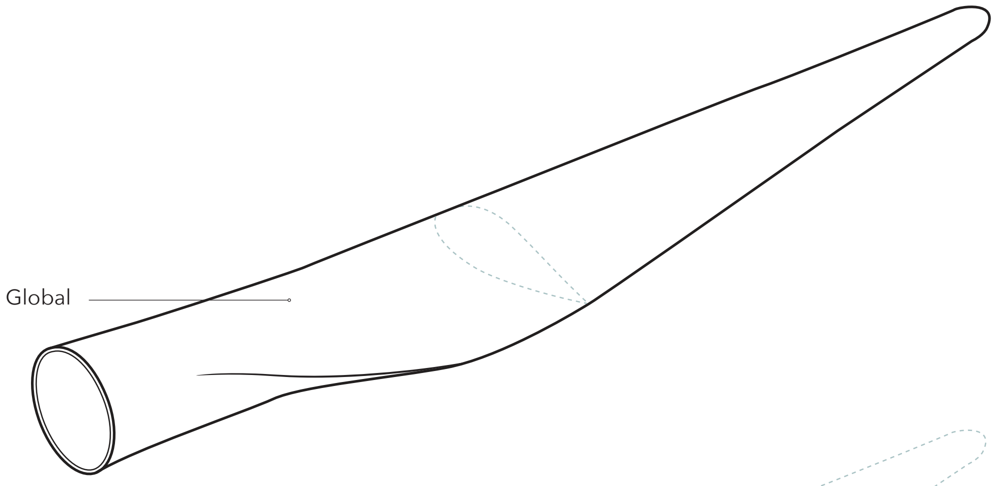


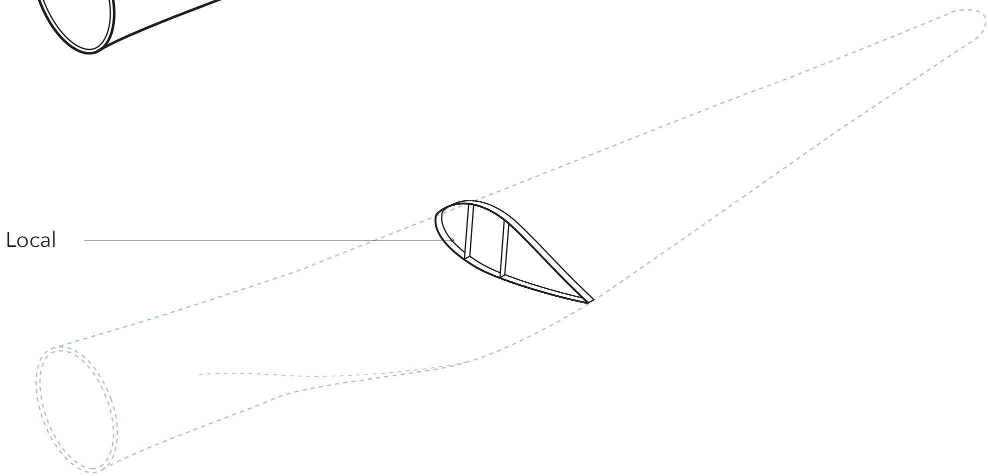


GLOBAL VS LOCAL

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

The stress values are far larger than the local stresses in the transverse plane. These additional stresses stem from the transfer of the load into the beam. The local stresses can anyhow have big importance in composite structures where the strength and stiffness is far larger in the blade direction.

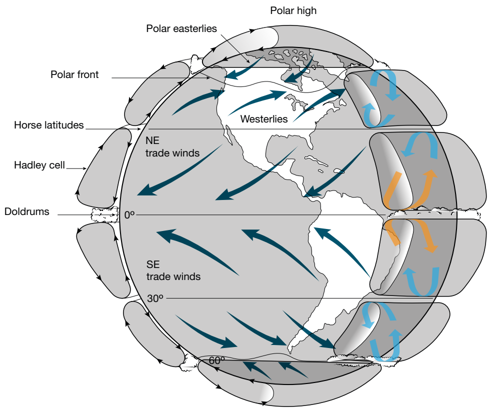




WIND CONDITIONS

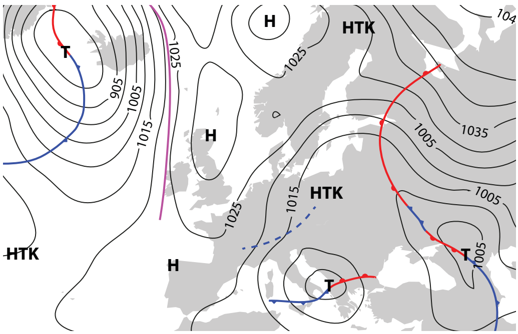
GLOBAL

Figure 1: 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.



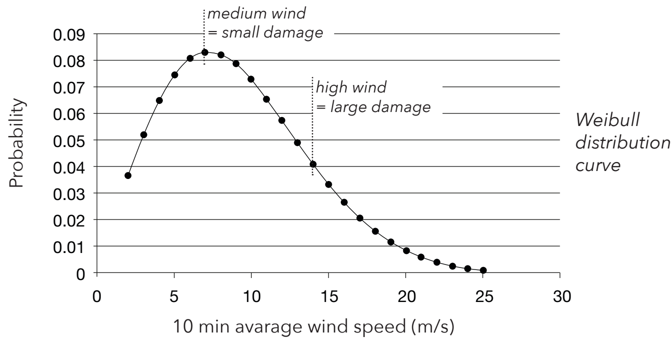
REGIONAL

Figure 2: 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.



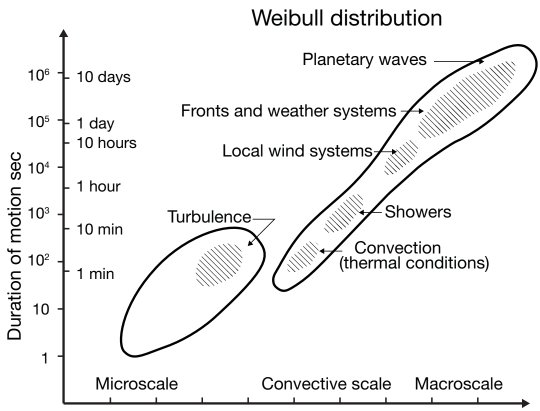
PROBABILITY

Figure 3: The probability density function of hours at a certain wind speed is typically given as a Weibull distribution.



SCALE & TIME

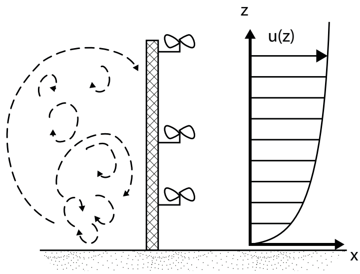
Figure 4: Weather system can roughly be classified into large system (meso-scale) driven by high and low pressure and micro scale driven by local roughness of the surrounding terrain. The meso scale effects are important for the total power production, whereas the micro scale effects are important for the turbine load level. Notice the relation between vortex size in meters (x-axis) and duration in seconds/days (y-axis).



TURBULENCE

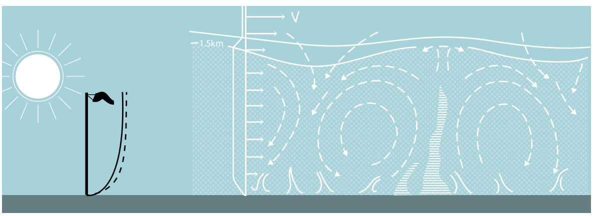
HEIGHTS

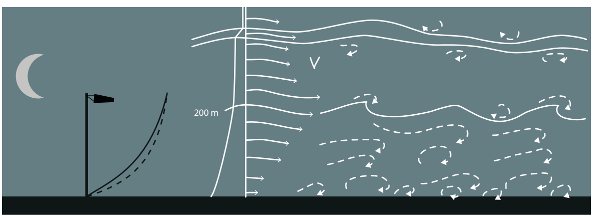
The type of terrain near the turbine has a friction level on the wind - also denoted a terrain roughness. The roughness causes a near surface boundary layer with increasing wind speed for increasing height. The roughness also creates turbulent vortices with length scales increasing with height.



TIME. DAY VS NIGHT

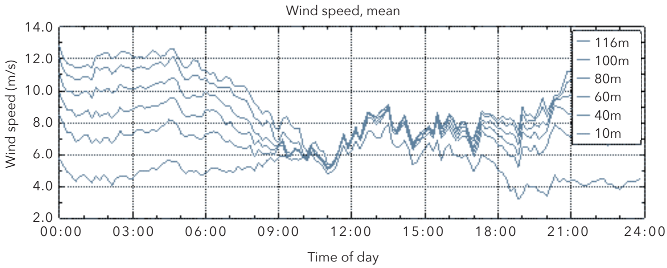
Temperature effects in the boundary layer has a direct impact on the turbulent flow. Warm air near the surface causes unstable conditions creating an increased turbulent mixing whereas cold air near the ground caused more low turbulent laminar flow – but with a large shear in the mean wind speed.





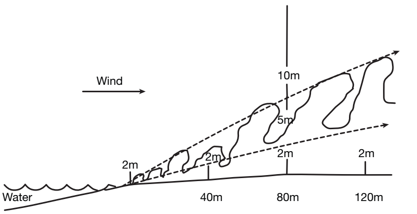
HEIGHT & TIME

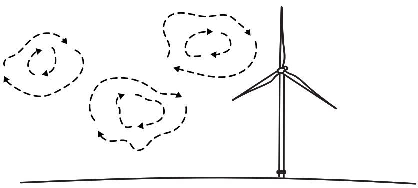
Measured wind speed in different heights at the Høvsøre test site. Cold temperature at night causes very stable conditions where the heating from the sun causes unstable conditions with a significant turbulent mixing.

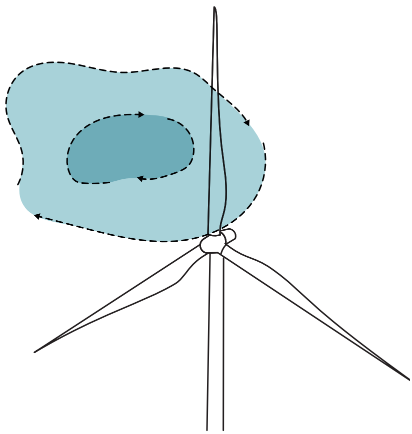


TERRAIN

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.



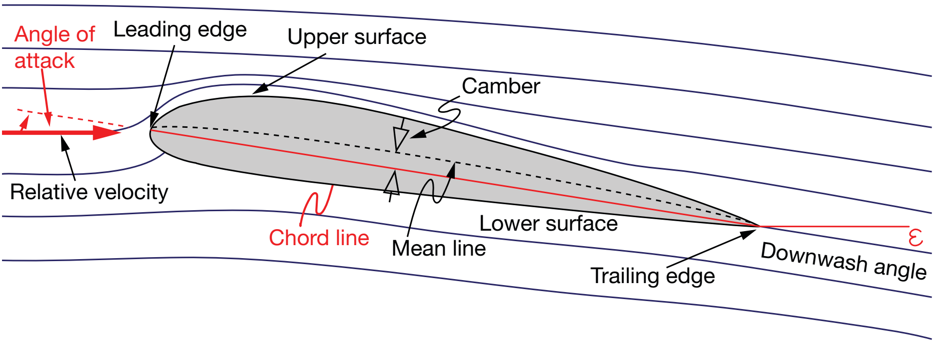




AERODYNAMICS

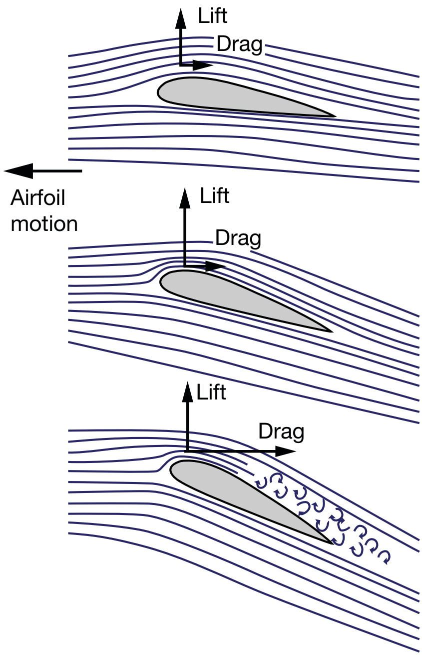
AIRFOIL TERMINOLOGY

Figure 1: 2D airfoil terminology



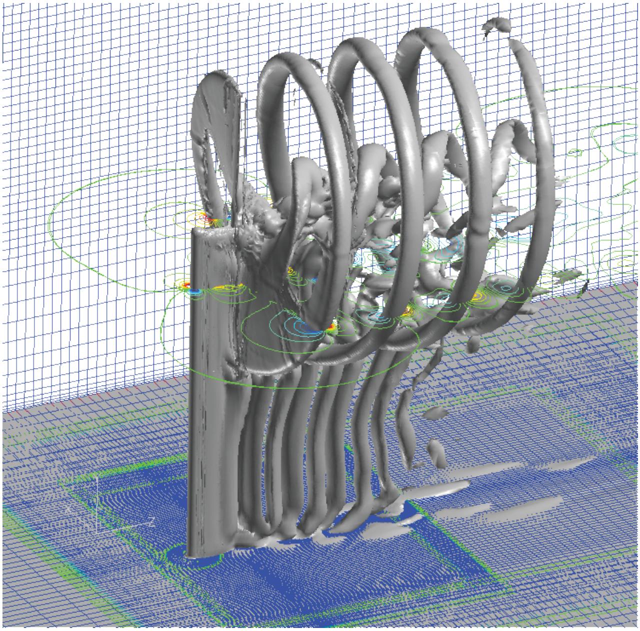
LIFT & DRAG

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.

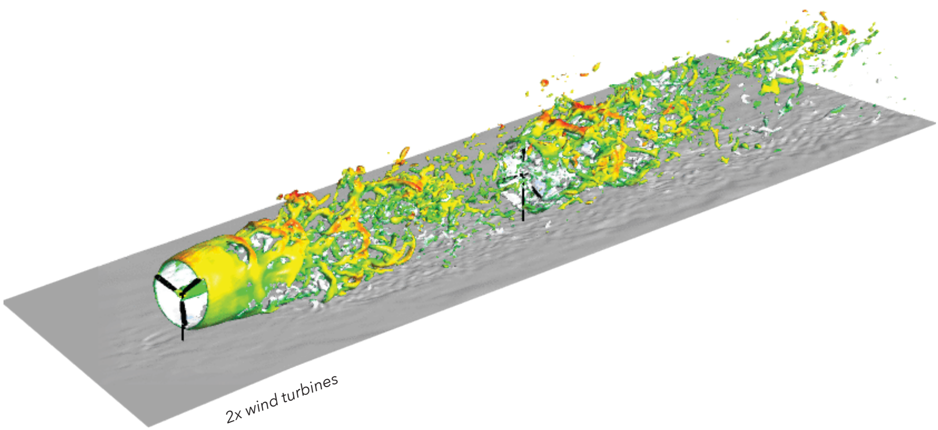


VORTEX

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.



1X wind turbine

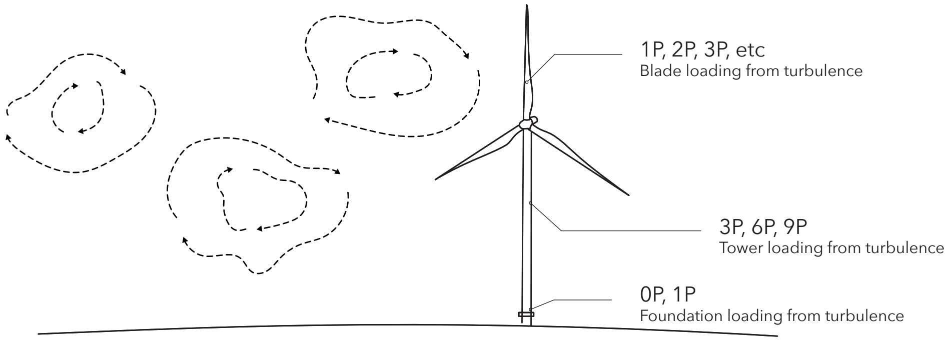


2x wind turbines

STRUCTURAL DYNAMICS

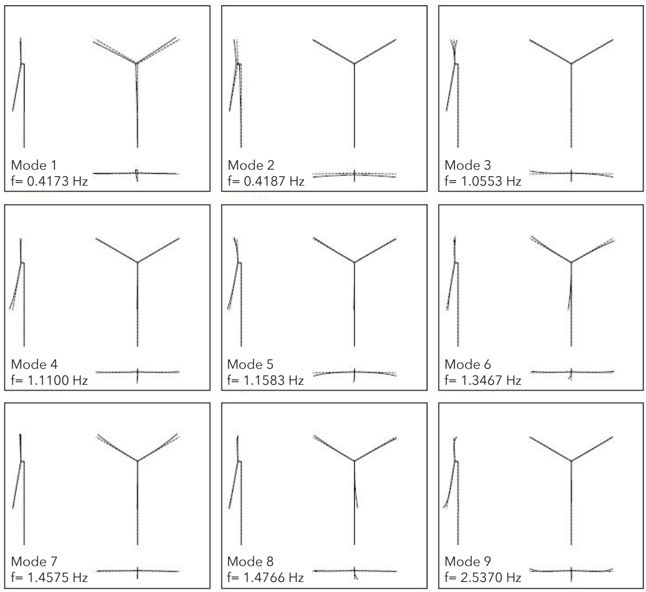
OPERATIONAL FREQUENCY

Figure 16: 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.



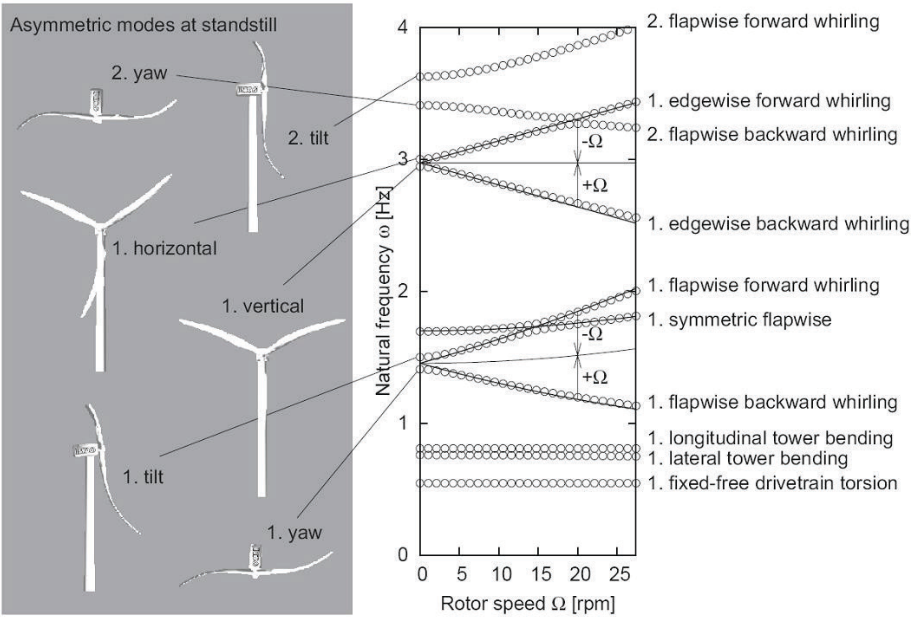
MODE SHAPES

Natural frequencies and mode-shapes 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 logi-tudianal), 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.



VIBRATIONS

NATURAL FREQUENCY

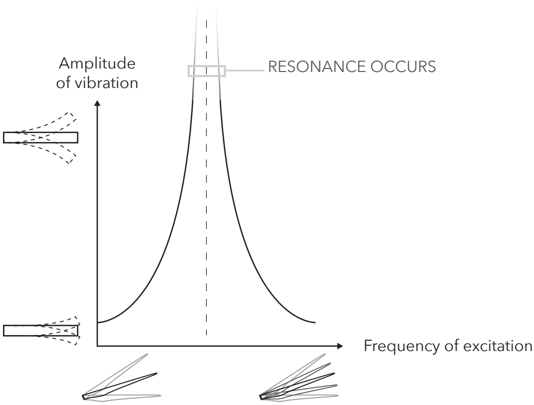
Blades have different natural frequencies depending on the direction of vibration i.e. flapwise, edgewise and twisting/torsion. Natural frequency are the inherent frequencies which a blade will adopt its free vibrations when set in motion by a single impact or a momentarily displacement from its rest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

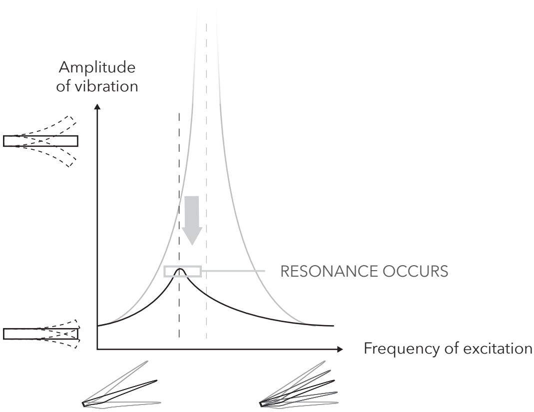
Resonance can occur when a blade is excited by external periodic forces at a frequency close to one of its natural frequencies. Small periodic forces at a resonant frequency can build up to produce large and violent oscillations of the structure.

DAMPING

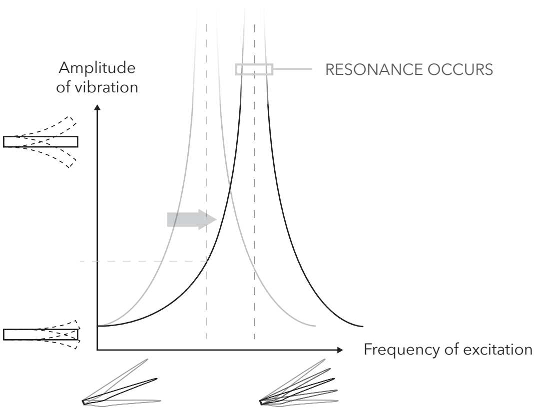
Damping reduces the amplitude of vibrations in a structure by dissipation energy from the system. Energy can be dissipated in the structure due to friction and generation of heat or by means of mechanical devices i.e. a viscous damper (dashpot).



NO DAMPING



WITH DAMPING



INCREASED STIFFNESS

FAILURE MODES

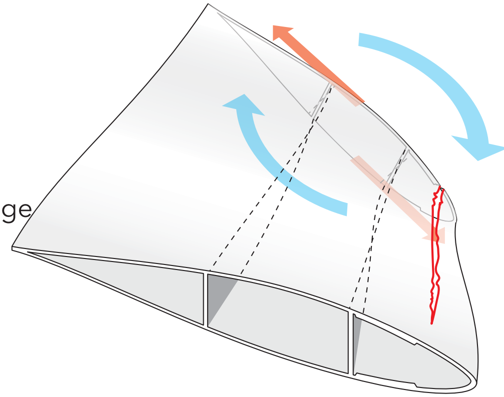
IN LEX PROJECT

OPERATIONAL FATIGUE

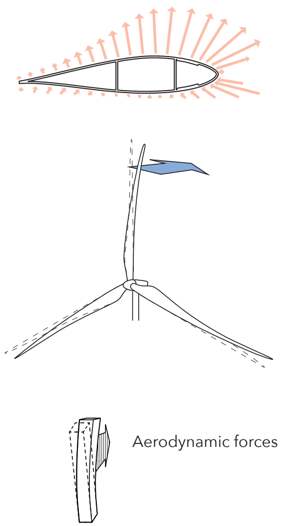
Normal operation

> Shear distortion

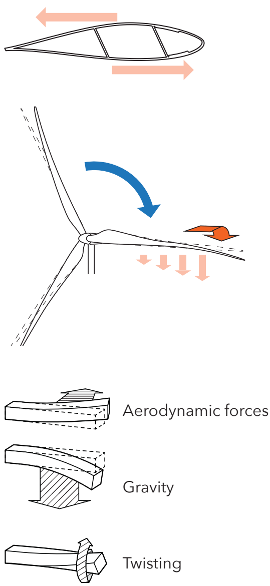
> Leading edge damage



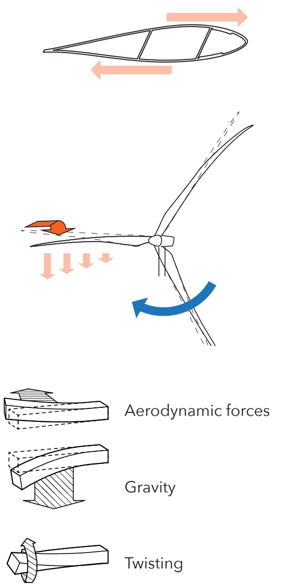
AERODYNAMIC FORCES



TWIST



COUNTERTWIST



AEROELASTIC INSTABILITY - TWO PHENOMENAS

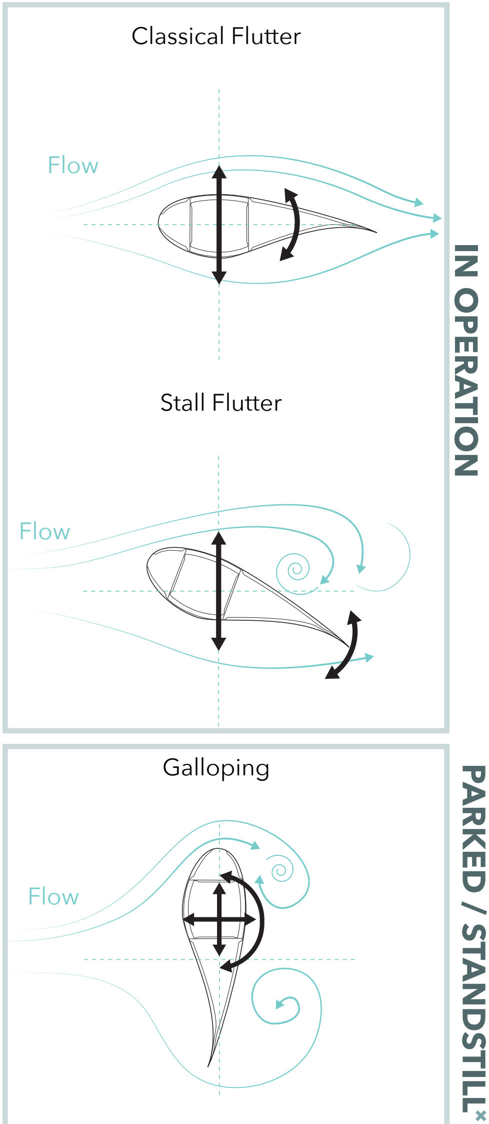
The phenomena of aeroelastic instability can occur due to the structural flexibility of wind turbines. Structural deformations induce changes in aerodynamic forces, i.e. operation above rated speed or during standstill or parked position. The additional aerodynamic forces cause an increase in the structural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

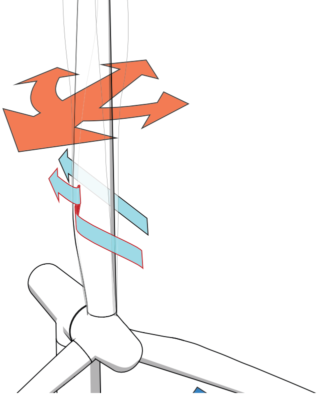
The additional forced vibrations interacting with one or two of the blade natural modes of vibration can result in violent self-feeding vibrations - such as classical flutter, stall flutter and galloping. May diverge catastrophically if resonance occurs.

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

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.





HYBRID TESTING/

HYBRID SIMULATION

Figure 1: Blade cut (not full-length blade test)

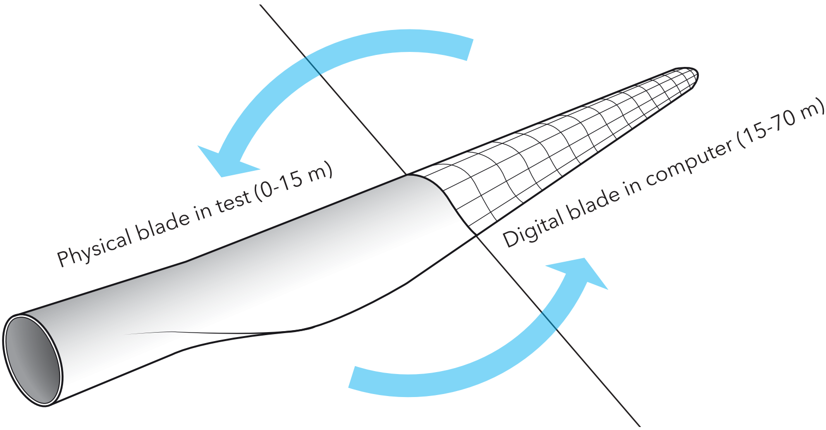


Figure 2: Dynamic testning by adding weight block to blade side

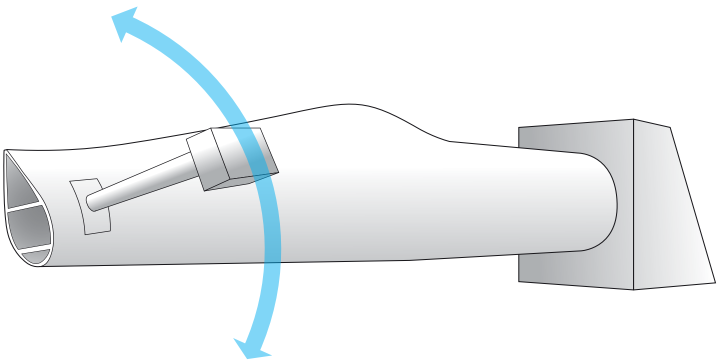
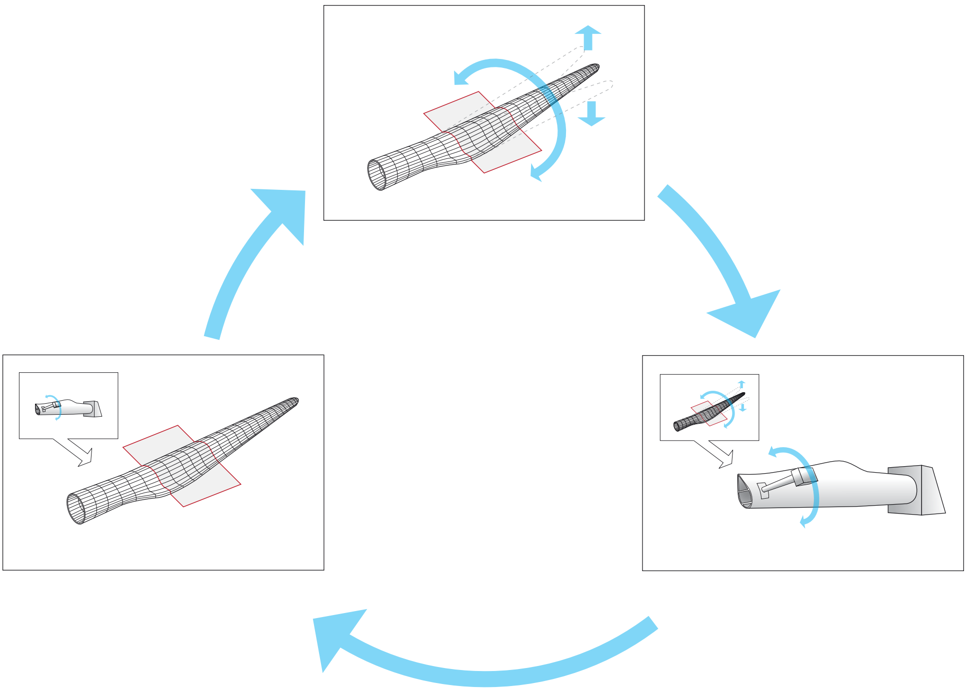


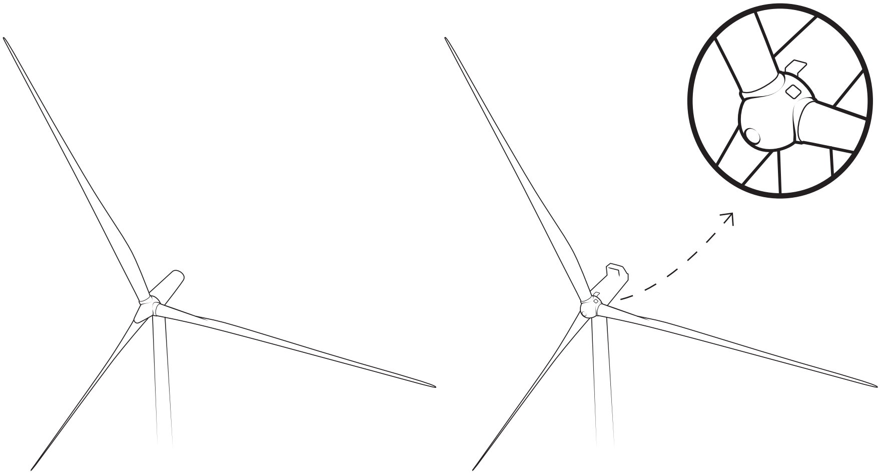
Figure 3: Dialogue between physical and digital blade



WORKING CONDITIONS

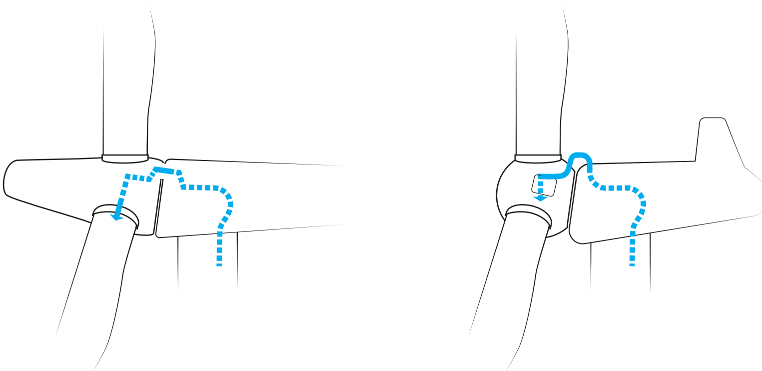
ACCESS

Basical 2 types of access - indoor or outdoor access



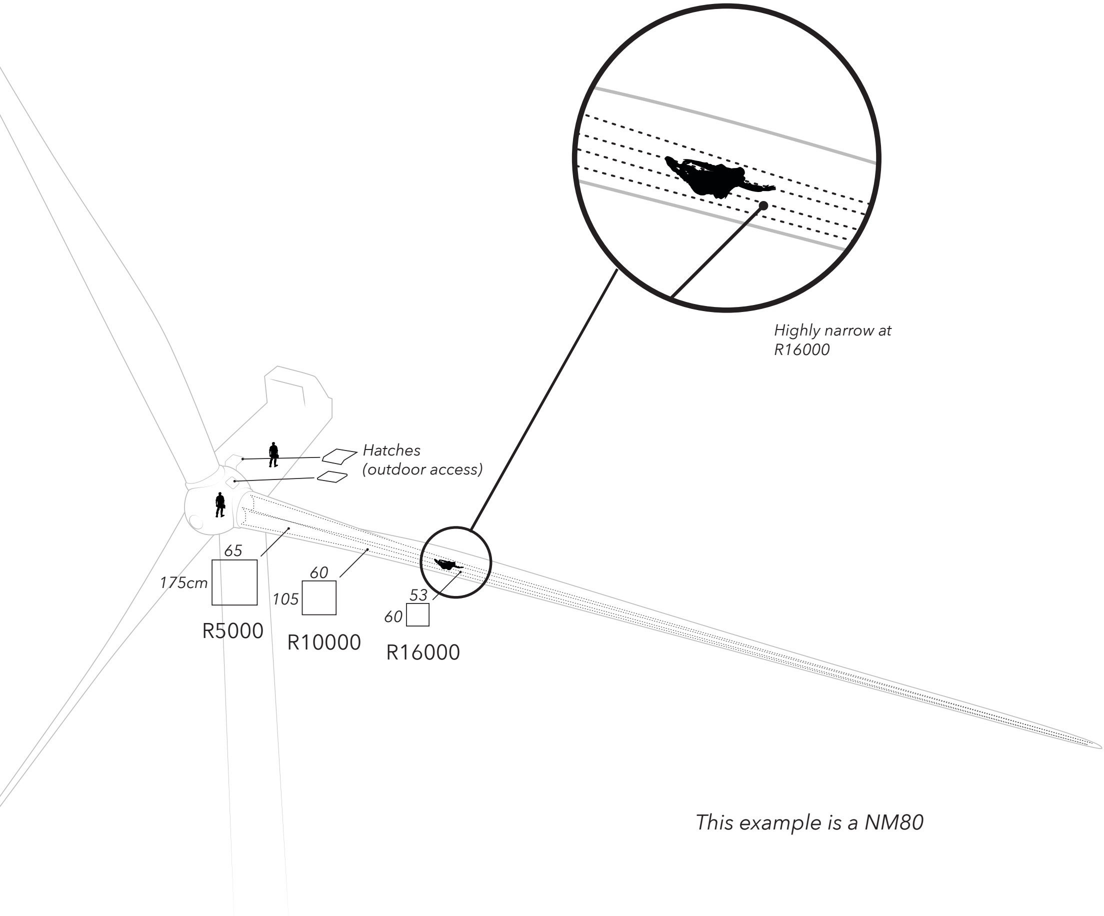
indoor
acces

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)

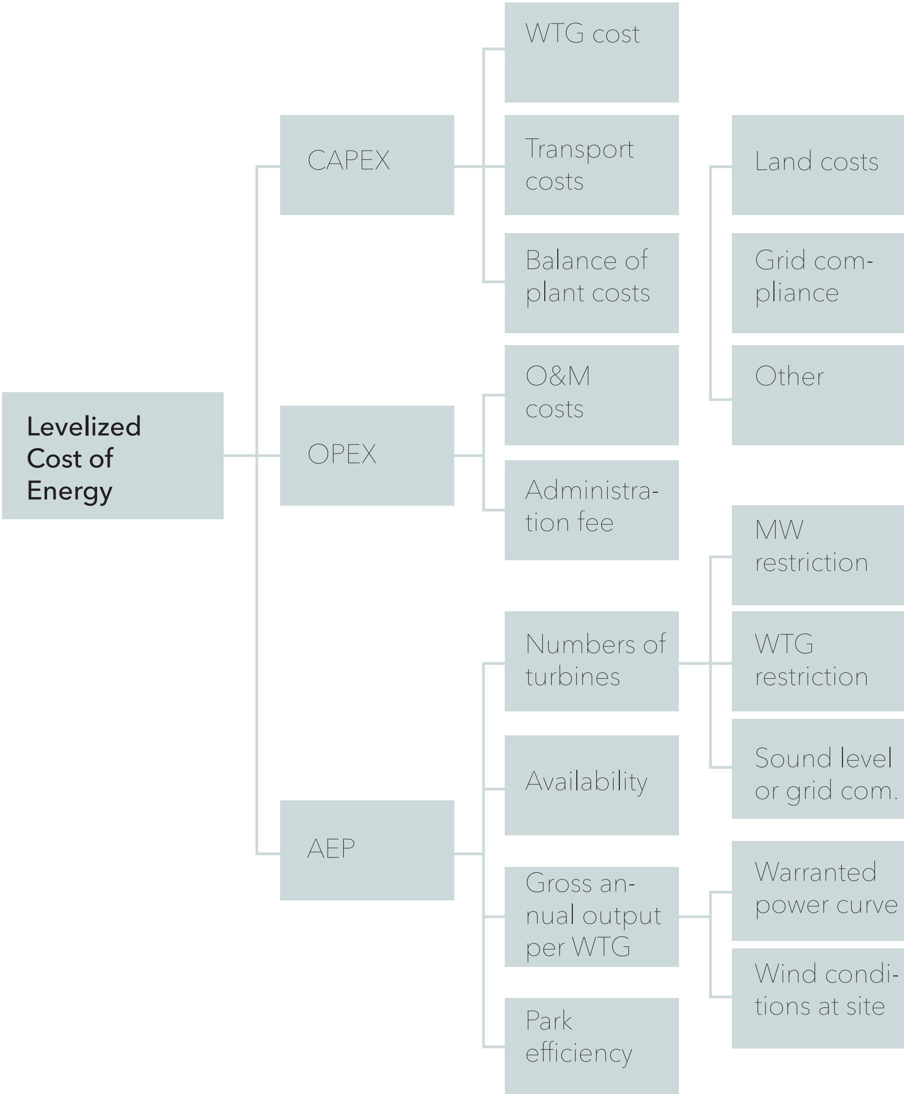
$$LCOE = \frac{CAPEX + OPEX}{AEP}$$

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

or

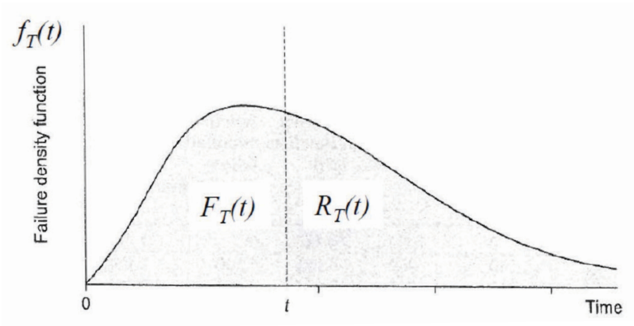
$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}}$$

LCOE	Levelised cost of energy in $Euro_{2012}$/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)


Levelized Cost of Energy
CAPEX
OPEX
AEP
WTG cost
Transport costs
Balance of plant costs
Land costs
Grid com-pliance
Other
O&M costs
Administra-tion fee
Numbers of turbines
Availability
Gross an-nual output per WTG
Park efficiency
MW restriction
WTG restriction
Sound level or grid com.
Warranted power curve
Wind condi-tions at site

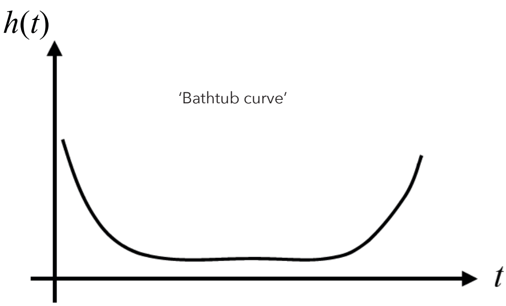
OPERATION & MAINTENANCE

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

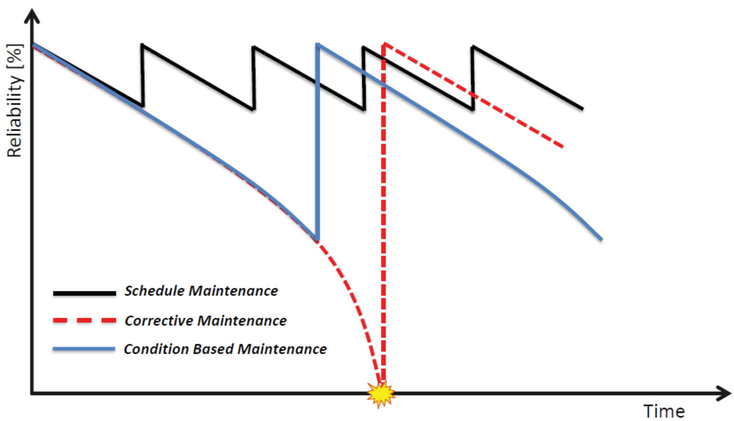
OPERATION & MAINTENANCE OF WIND TURBINES

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



IEC REFERENCES

WIND TURBINE STANDARDIZATION

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.

NOMENCLATURE

AEROELASTICITY
is 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

(NEW TERM)
(Description)

EUDP | LEX Project
Stiffening of wind turbine blades - mitigating leading edge damages

Energiteknologisk udvikling og demonstration