https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

eawe european academy of wind energy
Open Access WIND ENERGY SCIENCE DISCUSSIONS

Repair of wind turbine blades: Experience and observations from India – A Review

Refugine Nirmal Ignacy Muthu[1], Leon Mishnaevsky Jr.[2], Saravanakumar Savadaiyan[1], Thamodharan Krishnaraj[1], Anthonyraj Premkumar S[1], Mohammed Farook S[1], Kadhirvel Boopathi[3]

[1] Windcare India Pvt Limited, 3/336, Pollachi - Dharapuram Rd, Gudimangalam, Tamil Nadu 642201, India.

[2] Department of Wind and Energy Systems, Technical University of Denmark, Roskilde, Denmark.

[3] National Institute of Wind Energy (NIWE), Chennai, India.

**Correspondence: Leon Mishnaevsky Jr (lemi@dtu.dk)*

Abstract. A large expansion of wind energy is planned in India. On the other side, older wind turbines are approaching the end of their lifetime. Improvement and quality of maintenance technologies of wind turbines are therefore significant for the successful expansion and support of wind energy generation in India. This paper summarizes the strategies, main challenges, and procedures of wind turbine blade repair in India. The influence of location and climate, methods of damage identification, and evaluation of the severity of blade damage, in addition to steps involved in leading-edge erosion, laminate, foam, web, and serration damage repair are presented. This overview of the current situation, methods, and technologies should provide the basis for the optimization of repair technologies, the development of new techniques, and thus the improvement of the reliability of wind energy generation in India.

1. Introduction

Fossil fuels are currently the major source of global energy production. They are burnt to produce energy. During this process, they emit carbon dioxide and other greenhouse gases which are by far the largest contributor to global warming. The transition from fossil fuel to renewable energy is required to stop global warming.

Although India has reduced its dependence on fossil fuels for primary energy sources by 4% from 2000 to 2022, fossil fuel consumption has increased by 160% (Hannah et al., 2020). Energy consumption in India is expected to grow from 1276 TWh in 2021 to 2172 TWh in 2030. To meet our energy demands, renewable energy sources have to increase at a rapid pace. As of March 2022, wind energy contributes 37.7% of total renewable energy in India. In July 2022 Indian Government announced new policies for achieving a target of 500 GW of renewable energy capacity (Sidharth et al., 2022). India is expected to install 19.4 GW of wind turbines between 2022 to 2026. As new turbines are expected to be installed, the old turbines are aging and approaching the end of their lifetime.

Composite blades of wind turbines are one of the rotating elements of wind turbines, and they are subject to very high mechanical and environmental loadings (Mishnavesky et al., 2022; Boopathi et al., 2021; mum4kids, 2016). The often-observed failure modes for composite blades are delamination, splitting of fibers, crack in gel coat (Olabi et al., 2021), leading-edge erosion (Olabi et al., 2021; Mishnavesky et al., 2021), foam or sandwich damage, shear web failure, and serration damage. Blades fail due to manufacturing defects, errors during installation or service, transportation, external factors like storms, lightning, hail, dust ice, and impact by foreign objects. According to Carrol et al (2015) for an offshore WT, the blades are the fifth biggest failure contributor at 6.5%.

The global wind energy market for operation and maintenance is expected to grow from $13.7 billion in 2016 to $27.4 billion in 2025, and in India, it is expected to increase from 5.6% in 2016 to 6.3% in 2025 (Global Data, 2017). Wind turbine blade maintenance and repair are quite expensive as the average cost for blade repair for offshore WT can go up to $30,000 and the average cost of a new blade could be $200,00 (Stephenson S, 2011). Downtime of a WT due to blade failure is shown to be 7% of the total technical downtime, that is, 18 h per year per turbine (Stenberg and Holttinen, 2010), and the annual probability of blade failure is 0.21% for each turbine

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

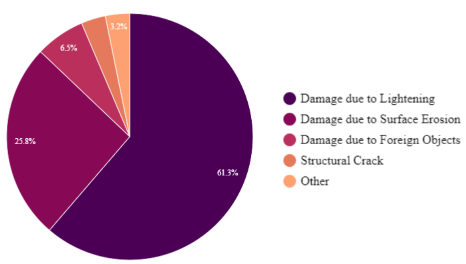
(Branner and Ghadirian, 2014). Two percent of turbines per year require blade replacements, mainly because of lightning strikes (Lantz, 2013). As of 2010, in the 1.5-2.1 MW wind turbine category, the average expenditures for blade repair are $88,000 for structural cracks, $23,000 for labor, and $72,000 for equipment (cranes). Non-structural crack repairs have an average cost of $13,000, with a labor expense of $4,000. In the 2.1–3 MW wind turbine class, the average expenditures for blade repair are $223,000 for structural cracks, $23,000 for labor, and $72,000 for equipment (cranes). Non-structural crack repairs average $12,000, with a labor cost of $4,000 (Martin et al., 2011). On a global scale, structural malfunctions are significantly lesser than the number of blade malfunctions (Pryor et al., 2022).

The durability of wind turbine blades is designed for a service life of 15 to 20 years, but regular maintenance and repair become imperative to prevent catastrophic failures as blades are subjected to significant mechanical loads, harsh environmental conditions, assembly damages, and manufacturing defects. Given these challenges, structural repair emerges as the most economical and practical solution to restore the blade's structural integrity, as replacing the entire blade is not cost-effective (Katnan et al., 2014). Therefore, the effectiveness of operation and maintenance, coupled with blade repair, plays a pivotal role in ensuring the reliability of wind turbines and minimizing downtime caused by blade failures. This work focuses on discussing the blade repair methods implemented in India, drawing insights from a survey conducted among various blade repair and service teams. The paper aims to provide a comprehensive understanding of how damage is evaluated and the necessary steps for addressing different types of damage.

2. Causes of Wind Turbine Blade Failures in India

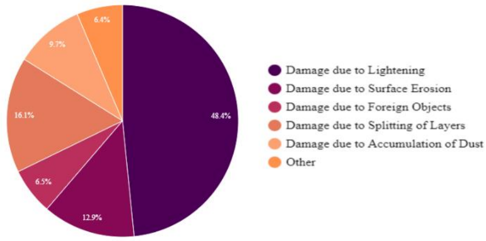
Two distinct surveys were conducted to estimate the occurrence of damage and gain insights into blade repair practices in India [Survey 1; Survey 2]. These surveys targeted wind turbine park owners, technicians, and service companies, ensuring the confidentiality of respondents. Both surveys delved into the root causes of blade failures, the frequency of such failures, materials used, repair methods employed, assessment procedures, and the associated costs of blade repair and inspection. A total of 35 responses were collected from blade service technicians, supervisors, and managers spanning various regions in India.

Structural repair of a single wind blade can cost up to $30,000, and a new blade cost, on average, about $200,000 (Pryor et al., 2022). These blades are typically fully exposed in the field, subject to challenging working conditions including high altitudes, atmospheric radiation, sand and dust, lightning, heavy rain, freezing rain or ice, snow, salt corrosion, and typhoons Given the prevalence of wind energy plants in open countryside and mountainous regions, along with extended operational durations and heightened blade soiling, lightning strikes have become a growing concern (Peng et al., 2023). Chou et al., (2013) demonstrated that 30% of blade damages are attributable to thunderstorms, closely followed by heavy rainfall at 28%. Both thunderstorms and heavy rainfall contribute to a higher frequency of lightning strikes. In most cases, blades damaged by lightning can be repaired, but replacement is occasionally necessary. Survey results presented in Fig. 1 highlight that in India, lightning strikes are the most common and severe form of damage, followed by surface erosion and impacts from foreign objects. Structural cracks cause the least damage, indicating that external forces pose a greater risk to blade integrity than structural weaknesses.



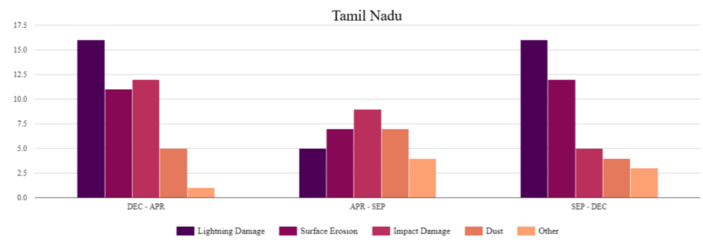
(a)

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

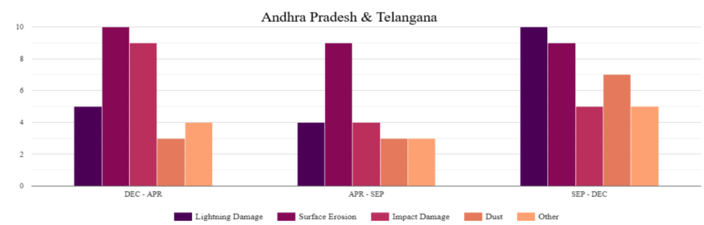


(b)

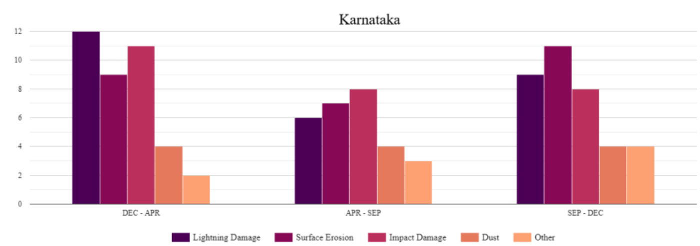
Figure 1: Survey results (a) Type of damage attended maximum by blade technicians, (b) Damage which has maximum severity.



(a)

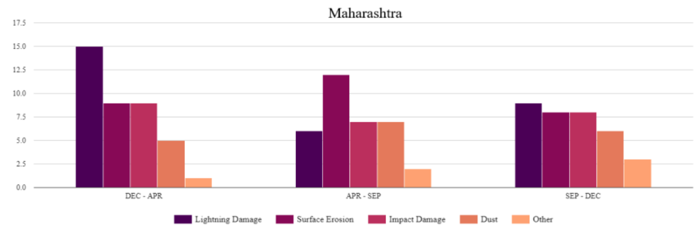


(b)

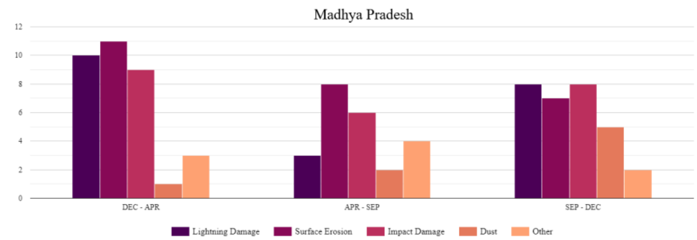


(c)

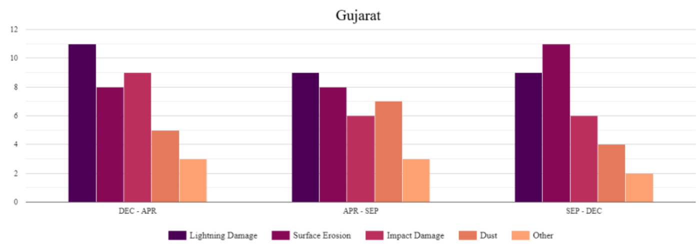
https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024



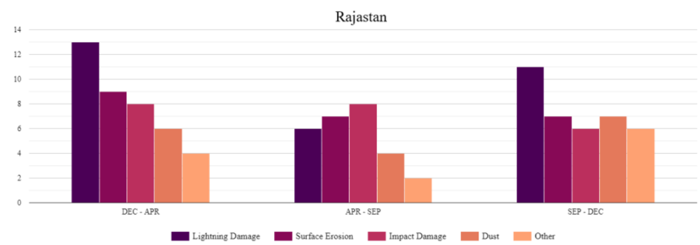
(d)



(e)



(f)



(g)

Figure 2: Survey results – types of failure at different parts of India in different months, (a) Tamil Nadu, (b) Andhra Pradesh and Telangana, (c) Karnataka, (d) Maharashtra, (e) Madhya Pradesh, (f) Gujarat, (g) Rajasthan.

Numerous studies have explored the influence of climatic conditions on wind turbine failures, emphasizing the pivotal role of climate, weather, and harsh environments in wind turbine (WT) reliability. Tavner et al., (2012, 2006) conducted a reliability analysis, revealing a robust correlation between WT failure rates and factors such as weather, wind speed, and temperature. Notably, Tavner demonstrated that humidity predominantly affects the

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

eawe european academy of wind energy
Open Access WIND ENERGY SCIENCE DISCUSSIONS

electrical system over the mechanical system. Further, Slimacek et al., (2016) emphasized the substantial impact of harsh environments on the reliability of WTs. WTs operating in conditions with factors like lightning strikes, high winds, and icing experienced stoppages 1.713 times more frequently than under normal conditions. Additionally, there was an observed increase in WT failure frequencies during winter months, attributed to higher wind speeds, lower temperatures, and icing (Reder et al., 2018). India has a variety of climatic conditions ranging from tropical in the south, hot and cold in the North, and dust in Rajasthan. These distinct climatic conditions affect the type of failures in those regions.

Figure 2 shows that from December to April lightning strikes caused the most damage in all states except Andhra Pradesh & Telangana, and Madhya Pradesh regions as these regions experienced surface erosion and impact damage the most during this time. From April to September states like Andhra Pradesh & Telangana, Maharashtra, and Madhya Pradesh experience large numbers of surface erosion damages while, states like Tamil Nadu, Karnataka, and Rajasthan experience impact damage. But Gujarat experienced lightning strikes followed by surface erosion during this time.

From September to December, lightning strike damages are the highest in Tamil Nadu, Andhra Pradesh, Telangana, Maharashtra, Madhya Pradesh, and Rajasthan followed by surface erosion except in Madhya Pradesh as it encounters abundant impact damage. Karnataka and Gujarat experience maximum surface erosion while Rajasthan is least exposed. Although Madhya Pradesh encounters more lightning strikes during this time comparatively it is lesser than all other states. The impact of climate extends beyond influencing the failure rate; it also affects the time required for repairs. Different climatic regions have varying effects on critical subsystems and failure causes in wind turbines. This necessitates the consideration of local climatic conditions when planning wind turbine operations and maintenance strategies for subsystems. For instance, in colder climates, rotor blade downtimes and failure rates are notably affected, resulting in longer downtimes and higher failure rates. Furthermore, in cold climatic regions, lightning emerged as a significant cause of rotor blade failures (Ozturk et al., 2018). This highlights the importance of tailoring maintenance strategies based on the specific climatic conditions of wind turbines to optimize their overall reliability and performance.

3. Repair Strategies in India

3.1. Challenges and difficulties faced by repair technicians

A blade repair technician is a specialized professional responsible for maintaining and fixing wind turbine blades. Their main job involves inspecting, identifying, and repairing any damages or defects in these blades. This includes visually checking the blades, using special tools to assess their condition, and making necessary repairs or replacements. Apart from repairs, these technicians may also perform preventive maintenance tasks like cleaning the blades, applying protective coatings, testing lightning protection systems, and conducting regular inspections to catch potential issues early on. One of the main challenges for these technicians is working at great heights. Repairing wind turbine blades often involves working at significant heights, which can be risky without proper safety measures. Technicians must be trained in fall protection, rope access systems, and equipment usage (Dangle Rope Access, 2023).

Figure 3 shows the main challenges faced by the technicians during blade repair. Most wind turbines are located in remote regions, so accessing them would be a hard challenge. Adverse weather conditions, such as high winds or cold temperatures, can hinder technicians from reaching the blades for repairs. Cold weather, in particular, can impact the composites used in the blades and their ability to cure (Wood, 2011). Advanced curing methods like heat blankets and UV curing can be used to reduce the curing time in low temperatures (Katnan et al., 2014). Climates in India are diverse and extreme making the blade repair work a challenging task. In the summer, the temperature might reach 45 plus degrees in Rajasthan (Jaisalmer), 40 plus in Gujarat (Bhuj, Naliya), and Andhra Pradesh (Anantapur). While the Satara region in Maharashtra experiences good rainfall for almost 9 months in a year. Hadagalli region in Karnataka experienced twist winds making it more difficult for technicians to repair the blade. Moreover, the repair operations are suspended if wind speeds exceed 23 meters per second. Occasionally, repairs may need to be done inside the blade, requiring approval for a fully confined space procedure before starting the work (Wood, 2011).

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

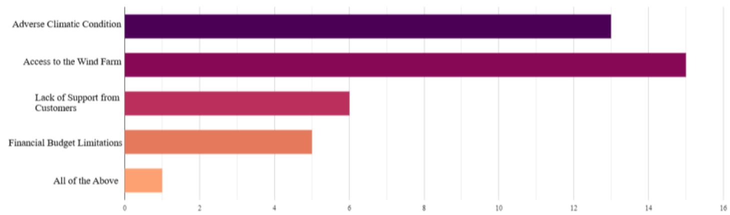
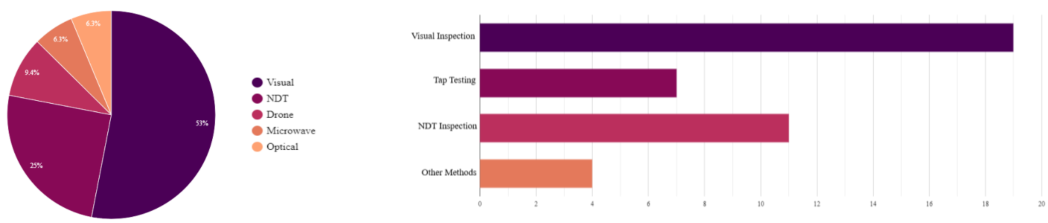


Figure 3: Survey results – challenges faced during blade repair.

3.2. Damage Identification

Blades are one of the largest components in WT. To function properly periodic inspection is required as any defect on the blades will affect the downtime of WT operation. Figure 4(a) illustrates the identification methods employed to understand the reasons for blade failure. Visual inspection, as shown in Fig. 4(b), emerges as the most utilized and cost-effective method alongside tap testing. Advantages like simple execution and the need for minimal equipment make it a feasible method for on-site tests although it is not an objective-based method (Andreisek et al., 2016). During the inspection technicians use a rope and tethering system (rope access method) or sky lift platforms to climb near the blades for inspection as shown in Fig. 5 and 6, respectively. During visual inspection, the outer surface of the blades can be inspected but they use tap testing to evaluate the internal flaws inside the blade. It is a sound-based approach where a wooden hammer is hit on the blade surface, a healthy blade would produce a sharp, crisp sound while a damaged or delaminated blade would produce a dull, hollow sound (Sofema Online, 2014).



(a) (b)

Figure 4: Survey result – (a) Affordable inspection method, (b) Methods to assess the blade repair area.

Figure 5: Blade Technicians inspect the blade using the rope access method. Image courtesy - Meeting the Challenge of Wind Turbine Blade Repair, reprinted from (Marsh, 2011).

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

(a) (b)

Figure 6: Blade Technicians inspecting the blade using sky lift platform (a) at the root, (b) at the tip.

As wind turbines continue to grow in size, traditional inspection methods raise safety concerns. Drone inspections (remote controlled) provide a safer alternative by capturing high-quality images that help identify issues such as missing bolts and damage on the blades. Non-Destructive Testing (NDT) techniques, including acoustic emission, vibration, and strain methods, are employed to monitor the structural health of the blades (Ding et al., 2023). Following visual and tap testing inspections, technicians assess the extent of damage. Based on the evaluation, technicians decide whether the damage can be repaired on the ground or requires work atop the wind turbine. Airborne repairs are suitable for addressing serration damage, leading edge erosion, and minor damages. In contrast, damages like foam damage, web damage, and laminates damaged after foam necessitate repairs on the ground. Windcare India Pvt Ltd blade technicians use a table, as shown in Table 1, to determine whether repairs will be conducted on the ground or atop the wind turbine. Figure 7 illustrates that the NDT techniques, such as ultrasonic and X-ray methods, aid in determining the depth of damage, while thermal imaging helps identify the damage location. These NDT methods are more suitable for ground inspections due to operational challenges associated with performing them on top of the blades.

Conventional Non-Destructive Testing (NDT) methods often necessitate direct contact between the inspection instrument and the blade, occasionally requiring the blades to be removed for assessment. Therefore, developing a new NDT technique that allows defect measurement from a significant distance is crucial (Sanati et al., 2018). Infrared thermography presents a non-contact alternative that captures thermal images using thermal cameras, which can be operated from the ground or mounted on drones. This method leverages the temperature differences caused by voids or cracks within the material, resulting in a temperature contrast in the thermal images. Active thermography, which involves an external heating source to heat the blade, poses operational challenges, particularly for large blades. In contrast, passive thermography utilizes natural heating sources, such as solar radiation, to heat the blade. The thermal contrasts that arise between intact and defective areas of the blade when exposed to solar radiation can be effectively captured using thermal imaging cameras. Galleguillos et al., (2015) employed passive infrared thermography to detect damages such as cracks and delamination. By mounting infrared cameras on unmanned aerial vehicles, they were able to capture thermal images efficiently, demonstrating that this approach significantly reduces inspection time. Similarly, Doroshtnasir et al., (2015) introduced a novel method for inspecting sub-surface defects in rotating blades from a considerable distance using passive thermography. This method included the development of an advanced data processing technique to mitigate environmental interferences. Sanati et al., (2018) investigated wind turbine blades using both active and passive thermography. Their study indicated that for passive thermography, the optimal times for detecting damages during daylight experiments are early morning and noon. They implemented various algorithms to enhance the quality and visibility of internal defects. However, their method was unable to detect defects smaller than 4 mm, irrespective of the depth at which these defects were located. While passive thermography offers a safe, reliable, and economical inspection method, its effectiveness is maximized under conditions of significant temperature contrast—such as a hot sunny day following a cold night or a cold evening after a hot sunny day. To address these limitations and enhance the reliability of the system, new methods need to be developed. These advancements could potentially mitigate the dependency on specific environmental conditions, ensuring consistent and accurate defect detection.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

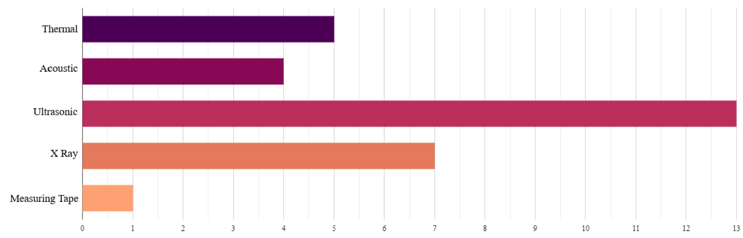


Figure 7: Survey results – methods to identify the depth of damage.

Table 1: Blade damage work assessment chart used in Windcare India Pvt Ltd.

Si. No	Damage Details	Location	Work
1.	Tip to 2.5m from tip	Tip of the blade	Sky-lift work
2.	Laminate damage under 2m	Any part of the blade	Sky-lift work
3.	Foam Damage more than 300mm	Any part of the blade	Ground Work
4.	Erosion	Any part of the blade	Sky-lift work
5.	Web Damage	Any part of the Web	Ground Work

On the ground, the inner section of the blades is examined using a combination of camera techniques and a drill-hole endoscope method. Cameras are employed to inspect the more expansive areas of the blade's cross-section. These cameras are positioned on tracks and move along with the blades, enabling technicians to assess any damage present in the blade's internal area. For the evaluation of smaller cross-sections or regions closer to the blade's web, two holes are created: one on the leading edge of the pressure side and another on the trailing edge of the suction side. As shown in Fig. 8, endoscopic cameras are then inserted through these holes to examine the damage. After the inspection, the adhesive is applied to the holes and allowed to cure for an hour.

(a) (b) (c)

Figure 8: (a) Endoscope Camera, (b) Endoscope hole, (c) Area inside the blade viewed using endoscope camera.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

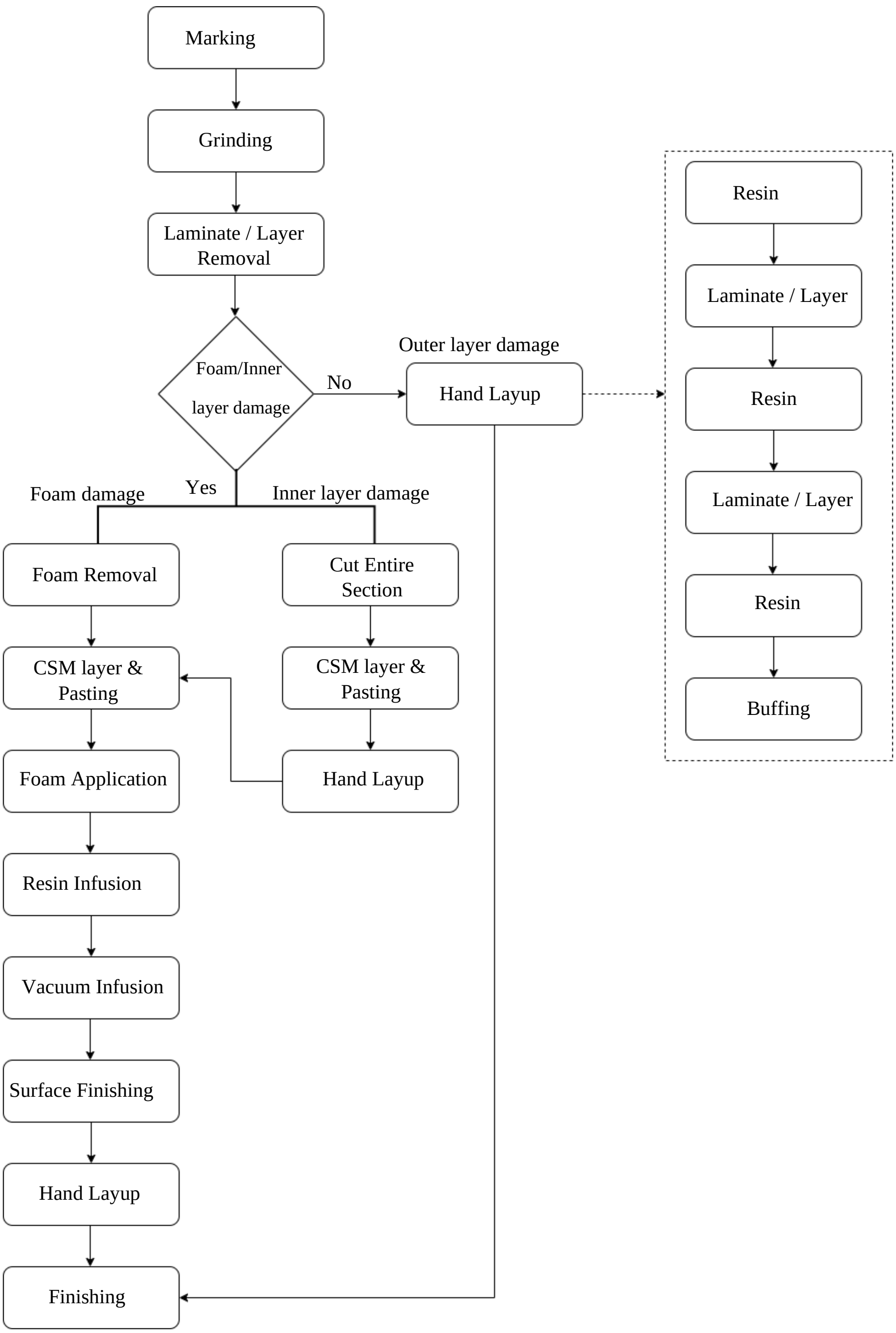


Figure 9: Schematic for Blade repair process in India.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

3.3. Repair Process

Composite materials used in turbine blades experience various forms of damage during operation, which can propagate under cyclic loading, thereby reducing the structural integrity of the blades. Effective maintenance and repair strategies are crucial to counteract these effects. Two common repair methods for composite blades are external patch repair and scarf patch repair. In external patch repair, an additional composite layer is applied to the damaged area of the blade's exterior. This technique is particularly effective for thin sections, although it can negatively impact aerodynamic properties. In contrast, the scarf patch repair method is better suited for thick sections and involves removing the damaged part of the laminate in a specific shape and bonding a similarly shaped patch into the void (Orsatelli J et al., 2023). This method provides better aerodynamic performance due to its smooth finish. Scarf patches can be classified into hard patches and soft patches. Hard patches consist of pre-cured patches bonded to the parent laminate with adhesive (Baker, 2006), while soft patches involve the use of prepregs that are directly cured onto the parent laminate (Whittingham et al., 2009). The parent material can be machined to a smooth, tapered finish or a stepped finish. While various repair techniques exist, assessing the quality of these repairs is a critical area of research. Mishnavsky et al., (2019) investigated different repair techniques for wind turbine blades using computational mechanics, considering geometrical, mechanical, and physical/chemical factors to optimize blade repair. He also developed computational models to study the effects of scarf angles, adhesive thickness, and void presence on repaired composite panels (Mishnavsky et al., 2020). Mishnavsky et al., (2022) found that repair strength and porosity depend on the method used, and demonstrated that voids induce residual stresses in the parent laminates. Although many researchers have studied composite repairs in aerospace, general, and external applications, comprehensive studies on the reliability of blade damage repairs are lacking. Bendemra et al., (2015) examined peak stress in tapered and stepped scarf repairs, finding that stepped repairs exhibit higher stress concentrations, which can be mitigated with additional plies and design modifications. Benyahia et al., (2011); Benyahia et al., (2014); and Xing et al., (2024) evaluated different patch shapes, assessing their impact on repair quality and post-repair strength. Lie et al., (2023) investigated the compressive strength and impact behavior of patched composites, showing that thicker patches reduce deformation and delamination, and that patch diameter has minimal impact beyond a certain size. Various methods have been used to estimate the reliability and service life of external composite repairs for pipes and concrete (Savari et al., 2021; Karbhari and Abanilla, 2007). While significant progress has been made in understanding and improving composite repair techniques, ongoing research is needed to enhance the reliability and effectiveness of these repairs in turbine blade applications.

In this section, the steps followed in the repair process in India are explained as shown in Fig. 9. Damages such as leading-edge erosion, foam/sandwich damage, layer/laminate damage, web damage, and serration damage are elaborated. The general repair process is elaborated in Appendix A.

3.4. Factors controlling the post-repair life expectancy

Another outcome of the review is the evaluation of factors controlling the life expectancy. Figure 10 shows the results of the survey, showing the factors influencing the post-repair lifetime. It can be seen that the life expectancy of the repair not only depends on the age of the blade but also the availability of spare parts and the products purchased. Most of the blades are designed and manufactured outside India and the unavailability of spare parts makes the blade repair costlier. Thus, blade service companies buy products from unauthorized suppliers which reduces the life expectancy of the repair.

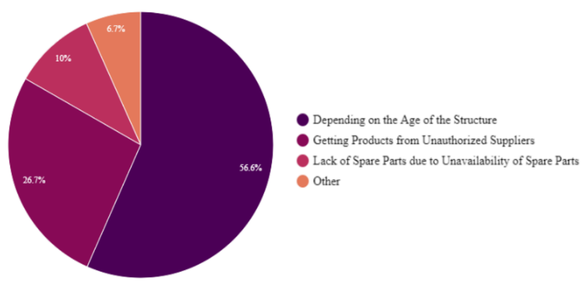


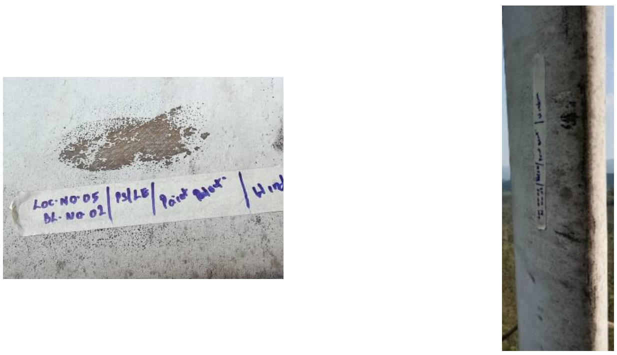
Figure 10: Survey results - factors influencing warranty period.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

4. Steps for repair of Specific Damage Mechanisms

4.1. Leading Edge Erosion

Leading edge erosion, as shown in Fig. 11, causes roughness around the blade and affects the aerodynamic performance, resulting in reduced efficiency (Olabi et al., 2021). Later, this may emerge into a serious problem as the damage can invade the structure. For these types of damages, repair processes like marking, grinding, and finishing will be followed.



(a) (b)

Figure 11: (a) Blade eroded at an arbitrary area, (b) Leading edge eroded blade.

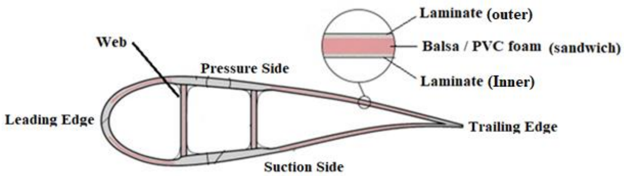


Figure 12: Blade cross-section (Aminzadeh et al., 2023).

4.2. Damages of laminates (Outer)

Figure 12 illustrates the various segments within the blade cross-section, comprising outer layer laminates, a foam layer, and inner laminates. When addressing damage to the outer laminate, the procedure involves grinding the layers and subsequently applying a hand layup process. Following curing, technicians undertake buffing and finishing processes. The layer configuration for repairing outer layer damage is shown in fig 13. The schematics shown in figs 13, 14, 15, and 17 illustrate the repair process, for the hand layup, upon curing, the alternating resin and laminate layers will integrate into a single layer. But in the vacuum infusion process resin flows into layers of laminate or foam and upon curing will integrate into a single layer.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

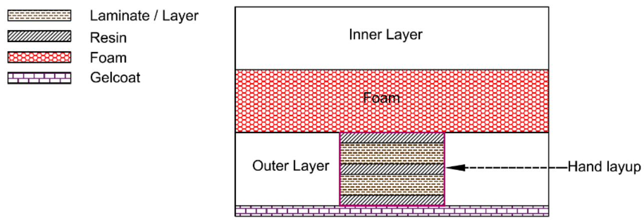


Figure 13: Outer laminate damage.

4.3. Foam Damage

For foam damage, the outer layers and foam will be carefully removed by grinding. After grinding, an adhesive will be spread over the area where the foam was removed. A layer of CSM (Chopped Strand Mat) along with the foam will be retained, and then a vacuum infusion will occur. However, after the vacuum infusion, the surface might become uneven, and therefore, a surface finishing procedure will be conducted to ensure a uniform surface. Once the surface is smoothed out, steps similar to those used for repairing outer layer damage will be performed (i.e., Hand layup). The layer schematic for foam damage is shown in fig. 14.

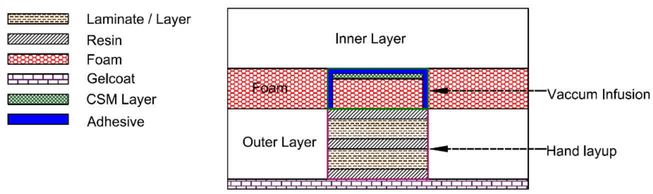


Figure 14: Foam damage.

4.4. Damages of laminates (Inner)

For inner layer damage, the affected area will be entirely removed, resulting in a hole. Two layers of CSM 300, each 100 mm larger than the hole, will be cut and adhesive will be applied. These CSM layers will be positioned on the inner section of the blade. The hand lay-up technique will be used to laminate the inner layers. Once the inner layers are cured steps similar to those used for repairing foam damage will be performed. The layer schematic for inner layer damage is shown in fig. 15. Table 2 shows the process that needs to be carried out for different types of damage.

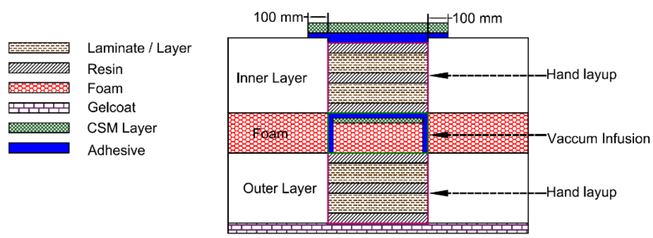


Figure 15: Inner layer damage.

Table 2: Types of damage and its required process.

Type of damage	Processes
Leading Edge Erosion	Marking, Grinding, Finishing
Damages of laminates (Outer)	Marking, Grinding, Layer removal, Hand layup, Finishing
Foam / Damages of laminates (Inner)	All the above-mentioned processes.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

4.5. Shear Web Damage

Shear webs are structural elements inside the wind turbine blades that offer shear stiffness (Cox and Echtermeyer, 2012). They transfer shear loads between the upper and the lower surfaces of the blade. If the damage in the web is more than 2m the blade is considered inoperable and it will be scrapped. Figure 12 shows two shear webs, one on the leading edge and the other on the trailing edge. The damaged shear web will be identified through the endoscopic camera approach. Figure 16 shows the image taken by the endoscopic camera of shear web damage. To evaluate the extent of the damage, a 50mm x 50mm hole will be created on the pressure side, either on the trailing or leading edge (depending on the shear web damage). If the hole is inadequate to assess the damage, it will be enlarged. Following inspection, the hole will be further expanded (approximately 100mm larger than the web damage size). The cross-section of the web structure shows that the web has outer laminate, foam, and inner laminate. Thus, damages such as laminate (inner), foam, and laminate (outer) damage might occur. The outer laminate damage can be addressed using the hand-layup technique as shown in fig.17 (a). However, in cases of foam or outer laminate damage, the entire affected region will be removed, and the repair process for outer laminate damage will be executed as shown in fig.17 (b).

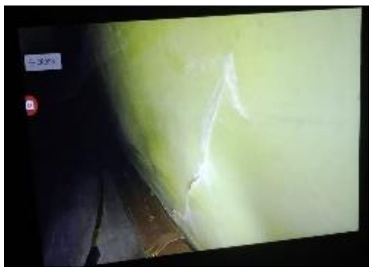
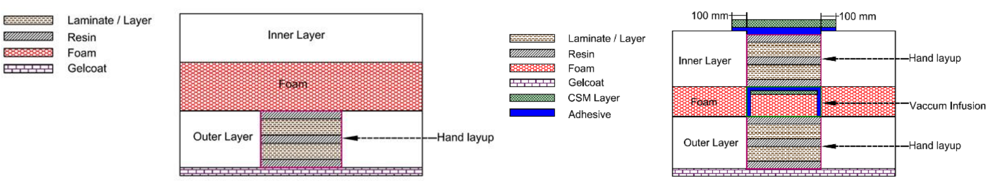


Figure 16: Shear web damaged portion of the wind turbine blade.



(a) (b)

Figure 17: Shear web damage - (a) Outer laminate damage, (b) Foam or inner laminated damage.

4.6. Trailing edge Serration damage

Trailing edge serrations are placed to reduce the aero-acoustic noise from wind turbine blades (Mathew et al., 2016). Serration damage replacement has a series of steps involving inspection, removal, climatic testing, and fixation. A detailed repair process is explained in Appendix B.

5. Checking

While performing blade repair technicians have a series of checks throughout the process.

i.Pendulum-holding

As shown in Fig. 18, a pendulum-like device will be suspended at the tip and center of the blades before the repair operation begins. These pendulums will ensure the orientational changes the blades go through before and after repair.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

WIND ENERGY SCIENCE DISCUSSIONS

(a)

(b)

Figure 18: Pendulum holding (a) Tip, (b) center.

ii.Temperature & humidity check

Before applying cleaner and glue during the serration replacement work and before the lamination process during blade repair, technicians carry out checks for temperature and humidity as shown in Fig 19. While checking the temperature should be within the range of 25 to 30 degrees Celsius and the humidity level should be above 70%. Figure 20 shows the temperature and humidity checking process during blade repair work.

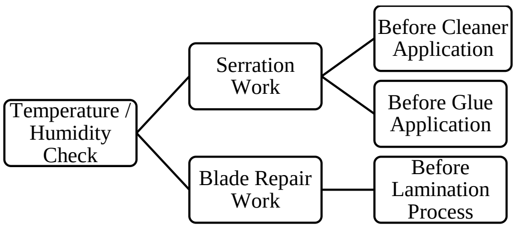
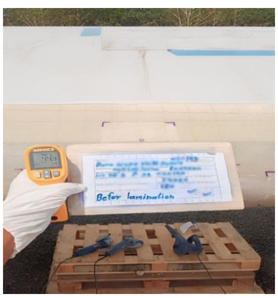
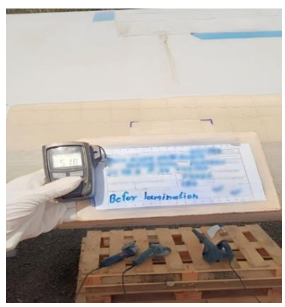


Figure 19: Temperature and humidity check schematic.



(a)



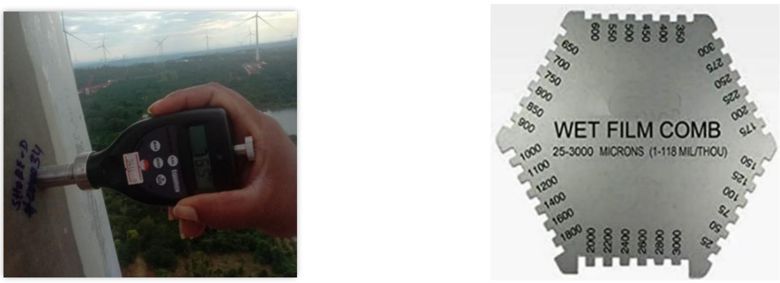
(b)

Figure 20: Before lamination during blade repair (a) Temperature check, (b) Humidity check.

iii.Hardness Test

The hardness test is used to determine the curing state of the laminates. The Sore D harness technique is used for testing. After lamination work, gel coat application, or glue application for endoscope camera assessment, we use this method to assess the curing state. The curing is completed once the value of 75N or more is reached. Figure 21 (a) shows the sore D harness test gauge.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024



(a) (b)

Figure 21: (a) Hardness test check, (b) Wet film thickness gauge.

iv.Wet film thickness check

Gel Coat thickness is measured using a Wet Film Thickness Gauge. The thickness of the Gel coat should be at least 600 microns. Figure 21 (b) shows the wet film thickness gauge.

6. Conclusions

In this paper, we presented a comprehensive overview of blade repair methods applied in India, focusing on the prevalent issue of lightning strikes leading to frequent blade failures. Our survey revealed variations in blade failure caused across different regions of India, underscoring the necessity for tailored operation and maintenance strategies. Despite the availability of various Non-Destructive Testing (NDT) methods, technicians predominantly rely on visual inspection and tap testing for their cost-effectiveness and robust on-site applicability.

Technicians employ rope access or sky lifts to evaluate damage severity on top of wind turbine blades, deciding whether repairs should take place on the turbine or the ground. The challenges posed by lower temperatures and high rainfall in India impact the curing process, with advanced techniques like thermal blanket heating and UV curing not widely adopted. Despite the availability of NDT methods like x-ray and ultrasonic, technicians often resort to the grinding method for evaluating damages layer by layer, citing the on-site operational difficulties of these NDT methods. Advanced methods like Passive infrared thermography can measure the defects from a distance by utilizing sun as the natural heat source. This method captures the thermal contrast between the normal surface and defects on the bladed. Though it has a limitation such as being effective during periods of high thermal contrast. Further developments enhance this NDT method making it more robust, compact, economical, and flexible.

Establishing effective repair damage guidelines is essential for the onsite assessment of wind turbine blade damage. We will develop a methodology that emphasizes critical aspects such as damage type, material integrity, damage depth, affected region, aerodynamic impact, and the cost and time required for repairs. This proposed approach aims to assist technicians onsite in deciding whether a blade should be repaired in situ, on the ground, or replaced entirely.

The paper discussed repair procedures for various blade damages in India, highlighting that leading edge erosion, outer laminate failure, and serration damages are primarily addressed on top of wind turbines. In contrast, damages like foam, web, and inner laminate are repaired on the ground. Technicians employ range checks to monitor crucial factors such as temperature, humidity, hardness, and wet film thickness throughout the repair process. The pivotal role of climate in blade operation and maintenance, coupled with the necessity for advanced curing processes and improved NDT methods, underscores the ongoing challenges faced by technicians. The meticulous repair processes outlined in the paper are vital for ensuring wind turbine blades' longevity and optimal performance.

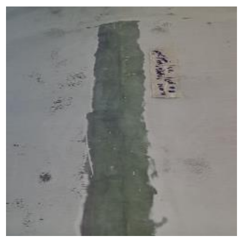
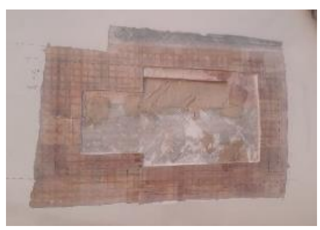
https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

eawe european academy of wind energy
Open Access WIND ENERGY SCIENCE DISCUSSIONS

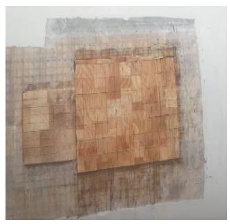
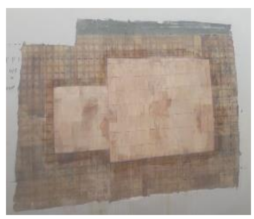
7. Appendices

7.1. Appendix A – General repair process

Table 3: General steps of wind turbine blade repair

Si No	Process	Description	Image
1.	Marking	• The damaged region of the blade will be marked. • Marking would be made 100 mm away from the damage in all directions.	 Marked blade.
2.	Grinding	• Gelcoat and paint are ground using power tools like AG4 and AG5.	 Grinded blade.
3.	Layer / Laminate removal	• Laminates are removed layer by layer using the grinding method. • The removed laminated would give the technicians the fiber orientations.	 Laminate removed the blade.
4.	Foam / Sandwich removal or cutting the entire section	• If the foam or the sandwich core is damaged the foam will be cut and removed. • A multi-Purpose oscillation tool will be used for cutting the foam. • If the inner layer (i.e., laminates behind the foam) is damaged the entire section is cut and removed. • The core material is made of wood balsa for a stronger core and PVC for a lighter core.	 Foam removed blade.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

<table>
<tr><td>5.</td><td>Pasting and CSM layer</td><td>The adhesive can be of liquid or gel form.
In liquid form resin and hardener will be mixed
In gel form resin, aerosol powder, and hardener will be mixed.
Resin and aerosol powder will be mixed in a 2:1 ratio.
In hotter regions, fewer resins will be used while in colder regions more resin will be used in the mixture.
The CSM layer will act as structural reinforcement for the adhesive layer.</td><td>Resin Hardener Ratio.<table><tr><td>Resin (1000 ml)</td><td>Hardener (ml)</td></tr><tr><td>General purpose resin</td><td>15</td></tr><tr><td>Epoxy resin</td><td>350</td></tr><tr><td>Vinyl Ester resin</td><td>10-15</td></tr></table></td></tr>
<tr><td>6.</td><td>Hand layup</td><td>Hand layup is one of the traditional methods used in blade repair.
The technician will apply a layer of resin followed by a layer of laminate.
This process continues till the correct number of laminates are placed.
Finally, a resin layer is applied</td><td></td></tr>
<tr><td>7.</td><td>Foam / Sandwich application</td><td>The foam is cut and placed at the damaged region.</td><td>
Foam-applied blade.</td></tr>
<tr><td>8.</td><td>Resin infusion</td><td>The resin is infused inside the foam.</td><td>
Resin-infused blade.</td></tr>
</table>

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

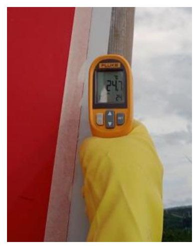
9.	Vacuum infusion	• Vacuum infusion is a technique that uses vacuum pressure to drive the resin into laminate (Thomas et al., 2019). • Vacuum infusion will be performed only if the foam is damaged or laminates (inner) below the sandwich panel are damaged.	 Vacuum infusion process.
10.	Surface finishing	• After resin infusion, the foam and the resin region will have an uneven surface. • To achieve smoothness and an even finishing, a sanding process will be performed.	 Blade after surface finishing.
11.	Finishing	• Two types of finishing are used in blade repair namely PU putty finishing or gel coat finishing. • In PU putty finishing, two layers of PU putty will be applied followed by two layers of PU paint • In gelcoat finishing, three layers of gelcoat will be applied followed by three layers of wax with gelcoat. • The gel coat needs to be cured for more than one hour.	 Gelcoat applied blade.

7.2. Appendix B – Serration Damage

Table 4: Repair of serration damage in the trailing edge

1.	Inspection	The blade is inspected for serration damage.	 Damaged serration.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

2.	Removal	Damaged serrations are removed	 Damaged serration removed.
3.	Buffing	After the removal of serration parts, the removed area will be buffed.	 Buffing process.
4.	Climate testing	• Before applying the cleaner temperature and humidity need to be checked. • Humidity should be above 70%. • Temperature should be within 25–30-degree Celsius.	 Humidity check before serration installation.  Temperature check before serration installation.
5.	Cleaning	• The buffed area is cleaned using a surface cleaner. • Adhesion promoter will be applied to these regions.	 After cleaning.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

6.	Serration fix	• After the application of adhesion, serration will be fixed. • Each serration will be placed with a gap as specified.	 After the new serration installation.
7.	Climate testing	• Before applying the cleaner temperature and humidity need to be checked. • Humidity should be above 70%. • Temperature should be within 25–30-degree Celsius.	 Humidity check after serration installation.  Temperature check after serration installation.
8.	Glue filling	• After the climate test glue will be filled on the serration parts. • Small holes on the serration parts will be used for the injection of glue.	 Glue filling on the hole of the serration.
9.	Gelcoat application	• A gel coat will be applied on the serration part. • A minimum curing time of 1 hr. or as per the instruction manual the gelcoat is allowed to cure.	 Gelcoat application.

Author Contribution: Leon Mishnaevsky Jr: Writing – review, Project administration, Funding acquisition, Supervision. **Refugine Nirmal Ignacy Muthu:** Conceptualization, Writing – original draft, Writing –editing, Data visualization. **Saravanakumar Savadaiyan:** Repair strategy, Blade inspection, **Thamodharan Krishnaraj:** Conceptualization, Repair strategy, Blade inspection. **Anthonyraj Premkumar S:** Project administration, Supervision. **Mohammed Farook S:** Survey. **Kadhirvel Boopathi:** Survey.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment: The authors acknowledge the financial support of the Ministry of Foreign Affairs of Denmark via Danida grant 19-M02-DTU "Maintenance and repair strategy for wind energy development" (maintainergy.dk). L.M. is grateful to the Innovation Foundation of Denmark for its support in the framework of project "WiseWind: New generation of sustainable wind turbine blades" (wisewind.dtu.dk/), No.2079-00004B, and to the European Commission for its support via Horizon project "Blades2Build: Recycle, repurpose and reuse end-of-life wind blades composites: A coupled pre- and co- processing demonstration plant", grant agreement 101096437.

8. Reference

1. Hannah Ritchie, Pablo Rosado, and Max Roser (2020) - "Energy Production and Consumption" Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/energy-production-consumption' [Online Resource]
2. Sidharth J, Harshal A, Rishab R India Wind Energy Outlook 2026 Published Available online: https://gwec.net/india-wind-energy-outlook-2026-published/, 2022.
3. Mishnaevsky, L. Root Causes and Mechanisms of Failure of Wind Turbine Blades: Overview. *Materials* **2022**, *15*, 2959, doi:10.3390/ma15092959.
4. Boopathi, K.; Mishnaevsky, L.; Sumantraa, B.; Premkumar, S.A.; Thamodharan, K.; Balaraman, K. Failure Mechanisms of Wind Turbine Blades in India: Climatic, Regional, and Seasonal Variability. *Wind Energy* **2021**, *25*, 968–979, doi:10.1002/we.2706.
5. Mum4kids Wind Turbine Accident Report Available online: https://mothersagainstturbines.com/2016/04/07/2016-wind-turbine-accident-report/comment-page-1/, 2016.
6. Olabi, A.G.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Salameh, T.; Abdelkareem, M.A.; Baroutaji, A. A Review on Failure Modes of Wind Turbine Components. *Energies* **2021**, *14*, 5241, doi:10.3390/en14175241.
7. Mishnaevsky, L.; Hasager, C.B.; Bak, C.; Tilg, A.-M.; Bech, J.I.; Doagou Rad, S.; Fæster, S. Leading Edge Erosion of Wind Turbine Blades: Understanding, Prevention and Protection. *Renewable Energy* **2021**, *169*, 953–969, doi:10.1016/j.renene.2021.01.044.
8. Carroll, J.; McDonald, A.; McMillan, D. Failure Rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines. *Wind Energy* **2015**, *19*, 1107–1119, doi:10.1002/we.1887.
9. Global Data, Global Wind Operations & Maintenance Market to Double by 2025 Available online: https://www.climateaction.org/news/global-wind-operations-maintenance-market-to-double-by-2025, 2017.
10. Stephenson, S. Wind Blade Repair: Planning, Safety, Flexibility Available online: https://www.compositesworld.com/columns/wind-blade-repair-planning-safety-flexibility(2), 2011.

https://doi.org/10.5194/wes-2024-55
Preprint. Discussion started: 2 July 2024

11. Stenberg, A.; Holttinen, H. Analysing Failure Statistics of Wind Turbines in Finland. *European Wind Energy Conference & Exhibition 2010 (EWEC 2010)* **2010**, *Vol 5 European Wind Energy Association (EWEA), 2010*, P 3985-3995.
12. Branner, K., & Ghadirian, A. (2014). *Database about blade faults*. DTU Wind Energy. DTU Wind Energy E No. 0067
13. Lantz, E. Operations Expenditures: Historical Trends and Continuing Challenges (Presentation) Available online: https://www.osti.gov/biblio/1082553, 2013.
14. Martin-Tretton, M.; Reha, M.; Drunsic, M.; Keim, M. Data Collection for Current U.S. Wind Energy Projects: Component Costs, Financing, Operations, and Maintenance; January 2011 - September 2011 Available online: https://doi.org/10.2172/1034220.
15. Pryor, S.C.; Barthelmie, R.J.; Cadence, J.; Dellwik, E.; Hasager, C.B.; Kral, S.T.; Reuder, J.; Rodgers, M.; Veraart, M. Atmospheric Drivers of Wind Turbine Blade Leading Edge Erosion: Review and Recommendations for Future Research. *Energies* **2022**, *15*, 8553, doi:10.3390/en15228553.
16. Katnam, K.B.; Comer, A.J.; Roy, D.; da Silva, L.F.M.; Young, T.M. Composite Repair in Wind Turbine Blades: An Overview. The Journal of Adhesion 2014, 91, 113–139, doi:10.1080/00218464.2014.900449.
17. Survey1:https://docs.google.com/forms/d/1L1IAr1qmuXvQWeDUC3lzB61EcEbfAPIErZpWAE323o0/edit?ts=64954d04
18. Survey2:https://docs.google.com/forms/d/1kD0DUg_b5OLOQ7ZTncTIezRZUb6uyPv4uS6cXY42eQ/edit?ts=64954d20
19. Peng, H.; Li, S.; Shangguan, L.; Fan, Y.; Zhang, H. Analysis of Wind Turbine Equipment Failure and Intelligent Operation and Maintenance Research. *Sustainability* **2023**, *15*, 8333, doi:10.3390/su15108333.
20. Chou, J.-S.; Chiu, C.-K.; Huang, I.-K.; Chi, K.-N. Failure Analysis of Wind Turbine Blade under Critical Wind Loads. *Engineering Failure Analysis* **2013**, *27*, 99–118, doi:10.1016/j.engfailanal.2012.08.002.
21. Tavner, P.J.; Greenwood, D.M.; Whittle, M.W.G.; Gindele, R.; Faulstich, S.; Hahn, B. Study of Weather and Location Effects on Wind Turbine Failure Rates. *Wind Energy* **2012**, *16*, 175–187, doi:10.1002/we.538.
22. Tavner, P.; Edwards, C.; Brinkman, A.; Spinato, F. Influence of Wind Speed on Wind Turbine Reliability. *Wind Engineering* **2006**, *30*, 55–72, doi:10.1260/030952406777641441.
23. Slimacek, V.; Lindqvist, B.H. Reliability of Wind Turbines Modeled by a Poisson Process with Covariates, Unobserved Heterogeneity and Seasonality. *Wind Energy* **2016**, *19*, 1991–2002, doi:10.1002/we.1964.
24. Reder, M.; Yürüşen, N.Y.; Melero, J.J. Data-Driven Learning Framework for Associating Weather Conditions and Wind Turbine Failures. *Reliability Engineering & System Safety* **2018**, *169*, 554–569, doi:10.1016/j.ress.2017.10.004.
25. Ozturk, S.; Fthenakis, V.; Faulstich, S. Failure Modes, Effects and Criticality Analysis for Wind Turbines Considering Climatic Regions and Comparing Geared and Direct Drive Wind Turbines. *Energies* **2018**, *11*, 2317, doi:10.3390/en11092317.
26. Dangle Rope Access, What Does A Blade Repair Technician Do? Available online: https://www.onropes.co.uk/what-does-a-blade-repair-technician-do, 2023.
27. Wood, K. Wind Blade Repair: Safety and Quality Available online: https://www.compositesworld.com/articles/wind-blade-repair-safety-and-quality, 2011.

28. Andreisek, G.; Korthals, D.; Grosse, C.U.; Seeber, B.U. The Virtual Tap Test – a Training System for Wind Turbine Rotor Blade Inspectors. *19th World Conference on Non-Destructive Testing 2016*.
29. Sofema Online, Basic Principles of TAP Hammer (or Coin) Testing Available online: https://sofemaonline.com/about/blog/entry/basic-principles-of-tap-hammer-or-coin testing#:~:text=The%20basic%20principle%20behind%20tap,emit%20a%20dull%2C%20hollow%20sound , 2023
30. Marsh, G. Meeting the Challenge of Wind Turbine Blade Repair. *Reinforced Plastics* **2011**, *55*, 32–36, doi:10.1016/s0034-3617(11)70112-6.
31. Ding, S.; Yang, C.; Zhang, S. Acoustic-Signal-Based Damage Detection of Wind Turbine Blades—A Review. *Sensors* **2023**, *23*, 4987, doi:10.3390/s23114987.
32. Sanati, H.; Wood, D.; Sun, Q. Condition Monitoring of Wind Turbine Blades Using Active and Passive Thermography. Applied Sciences 2018, 8, 2004, doi:10.3390/app8102004.
33. Galleguillos, C.; Zorrilla, A.; Jimenez, A.; Diaz, L.; Montiano, Á.L.; Barroso, M.; Viguria, A.; Lasagni, F. Thermographic Non-Destructive Inspection of Wind Turbine Blades Using Unmanned Aerial Systems. Plastics, Rubber and Composites 2015, 44, 98–103, doi:10.1179/1743289815y.0000000003.
34. Doroshtnasir, M.; Worzewski, T.; Krankenhagen, R.; Röllig, M. On-site Inspection of Potential Defects in Wind Turbine Rotor Blades with Thermography. Wind Energy 2015, 19, 1407–1422, doi:10.1002/we.1927.
35. Orsatelli, J.-B.; Paroissien, E.; Lachaud, F.; Schwartz, S. Bonded Flush Repairs for Aerospace Composite Structures: A Review on Modelling Strategies and Application to Repairs Optimization, Reliability and Durability. Composite Structures 2023, 304, 116338, doi:10.1016/j.compstruct.2022.116338.
36. Baker AA. Development of a hard-patch approach for scarf repair of composite structure. Defence Science and Technology Organisation Report TR-1892; 2006. p. 19.
37. Whittingham, B., Baker, A., Harman, A., & Bitton, D. (2009). Micrographic studies on adhesively bonded scarf repairs to thick composite aircraft structure. Composites Part A: Applied Science and Manufacturing, 40(9), 1419–1432. https://doi.org/10.1016/j.compositesa.2008.12.011
38. Mishnaevsky, L. (2019). Repair of wind turbine blades: Review of methods and related computational mechanics problems. Renewable Energy, 140, 828–839. https://doi.org/10.1016/j.renene.2019.03.113
39. Mischnaewski, L., & Mishnaevsky, L. (2020). Structural repair of wind turbine blades: Computational model for the evaluation of the effect of adhesive properties. Wind Energy, 24(4), 402–408. https://doi.org/10.1002/we.2575
40. Mishnaevsky, L., Frost-Jensen Johansen, N., Fraisse, A., Fæster, S., Jensen, T., & Bendixen, B. (2022). Technologies of Wind Turbine Blade Repair: Practical Comparison. Energies, 15(5), 1767. https://doi.org/10.3390/en15051767
41. Bendemra, H., Compston, P., & Crothers, P. J. (2015). Optimisation study of tapered scarf and stepped-lap joints in composite repair patches. Composite Structures, 130, 1–8. https://doi.org/10.1016/j.compstruct.2015.04.016
42. Bachir Bouiadjra, B., Fari Bouanani, M., Albedah, A., Benyahia, F., & Es-Saheb, M. (2011). Comparison between rectangular and trapezoidal bonded composite repairs in aircraft structures: A numerical analysis. Materials & Design, 32(6), 3161–3166. https://doi.org/10.1016/j.matdes.2011.02.053

43. Benyahia, F., Albedah, A., & Bachir Bouiadjra, B. (2014). Analysis of the adhesive damage for different patch shapes in bonded composite repair of aircraft structures. Materials & Design (1980-2015), 54, 18–24. https://doi.org/10.1016/j.matdes.2013.08.024
44. Xing, R., Wang, F., Yang, Y., & Li, G. (2024). Optimization of Composite Material Repair Patch Shape Based on Strength Analysis. Applied Sciences, 14(11), 4397. https://doi.org/10.3390/app14114397
45. Liu, H., Liu, J., Hall, Z. E., Brooks, R. A., Crocker, J. W., Joesbury, A. M., Harper, L. T., Blackman, B. R., Kinloch, A. J., & Dear, J. P. (2023). Modelling the effects of patch-plug configuration on the impact performance of patch-repaired composite laminates. Composites Science and Technology, 233, 109917. https://doi.org/10.1016/j.compscitech.2023.109917
46. Savari, A., Rashed, G., & Eskandari, H. (2021). Time-Dependent Reliability Analysis of Composite Repaired Pipes Subjected to Multiple Failure Modes. Journal of Failure Analysis and Prevention, 21(6), 2234–2246. https://doi.org/10.1007/s11668-021-01273-w
47. Karbhari, V. M., & Abanilla, M. A. (2007). Design factors, reliability, and durability prediction of wet layup carbon/epoxy used in external strengthening. Composites Part B: Engineering, 38(1), 10–23. https://doi.org/10.1016/j.compositesb.2006.06.001
48. Olabi, A.G.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Salameh, T.; Abdelkareem, M.A.; Baroutaji, A. A Review on Failure Modes of Wind Turbine Components. *Energies* **2021**, *14*, 5241, doi:10.3390/en14175241.
49. Aminzadeh, A.; Dimitrova, M.; Meiabadi, M.S.; Sattarpanah Karganroudi, S.; Taheri, H.; Ibrahim, H.; Wen, Y. Non-Contact Inspection Methods for Wind Turbine Blade Maintenance: Techno–Economic Review of Techniques for Integration with Industry 4.0. Journal of Nondestructive Evaluation 2023, 42, doi:10.1007/s10921-023-00967-5.
50. Cox, K.; Echtermeyer, A. Structural Design and Analysis of a 10MW Wind Turbine Blade. *Energy Procedia* **2012**, *24*, 194–201, doi:10.1016/j.egypro.2012.06.101.
51. Mathew, J.; Singh, A.; Madsen, J.; Arce León, C. Serration Design Methodology for Wind Turbine Noise Reduction. *Journal of Physics: Conference Series* **2016**, *753*, 022019, doi:10.1088/1742-6596/753/2/022019.
52. Thomas, S.; Hosur, M.; Chirayil, C.J. *Unsaturated Polyester Resins*; Elsevier, 2019;