Green Roof Team
Sustainably Green Solutions

Understanding the Design Life of Small Wind Turbine Blades: Factors and Considerations

Author: Sofia Alonso

Table of Contents

I. Introduction

A. Significance of design life in small wind turbine blade performance and longevity

The design life of a small wind turbine blade refers to its intended operational duration or estimated lifespan under specific operating conditions. This critical factor significantly influences the blade's performance, longevity, reliability, and economic viability.

When engineering a wind turbine blade, striking a balance between maximizing performance and ensuring structural integrity throughout its design life is crucial. This optimization process enhances the blade's energy capture efficiency and aerodynamic performance while preventing premature degradation or fatigue. Design life holds great significance for blade performance, as engineers must ensure the blade's structure can withstand the various operational loads, often on the order of magnitude of 10^8 cycles.

Material selection also plays a vital role in determining the design life. More durable materials tend to be costlier contributing to increased overall initial expenses. However, longer design life yields a higher return on investment, as it extends the revenue-generating period and potentially reduces maintenance and repair costs compared to blades with shorter design lives.

Furthermore, extending the design life of wind turbine blades brings environmental benefits. It helps reduce the negative impact associated with the manufacturing and disposal of turbine components by minimizing material consumption and waste generation. Emphasizing a longer design life supports sustainability and aligns with environmentally conscious practices.

B. Overview of factors influencing the design life of blades

The lifespan of a wind turbine blade can be affected by a multitude of factors including:

- **Weather conditions:** Extreme weather conditions can significantly reduce the lifespan of a wind turbine blade. This is why blade design needs to be site specific and the wind and rain profiles of the area need to be investigated in advance. Moreover, lightning strikes can severely damage blades if lightning protection technology is not implemented.
- **Materials and manufacturing techniques:** the durability, load bearing capability and fatigue strength of materials has an impact on the design life of blades. The manufacturing process can also help either enhance or undermine material properties thus affecting the life of the blade.
- **Loads and stresses:** the number of loading cycles as well as tensile and compressive stresses blades have to continuously withstand also has an impact on the life of the blade. The larger the loads, the lower their expected lifetime.
- **Maintenance:** regular inspection and maintenance is key to ensure the longevity of blades.
- **Environmental factors:** exposure to humidity and high or low temperatures, salt, etc. can reduce their lifespan due to material corrosion.

II. Environmental Factors

A. Discussion on the impact of environmental conditions on blade degradation and fatigue

Wind turbine blades are subjected to environmental and mechanical loading during the operational service time. These include but are not limited to cyclic deformation, sand, rain, corrosive contaminants, icing, moisture, substantial temperature variation, lightning strikes, bird impacts… A detailed understanding of the effects of these events on the design life of the blade is required for a reliable prediction of failure modes, plan for maintenance and mitigate the degradation process. The graph below shows the results of a survey conducted by John Wiley and Sons to determine the most common wind turbine blade failure mechanisms.

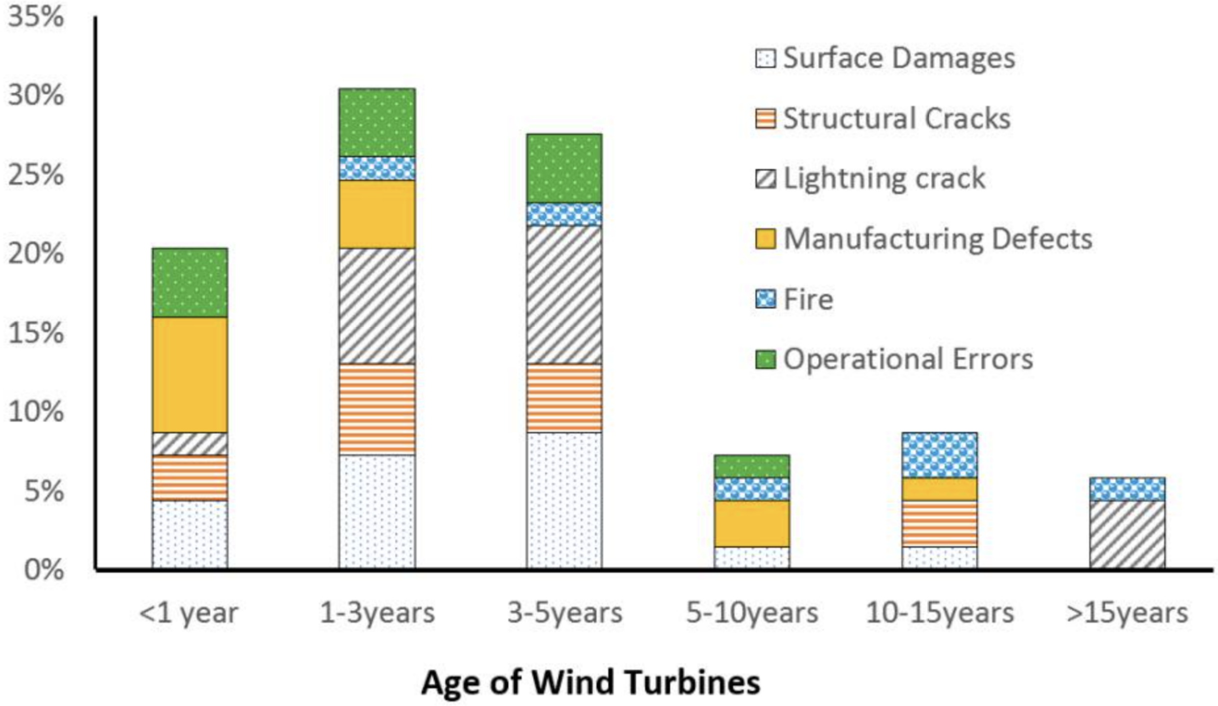

Figure 1: Results of the survey to blade service companies on failure mechanisms of blades[1]

Different regions typically show different damage mechanisms. For this analysis, the blade is subdivided into the blade tip, leading edge, trailing edge, tapered areas, ply drop and root region.

Blade tip: the speed at the tip is much greater than at the root making this region more vulnerable to erosion. Lightning usually also strikes the blade near the tip which can lead to separation of high and low pressure skins near the tip or the separation of the skins from the shear web.

Leading edge: this region is subjected to rain, hail, sand, and other impacts such as birds. If surface damage is not repaired quickly, it can lead to severe cracking and water penetration.

[1] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9101399/

Trailing edge: the failure of this area is mainly caused by edgewise moment as well as flapwise and worsion moments. It typically fails by debonding in the adhesive joint or by buckling.

Tapered areas, ply drop and root region: this is mainly the area of transition from cylinder to airfoil and this sharp transition makes this region buckling sensitive. Stress concentrators are very common in areas with thickness transitions and this can lead to ply delamination at low strains due to interlaminar shear effects in the matrix.

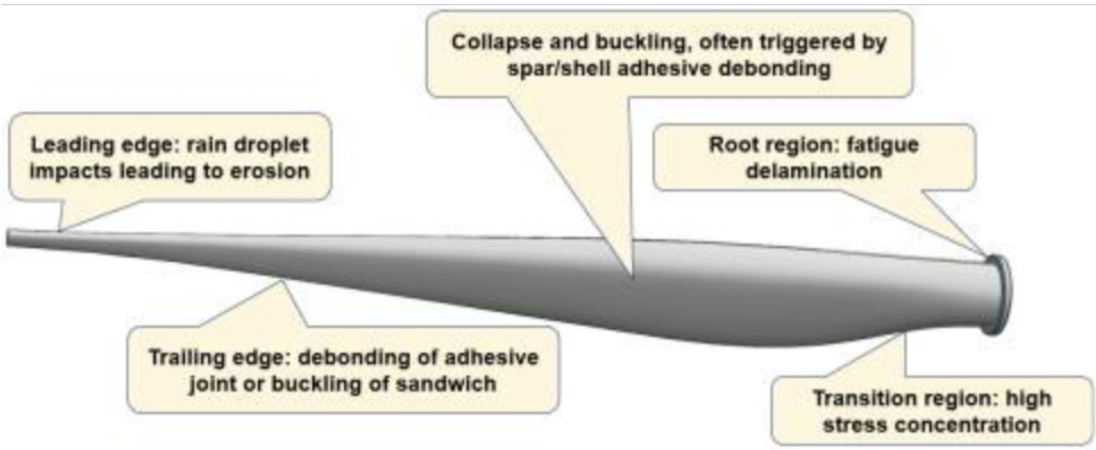

Figure 2: Locations and failure mode for each location.[2]

We can thus conclude that the most prone to fail regions due to the environment are the tip and the leading edge since the high velocity of the tip leads to higher erosion due to environmental factors such as rain.

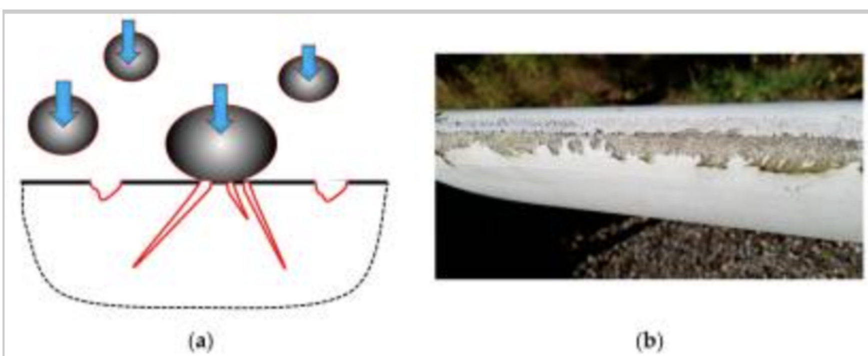

Figure 3: Blade erosion due to rain droplets[3]

[2] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9101399/

[3] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9101399/

B. Factors such as wind loads, temperature, humidity, and UV exposure

Wind speed and direction: wind is the driving force of wind turbines and has a very high impact on blade fatigue and lifespan of the rubine blade. High wind speeds lead to excessive loads, material fatigue and accelerated wear. Moreover, changes in wind direction can also vary the load and stresses potentially causing fatigue failures over time.

Icing: icing has a very negative impact on wind turbine blade aerodynamic performance and safety. Icing leads to increase in mass on the blade, changes in the aerodynamic shape, unusual tower vibrations, less torque and power losses. Annually, it leads to a reduction in energy production of 17% and reduces the power coefficient in the range of 20-50%. Techniques for icing mitigation include passive techniques such as hydrophobic paint or active techniques such as heating the blade with built in electric foils or heated air that are utilized to remove ice from the blades. Moreover, the blade imbalances due to increased weight and poor weight distribution can cause additional stress on the blades in regions that are not reinforced or typically high load bearing regions contributing to increased fatigue.[4]

Rain: rain promotes the erosion of primarily the blade's leading edge increasing the surface roughness and increasing the aerodynamic drag coefficient of the blades, leading to lower power performance and losses in energy production. The loss in energy production can be as high as 25%.

Temperature: extreme hot and cold temperatures can also have very severe effects on fatigue of blades. In particular, temperature fluctuations which cause thermal expansion and contraction lead to the formation of cracks and delamination. Temperature fluctuations can also alter the mechanical properties of materials, making them more susceptible to fatigue.

Humidity: can lead to blade erosion and corrosion, this is of particular concern in coastal regions. Moisture penetration can weaken composite materials, reducing the blade's structural integrity.

Pollution and other contaminants: these particles can adhere to the blade's surface and cause surface erosion.

UV radiation: prolonged UV exposure can break down the molecular structure of composites used in blades and reduce material strength, stiffness, and overall mechanical properties which can lead to a reduction in the lifespan of the blade. The leading edge is the most vulnerable part to erosion caused by UV radiation. Radiation can also contribute to the formation of microcracks and delamination.

[4] https://link.springer.com/article/10.1007/s13369-021-06357-1

III. Material Selection for Extended Life

A. Considerations for selecting materials with enhanced durability and longevity

The high strength to weight ratio of composites when compared to other engineering materials such as metals or woods is significantly reducing the weight of wind turbine blades. Currently the majority of blades are made out of fiberglass and assembled by hand. If the transition to carbon fiber and automated machining like CNC process happens, the weight of the blades could decrease by 25% with improved mechanical performance.[5] In addition, lighter weights lead to lower loads and the rotor and the tower portion of the blade could also considerably decrease in weight. A switch to carbon fiber could also increase the lifetime of wind turbine blades since carbon fiber has higher fatigue resistance.[6] The decrease in weight also improves turbine efficiency since blades can be manufactured to be 5m/16 feet longer than traditional blades, increasing the sweep area of blades without any additional weight gain.[7]

The use of carbon fiber also comes with its disadvantages which is an increase in cost and is very vulnerable to fiber misalignment. Carbon fiber can be up to 10 times more expensive than carbon fiber. Other composite alternatives to carbon fiber/epoxy are glass fiber/epoxy (which is the most widely used in industry because of its lower cost despite its weight to strength ratio and lower fatigue resistance) and kevlar/epoxy is another alternative with better performance than glass composites but lower performance than carbon fiber composites.

However, all these fibers are non-biodegradable and have negative effects on the environment because of the lack of recyclability of such at the end of their design life. Natural fiber composites such as pineapple/epoxy, sisal/epoxy, bamboo/epoxy, flax/epoxy are partially biodegradable and being researched to use in the wind turbine blade industry. Sisal/epoxy and flax/epoxy composite materials in fact offer high tensile strength, have low weight, and have good fatigue resistance.[8]

An alternative to the matrix, which as of today it is often epoxy resin, are thermoplastics. Thermoplastics are more eco-friendly and can potentially show better properties than epoxy resins including improved fatigue resistance. NREL built a 13m thermoplastic blade and tested it at the Flatirons Campus. Thermoplastic blades have similar stiffness to an epoxy blade. After simulating 20 years to evaluate durability, the blade showed 5 to 7 times higher levels of structural damping than the epoxy blade suggesting that this can expand the lifespan of the entire

---

5 https://www.windsystemsmag.com/decreasing-turbine-weight/

6 https://www.sandia.gov/labnews/2021/01/29/carbon-fiber-for-wind-turbine-blades-could-bring-cost-performance-benefits/

7 https://www.compositesworld.com/articles/wind-turbine-blades-glass-vs-carbon-fiber

8 https://www.mdpi.com/2504-477X/7/5/197#:~:text=One%20of%20the%20most%20crucial,%2C%20durability%2C%20and%20environmental%20resistance.

turbine. Thermoplastics also have the advantage of being able to reheat at just the point of repair and reshape facilitating repair jobs and also perform better in marine energy applications, making them suitable for offshore wind turbines due to lower corrosion in such environments.[9]

B. Evaluating the performance and reliability of materials under different conditions

Before deploying any wind turbine blade, testing is crucial. With this comes replicating the harsh conditions wind turbine blades will be exposed to which can help prevent structural damage and increase the design life and reduce the cost of unplanned maintenance.

Databases that are wind turbine specific that collect environmental conditions such as temperature, UV, humidity, rain droplet size distribution… are very limited if not nonexistent. Instead, companies typically used that collected by oil and gas industries. Consequently, accelerated coating, weathering and rain erosion tests may be somewhat misleading.[10]

Apart from environmental testing, which would be more reliable with better and more site specific databases, there still is a multitude of tests that can be performed on wind turbine blades including

- **Fatigue testing** to evaluate how the blade will respond to cyclic loading due to wind variations and the rotation of the blade.
- **Impact testing** to evaluate blade resistance to impact from debris, hail, bird strikes… it assesses how well the material can absorb and distribute shocks.
- **Corrosion resistance testing**
- **Material characterization** scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR) can provide insights into the material's microstructure and preemptively identify any defects.
- **Finite element analysis (FEA)** can simulate blade behavior under different loading conditions.
- **Long-term monitorin**g can provide valuable data on material performance over the years to improve designs and material choices in upcoming designs.

[9] https://www.nrel.gov/manufacturing/comet-wind-blade-resin.html

[10] https://www.ingenia.org.uk/getattachment/74df541e-203f-4a0b-9e15-cd7c42207362/futureproofing-the-next-generation-of-wind-turbines-blades.pdf

IV. Structural Design and Maintenance

A. Design strategies for improving blade strength, resistance to fatigue, and damage tolerance

An ideal blade design provides high performance, high efficiency and competitive costs whilst meeting the industry standard of 20 year lifespan. To do this, during the design several factors are considered, including blade strength and stiffness (wing tip deflection) as well as weight considerations (of particular importance given the industry's tendence of increasingly longer blades to maximize sweep area).

Composite materials seem to be a good solution for maximizing strength while minimizing weight since they have a very high specific strength and specific stiffness, however there are many variables that need to be considered such as type of composite, type of matrix, fiber orientation, stacking sequence, thickness…

There is aerospace proven optimization software such as HyperSizer, developed by NASA as a structural sizing and optimization software package and currently commercialized by Collier Research Corporation. HyperSizer evaluates composite and metallic designs and searches for ways to minimize weight and maximize strength. This software has been extensively used in the design and validation of NASA Ares I and V Launch Vehicles as well as Goodrich engine structures and Bombardier's Learjet. The software's crossover to the wind industry can be very powerful and Collier and Sandia National Labs have begun collaborating to use HypeSizer to optimize a new 13.2 MW 100 meter blade to demonstrate the software's capabilities. [11]

HyperSizer optimization starts with a finite element analysis (FEA) to determine internal loads and deflections. These results are then used to conduct a trade study for a blade characteristic which could be laminate strength and stability. It automatically analysis millions of possible designs in a ply-by-ply, even finite-element-by-element process, to a multitude of failure criteria- The design is then exported again into the FEA and the iterative process is repeated for other additional characteristics such as stiffness until a final blade design is reached that meets a target for strength, weight, performance, and cost.

HyperSizer can also be used to complement FiberSIM (open software that offers capabilities for analysis and design within the manufacturing environment allowing the user to find the most feasible product design for composites[12]) and CATIA (3D CAD design). The combination of these software can help the designer optimize

- The total number of plies dropped
- The simultaneous occurrence of ply drops and adds
- The alternation of ply drops with continuous plies
- The number and pattern of laminate zone sand transition boundaries

[11] https://www.windsystemsmag.com/improving-wind-blade-manufacturability/

[12] https://oneplm.com/fibersim/

B. Importance of regular maintenance and inspections for ensuring prolonged design life

Regular inspections and maintenance play an important role in failure prevention and ensuring the prolonged design life of wind turbine blades. Wind turbine blades are complex structures and curvatures based on multilayer structures with varying thicknesses made from fibers and resins such as epoxy. Despite being designed to operate for a minimum of 20 years, there are certain challenges that reduce the lifespan of blades such as being damaged by wind particles and other environmental factors, being constantly exposed to strong tension and twisting… Technology is thus needed to periodically ensure the conditions of the blade and start sustainable predictive maintenance programs which to this date are not yet widely used. Companies such as Arborea Intellbird are starting to create multirotor drones for the inspection of wind turbine blades. Whereas other previous technology such as Remotely Piloted Aircraft Systems (RPAS) took pictures of the entire structure with high resolution, which provided an excess of information and data that could not be possibly processed effectively, drones can provide "multisensory measurements and generate high-quality repeatable data".[13]

Onsite inspections are still crucial for the viability of wind turbine blades, and developing software to handle this information effectively and efficiently is also key. There are some software platforms such as WEb Blade that allow the inspector to solve the processing step by automating the inspection of data and generating blade mapping and measuring the severity of damage more accurately. This technology has already been implemented by Iberdrola.

V. Testing and Validation

A. Testing methodologies to assess the design life of small wind turbine blades

- **Fatigue testing:** used to verify the durability of the blade with a sinusoidal loading profile. They may contain anything between 1 to 5 million loading cycles. They are usually performed in the flap and lead-lag directions. There are two types of tests: single axis testing ((both flapwise and edgewise loads are applied separately) and dual axis testing (both flapwise and edgewise loads are applied simultaneously thus simulating the environment the blade will be exposed to more accurately) and two methods can be used to apply these loads: forced displacement (use long strong actuator or bell cranks and pushrods to force the blade to a prescribed displacement, it works well in the edgewise direction but not in the flapwise direction because too long of actuators are required) and resonant oscillation testing (uses an oscillating mass driven by an actuator attached to the blade through a frame).[14]

[13] https://www.mapfreglobalrisks.com/en/risks-insurance-management/article/in-depth-digital-inspection-of-wind-turbines/

[14] https://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1571&context=theses

- **Static load testing:** the main goal is to see the blade's deflection under a load to see the critical load before failure. Results of a deflections analysis can be seen in Figure 4.2.

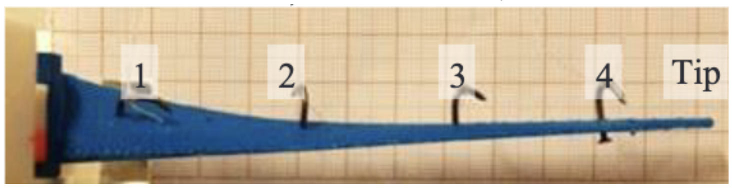

Figure 4.1: 3D printed blade subjected to the test

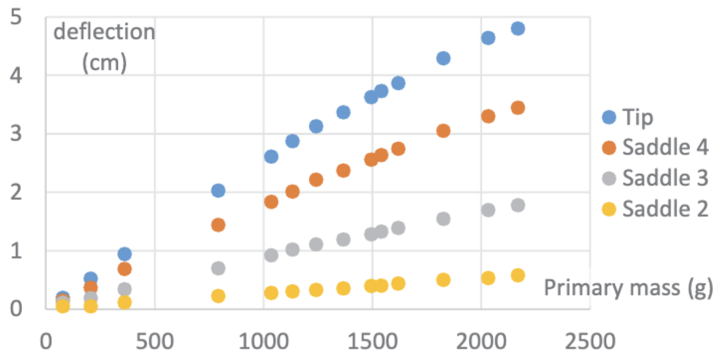

Figure 4.2: Results of a deflection analysis on a 3D printed blade.

- **Damage tolerance testing**: There are several tests that can be conducted to evaluate the damage tolerance of wind turbine blades, these are summarized in Figure 5.

Type of Testing	**Output**
Double Cantilever Beam	Mode I fracture toughness (G_{IC}), failure modes
End-Notch Flexure	Mode II fracture toughness (G_{IIC}), failure modes
Drop-Tower Tests for Impact Resistance	Energy absorbed, peak force, damage extent
Compression After Impact	Compressive failure loads/residual strengths for varying impact energies
Tension or Compression Tests of Notched Laminates	Failure stress, modulus retention ratio, stress concentration factor

Figure 5: Common tests in damage tolerance evaluations and associated outputs[15]

[15] https://www.osti.gov/servlets/purl/1825355

- **Environmental exposure testing:** erosion by UV exposure, rain, dust, humidity, temperature, ice etc. can lead to detrimental effects in the blade's lifespan and performance, it is for this reason that tests to evaluate how effective protective coatings or anti-icing technology are. One of the most commonly performed tests in wind turbine blades is the rain erosion test.
    - Rain erosion testing (ASTM G73-10) can simulate, and accelerate, erosion and exfoliation of the surface of wind turbine blades and help improve the longevity and erosion resistance of wind turbine blades. Typically, profiles are coated by the designer with the leading edge protection material that they want to test. In the testing facility, the specimens are accelerated to a speed (typically 160 m/s) and then the nozzles simulate a droplet size of 1-2 mm and a rainfall intensity of 30-35 mm/h for a specified interval of times. Every 30 minutes, images are taken to document the erosion process of the leading edge (the most affected region). A sample result is shown below. The surface with the lowest slope (surface 3) has the highest rain erosion resistance. [16]

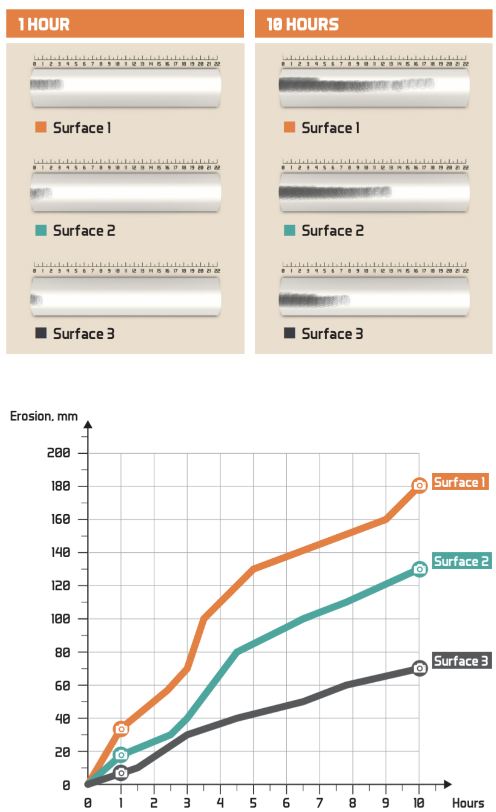

Figure 6: Rain erosion resistance of 3 sample blades

[16] https://www.polytech.com/media/1077/polytech-rain-erosion-astm-g73-10.pdf

- **Modal analysis:** used to identify natural frequencies, damping characteristics and mode shapes of wind turbine blades. There are two excitation techniques, the transient excitation or free vibration or the continuous excitation of forced vibration. Continuous excitation is typically performed with electromagnetic or hydraulic excitation to produce swept sine vibration, white noise excitation… whereas the transient excitation is usually associated with an impulse force loading or a release from an initial deflection. An example of the test results are shown in figure 7.[17]

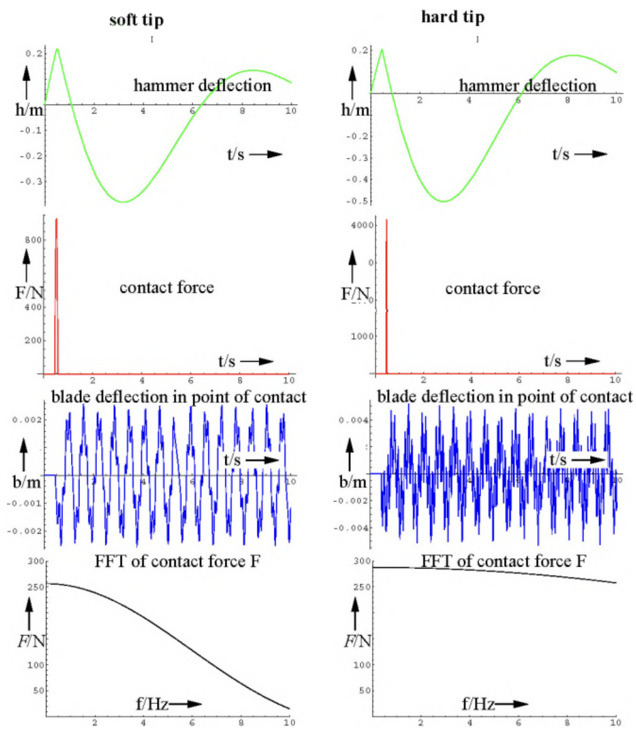

Figure 7: Hammer excitation of the blade applying two different stiffnesses of the hammer head.

- **Non-Destructive Testing:** uses methods such as ultrasonic testing, radiography and thermography to inspect the blade's internal structure for possible damages that are not detectable by a visual inspection.
- **Computational Simulations:** FEA can also help model the blade behavior under different loading conditions.

[17] https://www.osti.gov/etdeweb/servlets/purl/20303832