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TNO report

TNO 2020 R10402 | Final report

Literature review of structural and non-structural wind turbine blade damage

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Copy no	2	
No. of copies	1	
Number of pages	26	(incl. appendices)
Number of appendices	0	
Sponsor	RVO	
Project name	TKI HER AIRTuB - Automated Inspection and Repair of Turbine Blades	
Project number	060.37797	

Summary

The AIRTuB project aims to develop a drone-based system that provides leading edge erosion inspection, structural damage inspection, and leading edge coating repair. The current report provides a thorough literature review of external and internal damage. As a result, the types and sizes of damage that need to be detected by an (automated) inspection system are indicated.

Design philosophy plays an important part in the way damage and damaging events need to be dealt with. The state of the art in wind turbine materials and design is that blades are manufactured with vacuum infusion, from glass- (and to some extent) carbon-polyester or -epoxy composites with balsa or polymer foam sandwich structures. The geometrical lay-out of a typical blade features main load carrying components and aerodynamic components in a hollow cross-section of a wind turbine blade.

Current blade design relies on the concept of a ‘safe life’, meaning that the blade is designed to operate for the design lifetime without structural damage, maintenance or repair. This leads to a ‘one size fits all’ design, which in some cases may be suboptimal (the actual life is shorter than, or exceeds, the design life). This is different from ‘damage tolerant design’, which is standard in aeronautical engineering, where the design is based on the premise that known damages are present, grow in a quantified manner, and can be acted upon in time. In comparison, with safe life design, the occurrence of damage is actually not taken into account in the operation of a rotor blade. Thus, the inspection methods targeted in AIRTuB are in the first instance aimed at inspecting unforeseen damage. In the future, they will be useful when blade design paradigms shift from safe life to damage tolerant.

Furthermore, a distinction is made in this report between structural and non-structural damage. In the latter case the main focus is on leading edge erosion, which is typically encountered in the blade tip area. For this damage type, a classification system is discussed. As a first approximation, structural damage is deemed critical when strength or stiffness degrade more than 1%; erosion damage is deemed critical when aerodynamic degradation (resulting in Annual Energy Production loss) outweighs the repair cost..

While occurrence, frequency and types of *erosion* damage in the field are scarcely documented, this is worse for blade *structural* damage. Reports of occurrences of blade structural damage in the field indicate manufacturing or design defects and, often, damage to blade root connections (bolts). Secondary damage due to lightning strike are combined in any statistics that are available. Mechanical tests on blades or blade parts carried out in the laboratory are best-documented, but under less realistic conditions than in the field.

A table with realistic minimum detectable damage sizes for both structural and non-structural damage is given in chapter 7 (Conclusions).

Contents

1 Introduction

1.1 Background

The AIRTuB project aims to develop a drone-based system that provides leading edge erosion inspection, structural damage inspection, and leading edge coating repair[1]. In this project, TNO Energy Transition is, among other contributions, responsible for the success of the work in WP1 ‘Sensor Package Development’. Among the deliverables are two overviews:
- Report on literature review of external and internal damage. (ECN-TNO)
- Report on suitable sensor technologies and a list of design criteria for the to-be-developed sensor for erosion and for internal damage. (NLR, ECN-TNO)

1.2 Goal

The current report aims to provide a literature review of external and internal damage. This will be done with a view to providing input to the second deliverable on suitable sensor technologies. To structure the research, several questions are answered:

- What is the state of the art of typical wind turbine rotor blade design?
- How does the design philosophy for wind turbine rotor blades influence inspection, maintenance and repair?
- What quality systems, inspection methods and quality targets are implemented in blade manufacturing?
- What damages are seen in the field? What are their locations and sizes?
- How does each instance of damage affect wind turbine operation?
- How can erosion/roughness on wind turbine rotor blades be measured?
- What level of erosion/roughness will lead to a relevant decrease in aerodynamic performance?
- When does blade erosion start affecting the structural properties of a blade?

1.3 Approach

The design philosophy plays an important part in the way damaging events and damages are dealt with. In Chapter 2, the design methods and philosophy for rotor blades are reviewed, to assess their influence on the work performed in the AIRTuB project.

A damage classification is made in Chapter 3. Damage experienced by wind turbines can be classified into two general groups: structural and non-structural. As non-structural damage, this report refers mainly to leading edge erosion, see Chapter 4. In this chapter, a classification of damages is also presented in order to quantify the requirements for sensors inspecting leading edge erosion on the blade

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[1] Ferry Visser et al., ‘AIRTuB (Automated Inspection and Repair of Turbine Blades)’, Projectplan Hernieuwbare energie 2019.

surface. Chapter 5 briefly discusses lightning damage. Structural damage is discussed in chapter 6, and overall conclusions are found in chapter 7.

2 Wind turbine rotor blade design

This chapter provides a brief overview of typical structural and material design of a rotor blade. It is not comprehensive, since limited information is available in the literature as blade designs are the intellectual property of designers and/or manufacturers, so not typically published. Nevertheless, indirect sources such as materials suppliers and researchers have presented blade lay-outs. Literature provides numerous images of the inside of a rotor blade. Most of this literature is generated by researchers, material suppliers and sensor developers, i.e. not by the blade manufacturers. A representative image (including a cross section with two separate webs) is reproduced from (Zangenberg, 2014) in Figure 1. This figure illustrates that the cross-section of a blade consists of components that are primarily structural (the 'main laminate' or spar cap laminate, and the webs), and less structural material such as the sandwich. Some cross sections feature structural trailing edge reinforcements.

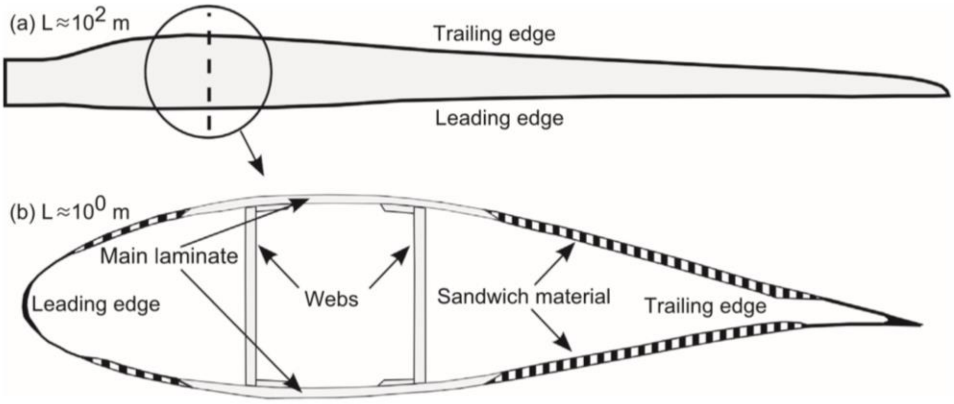

Figure 1: Sketch of a wind turbine rotor blade and main structural components, reproduced from (Zangenberg, 2014)

2.1 State-of-the-art blade designs and materials

A comprehensive overview of the history of wind turbines is provided by (Joncas, 2010), aimed at putting use of thermoplastic composites in future blades into perspective. Current blade technology predominantly relies on thermoset polymer technology. His overview ends with the (then) state-of-the-art designs, consisting of separately moulded pressure- and suction side bonded together at the leading and trailing edges, and at the spar structure (consisting either of a box beam or separate webs).

Glass fibre reinforcement is used most, while limited quantities of carbon fibre are used in spar caps and edge reinforcements. The sandwich materials' primary role is to maintain aerodynamic geometry. Sandwich panels consist of glass-fibre reinforced composite skins and balsa or polymer foam cores. There are bondlines at the trailing and leading edge and at the transition from main laminates to webs; the bondline consists of a combination of an overlaminate and adhesive, sometimes just of an adhesive bonding paste, which is typically a glass-filled polymer.

2.2 Future blade designs and materials

The main future challenge for wind turbine blades is to develop much more recyclable designs, possibly with increased use of thermoplastics. But for thermoplastics to be accepted in blade design, Joncas asserts that first the two classical hurdles must be overcome: increasing confidence in mechanical properties and further development of manufacturing processes.
Material developments that are currently mentioned in the field are increased use of (infusible) thermoplastics, hybrid reinforcements, and nano-additives. These are briefly discussed below from an inspection and repair perspective.

2.2.1 Thermoplastics

Not only do thermoplastics offer new possibilities for recycling, they also open up new design possibilities - including internal ribs (similar to the inside structure of an aircraft wing) to maintain aerodynamic shape - which might help in reducing sandwich core material requirements.
Inspection of thermoplastic composites using standard acoustic methods might be hampered by the different acoustic impedance and speed of sound of the polymer with respect to thermosets.
The damage initiation and growth behaviour of thermoplastics is different from composites with a thermoset matrix. In particular in terms of crack growth, more ductile and damage tolerant behaviour can be expected. In addition, repair of damage needs to be redefined compared to that in thermosets. For instance, repair patch fixation and consolidation can be performed with heat or welding. Potentially, geometry such as scarf angles may be different due to the different long-term (fatigue, creep) behaviour of the composite’s matrix. For smaller damages, e.g. pitting in leading edge erosion, it is conceivable that these could be ‘smoothed out’ by a to-be-developed device.

2.2.2 Hybrid reinforcements

In recent years, hybrid reinforcements have been developed for use in e.g. wind turbine blade spar caps. These consist of alternating layers of carbon and glass textiles, sometimes prefabricated as hybrid non-crimp fabrics. This material can be seen as a partial replacement of glass fabric with carbon fabric to increase strength and stiffness at minimal cost. The added thickness of the glass fabric additionally provides support against global buckling. The glass layers are typically more permeable for the liquid resin during manufacturing, improving infusibility of the hybrid material.
Some challenges can be identified regarding inspection and repair of these materials. First of all, the material is partly conductive, so that inspection using e.g. TeraHerz methods is not possible, while opening up opportunities for e.g. eddy current inspection. Structural repair of hybrid materials might require added complexity in preparation of the repair area and the patch. It would be even more advisable to use original textiles than in a non-hybrid material, as layers would be stitched together and this would be best to be reflected as well in the repair patch. In addition, due to the relatively large stiffness jumps in thickness direction, a stepped repair might need

to be prepared with unequal steps, to accommodate larger bonding areas for the stiffer layers in comparison to the more flexible layers. This would also imply that patches would have to be prepared with e.g. a smaller glass layer stitched to a larger carbon layer.

2.2.3 *Nano-additives*

Addition of nanomaterials to improve stiffness, damage tolerance, and fibre-matrix bonding has been the topic of intensive research in recent years. Much of the research focusses on the manufacturing and dispersion of the nano-additive.
Nano-additives might offer advantages in terms of inspection for damage. It can be conceived that nano-additives might be developed that respond to cracking in a way that existing or novel inspection methods can operate with improved resolution and accuracy.
Similar challenges as in manufacturing can be expected in the repair of a nano-reinforced composite. Ideally, a similar dispersion of a nominally identical nano-additive should be used in a repair patch. Alternatively - and potentially more practically - the repair patch can be tuned to have the same stiffness without the nano-additive, e.g. by increasing fibre volume fraction. The impact on overall blade behaviour can thus be negligible while simplifying the patch preparation.

2.2.4 *3R (Recyclabe, Reprocessable, Repairable) resin systems*

A new development is in (bio-based) epoxy systems with a 'reshufflable' cross-link chemistry (see e.g. https://www.compositesworld.com/news/bio-based-recyclable-reshapable-and-repairable-3r-fiber-reinforced-epoxy-composites-wins-award).
Allegedly, this resin can be heat treated to remove damage, potentially removing the need for traditional repairs. It is not clear if this material allows for patches to be bonded by e.g. heat treatment to a damaged substrate in case this is required to repair more severe layer damage.

2.3 Design method

Rotor blades are part of an integral wind turbine design, and are mostly governed by design guidelines such as IEC-61400-1, 23 (design requirements and full-scale testing), and DNVGL-ST-0376. Integral wind turbine simulation using pre-defined load cases generates the loads on the blades and through in-house tools and expertise a designer develops the laminate lay-out, taking into account boundary conditions such as cost, certification, and manufacturability. More advanced blade design tools include non-linear finite element analysis and aeroelastic methods.
Cost mainly affects material selection and manufacturing method selection; this is the main reason that glass fibre is the most used reinforcement fibre and vacuum infusion the dominant manufacturing method.
Certification influences the design in the sense that the structure is dominated by the design philosophy, but also in the sense that minor changes in design may allow for shorter certification procedures (e.g. a minor increase in blade length could be accommodated by an earlier type certificate).
Manufacturability is currently governed by vacuum infusion and manual labour considerations, with the most 'extreme' deviation from industry average procedure the one-shot technology employed by Siemens-Gamesa (IntegralBlade) in some of their blades.

2.4 Design philosophy

The standard design philosophy used in aeronautical engineering is ‘damage tolerant design’, where the design is based on the premise that known damages are present, grow in a quantified manner and can be acted upon in time. However, wind turbine rotor blade engineering currently adheres to a ‘safe life’ approach, meaning that the blade is designed to operate for the design lifetime without structural damage, -maintenance or -repair.

Thus, the inspection methods strived for in AIRTuB are in the first instance aimed at inspecting unforeseen damage. In the future, the additional methods proposed will be useful when blade design paradigms shift from safe life to damage tolerant.

2.4.1 Current method: Safe life design

Since operational conditions are not known 100% in advance and the blade needs to be certified for the design life, the safe life approach leads to a ‘one size fits all’ design, which in some cases may be suboptimal (actual life is shorter or longer than design life). The occurrence of damage is not taken into account in the operation of a rotor blade with this design background. Therefore, inspection, maintenance and repair are not part of the standard operational procedures. Nevertheless, inspections are in practice carried out because of anomalies in operation (vibrations, visible damage), or as a pre-end of warranty check.

2.4.2 Possible future method: Damage tolerant design

Damage tolerant design inherently leads to a lighter design and therefore can be of interest for very large rotor blades.
However, there are some challenges to overcome before damage tolerant design can be achieved:

- **Materials must be designed to exhibit known crack initiation and growth.** For a material to be damage tolerant, the fracture stress must be significantly higher than the stress that marks the end of the linear elastic behavior. Furthermore, crack growth must be stable, which can be attained by ‘the load level for unstable crack growth should be significantly higher than the load level that initiates crack growth’ on a material level, and on a structural level this means that the released energy per unit of new crack area should be equal to or less than the energy required to advance the crack in order to achieve stable or no crack growth. The released energy depends on magnitude of load, elastic properties and the shape of the structure. As (M.McGugan, 2015) mention, potential damage tolerant design avenues include laminates with off-axis fibres, tailored interface toughness and bridging fibres between composite layers or in joints, e.g. (Sørensen, 2004);
- **Robust and cost-effective structural health monitoring techniques** must be developed and incorporated in operations and maintenance of wind turbine blades;
- **Design and testing guidelines must allow for damage tolerant design.** For instance, a concept such as ‘structural repair manual’ could be implemented (like in aeronautical engineering) which a priori lists all known damage modes and

their tailored repair solution. Design for damage tolerance not only relates to the material and structural models used in design, but also in creating accessibility and inspectability around critical blade areas. Currently, design and testing guidelines are still geared mostly towards safe life design.

In any structure, damages may occur that were not taken into account during the design phase. There are various potential reasons for this:

- A damage mechanism was not known by the design team;
- A damage mechanism is not sufficiently understood;
- Operational circumstances are different than assumed in design;
- A manufacturing error has led to damage;
- Damage by blade transport and handling.

These are the damages that will be encountered in inspection of blades designed according to the current state-of-the-art.

2.5 Quality assurance in blades

Before the blade leaves the factory, a quality assurance check is performed. On a blade scale, this can incorporate mass and centre of gravity measurements and checks on the blade aerodynamic geometry, see e.g. (T. Kramkowski, 1997).
A recent overview and specifications of surface scanning of the blade in order to make a model/digital twin and to detect surface flaws is provided by e.g. (Rasmus A Lyngby, 2018). This equipment has a resolution of ca. 50micrometer.
Sources that report on waviness in blades, e.g. (Sunil Kishore Chakrapani, 2013), give waviness dimensions in the order of 2-3cm width and a couple of mm in thickness direction. A review of advanced detection methods, including X-ray and TeraHerz inspection used reference samples with flaws of a couple of mm to up to 5cm (Robert W. Martin, 2018).
The extent to which these flaw dimensions are representative for post-manufacturing quality assessment system could not be determined, as no details of such system are made available by manufacturers, but repair seems to be common practice, according to (Leon Mishnaevsky Jr., 2017).
There are some OEMs supplying scanning technology specific for wind turbine blades in the factory and in the field[2,3].
To the extent that the damage sizes were reported in the literature, the minimum detectable damage size for the AIRTuB drone has been selected to be higher (Table 3), on the premise that critical damage in the factory would have been repaired and so larger damage will be detectable in the field.

[2] https://forcetechnology.com/en/services/automated-ultrasonic-inspection-equipment-pscan-wind
[3] https://www.olympus-ims.com/fr/applications/shear-web-bonding-inspection/

3 Damages in wind turbine rotor blades

Contrary to what is expected in blades built according to the safe life approach, blades will suffer damage during their operational lifetime. The damage varies per case. Nevertheless two factors have been identified as the main causes for blade damage. These are the blade tip rotating speed and the environment. (Fraunhofer, 2017) (TNO, 2019)

Offshore and nearshore turbines are more likely to suffer from regular damage due to the environmental conditions. Higher wind speeds, constant rain and higher concentrations of small particles are to be expected from these locations. Offshore environments also do not have a restriction on the maximum rotating blade speed as noise pollution is not of particular concern, allowing for tip speeds of up to 350 km/h (Fraunhofer, 2017). This set of conditions makes wind turbines installed offshore more susceptible to experience blade damage. (Yang, 2014)

Development of larger wind turbines (with subsequently larger rotor blades) will increase the occurrence and intensity of blade damage unless measures are taken to protect the tips from the increasing operational speeds.

3.1 Structural and non-structural damage classification

A literature review has shown that there is currently no standardized classification system for rotor blade damages. For this report, the damages are divided into two main types: structural and non-structural.

The structural type comprises damage that compromises the design lifetime of the blade, usually by decreasing the structural strength and stiffness. Internal cracks on the laminar composite structure are an example of this as they lower the resilience to stress of the blade and lead to larger internal defects which in turn might cause a structural failure.

The non-structural class includes damage where the blade performance is affected without directly compromising the structural integrity of the blade, i.e. when the outer coating is eroded without affecting the inner composite laminate section. It must be stressed that this kind of damage might indirectly lead to a shorter than designed lifetime of the blade by promoting a structural damage.

3.2 Damage intensity criteria

This report establishes the damage intensity criteria shown in Table 1: two thresholds per damage class.

For non-structural damage, the **affected** threshold refers to the point where the damage in the non-structural section of the blade (such as the gelcoat) is intense enough to disturb the aerodynamic performance up to a point when the associated degradation of the Annual Energy Production (AEP) is large enough to outweigh the associated costs of repairing the blade. The **critical** threshold refers to the point where the damage is intense enough to not only affect the aerodynamic performance of the blade, but also compromise the structural integrity of it in various ways, i.e. by allowing the permeation of water inside the laminate structure.

For structural damage, the **affected** threshold refers to the point where the damage in the structural section of the blade degrades the strength and/or stiffness of the same by 1% with respect to its original maximum. The **critical** threshold refers to the point where the damage in the blade structure is large enough that it will lead to a reduced operational life than originally designed.

Table 1. Damage intensity criteria thresholds.

	Affected	Critical
Non-structural	Aerodynamic degradation cost outweighs repair cost	Structural components start to be affected
Structural	≥ 1% degradation on strength/stiffness	Design life non reachable anymore

3.3 Effect of blade damages on energy production

Blade damage not only reduces the lifetime, but leads to a decreased AEP. A direct effect on the AEP is through unscheduled downtime. Blade damage also affects the AEP by reducing the aerodynamic performance of the blades.

Blades yield the maximum aerodynamic power when operating under design conditions: a smooth, clean and damage free outer surface, and a strong, stiff support structure that maintains the correct airfoil shape. Any change in these conditions will results in a *different than designed* aerodynamic performance. A study performed by Woobeom, and a later follow up study performed by Heejeon suggest that some wind turbine control systems mitigate part of this effects. (Woobeom Han, 2017) (Heejeon & Bumsuk, 2019)

Non-structural damage—such as erosion of the outer layer—modifies the airflow around the airfoil, mainly increasing the drag and decreasing the lift, which in turn reduces the energy extracted from the wind, lowering the turbine power output. This leads to a reduced AEP compared with what could be delivered from a clean, damage-free blade. (Bak, 2020)
It is worth noting that damage that *subtracts* material, such as erosion, is not solely responsible for a decreased aerodynamic performance. Surface contamination, such as the accumulation of solids, has a comparable effect. (Caboni, 2020) (Woobeom Han, 2017)

4 Non-structural Damage – Leading Edge Erosion

Leading edge erosion (LEE) is one of the most common causes of non-structural damage suffered by a wind turbine blade. A continuous high speed impact of rain droplets, hail, suspended salt and other kinds of small atmospheric particles on the leading edge causes removal of surface blade material. This phenomenon modifies the leading edge surface shape and increases its roughness, which in turn modifies the lift and drag aerodynamic properties of the airfoil. Shifting from the optimal aerodynamic properties reduces the amount of kinetic energy that can be extracted from the wind, lowering the power yield (Sareen, 2014).

Although LEE does not compromise the structural integrity and lifetime of the blade directly, all the studies consulted suggest that its later stages promote the degradation of the blade's internal sections by allowing moisture and other environmental particles to access the structural components, promoting degradation of the structural properties (stiffness and strength) and thereby reducing the lifetime.

The literature suggests that LEE should be expected to occur more frequently and with higher intensity in larger turbines and offshore locations (Yang, 2014). The main reasons relate to:

1. the higher tip speeds expected from larger rotors;
2. the harsher environment offshore; and
3. the lack of noise-related regulatory speed limitations on offshore turbines compared with their onshore counterparts.

The Dutch government is planning an expansion of the offshore wind capacity up to 11 GW for 2030: 11 times the installed capacity in 2019 (Government of the Netherlands, 2020). Considering this, the effectiveness of available LEE prevention, protection and repair methods will have a large impact on whether these targets are easily met.

4.1 LEE mechanisms

Different conditions—associated either to the turbine itself or to the environment where it is located—have a direct influence on the likelihood LEE occurs. The impact speed of the rain with the blade is directly proportional to the likelihood of an erosion occurrence. This speed is dependent on factors such as the length of the blade, the drivetrain, and speed limitations set by the location[4]. On the other hand, the environment on which a wind turbine is located will have characteristic types and concentrations of suspended particles, as well as likelihood of rain. (TNO, 2019)

For wind turbines placed offshore, conditions are more favorable for LEE development. Higher rain rates and salt particles concentration together with lower or no speed restrictions make blades more vulnerable to LEE than their onshore counterparts (Woobeom Han, 2017), (Heejeon & Bumsuk, 2019), (Eneco, 2018).

[4] Speed of wind turbine rotor blades is often limited for on-shore wind turbines due to noise constraints. This speed limitation also limits the maximum power the turbine can extract from the wind.

This also suggests that a higher concentration and erosion severity can be expected on the blade region closest to the tip, as this is where the highest speeds are experienced.

Studies suggest that erosion is a mechanism with characteristics similar to material fatigue. The impact of a rain droplet or atmospheric particle by itself will not cause material removal, but a repetitive impact over the same surface will fatigue the material, causing chipping off of the material (Springer, Yang, & Larsen., 1974). n interesting visualization of this erosion mechanism as a fatigue progression, by defining phases in which the erosion progression transitions from linear to random, as a result of involving different material layers once the external gelcoat layer is penetrated (Veraart, 2017). It is noteworthy to mention that TNO has an in-house model that predicts the erosion due to fatigue on materials (H.M. Slot, 2015).

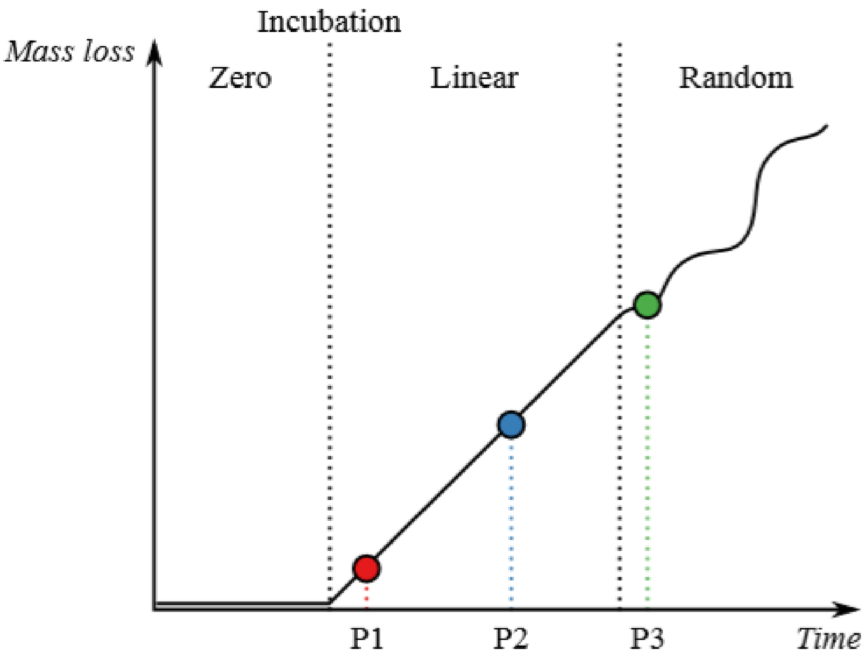

Figure 2. Erosion versus time. (Veraart, 2017). This work defines 3 phases of erosion progression. The erosion is defined and measured in this work by the subtraction of material reflected in a loss of mass. A transition from a linear loss of mass to a random loss of mass is explained by a transition from an erosion of a single material (gelcoat), to an erosion of multiple materials (gelcoat, non-structural composite, structural composite).

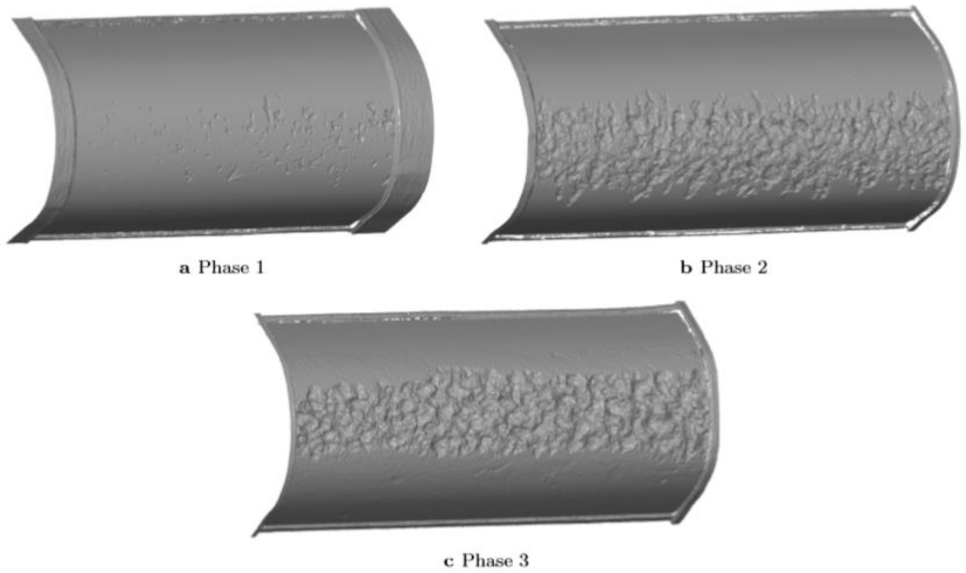

Figure 3. Leading edge erosion progression. (Veraart, 2017). This image illustrates 3 phases of damage. On phase 1 and 2, the gelcoat is the only material to be removed. On phase 3, the composite material is also lost.

4.2 LEE life cycle

Studies suggest the life cycle of LEE starts as minor chipping of the external coating, also referred as *pits*. These features are described as non-deep [0.1mm-0.3mm] and small [0.5mm-4mm]. After a high density of pits are formed in the surface, they tend to form close together and eventually merge into larger features known as voids. This features have irregular shapes, and are both larger [10mm-40mm] and deeper [0.3mm – 0.8mm] than pits (Gaudern, 2014), (Bak, 2020).

Figure 4 LEE life cycle. From left to right it can be seen a progression of LEE from a stage 1 up until a stage 5 category. Small pits overlap and become larger dents, which also overlap within each other until larger pieces of coating are removed. On the far right hand side

it is appreciated how an extreme case of LEE leads to a delamination, exposing the structural component to degradation.

4.3 Proposed LEE classification

An extensive literature research showed the lack of an uniform standardized classification system for LEE, both in the academic as well as in the industrial sector. This leads to having *ad hoc* classifications per academic work and per company. Despite this, similarities were found among most of the studied works. Among the similarities in the consulted classification methodologies, the use of 5 stages for damage progression proved to be universal.

Usually, the point where academic and industrial works differ is in the inclusion of the laminate exposure (delamination) into the erosion classification. Academic literature usually separates structural and non-structural damage into different classifications (Sareen, 2014), (Gaudern, 2014), (Schraam, 2017). In contrast, the industry tends to summarize and classify their findings in the field under a single classification. This results in defining the maximum stage for LEE by including both a heavy structural damage, such as a heavy delamination of the surface coating, together with a heavy laminate deterioration (Eneco, 2018), (Woobeom Han, 2017).

Other relevant properties are given different weights per work. Some of the most important properties that can describe a LEE are:

- Type of features, such as surface roughness, holes, added material (dirt accumulation), or delamination.
- Affected area chordwise
- Affected area lengthwise
- Location of damage, such as tip, root.
- Deepness of feature
- Area of feature
- Amount of removed material (in mass units)
- Amount of added contaminant material (in mass units)
- Density of features (number of features per given area)

Based on the aforementioned literature review, this work proposes a LEE classification that relates the stage of the damage with the impact on power and, consequently, energy production. This classification has in mind the goal of the AIRTuB project: understanding the impact that different damage types have on operation, lifetime and energy production.

Figure 5 shows the classification, based in the 5 stages presented by (Gaudern, 2014), and how a decrease in AEP can be related to each one. A stage one LEE is comprised of multiple pits. A stage 2 to four LEE is formed by gauges with increasing diameter and depth. A stage five LEE is represented by a coating surface delamination, leaving the internal laminate exposed to the elements.

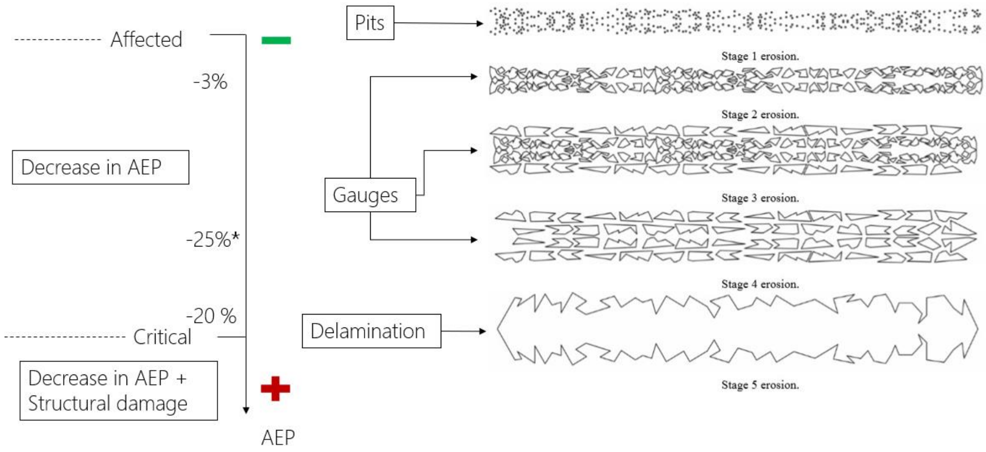

Figure 5. 5 stages of erosion. Based on (Gaudern, 2014). This work proposes that even a small stage erosion can impact AEP in up to 3% and peak at up to 25% decrease in a stage 4-5 erosion. It is interesting to note how a stage 5 erosion is expected to have a lower impact on AEP than a stage 4 erosion, comprised of multiple features.

4.4 Insights of LEE on 2 Dutch offshore wind farms.

The blade maintenance operations of the Princess Amalia Wind Park (PAWP) and Luchterduinen (LUD) was investigated, and insightful information from a wind farm operator (ENECO)side into LEE was obtained. The context of the observed data is the following:

- The maintenance operations dated from 2016 and 2017, and transition between different leading edge protection products was ongoing.
- PAWP has a capacity of 120MW comprised of 60 Vestas V80 2MW wind turbines. The wind farm became operational in 2008.
- LUD has a capacity of 129 MW comprised of 43 Vestas V112 3MW wind turbines. The wind farm became operational in 2015.
- PAWP had yearly inspection and maintenance campaigns since 2014.

The documentation showed that the most common damages experienced by PAWP and LUD over the 2017 period were related to LEE (over 90%).The overall damage likelihood of occurrence seen is the following:

1 LEE
2 Lightning strike protection system
3 Blade collar damage
4 Non-protected lightning strike
5 Structural damage

The documentation also showed that the typical intensity of the damages was mild. This statement is in-line with the common wind farm operator practice of not allowing identified damage to become critical. Medium intensity—stage 2 and 3 (out of 5)—damage types have the highest share of occurrences on the tip region with 55%, while lower intensity stage 1 damage types were seen in 43% of occurrences. Higher intensity damage, which can be considered transition states into structural damage, were seen in 2% of the occurrences. This distribution of intensities was similar in the mid chord region and appears to differ in the max chord region, which has a larger share the higher intensity damage types.

Furthermore, the amount of observed damages vary per blade region, being more frequent on the tip region [60%], followed by the mid chord region [36%] and a lesser amount observed on the max chord region and root [4%].

4.5 Expected Annual Energy Production losses from Leading Edge Erosion

The literature differs greatly on the expected AEP loss to be expected due to LEE. Some studies predict drag increases on the order of up to 500%, and AEP losses of up to 25% (Sareen, 2014). However, it must be stressed that these studies dismiss the effect of control on the energy production. In contrast, studies that do take this into account suggest that pitch control should offset the effects of increased drag by adjusting the angle of attack accordingly. In these cases, the predicted decrease in AEP is estimated to be around 4% for a 5MW NREL reference wind turbine (Woobeom Han, 2017). As a remark, all of these estimations follow different approaches to lift/drag estimation: some with wind tunnel testing and others with numerical modelling.

Regardless of the large range in results, some conclusions can be drawn from the literature evaluation:

1. Both tunnel testing and models suggest than a milder LEE stage can already decrease AEP by at least 3-5%, so long as there is a large concentration of damages (pits) in the surface. (Gaudern, 2014)
2. Pitch controlled wind turbines offset the effects of added drag on power production. This can be only seen when the wind turbine operates at rated wind speed conditions and above. The power, and subsequent AEP, losses are therefore only experienced under the lower than rated speed zone. Stall controlled turbines do not appear to have this effect. (Woobeom Han, 2017), (Heejeon & Bumsuk, 2019).
3. Some studies suggest that AEP decreases proportionally with the progression of LEE up to a stage where a large amount of features in the form of voids are present (stage 4, deep and wide). After this point, an erosion progression will result in a delamination, which is a single feature. This single feature has a lower detrimental effect on power production than multiple deep and wide features (Gaudern, 2014) (Schraam, 2017). Nevertheless, not all studies support this claim (Sareen, 2014) (Woobeom Han, 2017).

4.6 Minimum size of erosion to be relevant for AEP purposes

We conclude that the minimum size of an erosion feature to be relevant for inspection should not be larger than a pit 0.3mm deep and 2mm wide. This erosion feature can be expected to have a detrimental effect on AEP of around 3%, if the density of the feature is high enough (400 features over a 2.5m span).

Type of Damage	Erosion Depth (mm)	Erosion Diameter (mm)	Decrease in AEP expected	Number of features
Pit	0.3	2	3% - 5%	400 over a 2.5m span

Table 2 Minimum erosion relevant for AEP purposes

5 Non-structural damage - Lightning strike

Wind turbines often suffer from lightning strikes due to their height, composition and locations where they are placed. High wind resource locations often coincide with high lightning activity ones (Dodd, 1983). Although the whole structure can be impacted by lightning strikes, the most common element to be impacted are the blades. It is also a fairly likely event to occur: one study showed that 8% of wind turbines can expect to receive at least one impact per year (Macniff, 2001).However, well maintained protection elements reduce the consequences of the impacts. An analysis of the maintenance data of a wind farm located in the Dutch coast of the North sea showed that less than 5% of the reported damage after an inspection campaign were attributed to lightning strikes, well below the damage attributed to LEE (Eneco, 2018).

Current wind turbines have lightning strike impact protection along the blades. This protection is comprised of receptors close to the tip that disperse the electric energy impact along the blade and then into the earth (Peesapati V. a., 2009). Thus, modern wind turbines suffer less catastrophic damage from lightning strike than their predecessors (Peesapati V. C., 2011). Nevertheless, after a lightning strike, maintenance in the blade receptor might be required as sudden increases in temperature causes superficial damage to the blade due to water expansion (LM, 2020). This damage can serve as an entry point for larger superficial damage, and lead water into the laminate, which can reduce the lifetime of the structural components as well.

Configurations typically used for lightning protection systems are reproduced in Figure 6 from (Peesapati V. C., 2011). In their papers (Peesapati V. a., 2009), (Peesapati V. C., 2011), they suggest that the data on which the IEC-61400-24 guidelines for testing the lightning protection systems are based lead to conservative design for large wind turbines.

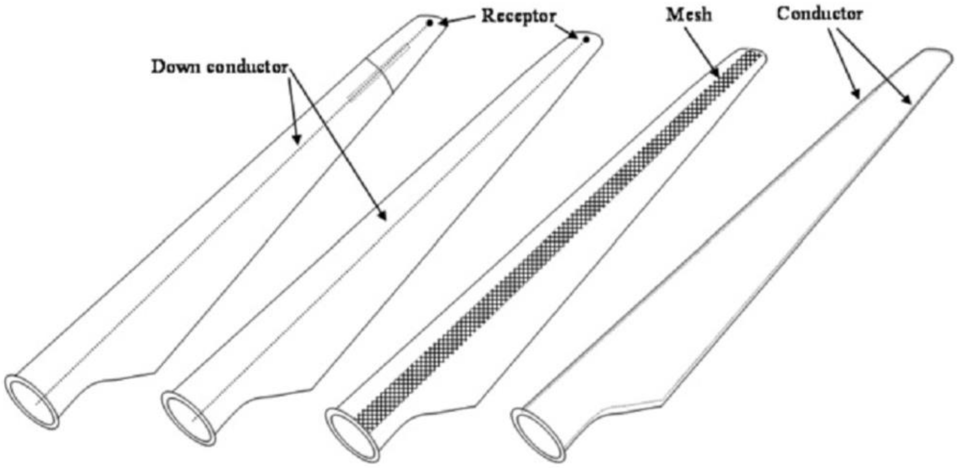

Figure 6: Typical lightning protection configurations (Peesapati, 2011)

6 Structural damage

Before going into the available damage statistics of blades in detail, it is worthwhile noting that recorded instances of total blade failures (where the blade detaches from the turbine, or breaks) are very uncommon. An overview of reported wind turbine accidents including blade failures is provided in (Farms, 2020). The total number of blade failures per year in that overview is less than 23 on average, with a maximum of 36 (on a world-wide wind turbine population of >300,000). The exact causes of the blade failures are not specified in this database.

Damages seen in the field are not extensively reported, so the actual amount of structural damage to blades that results in downtime and repair is much higher that stated in the previous paragraph.

In a phone survey conducted in 2008 with 4 wind power plants including over 400 turbines, it was reported that 80 blades were replaced (of which 40 blades in one farm, due to non-structural issues). This implies that ca. 3% (40 blades in 400 three-bladed turbines) of the blades in these 4 power plants failed due to other issues, potentially including structural issues. This survey was then the basis for an extensive effect-of-defect structural materials research, based on potential manufacturing-induced failures, culminating in a thorough report on the effect of in-plane and out-of-plane waviness in spar cap laminates (Nelson, 2017). A failure rate (per turbine and year, normalized with total recorded failures) for turbines >1MW is reported by Reder (2016), at ca. 4% . An overview of failure rates for rotors from various reports is reported by (Branner & Ghadirian, 2014) to be between 0.04 and 0.29 (annual rotor failure rate).

(Marín, 2009) and colleagues performed a failure analysis of a systematic failure that occurred in the blade root–-airfoil transition in a 300kW blade in 2005, and concluded that this was the result of a combination of aggravating factors related to design (excessive ply-dropping over a short distance, eccentric loading) in combination with a starter crack in the gel-coating, as well as manufacturing defects (including lack of resin). They did post-mortem research, including taking slices of the section under investigation and ashing parts of that section to verify the lamination plan.

Since blades are safe-life designed, the occurrence of structural damage (that is not related to lightning strike or erosion damage) typically gives rise to the suspicion of manufacturing defects.

Damages from full-scale tests in laboratories are reported to some extent, but it is always the question to what degree the reported damage relate to the damages in the field.

(Bent F. Sørensen, 2004) and colleagues presented the results of a post-fatigue series of static tests-to-failure on one Vestas V52 25-meter long blade, tested in different parts and configurations. The damage observed in this particular test blade was classified into 7 types, however, these types were derived from one blade, meaning that some damages might be typical for that particular design, and not representative of typical damage in the field. Further, the damage was observed after three full-scale quasi-static tests carried out on the same blade and leading to blade failure. Neither the type of loading, nor the fact that these are post-mortem observed damages, increase the relevance for damages targeted by Structural Health Monitoring (SHM)-techniques during operation. Despite their laboratory environment character, the damage types reported earlier by Soerensen are reported by (Ciang, 2008) as well as (Shohag, 2017) to be ‘typical’.

7 Conclusions

This study conducted a thorough literature review to guide the development of a (autonomous) remote wind turbine blade inspection system, principally by defining guidelines on the damage that the sensing sub-system should be able to detect when performing an inspection.

Current blades have a somehow typical structural lay-out (spar caps, webs) augmented with aerodynamic geometry components (sandwich panels), and consist of predominantly glass-fiber reinforced composites, limited amount of carbon fiber reinforcement, thermoset resins and balsa or polymer foam.

The design philosophy for a wind turbine blade currently is ‘safe life’, rather than ‘damage tolerant design’, which implies that very limited provisions are made for inspection, maintenance and repair (since all components are expected to last the entire lifetime). This also implies that the design is conservative since the benefit of damage tolerant design is the possibility to design lighter structures.

A clear picture of quality assurance systems in blade factories could not be achieved.

A review of the blade maintenance operations for 2 offshore wind farms located in the north sea, over a 2 year period, revealed that over 90% of the damages identified after inspection were LEE related. The need for replacement of lighting strike protection systems was the second most common identified damage, although nowhere close to LEE. Structural damages were present in only 2% of the inspected damages.

Most common intensity of LEE damages, present over a period of 2 years, were of stage 1 to 3 (mild). As expected, highest share of LEE reported cases were observed in the blade tip region.

Finally, it can be concluded that LEE typically results in a 2% to 4% annual energy production (AEP) loss for the most common damage type. Nevertheless, extreme scenarios could have an up to 25% loss in AEP. The study also concludes that higher energy losses are to be expected for turbines that do not have a pitch control system. Nevertheless, it should be noted that these claims are based on model predictions and wind tunnel tests. No field data or experiences from operators were found to sustain this claim. Finally, Table 3 summarizes the minimum detectable damage characteristics to be considered by a sensing system.

Table 3. Minimum detectable damages.

Type	Location	Minimum detectable depth [mm]	Minimum detectable diameter [mm]	Motivation
Leading edge erosion	20-30% outboard,	0.3	2	Critical

	leading edge. Superficial			
Lightning	Near receptors (blade tip and mid-airfoil, pressure and suction side, black spots)	0	15	Typical lightning damage, repairable
Structural (gelcoat cracks indicating deeper damage)	Trailing edge	0	Hairline, 100mm length	Larger than Quality Assurance
Structural (delamination in root laminate)	20% inboard	75	100	Larger than Quality Assurance
Structural (delamination in outer skin-core bond of sandwich)	60% inboard, sandwich panels between spar caps and leading/trailing edge	2 - 5	100	Larger than sandwich block grid size
Structural (bondline tunneling or disbond cracks)	Web-spar cap, leading/trailing edge	0 - 30	Hairline (tunneling) or 25 (disbond)	Larger than Quality Assurance

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