RP 301

Recommend Practices for Wind Turbine Blades

AMERICAN CLEAN POWER

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Preface

The following Recommended Practice is subject to the Safety Disclaimer and usage restrictions set forth at the front of AWEA Operations & Maintenance Recommended Practices, Second Edition. It is important that users read the Safety Disclaimer and usage restrictions before considering adoption of any portion of this Recommended Practice. Furthermore, it is the responsibility of the user or the inspector to adhere to industry best practices for safety procedures, which involve conducting a hazard assessment, identifying and recognizing critical situations, such as an imminent structural failure, before starting any wind turbine foundation inspection or maintenance activities.

Acknowledgements

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1 Introduction

This Recommended Practice provides detailed recommendations for wind turbine blade maintenance, bringing forth the clean energy industry's best practices for inspection, transportation, repair, and maintenance. It is designed to support asset owners, operators, third-party service providers, and maintenance personnel in optimizing blade longevity and performance.

The recommendations apply to all blade types. While the document is based on general industry best practices, it should be used in conjunction with original equipment manufacturer (OEM) specifications, regulatory guidelines, and site-specific maintenance protocols.

The scope of this guide encompasses all major aspects of wind turbine blade maintenance, from initial inspections and transportation considerations to repair strategies and long-term maintenance planning. It covers both external and internal blade inspections, preventive maintenance techniques, and structural repair methods, ensuring a holistic approach to blade care. Additionally, safety procedures and technician skill requirements are outlined to support safe work practices. This Recommended Practice aims to enhance operational efficiency and mitigate the risks associated with blade degradation and structural failures.

Figure 1: Hopkins Ridge Wind Farm

2 Blade Maintenance Program Considerations

2.1 Overview

Blade maintenance throughout the entire life cycle for safe and reliable operations at reasonable costs consists of the following key elements:

- Establishing a blade maintenance program
- Effective planning and management of blade inspection and repair campaigns
- Establishing requirements for qualification of third-party vendors or independent service provider contractors and blade maintenance technicians
- Documentation and reporting of blade inspection and repairs

2.2 Blade Maintenance Program

A blade maintenance program is intended to establish a documented strategy, plan, and requirements for inspection and repair throughout the full operational life cycle as follows:

- Pre-commissioning
- Post-commissioning
- Operation
- Lifetime extension or decommissioning

Figure 2 illustrates the general life cycle of blade operations in a wind farm project, with examples of inspection and repair objectives that are considered in a blade maintenance program.

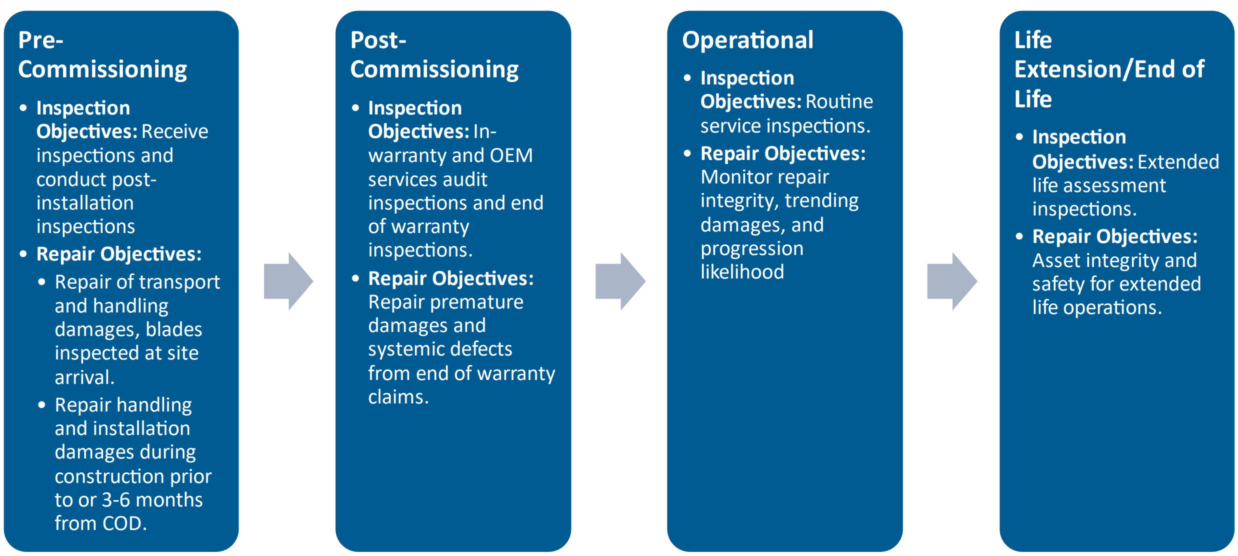

Figure 2: Wind farm/blade life cycle and where inspection and repairs typically are done

Plans and requirements continually evolve throughout each phase of a wind farm life cycle. Tailored inspection and preventive or corrective repair strategies for blades are developed to address the risk and economic needs of the wind farm based on a continuous cycle of:

- Condition monitoring
- Risk assessment
- Corrective maintenance and PM
- Continuous improvement (see Figure 3)

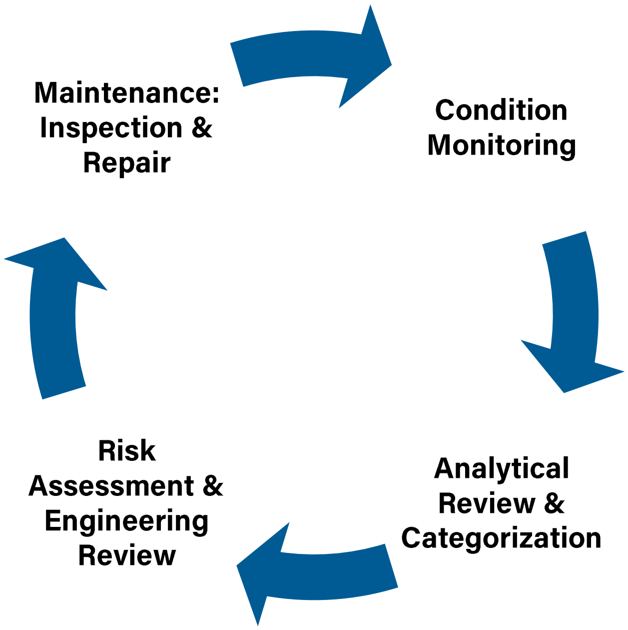

Figure 3: Continual cycle of blade operations and maintenance

2.3 Blade Inspection and Repair Campaign Management

Blades are typically inspected by a condition monitoring principle on time-based intervals. In current industry practice, it is common to perform annual blade inspections with a visual method, either using a ground-based or drone-mounted camera.

In general, repairs are scheduled as preventive and/or corrective based on findings observed and tracking of the condition and progression of the damage. Findings from inspections are typically reviewed and assessed on its impact to the blade's structural integrity before a decision is made to prioritize and plan for repairs within the upcoming repair season or to defer repairs and put in place a plan for monitoring (see Figure 4).

It is possible that the conditions of the findings previously planned for repairs exhibit minor or major progression during the time lapse (sometimes six to nine months) between repair scoping, budgeting, and securing blade maintenance teams to mobilize to site for the start of the repair campaigns. As a result, adjustments to and re-prioritization of the blade repair scope and budgets may be updated based on the observed conditions of the previously identified damage using the following year's annual inspection campaign results (if available) or a follow-up inspection at the start of the repair.

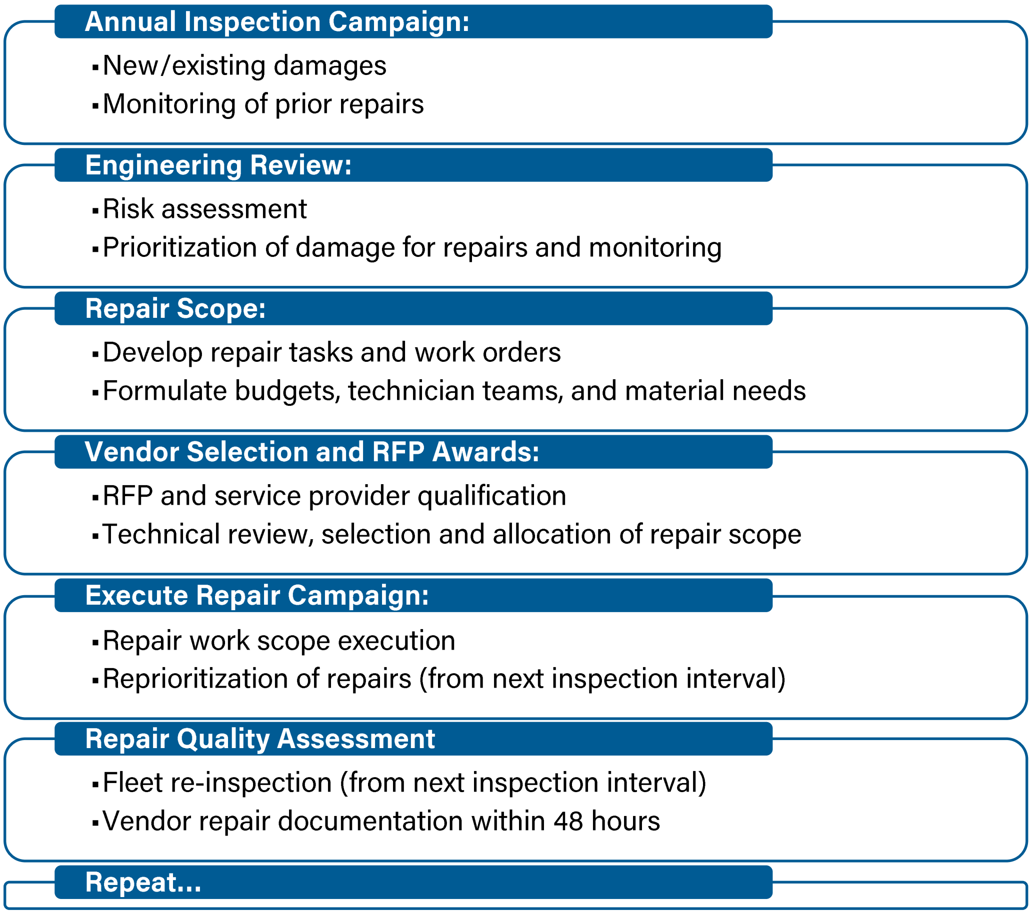

Figure 4: Blade Repair Management Cycle

2.4 Blade Repair Service Providers

Service providers for blade inspection and repairs should document technician training such as skill level and capabilities (via type of inspection methods and types of blade repairs), training and certification dates, and field experience (via years of inspections and repairs).

The training of technicians for blade maintenance should include general knowledge of blade structural design architecture, materials, and manufacturing process. In addition, training requirements for blade maintenance personnel should cover general safety certification, composites and repair process, and methods for safe access (including external and internal access and of blades and external access using assisted blade platforms, ropes, man-baskets, and other methods).

The responsible party contracting service providers or hiring blade technicians should have a system to manage requested data so that it enables evaluation of vendor pre-qualification requirements, safety and composite repair training certifications, quality records for tracking timeliness of repairs and inspection, and the provision of maintenance documentation.

2.5 Blade Data Management

Blade OEM documentation that is typically requested at the time of purchase or service lift of blades is helpful for understanding the make, construction, and specification of blades within the operating fleet.

Blade-specific information that should be sought after in the OEM documentation includes the following:

- Allowable environmental operating and serviceable limits
- Blade serial number, manufacturer, manufacturing location, and batch production dates
- Nominal blade manufacturing weight (total with or without bolts), center of gravity location, including tolerances for blade weight, balance mass, mass moment deviation within a rotor set, and center of gravity location tolerances
- Blade balancing procedures for aerodynamic and mass imbalances, including balance box location(s), allowable balancing materials, and blade pitch angle alignment tolerance
- Specifications for blade length, root diameter, bolt circle diameter, maximum chord and tip chord lengths, prebend or tip offset from blade centerline
- Root connection type (i.e., T-bolt or embedded insert), number and type of bolts, including corrosion protection specification
- Blade structural configuration (structural shell, spar box, etc.) definition, including the number of spar caps and shear webs
- Blade handling, transporting, and installation manuals that include allowable lifting and handling locations and processes
- Specifications for positioning and part numbers of aerodynamic devices, such as vortex generators, trailing edge serrations, stall barriers, and diffusers
- Leading edge protection type and length extent applied from the factory, including recommended maintenance interval of the leading edge
- RAL color specification and surface finishing requirements for coating and filler material applied for UV protection of blades
- Manuals for operation and maintenance of blade subcomponent systems, such as the LPSs, anti-icing and de-icing systems, and in-blade sensor systems

Blade inspection records should include reports with consistent details of findings, photos documenting the damage or defect conditions with photocard detailing minimum information to establish traceability to the site location, turbine ID, blade serial numbers, inspection dates, method and equipment used, and inspection team or company to enable consistent pattern tracking damage or defect occurrence or recurrence, criticality or severity development, and dimensional growth or condition progression. Consistent inspection cycles and supporting documentation of findings serve as a baseline to track the likelihood of critical damage progression and to detect early signs of damages or defects that can be addressed with a preventive repair campaign to avoid escalation of maintenance costs and downtime.

Blade repair records should include specifications and requirements for safety protocols, training and qualifications of technicians, photos documenting the repair materials, laminate plan and process, and critical to quality checkpoints to enable quality assessment of repairs. If OEM repair instructions are not available, it is recommended that the repair specifications should be designed and engineered with expert review prior to executing the repair. Consistent recordkeeping of blade repairs serves as a baseline to standardizing the common damage repair processes and refining quality requirements for continuous improvement. Additionally, the insights that are available in repair reports provide further details as to whether the potential root causes for the occurrence of the damage or progression of the defect have been fully eliminated or require further investigation for an engineered corrective solution.

Blade maintenance documentation should be prepared for every inspection and repair performed, and every effort should be made to retain all inspection and repair records for the intended operational life cycle of the blade. Preferably, when the inspection or repair is performed by third-party service providers or the OEM, the inspection and repair reports should be requested by the owner-operator and delivered as soon as possible. In some cases, the completion and delivery of blade maintenance documentation is a condition for returning the wind turbine to operations. A centralized database such as a blade asset and maintenance management platform that is designed to store comprehensive blade OEM, inspection, and repair documentation throughout its life cycle is recommended to enable ease of implementation.

Figure 5: AES Mountain View Wind California

3 Inspections

3.1 Areas of Inspection

The purpose of inspections is to enable the detection, interpretation, and response to irregularities in or damages to the blade. Visual inspections of all aspects of the wind turbine blades should be performed at least every two years, unless otherwise specified in the wind turbine maintenance manual. Selected additional inspections may be needed after environmental incident events (discussed in Section 3.7.1) or when subsurface or serial defects are suspected (discussed in Section 3.6). Wind turbine blades need to be checked in detail, and their condition is to be documented, regardless of whether damaged or other anomalous findings are present. The documentation of findings is discussed in Section 3.3 and Section 3.8. The blade inspection data should be checked in detail by a reputable technical expert. A breakdown of the blade by its major components is provided in Table 1, along with recommended areas of inspection and damages. Note that not all aspects of this table are relevant to all blades.

Sometimes, the response to inspection findings is the decision to repair the blade._Blade repair costs can increase as the need for repair grows and may eliminate the ability of the blade to be repaired altogether. For example, an open damage on a blade may allow moisture ingress into the blade core materials, which could lead to much more extensive damage and thus, a more costly repair.

Figure 6: AES Laurael Mountain Wind Farm Facility, West Virginia

Table 1: Areas of Inspection

Component to Be Checked	Description	Inspection Checkpoints
Blade Body		
Leading Edge	The leading edge is the region at the front of the airfoil. This portion of the blade hits the wind first during normal operation. The aerodynamic shape and smoothness of the leading edge significantly impact the turbine's annual energy production.	The leading edge should be inspected for evidence of leading edge erosion and transverse and longitudinal cracks.
Root	The blade root is a thick laminate cylinder. It transfers the bending moment of the blade to the pitch bearing in a uniform way.	Special consideration should be given to checking for crack or delamination damages at or near the blade root. Consider performing internal inspections of the root in addition to periodic external inspections.
Shear Webs	The shear webs are a reinforcing material internal to the blade shell and carry the shear loads of the blade; functionally I-beams.	Shear webs should be inspected for evidence of material damage and laminate defects. Special attention should be paid to the bonding of the web feet for continuity and any delaminations.
Shell	The shell of a blade is composed of a combination of laminate and core material. The external shell of the blade body is aerodynamically shaped to generate lift and is coated with a protective topcoat. The internal shell does not have a protective topcoat, so the laminate material is visible.	Both internal and external portions of the blade should be inspected for evidence of damage (such as cracks, holes, chips,, and delamination), manufacturing defects (such as air inclusions), and other anomalous findings (such as offset positioning of auxiliary components). The outboard third of the blade (i.e., near the tip) should be visually checked for evidence of a lightning strike, such as burn marks and regions of delamination. In addition, the external portion of the shell should be visually inspected for evidence of drainage and oil contamination. The internal portion of the shell should also be inspected for evidence of manufacturing defects, such as dry fibers, laminate wrinkles, air inclusions, and gaps in the layup. The

Component to Be Checked	Description	Inspection Checkpoints
		blade pitch angle and moment balance should be documented.
Spar Caps	Spar caps are sheets of mostly unidirectional laminate fibers. Spar caps are intended to resist torsion, increase flapwise stiffness, and carry the shear loads from the webs to the root.	Externally, spar caps, including adjacent shell panels, should be analyzed for cracks, wrinkles, and surface delaminations. If the spar cap is made of carbon fiber, pay close attention for any lightning flashover damage. When inspecting spar caps internally, additional focus should be given to inner skin disbonds at the location of the web's adhesive bonds.
Trailing Edge	The trailing edge is the point at the back of the airfoil (opposite the leading edge).	The trailing edge should be inspected externally for evidence of bond splits or transverse cracking and internally for evidence of bond splits or adhesive voids.
Auxiliary and Add-on Components		
Drain Hole	Most modern wind turbine blades have drain holes to allow liquid material inside the blade to exit.	Drain holes should be inspected for clogs because clogged drain holes can lead to more severe lightning damage due to the rapid expansion of trapped liquid in the blade.
Flow Elements	Also known as aerodynamic devices, the flow elements are designed to affect the airflow around a blade to improve performance. Examples include turbo rills, vortex generators, leading edge turbulator or "zig-zag" tape, micro swirl prong bands, stall strips, and gurney flaps.	If a blade has flow elements, they should be visually inspected for their presence (to ensure that they have not fallen off) and for full attachment to the blade (to ensure that they are not hanging off). Flow elements should also be inspected for indications of lighting damage, such as scorching.
Leading Edge Protection (LEP)	LEP is a protection applied the leading edge of the blade (typically the last one-third of the blade). LEP can be paint, tape, shell, or precast shields. It is intended to provide resistance to environmental factors, such as erosion, rain, dirt, or bugs.	LEP is not mandatory. If it is present, confirm that the material is not peeling off and that the shell is not eroding.

Component to Be Checked	Description	Inspection Checkpoints
Lightning Protection System (LPS)	Modern blades are equipped with an LPS, which is designed to provide a preferential path to ground for lightning strike energy to prevent the energy from traveling through and damaging other turbine components.	IEC 61400-24 requires field testing and inspection frequencies to be defined by the blade manufacturer. The LPS should be inspected, tested, and maintained according to the turbine operations and maintenance manual at a minimum. If not defined by the manufacturer, IEC 61400-24 requires yearly physical inspection and continuity testing every two years for systems of lightning protection level (LPL) I and II and every four years for LPL III and IV.
Rain Collar	Rain collar is a sleeve at the root of the blade that protects the pitch bearing and hub from water and consequently corrosion.	Confirm that the rain collar is present and located in the correct place. Check the rain collar for damages, such as cracks.
Tip Extender/Jointed Blade Tip	Also known as a rotor blade extension, this is a retrofit that is pulled over the end of a blade, intended to increase the length of the blade and thus the energy production of the turbine. In a similar vein, some larger wind turbine blades are formed in two separate sections and joined together onsite.	The method of attachment of the extender/blade joint determines the inspection checkpoints. If the tip extender is bolted on, it should be checked for looseness and corrosion at the bolts and weld seams. If the extender is composite and attached via adhesive the adhesive bonds between the extender and the blade should be visually inspected for separation, cracks, defects, or delamination. The tip itself should be inspected visually for the same defects as the rest of the blade body.
Tip Stall Mechanism	Also known as deployable tips, this is an older technology and is not commonly included for blades longer than 30 m because the components require extensive maintenance. Deployable tips are intended to increase braking force to prevent turbine runaway situations.	For blades that do have a tip stall mechanism, the tip stall mechanism should be inspected regularly for function, play, grime, alignment, and cracks. Subcomponents to inspect include the spring system, guide tube, damping plate, index pins, bolts, and crossbolts. The spring system used to deploy the tip is susceptible to fatigue damage over time.

3.2 Critical Regions

The geometry and physics of wind turbine blades have a strong influence on the regions of the blade that are most susceptible to severe damages. These regions include high-velocity regions, transitional and tapered regions, and interface regions.[1]

High-velocity regions include the blade tip and leading edge (Figure 7). Due to the physics of rotating objects, the blade's tip is moving at a much greater linear velocity than the root. This means that impurities in the air, such as rain, hail, and sand, strike the blade tip at very high speeds. The leading edge of the blade is the portion of the blade that is oriented into the wind and therefore takes the initial impact of impurities in the air. As discussed in Section 3.6, this makes the tip and leading edge of the blade susceptible to more severe impact and erosion damage compared with the rest of the blade. Other damages that are common in this region include damage due to lightning strikes, such as holes, delamination, chips, and scorching, and auxiliary component damage, such as damage to lighting receptors and vortex generators.[2]

Transitional and tapered regions include the shape transition region where the root cylinder transitions to the more complex airfoil shape and ply drops wherein the number of laminate layers is reduced as the distance from the root increases (Figure 7). These areas are more susceptible to local interlaminar stress concentrations due to geometric complexity, which can result in laminate panel buckling at the maximum chord, or ply delamination at areas of thickness transition.[3] It is also important to consider the structural integrity of the root of the blade because the root is one of the most highly loaded portions of the blade. Cracks at or near the root of the blade are considered structurally critical. Manufacturing defects, such as dry fibers or laminate wrinkles, can exacerbate issues in transition and tapered regions.

Interface regions include adhesive joints, such as between the shear webs and blade shell, and bondlines, such as the trailing edge. Shear webs carry the shear loads of the blade, whereas the spar caps carry the shear loads from the webs to the root. Disbond of the shear webs from the blade at the root transition zone is becoming an increasingly common cause of blade failure as blades grow larger.[4] The trailing edge is susceptible to failure at the adhesive bond because of peeling stresses and to buckling failure of sandwich panels.[5] Trailing edge bond splits can lead to full unzipping, also known as banana peeling, of the blade if appropriate mitigation or repair

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[1] Mishnaevsky Jr., L. Root Causes and Mechanisms of Failure of Wind Turbine Blades: Overview. *Materials (Basel)* 2022;15(9):2959. https://doi.org/10.3390/ma15092959.
[2] Haus, L. and Myrent, N. Wind Turbine Blade Maintenance: Nomenclature, Visual Inspection, and Anomaly Classification. EPRI: 2023. Product ID: 3002026664.
[3] Haus, L. and Myrent, N. Wind Turbine Blade Maintenance: Nomenclature, Visual Inspection, and Anomaly Classification. EPRI: 2023. Product ID: 3002026664.
[4] Bladena. Bladena ApS' Post. *LinkedIn*, 16 June 2021, www.linkedin.com/posts/bladena_torsion-in-blades-activity-6810785085491621888-sDxl (accessed 12 December 2023).
[5] Haus, L. and Myrent, N. Wind Turbine Blade Maintenance: Nomenclature, Visual Inspection, and Anomaly Classification. EPRI: 2023. Product ID: 3002026664.

measures are not taken. Manufacturing defects, such as bond voids, can exacerbate issues at interface regions.

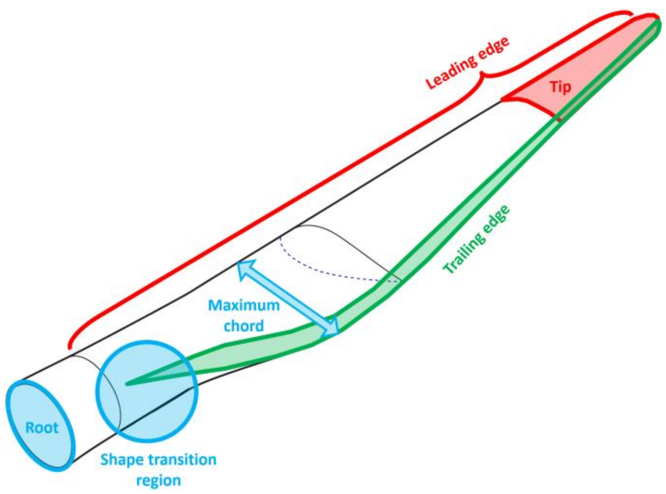

Figure 7: Illustration of the critical regions of a blade. Modified from Bladena, *Wind Turbine Blades Handbook*, 2022 ed.[6]

It should be noted that critical regions can vary due to several factors, including blade design, age, manufacturer, and operating environment. The critical regions described in this section are intended to be generic and should be applicable to most blade eras and designs, but it is important to consider your own unique blades, their operating environment, and any information provided by the blade manufacturer either in the original operations and maintenance (O&M) manual or as an update to the recommended blade maintenance practices.

3.3 Pre-Purchase Audit

In addition to the inspections detailed in Section 3.1, documentation on the blade set should encompass the blade weight, the blade's center of gravity, manufacturing date, allowable manufacturing thresholds for defects, and repairs made to the blade before delivery, including rework to bondlines, lamination defects (i.e., wrinkles), dry spots, and leading edge reshaping. This information should be kept with the rotor set's O&M record for the life of the rotor. Per International Electrotechnical Commission (IEC) 61400-1, it is recommended that the quality system comply with the requirements of ISO 9001.[7]

3.4 Delivery and Commissioning Inspections

Depending on the owner's capabilities, delivery and commissioning inspections may be performed in-house or contracted to a third-party service. To have assurance about the quality of the blades

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[6] Bladena. *Wind Turbine Blades Handbook*. 2022 ed. KIRT x THOMSEN: 2022.
[7] IEC 61400-1, *Wind turbines – Part 1: Design requirements*. 3rd ed. International Electrotechnical Commission: 2005.

prior to commissioning, external and internal inspections can be performed. Performing only an external or internal inspection may result in the oversight of a defect, damage, or missing components as some defects, damages, and components can be found only inside or outside of the blade. During the inspection, verify any repairs disclosed in the pre-purchase audit, ensure that all components are accounted for, and inspect for any undisclosed repairs or damage.

Potential defects or damages that would not be disclosed in a pre-purchase audit could be any damage caused during transportation. Some scenarios that may arise during transportation that will affect performance of the rotor are disconnected LPS, plugged or clogged drainage holes, and impact or handling damage. Prior to commissioning, ensure that the drainage holes are not plugged and the LPS is properly connected.

The delivery and commissioning inspection may be performed after the blades have already been installed onto turbine, but the inspection will take longer compared with the inspection of blades on the ground. Other items to inspect are whether the rotor sets are installed in proper and consistent order as suggested by the OEM.

3.5 Post-Installation Inspection

It is highly recommended to perform and document a full visual inspection of all surfaces of the blade within 60 days of commissioning. The inspection should minimally include photographic documentation of the full external surface of all four sides of the blade (PS, SS, LE, and TE), regardless of whether or not anomalies are present. When reasonably feasible, documentation of the condition of the internal surfaces of the blade is encouraged as well. The purpose of this inspection is to find damage that may have occurred during handling and/or installation, and to document the baseline condition of the blade. The results of this inspection should be stored for the life of the wind park.

3.6 Ongoing Inspections

3.6.1 Overview

Part of a consistent O&M recommended practice is to have a documented, ongoing inspection plan requiring all turbines to be inspected on a regular basis. Extra inspections on problematic blades are highly recommended, as are higher inspection rates on previously repaired blades. Findings should be thoroughly documented (see Section 3.8).

3.6.2 External Blade Inspections

Currently, typical industry blade inspection practice involves periodic external visual inspections on a one- to two-year basis. External visual inspections are typically performed using an unmanned aerial vehicle (UAV or drone) but can be accomplished using various inspections methods, including the following:

- Ground-based inspection
- Rope access inspection

- UAV inspection
- Crawler inspection

3.6.3 Internal Blade Inspections

There have been numerous instances of blade damages or defects that begin internally and then slowly (or quickly) propagate externally. In these cases when the damage has progressed to the point where it is visible externally, there is a risk of a catastrophic blade failure.

The traditional method for executing internal blade inspections has involved sending humans inside of blades to visually inspect the internal surfaces and structure. This method comes with many challenges, including safety, weather impacts, and the fact that a human can physically access only about 50% of the internal blade surface. An internal blade inspection in many cases can be completed only by “confined space” trained technicians and falls under the Occupational Safety and Health Administration (OSHA) guidelines for permit-required confined space entry.

There are numerous alternative technologies and tools currently available or being studied, specifically for internal blade inspections, including the following:

- Various iterations of internal crawlers or robots
- 360-degree winched cameras
- Internal (caged) drones
- Leave behind cameras

There is no one-size-fits-all formula for how and when to complete internal inspections. An internal inspection program should ultimately be determined based on the risk of particular blades. Some potential times to consider an internal inspection could include the following:

- Initial delivery
- End of warranty
- End of contract
- On a semi-regular basis depending on the wind farms’ particular blade risk(s)
- After a significant lightning storm depending on the risk to the LPS and whether a direct hit to the turbine is either known or highly suspected

3.6.4 As-Needed Inspections

As-needed inspections are typically performed in cases where damage is suspected but the extent may not be clear, such as in the case of serial defects or the aftermath of a lightning strike. Inspection methods may include the following:

- Rope access visual inspection
- Ultrasonic inspection
- Sonic inspection (tap testing)
- Electromagnetic inspection
- Thermography
- Shearography

- Radiography
- Microwave

In all of these cases, the technician performing the inspection should have experience with the technology, its application to wind turbine blades, and what they're looking for.

Dynamic visual inspections are another type of inspection that can be performed to detect issues that are only visible when the blade is operating, such as localized buckling. Dynamic visual inspections can be conducted, as needed, with a high-speed video or camera, telephoto lens, and laser pointers.

3.7 Event-Driven Inspections

3.7.1 Environmental Incident Inspection

3.7.1.1 Overview

Immediately following an environmental incident, a ground-based visual inspection for obvious blade damage should be conducted. Based on those observations, additional inspections should be performed. Examples of common and/or critical environmental incidents are discussed in more detail in this section, along with important considerations associated with each incident type.

3.7.1.2 Lightning Events

Because lightning tends to strike the tallest object in an area, lightning strikes pose a risk to wind turbine blades. To help mitigate this risk, wind turbines are equipped with a LPS. The purpose of the LPS is to provide a preferential path to ground for lightning strike energy to prevent the energy from traveling through and damaging other turbine components.[8] A blade's LPS is designed to protect the integrity of the blade to a specific lightning protection level (LPL). IEC 61400-32 specifies four LPLs, Levels I to IV.[9] Each LPL is defined by peak current, specific energy, charge transfer, and rate of current rise. The specific design requirements are detailed in IEC 62305-1.[10] IEC 61400-24 requires that the LPS intercept and conduct the majority of strikes to the turbine without causing function-impairing damage to the turbine. Damage is expected and allowed by the standard in two cases: (1) the lightning strike exceeds the design limits of the LPS or (2) the damage does not impair the functioning of the wind turbine.[11]

The likelihood of a lightning strike is influenced by a combination of parameters, including a site's average cloud-to-ground flash density, site elevation above sea level, the time of year, the presence

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[8] McLaughlin, C. Lightning Protection for Wind Turbines: Industry Overview and Technology Update. EPRI: 2024.

[9] IEC 61400-32, Wind energy generation systems – Part 32: Operations and maintenance of blades. International Electrotechnical Commission: 2024.

[10] IEC 62305-1, *Protection against lightning – Part 1: General principles*. 3rd ed. International Electrotechnical Commission: 2024.

[11] IEC 61400-24, *Wind energy generation systems – Part 24: Lightning protection*. 2nd ed. International Electrotechnical Commission: 2019.

of nearby tall objects or terrain formations, an object's equivalent collection area, and the operational state of a wind turbine.[12] Some regions have increased instances of upward lightning in the winter (i.e., winter lightning). Upward lightning is most common during storms with low clouds and typically attaches to tall structures, especially tall structures on hill tops.[13] In addition, some research has suggested that upward movement of a wind turbine blade influences the electrical field between the turbine and clouds and may incite lightning to attach to the turbine.[14, 15] The presence and magnitude of these conditions at one's site should be considered when attempting to understand the likelihood of a lightning strike event.

Lightning strike damage is commonly found in the outboard portion of the blade, at or near the tip of the blade. It is important to note that the extent of the external damage to the blade does not necessarily reflect the internal condition of the blade. Following a suspected lightning event, the blades should be inspected for evidence of a lightning strike, including, but not limited to, laminate damage, bond damage, or damage to the LPS (Figure 8a). Laminate damage can be indicated by burnt or missing paint; charring near LPS receptors, at the blade tip, or main spar; or regions of frayed laminate or delamination. Bond damage can be indicated by a split in the trailing edge or an open tip (Figure 8b). The LPS should also be inspected for damage. A compromised LPS can be indicated by missing hardware, such as lightning receptors; disconnected, severed, or frayed LPS cable at the blade root; or heavy scorching to the various components of the LPS.[16]

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[12] McLaughlin, C. Lightning Protection for Wind Turbines: Industry Overview and Technology Update. EPRI: 2024.

[13] McLaughlin, C. Lightning Protection for Wind Turbines: Industry Overview and Technology Update. EPRI: 2024.

[14] Radičević, B. M., Savić, M. S., Madsen, S. F., and Badea, I. Impact of Wind Turbine Blade Rotation on the Lightning Strike Incidence – A Theoretical and Experimental Study Using a Reduced-Size Model. *Energy* 2012;45(1):644–654. https://doi.org/10.1016/j.energy.2012.07.032.

[15] Montanyà, J. Overview of Lightning Interaction and Damage to Wind Turbines. 2017 INMR World Congress, Barcelona-Sitges, Spain, 5–8 November 2017.

[16] Thom, D. Wind Turbine Blade Maintenance Guidelines: A Comprehensive Guide to Optimizing Blade Performance. EPRI: 2014. Product ID: 3002001502.

(a) Significant Delamination

(b) Trailing Edge Blowout

Figure 8: Examples of Damage Due to Lightning Strikes

3.7.1.3 Extreme Wind Events

Extreme wind events can include shear events, peak wind speeds, and rapid changes in wind speed and direction.[17] Wind turbine blades are designed and manufactured according to the wind classifications set by the IEC. The IEC wind classes are based on the annual average wind speed, turbulence intensity, and extreme 50-year wind gust magnitude and frequency.[18]

Wind turbines are designed to safely withstand the wind conditions defined by their wind turbine class for at least 20 years and to produce electricity at wind speeds from their cut-in wind speed to their cut-out wind speed. High-wind events can lead to increased blade deflection and dynamic loading of the blade root and blade-to-hub connection. Environmental events such as severe thunderstorms, tornadoes, tropical storms, and hurricanes can produce extreme wind conditions. Blade inspections of wind turbines in regions that frequently experience extreme wind loading should include an inspection of the structural integrity of the most highly loaded aspects of the wind turbine blade, such as the root and the midspan.

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[17] IEC 61400-1, *Wind turbines – Part 1: Design requirements*. 3rd ed. International Electrotechnical Commission: 2005.

[18] IEC 61400-1, *Wind turbines – Part 1: Design requirements*. 3rd ed. International Electrotechnical Commission: 2005.

3.7.1.4 Extreme Temperature Events

The operational temperature range for a standard utility-scale wind turbine is given as −20 °C to 50 °C (−4 °F to 122 °F) by IEC 61400-1.[19] Extreme cold can impact wind turbine blades in the circumstances where water ingress has occurred. Icing of a rotor blade generally occurs in the fall–spring months but is more common in higher elevations or at site locations in colder climate zones.[20] When water freezes, it expands. If water has penetrated areas of exposed laminate or core material and freezes during a freeze event, existing damages can be exacerbated. Additional attention should be paid to areas of exposed laminate or core, such as cracks, delamination, or regions of erosion, following a freeze event.

3.7.1.5 Erosive Events

Other environmental conditions that should be considered when planning blade inspection type in frequency are rain, hail, and dust storms. Locations that experience increased rainy or dusty conditions may be more susceptible to leading edge erosion. Leading edge erosion is a damage mode wherein the surface of a blade experiences gradual material loss over time due to the impact of hydrometeors, such as rain droplets and hail, or atmospheric particles, such as dust (Figure 9). This loss of surface material leads to increased surface roughness, which has been shown to have a significant effect on the wind turbine's annual energy production.[21] Sites that are deemed to experience increased frequencies of rainstorms, hailstorms, or dust storms should pay special attention to the leading edge surface of their blades during external visual inspections.

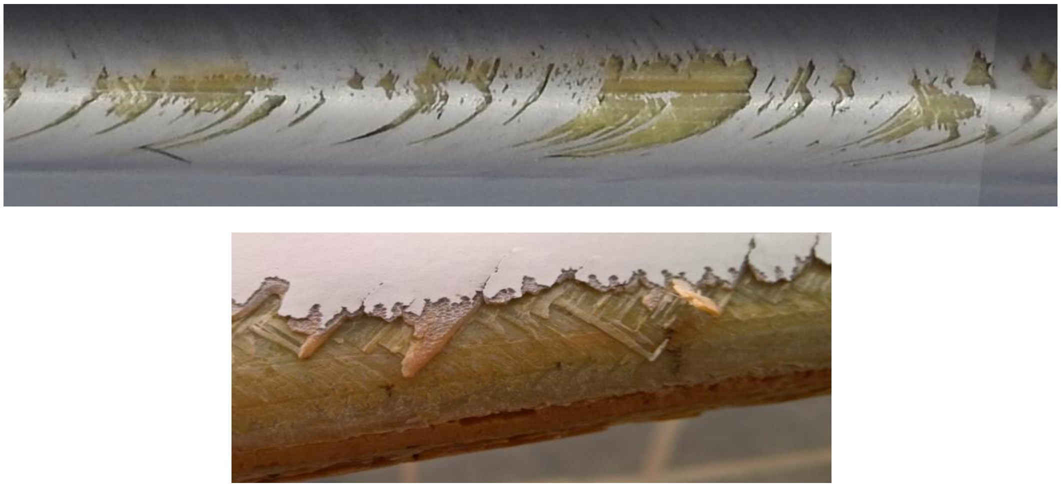

Figure 9: Examples of Severe (Category 5) Leading Edge Erosion

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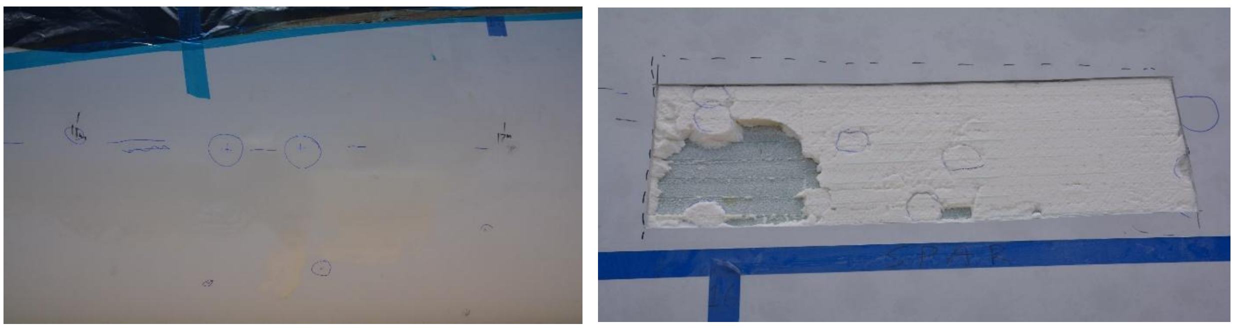
[19] IEC 61400-1, *Wind turbines – Part 1: Design requirements*. 3rd ed. International Electrotechnical Commission: 2005.

[20] Thom, D. Wind Turbine Blade Maintenance Guidelines: A Comprehensive Guide to Optimizing Blade Performance. EPRI: 2014. Product ID: 3002001502.

[21] Hasager, C., Mishnaevsky Jr., L., Bak, C., Bech, J. I., Fæster, S., and Johansen, N. F.-J. How Can We Combat Leading-Edge Erosion on Wind Turbine Blades? *DTU International Energy Report 2021: Perspectives on Wind Energy*, pp. 134–142. DTU Wind Energy: 2021. https://doi.org/10.11581/DTU.00000214.

3.7.1.6 Ice Events

Ice events include hailstorms with hail of a notable size (e.g., larger than 25 mm or 1 in.) and major ice storms during which significant accretion of ice on the blades was observed or suspected and during which it was also observed or suspected that such ice may have fallen from the blades striking other blades. Following an ice event, blades should be inspected if they are known or suspected to be susceptible to damage from impact by ice. Blades with shells utilizing very thin composite facesheets (e.g., blades utilizing central spar structures and lightly structural shells) are particularly susceptible to such damage. Damage can often consist of delamination of facesheets from core with minimal visible damage on the exterior surface. Visual inspections should employ binoculars or a drone and, if needed, a nondestructive examination. Figure 10 illustrates an example of the visible indications following damage due to large hail as well as the internal damage that was revealed by a destructive inspection performed as part of the blade repair.



(a) Small Exterior Indications (b) Internal Damage Revealed by Destructive Inspection

Figure 10: Example of Damage Due to Impacts from Large Hail

3.7.2 Destructive Inspection

Destructive inspection is the process of carefully removing material from a zone of damage for the purpose of revealing information useful for furthering understanding of the nature of the damage. Such processes might include grinding, cutting, or other means of material removal. Destructive inspection is not a normal part of routine maintenance of a blade and is generally performed only as part of an investigation of the root cause of a damage or failure event. Destructive inspection as part of a root cause analysis (RCA) investigation is recommended when alternative methods of inspection, such as visual inspection or nondestructive testing, are suspected of not fully revealing latent contributors to the formation of damage.

Destructive inspection may be performed independently of a repair, or it may be performed in conjunction with a repair. The difference between the material removal performed during an inspection and that during a repair is that, during the inspection, the material is removed carefully in stages to reveal useful information, which is measured, annotated, photographed, and otherwise recorded as part of the inspection. For example, the outer skin may be removed layer by layer to reveal evidence of laminate wrinkles or other defects, and then the core might be inspected for defects, continuing through the remaining layers of the blade. The plan for a destructive inspection should be developed by engineers responsible for the RCA and should be designed to reveal information useful for the RCA. However, it is often necessary to adjust the plan of inspection in response to information revealed during the inspection. If possible, engineers performing the RCA should be present or otherwise available during the inspection to help guide these adjustments.

The extent of material removal performed as part of a destructive inspection can be limited to removing the same material that would be removed as part of a repair. That is, a destructive inspection should not normally increase the extent of damage to the blade or increase the scope of the subsequent repair. However, in some unusual circumstances, it may be appropriate or even necessary to damage parts of the blade as part of the destructive inspection that are not otherwise obviously damaged. One example of this may be the need to take a small sample of undamaged material for the purposes of performing laboratory testing of the characteristics of the blade material to establish whether there are issues with the blade materials. Another example is when a mechanical defect in the blade structure is observed at the periphery of damage, it may be necessary to continue the destructive inspection beyond the edge of the damage to reveal the extent of the underlying defect if it is determined that the defect is significant and requires removal as part of a repair.

3.7.3 Reconstruction of Damaged Blade

One special type of inspection consists of the reconstruction of blades exhibiting substantial damage when numerous parts of the blade have separated. A principal example of this situation is when a blade fails catastrophically during operation, resulting in liberation of substantial portions of the blade, multiple pieces of which may be scattered in a debris field around the base and downwind of the turbine. Investigation of the root cause of such failures is generally warranted. Such an investigation would generally include careful mapping of the debris field. Each piece of debris is generally annotated with a distinguishing number, measured, and photographed, and the location of each piece relative to the tower is measured and noted. It is often useful to use overhead photographs taken by drones to help map the debris field. After this mapping, all of the pieces are gathered, and an attempt is made to properly assemble all the pieces to reconstruct the blade. This process is useful in identifying the patterns of damage within the blade and helpful in detecting locations of damage initiation and evolution. The locations of the various pieces within the debris field can help with the process of determining the sequence of failure events.

This process should begin as soon as possible after the failure event to help avoid exposure of debris to weathering that can obscure evidence that is critical to the performance of the RCA. Exposure to ultraviolet (UV) radiation, rain, snow, mud, and other moisture can degrade fiber-reinforced laminates and core materials, particularly balsa, in ways that can obscure the condition of the blade at the time of failure. If engineering resources are not available to perform an RCA immediately, it is preferable for site personnel to collect all pieces in the debris field as soon as possible and properly store them protected from the elements until such time as a reconstruction can be performed. However, prior to collecting the pieces, it is important for site personnel to map the debris field to the extent possible.

3.8 Documentation of Findings

3.8.1 Overview

It is critical to document inspection findings thoroughly because effective documentation facilitates effective analysis. The goal of inspections is to gain sufficient understanding of the condition of a blade and to facilitate timely detection of and response to abnormalities, such as damages or defects. Inspection findings should be documented with sufficient detail to achieve this understanding and retained for the life of the wind park.

3.8.2 Photo Quality

Images recorded during an inspection should be of sufficient quality to enable assessment of the condition of the blade. The image should be of sufficient contrast, resolution, lighting, angling, framing, and context, and should satisfy the following requirements:

- Images should be captured in the highest resolution.
- Images should be clear and in focus.
- External inspections should be completed during the day to ensure adequate sunlight.
- The environment should be illuminated while taking the photo if the area to be photographed is in a low light environment (such as inside the blade). The photographed area should be provided with sufficient lighting to clearly see the subject and context of the photo but not overexposed to produce glare.
- Images should have sufficient contrast so that an educated viewer can understand the content and context of the image.
- Images should be taken face-on where possible.
- The selected camera lens should minimize distortion.
- When findings are present, the finding should represent approximately 30-70% of the image. However, smaller findings may represent a smaller proportion of the image.

Images recorded during an inspection should not be deleted from the camera during the inspection unless they lead to confusion following the inspection.

When relevant, sometimes inspection photos will include a mark-up, which typically includes writing directly on the blade to provide bounding, context, and information on the findings. In these cases, black markers should not be used when writing on the blade. Sometimes, a photocard is presented alongside a markup. In these cases, information recorded on the photocard should be written legibly and the photocard should be included in the photo of the finding markup without blocking the finding or any critical contextual information.

3.8.3 Finding Severity

Table 2 outlines severity rankings and their corresponding characteristics and recommended actions. Engineering judgement, considering one’s own specific blades, their design, history, and operating conditions, should always be applied when assigning a severity ranking to a finding.

Table 2: Characteristics and Recommended Actions of Finding Severity[22]

Severity	Characteristics	Action
1	Minor variances from supply specifications but within industry typical tolerances; may affect the appearance of the blade.	• Repair is not needed. • Continued operation is appropriate. • Additional monitoring is not needed.
2	Minor damage or defects that exceed supply specification acceptance criteria; multiple cosmetic findings and/or a single major cosmetic finding.	• Repair is not required; evaluate benefit. • Continued operation is appropriate. • Additional monitoring depends on assessment of risk but may not be needed.
3	Moderate to minor structural damage or manufacturing defects in noncritical areas; internal inspection may be needed to determine the extent of the finding.	• Repair within a limited number of months of observation. • Continued operation is appropriate. • Additional monitoring depends on assessment of risk.
4	Significant damage or defects that have notable impact to structural capability and/or aerodynamic performance.	• Repair within a limited number of months of observation. • Continued operation is dependent on engineering evaluation. • More frequent monitoring is required until repaired.
5	Severe degree of damage or defect such that there is a high risk of imminent failure.	• Repair or replacement is required. • Continued operation is not safe until the repair or replacement is complete, or until a full engineering evaluation has been performed.

3.8.4 Finding Classification

Classification of findings into a defect/damage type category should be capable of supporting various blade generations, makes, and models and will help determine the failure mode, complexity of repair, and root cause.

There are many categories widely used across the industry. It is recommended that one uses the categories (typically, two to three levels of parameters) that are most relevant to the OEM and repair technicians when making this determination. Using multiple levels of parameters for every observation ensures sufficient information is captured to completely describe a finding. To keep consistency, the classification system should not be biased by subjectivity of the observer and remain as objective as possible.

[22] A White Paper on Wind Turbine Blade Defect and Damage Categorization: Current State of the Industry (3002019669) (https://www.epri.com/research/products/000000003002019669)

For that reason, the following is recommended:

- Primary typing, specifying damage type (e.g., crack, delamination, bonding issue, erosion, etc.)
- Sub-type, specifying damage details (e.g., crack pattern type, etc.)
- Avoid indication of damage root cause (such as lightning strike) in the classification as this can be highly subjective

An example of a well-documented finding classification is as:

- Primary type: Crack
- Sub-type: L-shaped

3.8.5 Finding Location

3.8.5.1 Overview

General location should be documented for each finding. This will aid in determining the risk of the finding. It has been commonly adopted that the location of a finding is specified by radial position with specified datum, blade side (pressure side (PS), suction side (SS), leading edge (LE), trailing edge (TE)), and chord position.

3.8.5.2 Chord Position

Chordwise position is often denoted by X. When present on SS or PS, the chordwise position should be specified as distance from the LE, either absolute or given as percentage of chord value at the given radial location. For situations where it is not reasonably feasible to measure the chordwise location relative to the LE or TE, other contextual structures may be used instead. For example, sometimes a finding is located internally between two shear webs. In this case, an alternative approach would be to measure the chordwise location relative to a clear landmark (such as the main shear web) and document the landmark in the measurement (i.e., chordwise location: X = 25mm from main web).

3.8.5.3 Spanwise Position

Spanwise dimensions are generally taken from either the center of the rotor radius and designated with R or from the root base of the blade and designated with Z. The datum (i.e., R, Z, or some other reference point that is defined) of the spanwise measurement should be documented clearly in the reporting of the spanwise location. When documenting the spanwise location of findings, the position of the most inboard portion of the finding (i.e., the side closest to the blade root) should be given as the spanwise location.

An example of a well-documented finding location is as follows:

- Affected component: Pressure shell
- Blade side: PS, TE
- Chordwise location: X = 100% chord
- Spanwise location: Z = 25 m

3.8.6 Finding Dimensions

3.8.6.1 Overview

It is essential to ensure accuracy of dimensioning of findings. When an inspection is conducted by a technician or with a newer technology (for example, LiDAR), the exact dimensions of the finding can be determined. This does not supersede the finding location data.

When possible, the spanwise and chordwise dimensions of a finding should be recorded. To dimension a finding, the spanwise and chordwise start and stop measurements are taken.

3.8.6.2 Spanwise Dimensions

The most inboard spanwise dimension is sometimes referred to as Z1, and the most outboard spanwise dimension of the finding is sometimes referred to as Z2. The spanwise dimension (sometimes referred to as Z) is the difference between Z1 and Z2. Spanwise dimensions are typically recorded in meters.

3.8.6.3 Chordwise Dimensions

Chordwise measurements can be taken from either the LE or the TE. Whichever datum is selected needs to be noted in the measurement. Where possible, the same edge should be used for both measurements. The chordwise dimension (sometimes referred to as X) is the difference between the two chordwise measurements made relative to the same edge. Chordwise measurements and are typically in millimeters.

It is useful to measure and document the length and width of the damage (which are relative to the damage itself), as well as the Z and X dimensions (which are relative to the blade axis, where Z is spanwise and X is chordwise), when measuring the dimensions of a finding. This approach is recommended for some findings such as cracks, where the crack length is critical information.

There are occasionally cases where the spanwise and chordwise dimensions cannot be recorded. This includes when the damage is on the bulkhead or shear web (i.e., a portion of the blade that does not align with the spanwise and chordwise axis). In these cases, the longer dimension should be recorded as the length, and the shorter perpendicular dimension should be recorded as the width.

3.8.7 Inspection and Finding Reporting

As part of the final inspection documentation, all images should be accompanied by the following information:

- Wind farm name
- Inspection date
- Inspection company and/or inspector name
- Unique turbine identification number or pad ID
- Turbine manufacturer and model
- Unique blade identifier (e.g. serial number or pitch validated blade position)
- Blade manufacturer and model

If findings are present, the following additional information should also be provided relative to the finding:

- Blade side (SS, PS, LE, TE)
- Component impacted (e.g., SS shell, PS shell, LPS receptor, spar cap, main shear web, etc.)
- Finding dimensions (spanwise, chordwise, length, and width)
- Spanwise location
- Chordwise location
- Visible material impacted
- Finding type classification and sub-type classification (if relevant)

Ideally, this information should be presented in tabular form, which facilitates review and analysis. Each entry should represent a unique finding. Images of the finding should be linked to its corresponding entry in the table.

3.9 Root Cause Analysis

RCAs are advised in several situations, including, but not limited to, the following:

- When serious damage is deemed to be repairable, but there are concerns that there may be an unobvious cause that needs to be corrected as part of the repair
- Damage or failure events suspected to be part of a pattern of serial damage and for which the cause needs to be identified in order to mitigate the risk to other blades

The RCA should follow rigorous methods, such as those defined in IEC 62740[23] or equivalent.[24] The RCA of a blade damage or failure event should not be confined to considerations of issues inherent in the blade and should not be based solely on an inspection of the blade. The RCA should consider, in addition to issues related to the blade design, manufacturing, handling, and maintenance, other factors related to the operation of the turbine and environmental factors. The RCA should incorporate all of the following at a minimum:

1. Data gathered as part of inspections of the blade, as defined in Section 3.8, including visual inspection, nondestructive testing, destructive inspection, blade reconstruction, and data from health monitoring prior to the formation of damage or the blade failure
2. Blade design and due diligence data, including the following:
    a. Data related to the original design and analysis of the blade
    b. Data related to the loads analysis of the turbine
    c. Data related to the site suitability analysis of the turbine and blades
3. O&M history of the blade, including reports of all inspections of the blade and reports of all repairs performed on the blade

[23] IEC 62740, *Root cause analysis (RCA)*. 1st ed. International Electrotechnical Commission: 2015.
[24] Mishnaevsky Jr., L. Root Causes and Mechanisms of Failure of Wind Turbine Blades: Overview. *Materials (Basel)* 2022;15(9):2959. https://doi.org/10.3390/ma15092959.

4. SCADA data and fault history for the operation of the turbine for an appropriate period of time in advance of the damage or failure event
5. Site meteorological tower data in advance of the damage or failure event
6. Data related to environmental events in the area of the wind farm, including windstorms, precipitation, ice storms, etc.
7. Data related to the history of lightning strike events at the site, if applicable to the investigation, and any lightning strike card data that may have been recorded for the specific blade or turbine in question

These data should be examined carefully to identify all factors potentially contributing to the initiation and evolution of damage in the blade. Rigorous methods of analysis should be employed to rule out factors deemed not to be contributors in the present case and to identify causal factors for which there is a finite probability of having contributed to the event. If possible, the probability should be quantified in percentage terms or at least in terms such as high, medium, and low probability. If possible, the necessary causal factor (previously known as the root cause) should be identified.

The RCA process should be carefully documented to identify all data examined, data that would have been helpful but that were not available, how the factors were identified and assessed, the conclusions of the RCA, and recommendations resulting from the RCA, including most importantly recommendations for corrective actions or other efforts to mitigate risk to other blades.

3.10 Continuous Monitoring

3.10.1 Types of Continuous Monitoring

Continuous monitoring of wind turbine blades is an expanding field and is aimed at optimizing the O&M of wind turbine blades. Continuous monitoring can be considered in a broader risk assessment approach to blades. The risk assessment approach will typically involve assessment of failure modes, likelihood and consequence of damage, and optimized frequency of monitoring, which would likely include a combination of inspections and continuous monitoring.

The three broad categories of continuous monitoring include damage monitoring, lightning monitoring, and operational monitoring. These are described in greater detail below.

3.10.1.1 Damage Monitoring

Damage monitoring includes structural and nonstructural damage monitoring. The structural health monitoring (SHM) focuses on damage that has the potential to cause significant or catastrophic failure, whereas the nonstructural damage monitoring focuses on damage that typically would be observed on the surface and as it increases in size can become more difficult to repair. These monitoring methods can be used to supplement, improve, and/or replace manual inspections.

Broadly speaking, the SHM involves a sensing system, a means of data acquisition, and a method of interpreting the collected data with the intent of detecting failure modes relevant to wind turbine blades. The broad categories of failure modes that are characteristic of wind turbine blades are fiber failure, buckling failure, bond failure, interfiber failure, sandwich failure, root connection failure, blade bearing failure, impact failure, and creep failure. The nonstructural damage may include erosion, lightning damage, debonding, impact, and cracks (longitudinal or transverse).

3.10.1.2 Lightning Monitoring

Lightning monitoring approaches are outlined in IEC 61400-32 Annexure L. Depending on the lightning intensity and risk of lightning damage (which may vary depending on blade design), different approaches may be taken ranging from thunderstorm warning systems (which operate with long-range electrostatic field detection) to direct measurement of lightning events on the tower or in blades.

3.10.1.3 Operational Monitoring

Operational monitoring of blades may include ice buildup, pitch alignment, and mass imbalance. These continuous monitoring methods are intended to help optimize the operation of the blade in terms of annual energy production.

The primary difference between continuous monitoring methods and manual inspection methods is that manual inspection methods are discreetly occurring activities, typically taking data at a frequency of every two years or less, whereas continuous monitoring methods constantly measure and record data. Continuous monitoring is useful for maintaining a gauge on some primary identifiers of blade health and can allow for early identification of possible problem blades and aid in prioritization and/or optimization of inspections. There are many methods by which this can be accomplished, but the approaches can be broken down into two broad categories: blade-based sensors and utilization of existing or additional non-blade-mounted sensors.

3.10.2 Blade-Based Sensors

Blade-based sensors can be either surface-based or embedded. Surface-based sensing systems are more commonly used. These types of sensors are not typically installed by the blade manufacturer and are more commonly installed as an after-market solution. The type of sensing system selected depends on the type of damage or failure mode requiring detection. Some of the common surface-mounted sensor systems are described in Table 3.

Embedded sensors are integrated directly into the laminate of the blade.[25] However, this method of continuous monitoring is not widely practiced across industry because it requires modifications to the typical blade manufacturing process, introduces a nonstructural inclusion in the blade's structure, and yields a sensor system that is difficult to access to maintain or repair.[26]

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[25] Malkin, M. Wind Turbine Blade Structural Health Monitoring: Methods and Benefits. EPRI: 2010. Product ID: 1021655.

[26] Malkin, M. Wind Turbine Blade Structural Health Monitoring: Methods and Benefits. EPRI: 2010. Product ID: 1021655.

Table 3: Types of Surface-Mounted Sensor Systems

Monitoring Method	Technology Readiness	How It Works	What It Can Detect
Gap Measurement	High	Displacement sensors typically between blade bearing and blade root.	Adequate connection of the blade root to the blade bearing.
Strain Monitoring	High	Use of strain gauges or fiber-optic Bragg grating sensors to measure deformations at specific locations.	Bending and shear loads, static events, and fatigue cycles.
Vibration Monitoring	High	Piezoelectric sensors; microelectromechanical systems (MEMS) sensors. Depending on the frequency range of the desired damage mode, position transducers, velocity sensors, accelerometers, or spectral energy sensors can be used to monitor changes in the vibrations of a structure.	Measures the dynamic response of the blade and spectral analysis. Changes in the dynamic response can indicate damage occurrence or progression.
Acoustic Emissions Monitoring (Passive)	Medium	Use of piezoelectric sensors or MEMS sensors to detect elastic waves generated by the motion of the blade material via measurement of structural strains. Alternatively, acoustic emissions sensors can be used to monitor the waveforms through the air with MEMS microphones. Changes in acoustic waveforms may occur due to the presence of damage.	Formation of a crack or other composite failure or rupture; propagation of existing damages.
Acoustic Emissions Monitoring (Active)	Low	Use of a method to excite the structure of the blade. A vibration sensor is used to read the resulting waveforms generated by the excitation and to monitor for variations in the typical sound profile of a blade's material.	Changes in the blade's structural integrity, such as formation of a crack or other composite failure or rupture; propagation of existing damages.
Optical Fuse Monitoring	Low	Optical fibers are embedded in a blade during manufacturing. Areas of blade damage will result in broken fibers, which no longer transmit light.	Useful for detecting the presence and location of damage to the laminate.

3.10.3 Non-Blade-Based Sensors

There are several systems available that remotely monitor the blades. These fall under the category of:

- Acoustic based and located at the base of wind turbine
- Vibration-based sensors on the nacelle
- Supervisory Control and Data Acquisition (SCADA)-based monitoring

Remote acoustic monitoring is based on the physical phenomenon that blade damage creates distinct sounds as the blade moves through the air, which can then be monitored remotely. The sound is generated by aerodynamic disturbances on the surface of the blade with air flow over damage. The change in sound is an early indicator of blade damage. This type of monitoring is cost-effective and easily retrofittable. It can provide an early warning when blade surface conditions change, presenting an opportunity to schedule a more targeted inspection. The systems currently do not indicate the type and location of damage.

Vibration-based monitoring on the nacelle can track natural frequencies and modes of the blades. Nacelle-based monitoring uses vibration sensors and can distinguish changes in blade vibration mode frequencies, which may indicate a change in condition. The presence of resonances of the blade can also be monitored. These systems are focused on known blade challenges.

SCADA systems can monitor the full suite of wind turbine sensors to assess conditions under which the blades operate, which may induce excessive loads and potential for damage.

4 Transportation and Storage

4.1 Transportation

All blades need to be shipped in compliance with the OEM transportation specification. The recommended practice is to have this specification on-site prior to the shipping of the blades to ensure that all specifications are met and to address any conflicting issues that could arise. The bracing and support of the blades should be inspected for proper cushioning and support on the leading edge, proper side support on the shell body to not induce longitudinal cracking, proper cinching of cargo straps as to not damage trailing edge, and proper bracing on the blade to prevent adverse flexing during transportation.

4.2 Storage

Storage of blades needs to be different based on the intended length of storage. Short storage periods, such as staging for installation, can vary if the blade is not exposed to undue mechanical strain or an environment that would compromise the blade's exterior structure.

Long-term storage needs to address the following:

- Protection from UV light
- Root bolts sealed from moisture

- Blade interior protected from rain, dust, and foreign objects, including small animals and insects from the interior of the blade
- Blade properly secured to the ground to prevent damage in high winds
- Blade properly supported to mitigate any mechanical stresses on the structure of the blade (leading edge, trailing edge, and shell wall)

5 Maintenance

5.1 Overview

Preventive maintenance (PM) schedules have been repeatedly demonstrated to be more cost-effective than responding to issues as they arise. There are many formats for maintenance schedules, but the key is to incorporate one that will be followed consistently by the site team. This could include having a third party conduct all PM and repairs on a long-term contractual agreement.

There are many visual and auditory inspections that can be used as part of the PM plan, which require little effort and do not entail interrupting the generation of power. High-speed digital photography for identifying lightning strikes, trailing edge cracks, and foreign object strikes can be conducted from the ground. Changes in the sound of the rotor set spinning can also be conducted regularly.

Typical PM plans will address the areas mentioned in Table 1. Additionally, as the rotors age, a representative set of rotors should be physically inspected for defects, wear, and damage by some form of blade access. The set of rotors physically inspected should change each year so that each rotor set is physically inspected regularly. This varies from farm to farm, but a 2- to 10-year rotation is common. Items identified with these inspections could alter the inspection rate and should be used to plan repairs to minimize costs. Repairs can be bunched to lower cost per turbine repaired.

The maintenance data collected for each blade and rotor set must be retained with the rotor set for the life of the farm and reviewed regularly for potential predictions on power loss, potential failures, and other key items.

Blades and rotors that continuously have more issues should have their PM scheduled more frequently to minimize reactive maintenance and to aid in understanding trends for the rotor set.

Per IEC 61400-1, each wind turbine model shall have a maintenance manual, which, at a minimum, consists of the following:[27]

- Maintenance requirements
- Emergency procedures
- Provisions for unscheduled maintenance

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[27] IEC 61400-1, *Wind turbines – Part 1: Design requirements*. 3rd ed. International Electrotechnical Commission: 2005.

- Identification of parts subject to wear
- Criteria for replacement of worn parts

PM activities for blades should include continuity checks of the LPS, drain hole cleaning, blade root fastener torque and pre-tension checks, and rotor balancing. These activities are discussed in greater detail below.

5.2 Continuity Checks of the LPS

Continuity checks of the LPS should be performed according to the requirements of the IEC 61400-24:2019/AMD1:2024 standard[28] or the OEM, whichever is more stringent.

5.3 Drain Hole Clean

Clogged drain holes can trap water in the tip of the blade, increasing stresses on the adhesive bonds and increasing the risk of a tip blow-out in the event of a lightning strike to the tip.

Drain holes near the tip should be checked when technicians perform blade maintenance or repairs to clear any clogged debris. Alternatively, drain holes should be cleaned of debris after two-to-three years of operation and every five years thereafter, to the extent that it is feasible and can be performed economically.

5.4 Blade Root Fastener Torque and Pre-Tension Checks

The blade root fastener's torque or pre-tension should be checked in accordance with the OEM's maintenance manual requirements. Or, in the absence of such requirements, it should be checked every year for the first eight years of operation. Following that, it should be checked as appropriately to reflect the experience during the first eight years and then checked annually in the last four years of design life.

Fasteners that are found to be out of tolerance for torque or pre-tension should be retorqued and re-tensioned per the OEM's specifications. Widespread issues with significant loss of tension in the fasteners, particularly if they continue after multiple rounds of re-tensioning, should be flagged as an indicator of a problem with the blade root that requires further investigation.

5.5 Rotor Balancing

5.5.1 Overview

Rotor imbalances may be one of the issues that surfaces during the operational lifetime of wind turbines. These imbalances can significantly affect the vibrational characteristics and response of major wind turbine components. In larger wind turbines, rotor imbalances are typically caused by relative pitch misalignment, changes to the blade aerodynamic characteristics, and an unbalanced

[28] IEC 61400-24:2019/AMD1:2024, Wind turbines – Part 24: Lightning Protection – Amendment 1. International Electrotechnical Commission: 2024.

mass distribution sustained through the lifetime of wind turbine installation, commissioning, and O&M.

Dynamic balance information should be required on all new installations after the rotor set is installed. It should also be confirmed that the information is still within the specification limits.

Two types of rotor imbalances – rotor mass imbalance and rotor aero imbalance – are discussed with further detail below.

5.5.2 Rotor Mass Imbalance: Static and Dynamic Balancing

5.5.2.1 Overview

All blades are mass-balanced and matched on static moment and/or mass moment for a rotor set at the OEM production location prior to shipping and delivery to site for rotor installation. The blades arrive at the farm intended to be part of a balanced rotor set. Confirmation of this should be conducted prior to installing the rotor set.

Assuming the set of blades remains on the turbine, the blades should be balanced. Balanced rotor sets can lose balance by a change in material weight (e.g., larger repairs), stiffness due to a large repair, or an inherent blade damage during its operational and service lifetime.

Typical values for balancing tolerance within a rotor set are in the range of 0.2–0.3% on static moment and/or mass moment of each individual blade from the others in the same set.

5.5.2.2 Expectation

Static mass/moment balancing should be performed at a minimum, with dynamic balancing as desired or required by the OEM any time a blade is substituted or swapped to complete or repair a rotor set.

Upon finding a rotor set, which needs to be brought into balance, weight should be added to the lightest blade(s) and weight should never be removed from the heaviest blade. Many OEMs build "weight boxes" into the blades at prescribed locations along the span that are typically found outboard toward the blade tip. These limited spaces along the blade are intended to be used for the infusion of dense curable resins or silica or mass-specific lead shots to adjust the balance as needed without having weights break free and rotate within the blade and/or reduce the structural strength of the blade.

There are many views on balancing. A statically mass-balanced rotor should be a balanced set, but it does not mean that it is dynamically balanced. Only after being assembled and hung can the set be tested for its dynamic balance. There are varied ways to determine if the rotor set is out of balance, including auditory, "bumping" the set on a windless day, and correlating data as to which rotor sets are always last to spin up in light winds.

5.5.2.3 Inspection

It is possible to have a blade increase in weight due to moisture uptake from a porous gel coat, plugged drain hole, or prolonged exposure of blade core material to the environment. This should also warrant an inspection of the rotor blade.

It is recommended that inspections for rotor balance be made after a major composite repair is determined to potentially result in significant weight addition and/or after detection of rotor imbalance from turbine condition monitoring systems.

5.5.2.4 Documentation

It is recommended that asset owner-operators establish traceability of blade serial number designation and records of mass, center of gravity, static moment, and/or mass moment data. OEM-specified locations of blade balance boxes and the balance mass should be added in these locations for their blades upon initial receipt of new blades at site during the construction phase.

Aerodynamical, relative, and absolute imbalance must be detected and corrected up front to avoid curing with weights, where adjustments to the pitch drive would be necessary.

As with all maintenance inspections and repairs, the balance measurements should be kept with the rotor set records throughout the turbine's life. This would include the blade serial numbers, the location on the blade where weight was added, the amount of material added to the balancing locations, and the final balance achieved.

5.5.3 Rotor Aerodynamic Imbalance: Pitch Set Angle Alignment

5.5.3.1 Overview

Rotor aerodynamic imbalance can occur when one or more of the blades have a different aerodynamic efficiency than the others within the same rotor set.

In summary, rotor aerodynamic imbalances are caused by, among other things, the following:

- Assembly and/or manufacturing errors resulting in different aerodynamic profiles between blades within a rotor set
- Different blade pitch angles (i.e., blade angle errors) during operation due to installation deviation from optimum zero or fine pitch set position
- Changes in the rotor blade geometry due to poorly executed repairs
- Changes in the profile characteristics of the rotor blade, possibly, due to the presence and extent of progression of leading edge erosion between each blade
- Ice or dirt accumulation on the blade surfaces during operation in icing conditions
- Additional aerodynamic installations (e.g., vortex generator, winglets, flaps, serrations, etc.), which are not evenly distributed or lost on one or more blades

Pitch misalignment of blades within the rotor set depends on incorrect blade installation, out-of-tolerance positioning of the top center (TC) or zero pitch marking on the blades, or on possible drifts of the pitch regulation system.

Typical allowable values for pitch set position within a rotor set are in the range up to +/− 0.3 degrees of individual blades from each other.

The consequences of an aerodynamic imbalance are an increase in vibrations, together with a reduction in power output, as the rotor blades are less efficient in capturing the energy from the wind.

5.5.3.2 Expectation

It is recommended that asset owner-operators maintain blades with the following considerations:

- Annual inspection and calibration of pitch set angle of the blades
- Monitoring or at least annual inspection and correction of possible drift in pitch variation
- Inspection and repair of leading edge erosion to maintain uniformity in blade aerodynamic profiles
- Inspection and repair of the condition of leading edge protection to maintain uniformity in blade aerodynamic profiles
- Inspection and repair of the condition of any additional aerodynamical installations (e.g., vortex generator, trailing edge serrations, etc.)
- Review of repair documentation to ensure that the profile characteristics of the blade geometry have not been impacted by poorly executed structural and/or nonstructural repairs
- Monitoring of ice accumulation and application of anti-icing solutions to reduce impact on rotor aero and mass imbalances
- Monitoring of dirt accumulation and, if necessary, cleaning of the blades

5.5.3.3 Inspection

Rotor aerodynamic imbalance can be detected for correction by a few or combination of methods:

- Visual inspection and confirmation of blade pitch set angles positioned and calibrated between the blade's TC marking and aligned with the hub or pitch bearing zero pitch angle set markings
- Pitch angle measurements using a combination of laser, LiDAR, and precision cameras from the ground
- On-blade sensors monitoring and detecting pitch angles at various span locations along the blade
- Vibration measurements in the drivetrain and SCADA or performance data

5.5.3.4 Documentation

As with all maintenance inspections and repairs, the pitch angle measurements and corrections should be kept with the rotor set records throughout the turbine's life. This would also include any documentation of the blade's TC marking positioning tolerance and production records of aerodynamic shape tolerance checks.

6 Safety

6.1 Overview

Repairing and maintaining rotors creates additional safety concerns beyond the concerns already presented on every wind farm. Safety should be considered first for maintenance and repair programs. This information below is meant to be an adjunct to an existing site safety program. As noted within the Safety Disclaimer and usage restrictions set forth at the front of AWEA Operations & Maintenance Recommended Practices, this information is meant for awareness, and all implementers of the processes are responsible for determining appropriate safety, security, environmental, and health practices or regulatory requirements.

6.2 Fall Protection and Rescue

All personnel who access the nacelle area of a wind turbine should be trained and certified to safely climb the tower and to perform self- and others rescue. Personnel should be trained in the dangers of working at a height, how to use and maintain lanyards, fall arrest harnesses, positioning equipment, and other climbing gear. In addition, personnel should be trained in the correct methods of dealing with emergencies, including suspension trauma and rescue.

Testing and certification should be obtained from a recognized third-party organization, such as ENSA, the American National Standards Institute (ANSI), or the National Institute for Occupational Safety and Health standards, which should include the following:

- Safety awareness
- Equipment fitting
- Care and inspection of equipment
- Risk assessment
- Restraint
- Fall arrest
- Work positioning
- Rescue
- Anchor selection
- Evacuation

6.3 Aerial Platform Competent User, Safe Access, and Rescue

External servicing of the turbine's blades can be performed up-tower utilizing suspended platforms or crane man baskets. It is critical that service personnel be trained and certified in the operation of vertical lifeline systems, rigging, and safe operation of the platform; self-rescue and assisted rescue using ANSI-approved automatic control descent devices. Specific areas to be trained and certified include the following:

- Safe use of vertical lifelines
- Establishing a safe work area

- Platform and rigging equipment inspection
- Rigging
- Pre-lift testing
- Platform components and assemblies
- Safe operation of the platform
- Tagline operation
- Assisted rescue
- Self-rescue
- Coworker rescue
- Sling angles
- Sling ratings
- Anchor point requirements

6.4 Rope Access

In addition to fall protection training, service personnel should be specifically trained and certified to the Society of Professional Rope Access Technicians or the Industrial Rope Access Trade Association standards for safe access strictly by rope suspension. Personnel should be trained and experienced in evaluating rope access equipment and systems, perform access techniques, and be competent in rescue procedures. Specific areas of training and certification should include the following:

- Safety standards and documentation
- Methods of access
- Care, inspection, use, and limitations of equipment
- Knots
- Rigging
- Anchoring
- Ascending and descending
- Rope-to-rope transfer
- Structure climbing
- Assessing risks
- Self- and coworker rescue

The OSHA 30 program provides training in general safety practices for construction and industrial environments. Specific areas of training are as follows:

- OSHA standards for hazardous conditions and practices
- OSHA's general safety and health provisions
- Occupational health and environmental controls
- Personal protective equipment
- Fire protection and prevention
- Rigging

- Welding and cutting
- Electrical standards and hazards
- Scaffolding
- Fall protection
- Excavations
- Concrete and masonry
- Decommissioning and demolition
- Ladders
- Hazards of confined spaces

6.5 First Aid and Cardiopulmonary Resuscitation

Because most wind farm sites are in remote areas, all field personnel must be trained as first responders in first aid and cardiopulmonary resuscitation (CPR). OSHA or American Red Cross guidelines should be followed so that personnel can recognize and care for a variety of first aid emergencies and perform CPR and care for breathing and cardiac emergencies.

6.6 Confined Spaces and Respirators

Working within the rotor and especially inside of wind turbine blades requires personnel to be trained in confined space access and the proper use of respiration gear. Training and certification for personnel should be done in accordance with OSHA 29 *CFR* requirements and include the following areas:

- Confined space identification
- Hazard evaluation
- Behavior of gases
- Oxygen deficiency
- Equipment use and care
- Respirator fit
- Ingress and evacuation

6.7 Skill Levels

Blade repairs tend to fall under two primary categories: cosmetic (nonstructural) repairs and structural repairs. Care is needed in ensuring that appropriate training and skill levels are available for either type of repair.

Simple cosmetic repair, if not performed correctly, can result in a loss of generation power and potentially lead to additional repairs. Structural composite repair, if not performed correctly, can result in a loss of blade integrity and potentially lead to additional costly repairs and failures.

On-site or independent service providers have varied skill levels for various types of repairs. This can include not only the type of repairs but also the blade access techniques, scheduling availability, and experience with various repair options and turbine platforms. For example, an excellent team for changing out a pitch motor may not be the best choice for repairing a lightning strike repair. Up-front discussion on these points will prevent issues after a repair is contracted and started.

Regardless of resources being used, training and certification through several programs and technical schools for composite repair should be part of the minimum acceptance level for skills, in addition to on-the-job field experience to conduct on-site composite repairs.

6.8 Wind Blade Repair Technician

Wind blade repair technicians are personnel or trained individuals who are working in the wind industry performing composite inspection and repair on wind turbine rotor blades. They must perform job functions safely and competently with composite materials, such as conducting inspections and executing blade repair procedures using work instructions and procedures, technical specifications, and process and quality control requirements. These personnel or trained individuals must be fully capable and have been made aware of the risks and hazards of performing blade inspections and repairs by various forms of access methods.

Blade composites repair training and certification should include a primary component of practical hands-on training, in addition to the theory.

6.9 Blade Repair Technician Skills

Repair technicians receive training under industry available certification programs and accepted training standards to perform composite repairs in the field. Training shall include both theoretical and hands-on content.

On-the-job training and development are crucial steps for repair technicians to advance through various levels of complexity on blade inspections and repairs. There is currently no specific standard that enforces the categorization of technician capability, skills, knowledge, and proficiency levels in performing blade composite repairs. Recommended repair technicians' skill levels are as follows:

- Level 1 – L1, Basic Blade Repair Tech
- Level 2 – L2, Intermediate Blade Repair Tech (intermediate composite lead)
- Level 3 – L3, Advanced Blade Repair Tech (advanced composite lead)
- Level 4 – L4, Technical Blade Repair Specialist and Supervisor

Table 4 outlines the recommended career growth and advancement of blade repair technicians. It should be noted that the skills and experience of technicians within a designated skill level (L1/L2/L3) may cover a wide range. Additionally, the time it takes to achieve a designated skill level is specific to each technician and their unique combination of skills, competence, and on-the-job performance. Staffing decisions should be managed such that the skill set staffed for the required repair is appropriate. Note that many service providers do not use the L4 designation and the L4 skills described here would generally be assigned to an L3 technician in their organization.

Table 2: Blade Repair Technician Skills

Technician Skills Level	Capabilities, Skills, and Responsibilities	Repair Types – Examples
L1 – Basic Introductory	• Basic knowledge of blade structure and composites, and ability to perform visual inspection of damage external or internal. • Knowledge of blade subsystems, such as LPS, balancing box, and bolted connections. • Knowledge of chemical safety and housekeeping, and basic ability to operate tools and equipment for composite repairs. • Knowledge and hands-on capability to measure and prepare repair materials and chemicals, fabric and core cutting for kitting repair layers. • Capable of performing functional testing of blade subsystems, such as conductivity-resistance measurements of the blade's LPS and components. • Capable of performing nonstructural/cosmetic repairs on blade and other composite structures of a wind turbine. • Capable of supporting L2/L3/L4 lead in repair process, including tool and equipment, composite repair material measurement and preparation, fiberglass fabric cutting as directed by the lead technician. • Support role to L2/L3/L4 lead in composites and performing basic access rigging setup and operation (e.g., taglines, up-tower rigging, and confined space). • Support role to L2/L3/L4 lead in composites and performing daily housekeeping of work area, preparation of materials for repair, and tasks related to documentation of repairs.	• Cosmetic repairs isolated to topcoat/paint and surface filler layer. • Installation and repairs of blade add-ons. • Internal and external inspections of blades. • Inspection and repair of the blade LPS and components. • Leading edge protection installation.
L2 – Intermediate, Composite Technician	• Intermediate-level composite technician with demonstrated proficiency in executing Category 1–4 repairs, with L3 support during advancement period. • Understanding of the various blade structure types and manufacturing methods across multiple brand technologies.	• Typical blade handling and construction damages. • In-service blade structural repairs on trailing/leading edge bond splits, trailing

Technician Skills Level	Capabilities, Skills, and Responsibilities	Repair Types – Examples
	• Capable of following repair work instructions and performing repairs according to the prescribed process and quality control requirements. • Capable of performing repairs on the blade externals and internals. • Capable of performing simple structural repairs that typically span up to 1 m wide/long and require up to five-layer lamination replacement repair of inner and outer skins (window-repairs). • Experienced in blade access rigging and capable of leading a team to access blades and perform repairs safely. • Experienced in assessing risk on repair safety and quality to make decisions on repair planning and execution. • Experienced in performing detailed damage inspection, including markup of identified damaged layers and scarfing map. • Experienced in performing several types of structural composite repairs (per examples provided). • Experienced in blade subsystem repairs, such as the LPS, performing blade balancing procedures, and installation of blade add-ons and leading edge protection.	edge chips, leading edge erosion repairs, and cracks and bond cap repairs; lightning damage repairs. • Simple tip reconstruction repairs.
L3 – Advanced, Composite Lead	• Advanced-level composite lead who demonstrated proficiency in executing Category 1–5 repairs and independently performed repairs without supervisory oversight. • Deep understanding of the various blade structure types and manufacturing methods across most brand technologies. • Proficient in blade access rigging and capable of leading a team to access blades safely. • Proficient in performing complex structural composites repairs, typically spanning >1 m requiring more than five layers above and/or below core removal.	• Deep structural repairs on shell sandwich panels and spar cap layers. • Specialized skills in carbon tip repair replacement, carbon spar cap repair including shear web removal or replacement, >1 m tip reconstruction that may require mold fabrication. • Splash mold fabrication.

Technician Skills Level	Capabilities, Skills, and Responsibilities	Repair Types – Examples
	• Proficient in performing complex structural repairs that involve multiple blade components or areas near key structural members, such as spar caps, shear webs, and leading/trailing edge bonding region. • Demonstrated knowledge of advanced repair materials and process, such as UV post-cure, carbon fiber fabric. • Capable in executing and performing supervisory oversight on composite repair steps, process, and quality assurance and quality control.	
L4 – Technical Specialist, Supervisor/ Trainer	• Technical specialist repair lead with demonstrated supervisory skills to execute repairs with multiple repair teams. • Deep understanding of the various blade structure types and manufacturing methods across all major brand technologies within the United States. • Demonstrated capability to effectively lead technician teams of L1, L2, and L3 in executing all types of repairs of various complexity from basic to advanced. • Demonstrated capability to mentor and train all technician levels. • Demonstrated capability to draft work procedures and quality checklists for repairs. • Demonstrated capability to develop and improve repair process and procedures.	• All scope scenarios listed in L1/L2/L3

7 Repair

7.1 Overview

The primary key to all repairs is to return the blade to the same physical strength, shape, and weight as it was commissioned. Usually, the exact same manufacturing process cannot be used to facilitate the repair. Thus, the repair may be thicker or heavier in the repair location to obtain the same structural strength as in the original location. Depending on the location and its critical performance function, the repair team will need to decide how best to complete the repair. Keep repair records for all forms of repairs to each blade.

This should include the location and type of repair, method to repair, and materials used to repair. All repairs conducted as the result of transportation, storage, and installation prior to commissioning should be included.

7.2 Blade Repair Steps

7.2.1 Pre-work

7.2.1.1 Step Description

Gather and verify asset information of the blade with the inspection report. The damage should be located on the blade and verified to be the appropriate damage to be repaired.

7.2.1.2 Documentation

Reporting should include the following:

- Turbine owner/operator
- Site name
- Turbine type: OEM and model
- Turbine number
- Blade type: manufacturer and model
- Blade index: ABC, 123
- Blade serial number: photo of blade nameplate or serial number (if accessible)

7.2.1.3 Acceptance Criteria

Acceptance criteria include the following:

- Pictures are in focus, and all writing can be clearly read.
- All data requested are present and correct.
- Photos have data card or metadata present in the pictures.

Figure 11 shows examples of acceptable photos.

Figure 11: Example of Blade Serial Number Marking and Nameplate

7.2.2 Damage Defect Inspection

7.2.2.1 Step Description

Identify and document the damage or defect before any material removal is completed as part of the repair process. The extent of the damage should also be documented after the surface coat is removed and before damaged laminate is removed. Often, the damage is larger under the surface coat, so this allows comparison to be made.

7.2.2.2 Documentation

Reporting should include the following:

- General damage location: internal or external.
- Shell – pressure shell (high-pressure shell, upwind) or suction shell (low-pressure shell, downwind)
- Longitudinal start and stop measurements, before and after surface coat removal, noted as either Z (distance from root end of the blade) or R (radial distance from the center point of the rotor diameter); units are typically meters (m) or millimeters (mm).
- Transversal or chordwise start and stop measurements, before and after surface coat removal, from which edge of the blade should be noted as trailing edge or leading edge; units are typically millimeters (mm).
- Pictures, before and after surface coat removal; two picture types are recommended for all pictures: close-up pictures showing details on the extent of damage and looking inside and openings in the blade and wide-angle pictures showing the damage with one blade edge (leading edge or trailing edge) in the picture to give context to the location of the damage.

7.2.2.3 Acceptance Criteria

Acceptance criteria include the following:

- Pictures are in focus, and all writing can be clearly read.
- All data requested are present and correct.
- Photos have data card or metadata present in the pictures. Note that in the photos included in this document, the data cards are generally omitted due to restrictions on disclosure of proprietary information.

Figure shows examples of acceptable photos of lightning strike damage annotated during an initial inspection.

Figure 12: Examples of Lightning Strike Damage Annotated During Initial Inspection

7.2.3 Damage Removal and Layer Identification

7.2.3.1 Step Description

Remove all damage to the blade. Determine the components that are present in the repair areas and potentially damaged, the fiber-reinforced laminate structure, and core materials in each component, and the bondline structure between components.. If the repair provider does not have access to the OEM laminate schedule for the affected components, the laminate structure should be characterized in terms of the types of fibers (i.e., glass or carbon). the number of affected layers, fabric types (e.g., unidirectional, double bias, triaxial), and layer orientations. Provide an area to begin mapping out the repair sequence.

7.2.3.2 Process Steps

Process steps are as follows:

- Damage removal
  - Gradually remove the damaged blade structure one layer at a time, allowing for careful identification of the layers as described above.
  - Consult engineering if the damage is affecting the spar before removing this structure.
  - Continue damage removal until all damaged structure is removed. If damage involves more than one component (e.g., shell, spar, shear webs, bonds), material should be removed carefully in each component, moving methodically through the

components. In the case of complex damage, material removal may require working from both the exterior and interior of the blade.
    - In some cases, engineering will allow small areas of damage to remain in the blade due to the consequence to the structure if it were to be removed.
    - It is common practice for the damaged inner skin to be left in the blade as a backer plate for the inner skin repair. In this case, ensure that there is healthy laminate surrounding any inner skin damage that remains.
- Bottom of defect (BOD)
    - After all damage is removed, a base should be made to allow for mapping out the repair.
    - In general, a minimum of 50mm x 50mm area of healthy laminate should be exposed. This gives confidence that there is not any damage or defect that cannot be seen due to the small size of the ground-out area. This also ensures that the smallest repair ply has enough healthy laminate to bond to.
    - It is common practice for the damaged inner skin to be left in the blade as a backer plate for the inner skin repair. In this case, ensure that there is healthy laminate surrounding any inner skin damage that remains.
- Layer Identification
    - The layers within the removed laminate should be identified in terms of the types of fibers (i.e., glass or carbon), the number of affected layers, fabric types (e.g., unidirectional, double bias, triaxial), and layer orientations.

There are several standard forms of glass fabrics that are commonly used in wind turbine blades. These need to be identified in a damaged blade to map out the repair. Each form has a unique pattern that emerges when it is ground into with a grinder. The blade technician can use this pattern to determine the form of glass fabric, fiber orientation within each layer, thickness of each layer, and sequence of the laminate schedule. Standard forms of glass fabric include the following:

- Biaxial or double bias glass, consisting of layers oriented at +45 and -45 degrees
- Unidirectional glass, primarily consisting of fibers oriented at 0 degrees
- Triaxial glass, consisting of layers oriented at 0, +45, and -45 degrees
- CSM (chopped strand mat)
- CFM (continuous filament mat)

While some OEMs use triaxial fabrics in constructing the blades, other OEMs use combinations of alternating layers of biaxial and unidirectional fabric. When grinding into a damaged laminate, it can sometimes be difficult to determine if the original construction was triaxial or a combination of biaxial and unidirectional fabrics. A triaxial laminate schedule can be repaired using either triaxial fabrics or a combination of biaxial and unidirectional fabrics.

It is critical to determine the thickness (i.e., depth) in millimeters of each layer of 0, +45, and -45 glass fibers in the laminate stack and the total thickness of glass oriented in each direction. One common technique is to lay a straight edge across the laminate, bridging the removed damage, and use a depth gauge to measure the depth to the bottom of each layer and to BOD. The total quantity of glass in each orientation will need to be accounted when designing the laminate repair. Glass fabrics are generally specified in terms of their areal weight (e.g., grams per square meter or gsm) and the areal weight of each layer in the fabric (e.g., for a triaxial fabric the weight of each of the 0, +45, and -45 layers).

While non-OEM repair providers may not have access to the OEM laminate schedule for damaged components, the areal weights of each layer can be determined from the measured thickness. For most blades that were manufactured using a vacuum-assisted resin infusion molding (VARIM) process, each 1mm of glass laminate corresponds to 1300 gsm of fabric. For example, a 10mm thick blade shell that is determined to consist of 4mm of unidirectional fibers and 3mm each of +45 and -45 degree fibers would suggest that a total of 13000 gsm of glass fabric was used to construct the shell, consisting of 5200 gsm of unidirectional fibers and 7800 gsm of biaxial fibers.

Carbon fiber-reinforced structures are mostly used in the construction of spars, consisting primarily of unidirectional fibers. Due to the variety of forms of carbon reinforcements that are used, it may be difficult to determine the number of layers that are present due to how it grinds compared with fiberglass. In some cases, the carbon fiber is a thick, pultruded profile without distinct individual layers. For this reason, carbon fiber damage should be characterized by measuring the depth of material that was removed. It is also critical to characterize the form of the carbon reinforcement (i.e., pultruded planks, consolidated prepreg, or infused dry fiber) to the extent possible. If this is not known from the OEM or other sources, then additional testing may be required to determine the form, such as a test for the fiber volume fraction. The form of the reinforcement strongly affects the fiber volume fraction of the material, which affects the strength and stiffness of the material. Repairs that are performed with forms of carbon that differ from the form of the original blade will need to compensate for potential differences in the material characteristics.

Balsa wood and foam are the two standard types of core material. The type and thickness need to be determined.

7.2.3.3 Documentation

Reporting should include the following:

- Photos of the damage removed and BOD established; two picture types are recommended for all pictures: close-up pictures showing details on the extent of damage and looking inside and openings in the blade and wide-angle pictures showing the damage with one blade edge (leading edge or trailing edge) in the picture to give context to the location of the damage.
- Longitudinal start and stop measurements, of BOD, noted as either Z (distance from root end of the blade) or R (radial distance from the center point of the rotor diameter); units are typically meters (m) or millimeters (mm).

- Transversal or chordwise start and stop measurements, of BOD, from which edge of the blade should be noted as trailing edge or leading edge; units are typically millimeters (mm).
- Description of the components that are present in the repair area and damaged
- Description of the fiber-reinforced laminate structure and core materials in each component. The laminate structure should be characterized in terms of the types of fibers (i.e., glass or carbon), the number of affected layers, fabric types (e.g., unidirectional, double bias, triaxial), and layer orientations.
- The type and thickness of core material should be identified as applicable.
- Description of the bondline structure between the components.
- Surface coat application with masking tape removed.

7.2.3.4 Acceptance Criteria

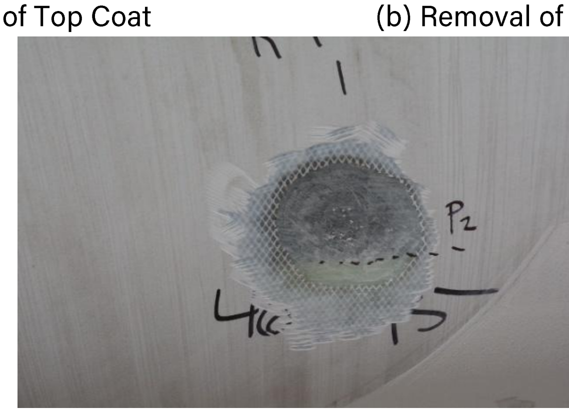
Acceptance criteria are as follows:

- Pictures are in focus, and all writing can be clearly read.
- All data requested are present and correct.
- Photos have data card or metadata present in the pictures.
- BOD is smooth and damage free (unless specified by engineering).

Figures 13-16 show examples of acceptable photos.

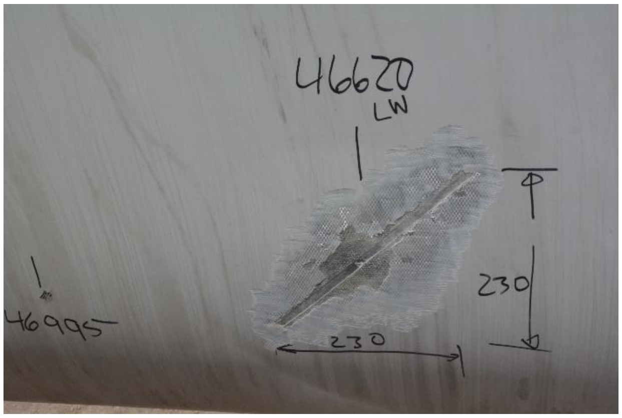
(a) Removal of Top Coat

(b) Removal of Some Glass Layers



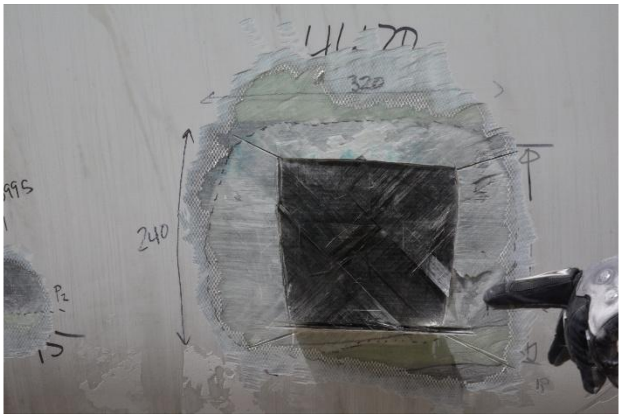
(c) Removal of Outer Glass Skin

Figure 13: First Illustration of Layer-by-Layer Removal of Damage Due to a Lightning Strike



(a) Removal of Top Coat

(b) Removal of Some Glass Layers



(c) Removal of Outer Glass Skin

Figure 14: Second Illustration of Layer-by-Layer Removal of Damage Due to a Lightning Strike

Figure 15: Illustration of a Grind to the Bottom of a Lightning Damage to a Carbon Spar Cap

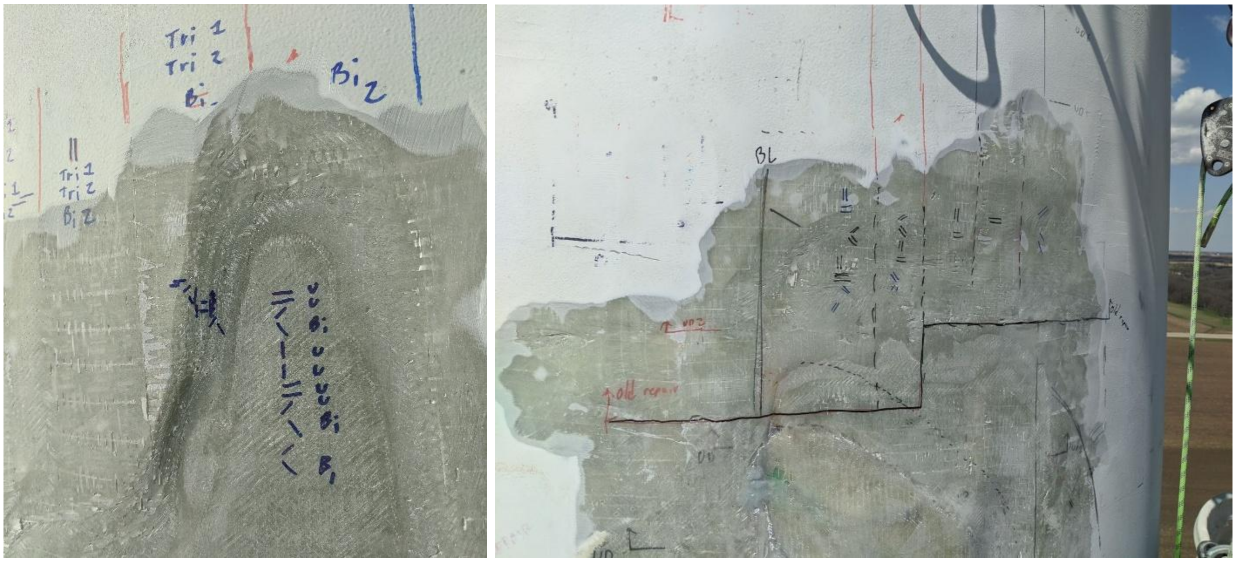


Figure 16: Examples of Annotations of the Layer Count and Layer Orientation

7.3 Repair Plan

7.3.1 Repair Layout

7.3.1.1 Step Description

After the damage removal process has been completed, the repair laminate schedule should be mapped so that surface preparation for repairs can begin. The laminate schedule should consider the original blade laminate schedule, number of damaged layers, and whether reinforcement layers are required.

The repair laminate plan is also determined based on damaged material type, fiber orientation, sequence, and depth or extent of layers as determined from the damage removal process, and after reaching the bottom of damage. For severe or complex damage for which handbook procedures may not be suitable, the repair laminate plan is typically provided by the OEM or service provider's engineering In which case the laminate plan must be prepared by personnel who are sufficiently qualified to understand the structural significance of the components being repaired, the nature of the materials used in the construction of the blade and for the repair, the critical differences between the OEM and repair materials, and other factors that might affect the structural integrity of the repair.

The laminate plan is transferred to the repair area before the scarfing and chamfering of the area are performed. The mapping of the plan will need to be approved by the OEM or service provider's engineering before proceeding to the next step in the surface preparation before lamination.

In the absence of design information, it is recommended that the repair plan is determined based on the observed material removed from the repair area and verified layer by layer for the material orientation. The material type is then used to determine the appropriate overlaps needed for the repair. It is not necessary to exactly replicate the original laminate schedule layer-by-layer. It is critical that the repair laminate sequence at a minimum ensures the same quantity of material (i.e., either thickness/depth or areal weight) in each orientation (i.e., 0, +45, -45) is replicated. However, the areal weights of the fabrics used in the repair may differ from those used in the original construction, so long as the totals in each orientation are matched or exceeded.

For repairs to carbon structures, it is critically important that differences between the form of the original structure (i.e., pultruded planks, consolidated prepreg, or infused dry fiber) and the form of the repair (typically prepreg or infused dry fiber) be accounted in designing the laminate plan. If a form with lower strength and stiffness characteristics than the original structure is used to perform the repair (almost always true for repairs to pultruded structures and also true if infused dry fibers are used to repair prepreg), then the thickness of the repair laminate will need to be increased relative to the depth of damage to compensate for the lesser properties.

Laminate repairs are performed as chamfered repairs. Chamfered repairs are defined by the minimum required overlap lengths per the OEM or a recognized standard (e.g., DNV-ST-0376[29]). Minimum required overlap lengths depend on the following:

- Material type and orientation (triax, biax, unidirectional fabric layers)
- Areal weight or mass per unit area for the fabrics
- Typical values of overlaps – per DNV-ST-0376
    - Triaxial fabrics: 75:1 (overlap-to-depth ratio) in the spanwise direction, 50:1 chordwise.
    - Biaxial fabrics: 50:1 in both directions
    - Unidirectional: 100:1 spanwise, 10:1 chordwise.

These minimum overlaps shall be satisfied unless appropriate engineering analysis demonstrates that lower values are acceptable.

More complex repairs involving multiple components in the blade will require a more complex repair plan, with laminate plans for each component as well as specifications for joining or bonding components as applicable.

7.3.1.2 Documentation

Reporting should include the following:

- For repair of severe or complex damage for which engineers developed a custom repair plan, work instructions should be prepared, including a schematic of the repair laminate plan for each damaged component and specifications for bonding components as applicable.
- A photograph of the completed repair map with the aid of a straight rule or measuring tape
- Zoomed-out pictures of overall layer mapping, clearly displaying all layers, spanwise and chordwise overlaps for all layers

[29] DNV-ST-0376, *Rotor blades for wind turbines*. Det Norske Veritas: 2024.

- Zoomed-in pictures of spanwise and chordwise overlaps for all layers with a straight rule or measuring tape

It is recommended to take photos of all four sides of the repair area, specifically in bigger repairs or when the full repair area cannot be fully captured in one photo frame.

7.3.1.3 Critical-To-Quality Parameters

The following factors are critical to quality for this step:

- Layer sequence, ply orientation, and its corresponding overlap dimensions must adhere to the prescribed and approved repair mapping plan.
- Layer sequence and material type with orientation should be highlighted on the repair area when marked up.
- Overlap dimensions in spanwise and chordwise direction should be highlighted with markings on the mapped repair area and with the help of straight rule or measuring tape for visual confirmation.

7.3.1.4 Acceptance Criteria

Acceptance criteria are as follows:

- Pictures of completed repair lamination map must be taken prior to the repair area grinding and chamfering step
- Clear photos displaying all layers adhering to the repair plan's ply sequence, each layer type, and fiber orientation
- Clear photos confirming that overlap dimensions match required laminate schedule provided and approved by the OEM, asset owner's, and/or service provider's engineering team, depending on who are the responsible parties.

Figures 17 and 18 show examples of acceptable photos.

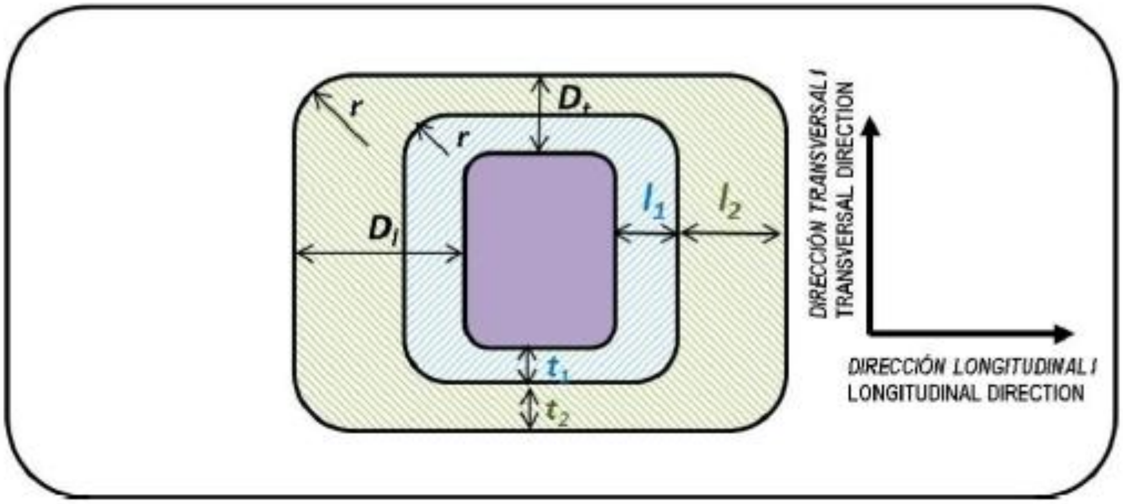


Figure 17: Example Repair Map with Markups and Measuring Tape

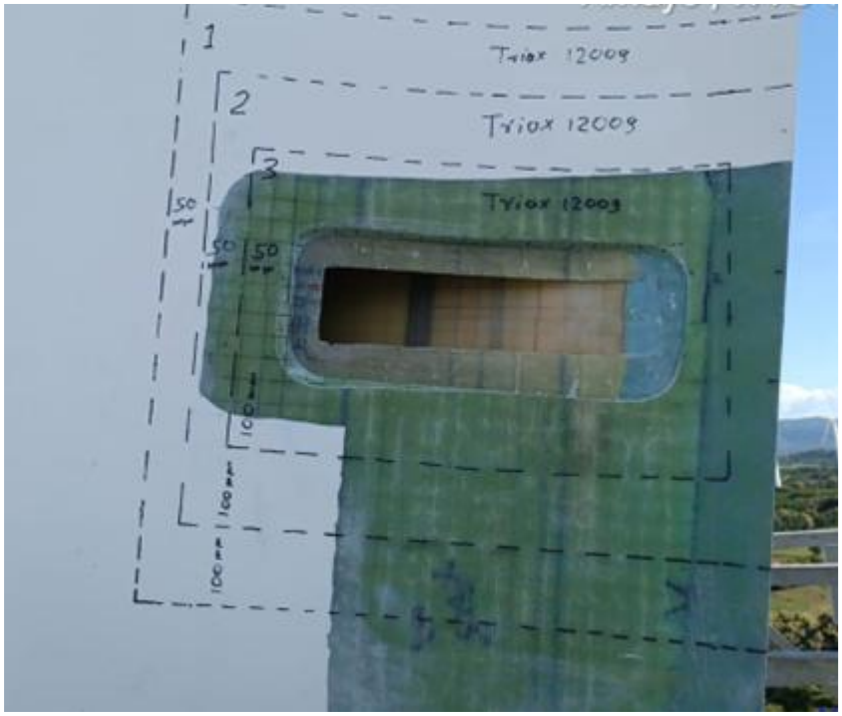


Figure 18: Example of the Laminate Plan Marked on the Repair Zone of a Blade

7.3.2 Scarf and Chamfer

7.3.2.1 Step Description

After the laminate schedule mapping has been approved, the surface is generally prepared for lamination by grinding and scarfing corresponding to the repair map. In the absence of engineering analysis justifying an alternative approach, the scarfing method prescribed here should be employed. Surface preparation may start by performing the layer-by-layer step-scarf by removing the required layers in each sequence of damaged material in the repair area. In the areas where repair layer will overlap with the blade, the original material layer corresponding to the laminate schedule will be exposed and removed according to the overlap dimension requirement.

After all layers have been scarf-chamfered using the angle grinder or sander, the result is a stepped chamfer surface area. While it is possible to apply lamination in this condition, it is recommended to chamfer the surface area to smoothly transition from layer to layer. The surface becomes a smooth ramp that allows the laminate to lay flat (preventing entrapped air) and to smoothly tie into the original material layers. As an alternative, it is also acceptable to start the grinding directly with the smooth beveled chamfer, omitting the step chamfer grind. Once the entire repair surface area is bevel-chamfered, the repair area is ready for the lamination step.

After the bevel-chamfering has been completed and the surface has been cleaned, layers can be laminated with the layers arranged smallest to largest or largest to smallest, according to the lamination schedule.

7.3.2.2 Documentation

Reporting should include the following:

- The completed scarf should be photographed from various angles (all four sides are recommended).
- Pictures of the stepped or chamfered scarfed repair area should be documented with the aid of a contour gauge or straight rule.
- Zoomed-out pictures of completed scarf, clearly displaying all layers, spanwise and chordwise overlaps for all layers.
- Zoomed-in pictures of completed scarf, capturing spanwise and chordwise overlaps for all layers with a straight rule or measuring tape.

7.3.2.3 Critical-to-Quality Factors

The following factors are considered critical to quality for this step:

- Rounded edges at the corners of the repair area.
- For step-chamfered repair, overlap dimensions for each layer should match.
- For beveled-chamfered repair, smooth transition between each layer in the repair (see Figure 19).

7.3.2.4 Acceptance Criteria

Acceptance criteria are as follows:

- Pictures of completed scarf-bevel must be taken prior to lamination.
- Correct layers must be removed in each layer step.
- Correct spanwise and chordwise overlaps must remain and represent the marked repair laminate schedule prior to grinding and sanding.
- Smooth transition between layers for chamfered repairs.

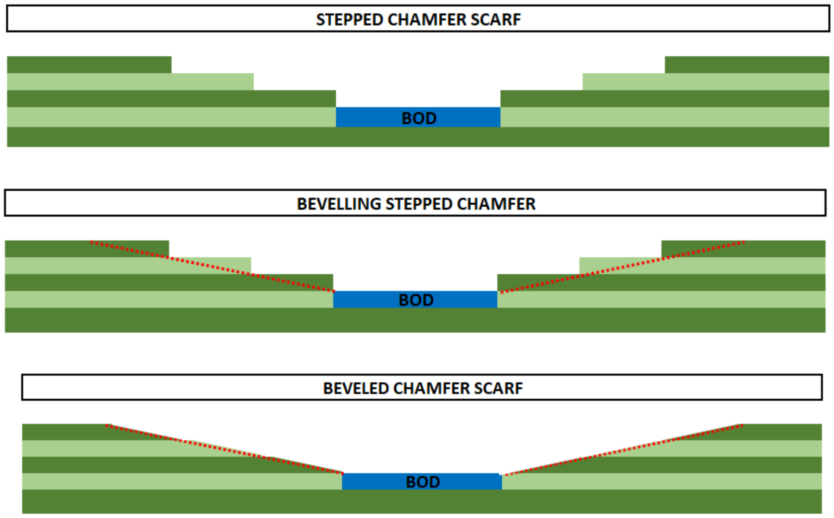


Figure 19: Example Diagram of Repair Scarf and Chamfer

7.3.3 Layup

7.3.3.1 Step Description

Layup includes mixing resin, wetting out fabric, and placing the layers in the repair region, including core material, if applicable. Application of a hardback, if repair requires replacement of inner and outer skins, would also be part of this step.

7.3.3.2 Process Steps

Process steps include the following:

- If hardback is to be applied, it should be adhered to the inner surface using a method to hold in place during cure, such as string and rigid bar to hold tightly against inner surface during cure of adhesive. This will provide a light surface to lay up on in order to replace the inner skin. (see Figure 20)
- Layers that were planned in the repair planning should be cut out to correct sizes, including core material. While ply layup order can vary with repair engineering approaches, the interface between the repair laminate stack and the native blade substrate surface must be treated as a critical to quality bond. It is highly recommended that a large ply down first laminate order or an added "tie-ply" variation be utilized to ensure the best possible interface contact be achieved.
- Resin amount should be estimated based on the total weight of the fabric to be applied, target fiber volume/weight fraction, and additional excess resin margin to account for tolerances in the estimation and waste material.
- Once resin amount is estimated, the correct hardener to resin mixture should be weighed out in separate containers (Figure 21).
- If vacuum consolidation is to be used, all consumable materials, such as release film, breather, vacuum bag, and tacky tape, should be cut ahead of the start of the layup. The vacuum pump and all hoses and gaskets should be inspected and ready for use. Tacky tape should be placed on the surface of the blade, with the exposed side protected, before the start of the layup so that materials can be quickly applied after the layup is complete.
- If the layup is used as a base surface for additional layups, peel ply is highly recommended to prepare the outer surface for bonding and protection from surface contaminates after curing. Peel ply can also be used to prepare the surface for finishing step.
- The curing blanket should be prepared and checked before the start of the layup to ensure its proper functioning and correct size for the repair.
- The temperature and humidity should be measured and checked with calibrated instruments before the start of the layup to ensure that it is within the specifications of the resin being used.
- Once all materials are prepared, the surface should be checked and cleaned right before the start of the layup. It is recommended to have a sanded surface that has been cleaned with compressed air or a clean rag. If isopropyl alcohol is used, it is recommended to be 99% to avoid any water residue to be left on the surface after wiping. Always use a clean rag to wipe the surface.

- A timer should be set before the start of mixing to record open time of the resin. This should be checked before applying vacuum bag or final curing to ensure that open time does not exceed manufacturer's recommendations.
- After all material is prepped and surface is clean, resin mixing can begin. Resin should be mixed according to the instructions for specific manufacture and type of resin. However, in general, resin should be slowly mixed by hand, thoroughly, for three to five minutes, minimizing the amount of air introduced into the resin.
- Once resin is mixed, the first layer closest to the inner surface should be wet out with an appropriate amount of resin. A roller and/or squeegee should be used to ensure that the resin is thoroughly introduced and wet out in the glass layer. (Figure 22)
- Once the glass layer is wet out, it can be placed on the repair surface, within the repair planning drawing.
- Each layer should be wet out and placed in the planned location, taking care to minimize shearing of the fabric and keeping ply orientation aligned with the orientation of the blade.
- Peel ply layer should be placed on top of the last layer.
- Once all materials are placed, if vacuum consolidation is to be used, the vacuum bagging materials can be added to the surface. Release film should go directly on top of the wet layers, then a breather layer to allow airflow, gasket placed out of the way of the repair layers, and finally the vacuum bag. (Figure 23)

7.3.3.3 Documentation

Reporting should include the following:

- Photos
- Surface prior to layup
- Resin and hardener weights, as well as total mixed weight (scale and container included in photo)
- Temperature and humidity at the start of the layup
- At least first and last layers placed on repair surface
- Vacuum bagging materials after vacuum is pulled
- Written documentation
- Resin and hardener individual weights, as well as total weight of mixed resin
- Temperature and humidity at the start of the layup
- Open time of resin (time between mixing and final layer placement or vacuum being pulled if vacuum consolidation is used)

7.3.3.4 Acceptance Criteria

Acceptance criteria are as follows:

- Temperature and humidity within specification of resin
- Mixing ratio within specification of resin
- Open time within specification of resin
- Little or no air entrapment in layers during layup

- Layers placed within repair map with correct overlap lengths
- If using vacuum consolidation, no significant air leaks during consolidation
- No wrinkles in layers
- Layers are placed in correct orientation within tolerance of approximately +/– 5–10 degrees

Figures 20-23 show examples of acceptable photos.

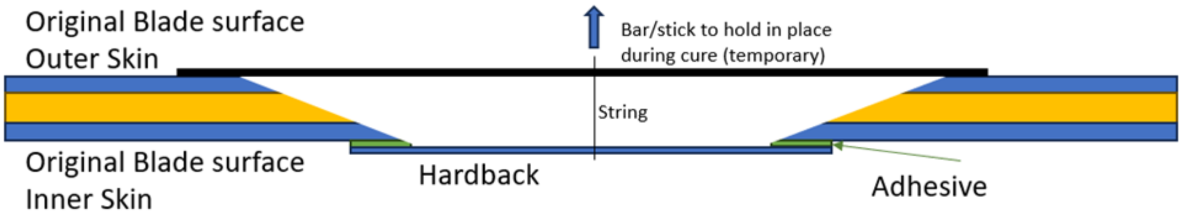


Figure 20: Illustration of the Use of a Back Plate to Repair Damage to the Inner Skin

Figure 21: Documentation of Weighing Out the Resin and Hardener

(a) Marking the Lamination Schedule

(b) Applying the First Layer of Laminate

(c) Finished and Bagged First Sequence

Figure 22: Example of Lamination During a Blade Repair

Figure 23: Documentation of the Vacuum Level

7.3.4 Cure

7.3.4.1 Step Description

The curing process is used to fully harden the resin and bring its glass transition temperature and material properties to the desired values by adding heat after the resin has gelled at room temperature.

7.3.4.2 Process Steps

Process steps include the following:

- Check that the heating blanket being used for the application is working correctly and independently verify with a thermocouple that the temperature set is the temperature reached.
- It is recommended to use thermocouples to verify cure temperatures reached on the blade surface, if possible.
- Ensure that the heating blanket is large enough to cover the repair layers. The cold zones of the blanket should be excluded from the size required for covering the layup.
- Set up the heating blanket and temperature recording devices to run for desired cure time and temperature, as per resin requirements.
- Verify that monitoring of the temperature is done manually, with IR gun and manual recording, or with data logging and a thermocouple, to ensure that there are no faults or temperature drops during the cure cycle.

7.3.4.3 Documentation

Reporting should include the following:

- Cure time and temperature through data logging and/or manual photos of the temperature of the surface with an IR gun and timestamp

7.3.4.4 Acceptance Criteria

Acceptance criteria are as follows:

- Cure time and temperature is within specifications of resin and/or process requirements of OEM.

Figure 24 shows an example of an acceptable photo.

Figure 24: Illustration of the Recording of the Cure Temperature and Time

7.3.5 Finishing

7.3.5.1 Step Description

Finish repair area back to original surface and color. It is important to avoid large surface deviations that could impact the airfoil. The surface coat is a UV protectant. All repairs should be protected from UV for long-term reliability.

7.3.5.2 Process Steps

- Surface preparation:
  - After laminate repair is cured, the repair surface should be smoothed with a medium- to high-grit sander to prepare the surface for filler application.

  - After sanding, the surface should be cleaned with a quick drying solvent (i.e., isopropyl alcohol).
- Filler application:
  - After sanding, an appropriate filer should be used to fill in any open pores or shallow areas of the repair. In general, nonreinforced filler should not be applied >3 mm in thickness.
  - After filler is applied to the surface and before it begins to cure, a plastic scraper or similar should be used to smooth the repair area, then filler should be allowed to cure.
  - Cured filler and repair should be sanded with a medium- to high-grit sandpaper, and repair area should be free of any large surface deviations.
- Surface coat application:
  - After sanding, the surface should be cleaned with a quick drying solvent (i.e., isopropyl alcohol).
  - Apply a masking tape boarder around the repair area. Ensure that all surface area within masking tape boarded is sanded and cleaned.
  - Ensure that surface coat is RAL color as the OEM-applied surface coat.
  - Surface coat should be mixed and applied according to the material specifications.
  - Remove the masking tape before surface coat is cured.
  - Allow surface coat to cure according to the material specifications prior to restarting the turbine.

7.3.5.3 Documentation

Reporting should include the following:

- Atmospheric conditions
- Temperature
- Humidity
- Photos of laminate surface cleaned and ready for filler application
- Photo of filler cured and sanded
- Photo of contour gauge applied to surface showing smooth surface prior to surface coat application
- Surface coat application with masking tape removed

7.3.5.4 Acceptance Criteria

Acceptance criteria are as follows:

- Pictures are in focus, and all writing can be clearly read.
- All data requested are present and correct.
- Photos have data card or metadata present in the pictures.
- Contour gauge shows smooth surface.
- All masking tape is removed from the blade.
- Final pictures show laminate fully coated and surface smooth.

Figures 25 and 26 show examples of acceptable photos.

Figure 25: Example of the Final Sanding of a Glass Repair over Foam Core

(a) Sanding of the Finished & Cured Laminate (b) After Paint and Drilling of Barrel Nut Holes

Figure 26: Example of the Finishing of a Blade Repair

7.3.6 Completion of Repairs

At the end of the repair, all of the documentation requirements enumerated in the previous sections should be compiled into a single report of the repair. The documentation should include careful photographic documentation of the repairs step-by-step, from pre-work through finish. All materials should be carefully documented, including suppliers, specifications, batch numbers, expiration dates, and quantities as applicable. All critical process specifications should be documented and, when applicable, documented photographically. All CTQs should be noted and, when applicable, documented photographically. The finished report on the damage and the repairs should be kept as a permanent part of the blade's maintenance record.