

# Failure mechanisms of wind turbine blades in India: Climatic, regional, and seasonal variability

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## Funding information

Danida Fellowship Centre; Ministry of Foreign Affairs of Denmark, Grant/Award Number: 19-M02-DTU

## Abstract

Results of a survey of failure mechanisms of wind turbine blades in India, observed by service companies, are presented. Surface erosion is the most often observed blade damage mechanism, followed by lightning strikes. Leading edge erosion can be observed even 1–2 years after wind turbine installation, while structural cracks are observed most often only 5–8 years after installation of the wind turbines. The most often emergency repair requests are connected with blade bolt replacement, followed by lightning strikes. Lightning strikes are registered relatively often, every 1–2 years, depending on climate. Lightning strikes are also most often observed in monsoon areas of India and are most common reason for the wind turbine downtimes.

## KEY WORDS

maintenance, repair, wind energy, wind turbine blades

## 1 | INTRODUCTION

The transition from fossil fuels to renewable energy generation is required to limit the global warming. The success of all the program of transition to renewable energy depends not only on the success of European or even Chinese programs, but to a large degree on the development of renewable energy in Global South, in developing countries, also located in subtropical and tropical regions. According to a study,<sup>1</sup> developing countries are responsible for 63% of current carbon emissions in the world.

India is a huge country, with very different regions and climate conditions. In this sense, the success of Indian wind energy program is critically important, setting the path for the success of wind energy expansion in other Southern countries, also including developing countries.

As one of signatories of the Paris agreement, India committed to cut greenhouse gas emissions intensity of its gross domestic product 33% to 35%, and increase non-fossil fuel power capacity from 28% to 40% by 2030. The Indian government has set a target to achieve 175 GW renewable energy capacity by the year 2022, including 60 GW from wind energy, which will be the largest renewable energy expansion program in the world. India is considered as a new hot spot for renewable energy investors, with one of the largest clean-energy expansion programs, an annual growth rate of 17.5% and increasing the share of renewables in the total energy mix from 6% to 10%.<sup>2</sup> In the first quarter of 2021, India commissioned 623 MW of wind turbine, with 230% increase over previous year, and 25% higher than in previous quarter.<sup>3</sup>

Gujarat, Karnataka, Andhra Pradesh, Tamil Nadu and Maharashtra are considered as leading states for their wind energy potential.<sup>4</sup> 95% of wind potential is concentrated in 5 states in southern and western India.<sup>5</sup> Wind energy has largest share in the total renewable energy installation in India with 67%.<sup>4</sup> Still, the offshore wind energy development is still in the early stage. The country has large potential for offshore wind, with

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its 7600 km of coastline, and well-developed onshore wind energy, which is currently the second largest renewable energy sources in India.<sup>4–6</sup> The Government of India has set two ambitious offshore wind targets, 5 GW by 2022 (this target will probably be missed) and 30 GW by 2030.

With quick expansion of wind energy, an important task of maintenance and quality control of wind turbines should be ensured. Wind turbines require repair quite often, and this can be rather expensive.<sup>7–9</sup> Carol et al.<sup>10</sup> observed that 6.2 minor repairs, 1.1 major repair and 0.43 major replacements are required in average per turbine per year.

Failure mechanisms of wind turbines depend on the local climatic conditions, types of loading, and environmental effects.<sup>11</sup> Low temperatures increase brittleness of components whereas temperature variations could cause thermal fatigue.<sup>12</sup> Lightning, icing, and high winds can drastically increase the failure rate of wind turbines.<sup>13</sup>

The high variations of weather conditions, typical for Indian regions, are expected to have a strong effect on the reliability of wind turbines. High temperatures and humidity in South India, strong temperature variations in Northern India, dust in Rajasthan and monsoon weather patterns can act as additional factors for the degradation of wind turbines.

In order to clarify the typical blade failure mechanisms and their dependency on the local climatic conditions, surveys among service and repair teams were carried out. Frequency of different damage mechanisms depending of region and age, most common blade failure mechanisms and downtimes reasons were identified. Further, the case studies and observations of degradation in India are presented. For the analysis, four independent data sources were used throughout the entire paper: two online surveys (prepared by DTU, NIWE, and Windcare), information from Repair logs of Indian service company Windcare, and the direct observations from Windcare's 110 turbines in a single wind farm from Tamilnadu, Dharapuram. The collected information does not provide root case study for the damage mechanisms; however, the author considers the information collected worth to share and useful both for scientist in this area and for practitioners.

## 2 | SURVEY: DAMAGE MECHANISMS OF WIND TURBINE BLADES

Wind turbine blades are one of the main contributors to the wind turbine failure statistics.<sup>14</sup> The typical observed damage mechanisms of wind turbine blades include skin/adhesive debonding, adhesive joint failure, sandwich debonding, delamination, splitting along fibers, and cracks in the gelcoat.<sup>15</sup> In Robinson et al.,<sup>16</sup> the blade failures are classified into root connection failure, catastrophic structural buckling or separation, leading edge, trailing edge, or other bond separation, lightning damage, erosion, and failure at outboard aerodynamic device. The wind turbine blades consist of laminates, foams, coatings, sandwich structures, and adhesive layers. With view on these elements, damage mechanisms of wind turbine blades can be classified as (a) surface damage (coating degradation), (b) polymer resin and/or interface damage, and (c) structural element damage (with broken structural fibers).<sup>7,8</sup> The surface damage can be caused by erosion (rain erosion, sand, and hail), or small object impacts. It reduces the aerodynamic performance of blades and energy generation. It does not prevent the wind turbine from functioning, but the defects grow, develop, and lead to the structural damage.

Reliability of wind turbines has been studied in several works.<sup>10,12–14,17</sup> Pfaffel et al.<sup>17</sup> provided the overview of results of different initiatives, which gathered data on the performance and reliability of wind turbines on- and offshore. To enable the result comparison, the authors mapped the system structure according to the Reference Designation System for Power Plants (RDS-PP®), and also observed significant differences between results.

In this paper, the authors sought to collect and analyze the experiences and observations of service teams of wind turbines (both special companies, wind farm owners, or original equipment manufacture [OEMs]). In some sense, the results to be collected are similar to “family doctors reports” and “ambulance call statistics” in medical research (which are surely less scientific than for instance medical research in special institutes).

In order to collect practical experiences of wind turbine repair companies and wind farm owners, two special surveys were prepared and sent to all main players in this area. The Survey 1<sup>18</sup> collected the information on Wind Turbine Repair and Maintenance (with questions on Installation site, capacity and number of turbines, age, manufacturer, climatic conditions, blade damage observed, how often damage observed, used maintenance strategies, maintenance approaches, downtimes, and challenges).

The Survey 2<sup>19</sup> collected the information on observed manufacturing defects, frequency of damage observation, age-damage type correspondence.

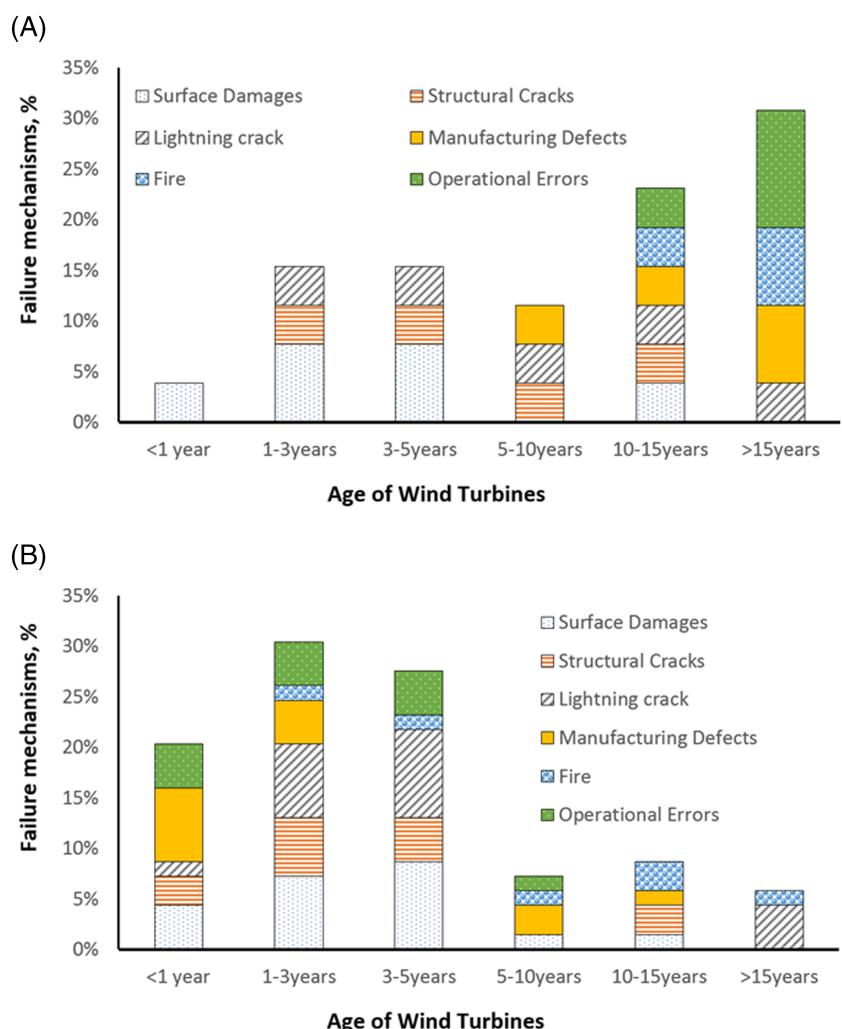
The main objective of Survey 1 was to add new knowledge on general O&M issues not specifically on blades: turbine type, observed failure types, turbine's environmental characteristics, frequency of failure types, and so forth. A total of 37 responses were obtained from respondents around the world, reported the observations on 26 wind farm locations, 5 in Europe (UK, the Netherlands, Greece, and Italy) and 21 in India (Maharashtra, Tamil Nadu, Gujarat, Madhya Pradesh, Karnataka, Madhyapradesh, and Andrapradesh). Thirty-two responses had indicated that their turbines were located onshore, and the rest had indicated that their turbines were located offshore. Responses show us the minimum rated capacity of the turbine was 250 kW while the maximum rated capacity went unto 4 MW. For the question on which wind turbine makes do you oversee in your daily work, respondents included makes from: Vestas, SiemensGamesa, GE, Enercon, Nordex, Leitwind, Suzlon, Inox, RRB, Senvion, Envision, Wind World India, Kenersys, RRB, AMSC, EWT, NEPC Micon, and Pioneer Wincon. Climatic conditions of the surveyed turbines in

response percentage are shown with most located in tropical–hot and humid (62.50%) followed by coastal areas (40.63%), heavy rainfall (37.50%), snowy regions (25.00%), deserted region (21.88%) and forested area (9.38%). The survey was open for both European and Indian respondents. Initial field data obtained by a combination of surveys and interviews with independent service providers, asset managers, and technicians have been used to address operation and maintenance challenges. Respondents were allowed to avoid publication of their company names, to prevent possible worries about negative effect of the reports on commercial interests of their companies or blade manufacturers. Respondents were asked to provide information about the regions where wind turbines were installed. Of the respondents, 63% shared their experiences about WT installed in tropical, hot and humid regions, 37% in heavy rainfall region, 42% in snowy regions, 5% in deserts, and 42% in coastal areas. Because the region characteristics overlap, the sum of percentages is over 100%. The age of wind turbines in parks varied from 1 to 14 years and even 18 years.

Results of the survey are summarized below. Figure 1 shows the frequency of observing of various wind turbine blade failure mechanisms, depending on the age of wind turbines, in Europe (a) and India (b). The results were normalized according to the total failure reports, obtained in the survey, which were 69 for India and 15 for Europe.

First, it is of interest to compare the most frequent damage mechanisms in Europe and in India, according to the ages of wind turbines. European wind energy industry is older, started earlier, is characterized by high concentration of competing wind turbine manufacturers, could probably accumulate more experience with larger wind turbines. Therefore, manufacturing defects, fire, and even operational errors determine the failure of wind turbines, reaching 5–10 years and more. Lightning strikes play role all the time, approximately at the same level. Surface erosion (leading edge) erosion becomes a problem from the first month after installation, and remains the main mechanism of wind turbine degradation from the 1st to the 5th year after the installation.

In India, wind energy industry started later, is generally younger and less “crowded” than in Europe. It can be the reason why operational errors and manufacturing defects are among main failure mechanism of recently installed wind turbines, even after installation or 1–3 years old.



**FIGURE 1** (A,B) Survey results: frequency of wind turbine blade failure mechanisms depending on the age of wind turbines

That leads to structural failure even in young, recently installed wind turbines (1–5 years, what is not observed in Europe). Lightning strikes are also more often observed in India, apparently due to monsoons (see climate analysis in Section 4). Leading edge erosion in India, as well as in Europe, is a big challenge from the first day after installation, increasing with time.

It is of interest that manufacturing defects are especially critical shortly after installation and again after 5–10 years of blade service. It leads us to the assumption that there are two groups of manufacturing defects: first group, which can trigger blade failure under common static load (thus, seen just after installation), and second group, which trigger fatigue failure after long-term service load (causing failure after many years).

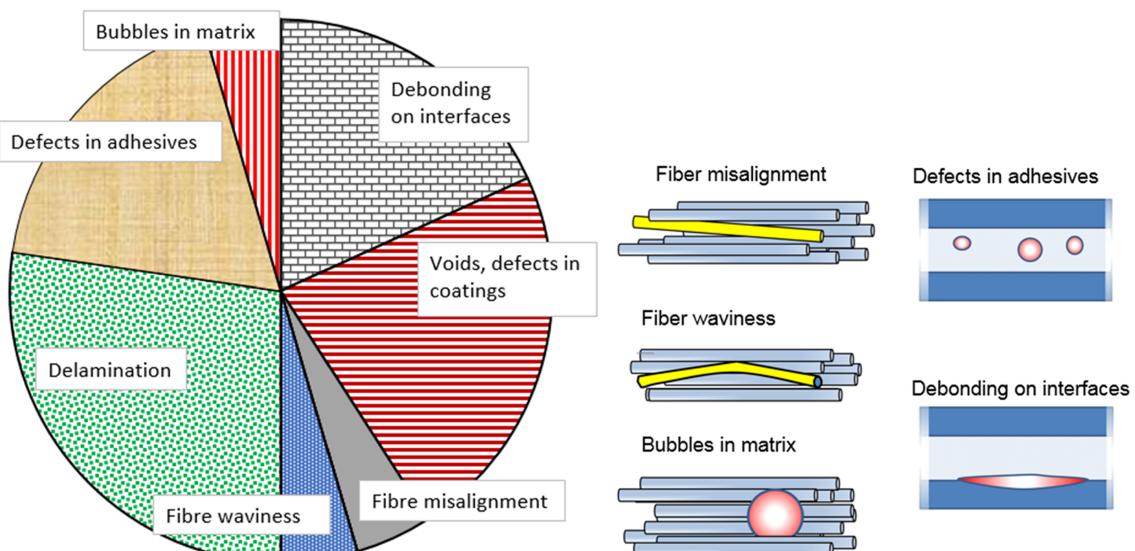
The time for the first observation of damages is different for different damage mechanisms. Surface damage (erosion) is typically observed in 1 year or 2–5 years after installation. Structural cracks are observed 5–8 years after installation of the wind turbines. Lightning strikes are registered relatively often, every 1–2 years, depending on climate.

Since the focus of the 1st survey was to understand the broad challenges surrounding wind turbine O&M, a question on main O&M challenges was included in the survey. It is interesting to see the variety of challenges reported: grease leakage issues, local skill availability, servicing turbines at remote locations, grid reactor replacement, delayed spare parts, issues with blade root pitch bearing connection, issues with service completion, damages to the transmission network, generator replacement issues, customer not interested in after sales service, delayed blade inspections, budget constraints for repair and maintenance, issues with SCADA connectivity, issues with crane accessibility and availability, and ageing impacts on wind turbine degradation. The systems and components that have caused big troubles for the respondents are shown in Table 1.

Figure 2 shows the frequency of different manufacturing defects, observed by service companies. Totally, 22 respondents (all from India) answered the question on which manufacturing defects they observed. The most common types of blade manufacturing defects reported were delamination, voids and defects in the coating, debonding on interface, defects in adhesives. Of the respondents, 4 observed debonding on interfaces, 5 voids and effects in coatings, 6 delamination, 4 defects in adhesives. Fiber misalignment, waviness, and bubbles in the matrix were noticed by 1 respondent each. Apparently, the frequency of observation of different defects reflects both frequency of defects and “observers bias” (when service teams which are called quite often to repair surface protection, do not really see the fiber misalignment deep in laminates). Other

**TABLE 1** The systems and components that has caused big troubles for the respondents

System name	Component name	Typical downtime for the component failure (hours)
Drivetrain	Grease leakage	48
Blades	Pitch controller	5
Generator	Stator overheating	10
Converter	Grid reactor	360
Control system	Pitch, yaw	8
Gearbox	Low speed shaft bearing	300



**FIGURE 2** Frequency of different manufacturing defects as observed by the survey respondents

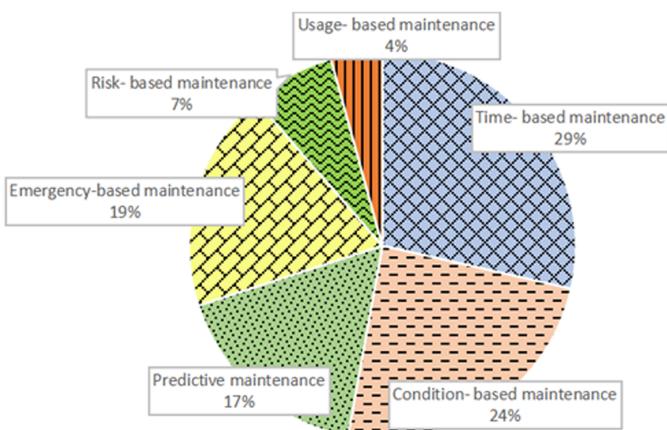
types of blade issues reported from the field include loosening of blade root studs, bolt crack, and issues with blade root pitch bearing connection. Components causing major turbine downtime in India include erosion, stator winding, grid reactor, cooling system, yaw and pitch control system, and stator overheating.

Further questions were related on how the damage is identified and repaired. Figure 3A summarizes the results of the survey with view on blade maintenance strategies. Respondents were asked to indicate the type of maintenance strategy employed in their wind turbine fleets, but not based on the damage type specifically. The following observations were collected with majority of the responses still sticking to time-based maintenance (74.07%) followed by latest technologies using condition monitoring sensors, condition-based maintenance (62.96%) and a quite proportion also adopting state of art predictive maintenance (44.44%). On the contrary, emergency-based maintenance (48.15%) is also quite popular. Apparently, there remain a large potential for the transition from time-based maintenance (regular inspections) or emergency-based maintenance to condition based maintenance.

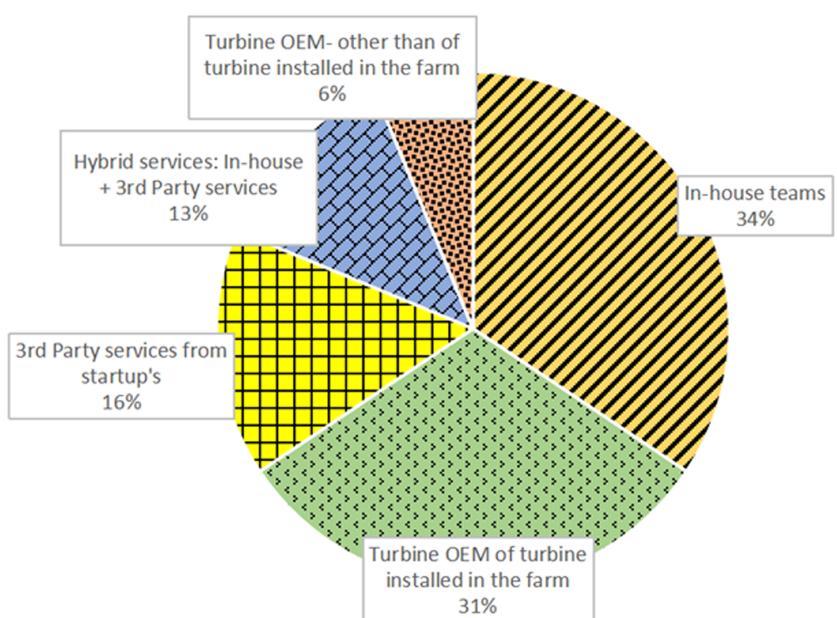
The most common maintenance strategy is time-based maintenance, that is, regular, routine scheduled inspections of wind turbines. Second common maintenance "strategy" is the emergency maintenance. Most often, the repair activity is carried out by the manufacturers of installed wind turbines, or (much more seldom) by the in-house teams of wind farm owners.

Figure 3B shows the statistics of teams responsible for service. Summarizes the results of the survey with view on blade maintenance strategies. It is of interest that large part of contract go to in-house service teams (50%), slightly more than long term service contracts offered by

(A)



(B)



**FIGURE 3** Maintenance strategy and repair realization

turbine original equipment manufacturers (45.45%) is seen. Also, rise of independent services offered by 3rd party startup's (22.73%) indicates owners, developers, and operators are very eager to explore other options including a combination of in-house and 3rd party startup services (18.18%).

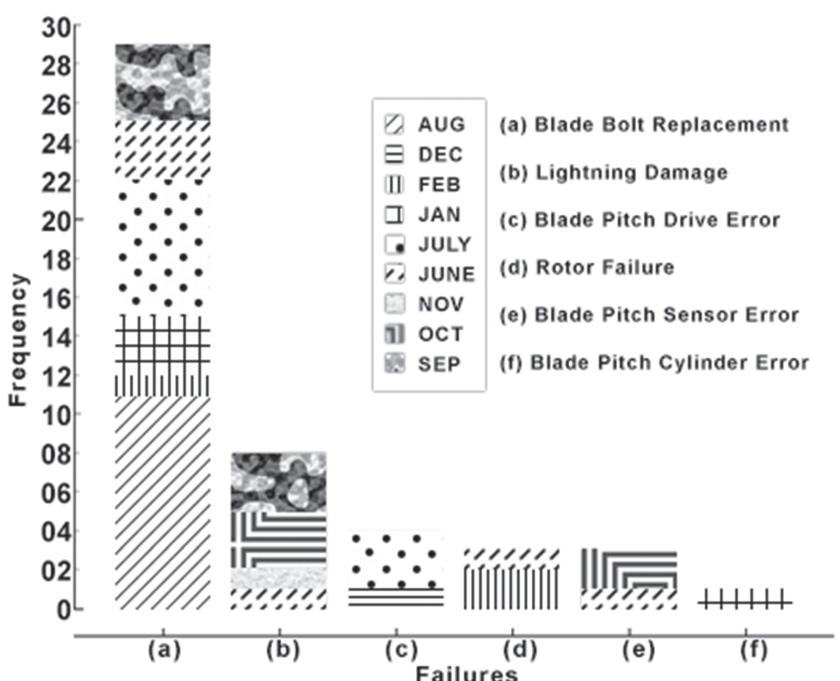
### 3 | SEASONAL VARIATIONS OF SERVICE AND MAINTENANCE REQUIREMENTS FOR WIND TURBINES IN INDIA

In this section, the observations of seasonal variations of service and maintenance requests of Windcare company are summarized. In Dharapuram region in Tamil Nadu, more than 20 wind farms are located. Here, the statistics for a wind farm with 110 wind turbines is presented, which are located approximately 108kms from the Palakkad pass. These 110 wind turbines belong to the same type in specification like gear-type and power capacity. These turbines have hub height ranging from 60 to 75 m from the sea level. The wind farm has spread across the regions with more than 40 km<sup>2</sup>. The regions are dry land with maximum precipitation range of about 5–20 mm between August and November while the minimum precipitation range of about 2–5 mm remains from the month of April to December and the month of January to March have less than 2mm precipitation. The high wind speed in the wind farm starts from the May to the middle of the September which ranges from 28–37 km/h, while the remaining months, that is, from middle of September to the month of April, the wind speed ranges from 5–11 km/h and 12–27 km/h. Also, the wind is blowing from the direction of West-Southwest to East-Northeast with a maximum of 693 hours/year, 2562 h/year and 250 h/year for wind speed range of 5–11 km/h, 12–27 km/h, and 28–37 km/h, respectively.

The failure categories like blade bolt damage, lightning damage, blade pitch drive error, rotor failure, blade pitch sensor error and blade pitch cylinder error are observed from all the 110 wind turbines and studied by Windcare India Pvt Ltd. It can also be evidenced that the blade bolt and lightning damage have frequently occurred and have major contributions from the total sample. Out of this major contribution, the blade bolt damage has high occurrence and may occur due to fatigue failure, stress concentration of bolts due to improper torquing sequence or washer misalignment, and strength reduction by corrosion due to lubrication failure or moisture intrusion.

The technicians and specialists of the company monitored the downtime of each wind turbines with respect to the type of the error occurred, and analyzed errors that are related to blade failures.

As differed from the Section 2, we consider here mainly emergency repair requests, not the routine maintenance operations, caused by regular inspections.



**FIGURE 4** Averaged frequency of failures of different element of wind turbines over years' month

### 3.1 | Seasonal variability of service and maintenance requests

Figure 4 shows the averaged frequency of failures of different element of wind turbines over years' month, estimated over all the 110 wind turbines, studied by Windcare India Private Limited. From Figure 4, it can be seen that the blade bolt replacement is the most often required repair operation, followed by the repair of lightning strike damage.

Figure 5 shows the error logs visualized along the months. From Figure 5, one can see that the blade bolt replacements took place continually from the month of January to February and from June to September. It is also notable that the selected region for the analysis has high wind speed season from June to September and the recorded wind gust were major from the month of May to September. The bolt replacement, most often required during the high wind season from May to September, is carried out by means of replacing the one-quarter of the bolts as nearby to the identified damaged bolts, that is, half of one-fourth on either side of the damaged bolts. Those replacement activities were in the form of reactive approach (after the occurrence of the error). While the blade damage due to lightning damage is a natural event, the blade bolt replacement is a critical failure factor, which can be reduced in order to decrease the downtime of wind turbines.

Wind turbines are quite often subject to inspections in the period of January to March, during the high wind season. Figure 6 shows the frequency of different events (repair and inspection) over these months. These blade inspections are mainly focused on the surface of the blades, not on bolts. There were no failures during the period of March to May.

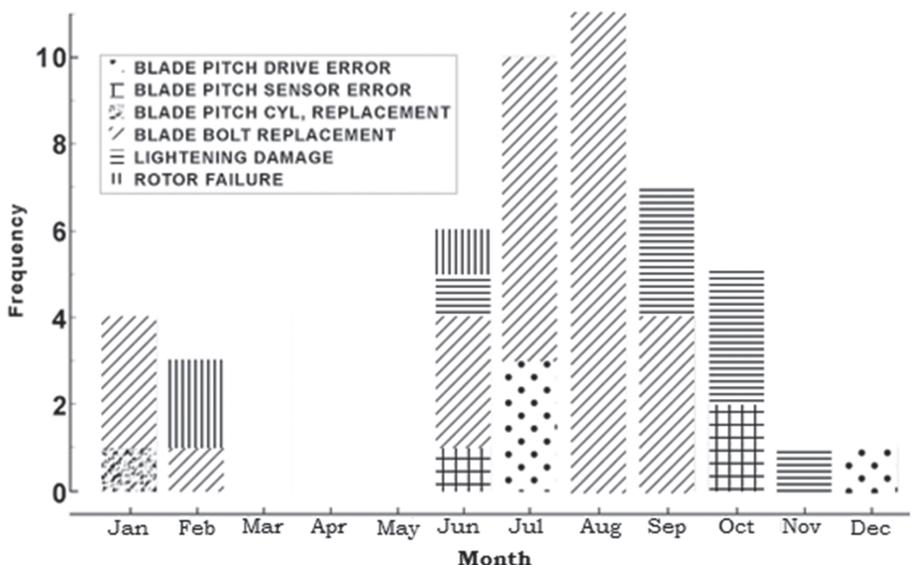


FIGURE 5 Frequency of different blade failure mechanisms, distributed over months

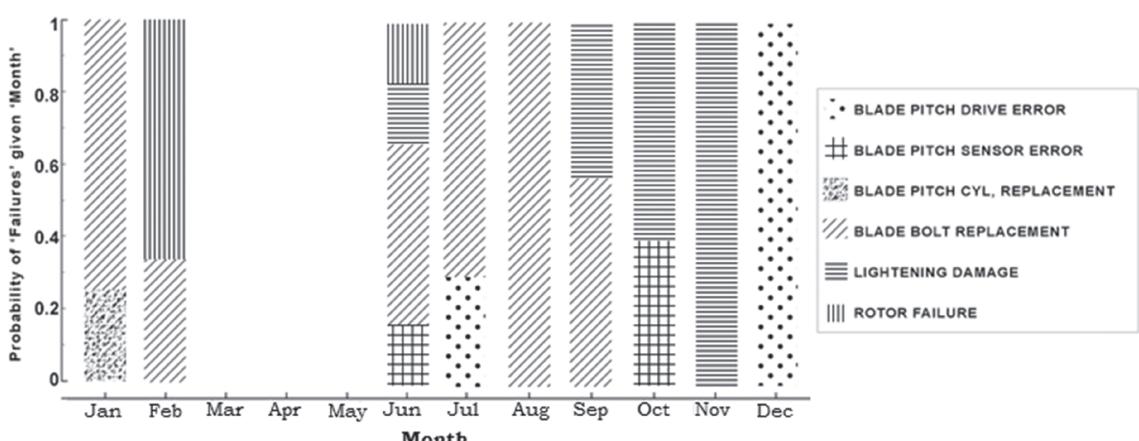


FIGURE 6 Frequency of different events (repair and inspection), distributed over the date

### 3.2 | Effect of monsoons

The main peculiarity of developing wind energy in South Asia is the monsoon periods, which represent extraordinary load on wind turbines. For instance, in the state Tamil Nadu, southwest monsoons (between June and September), northeast monsoon (between October and December), and cyclonic rainfall (in November) define the climatic situation. Apart from surface load, which can be expected to increase the blade erosion, monsoons have strong effect on the lightning frequency.

From Figure 5, one can see that the lightning damage has occurred frequently from September to November, especially often in September and October, most often during Northeast monsoon (see Figure 7).

From Figure 7, one can see that most of the downtime has occurred between June and November, which includes higher amount of blade bolt replacements. Also, it is observed that the blade bolt replacement error has occurred randomly among all the 110 WTG's.

## 4 | REGIONAL VARIATIONS OF FAILURE MECHANISMS

In the following section, regional variations of different failure mechanisms and downtimes are explored. The blade failure statistics was collected in India in the period 2017–2021. In total more than 400+ failures were reported and observed.

The downtime in days against the type of failure observed in overall India is shown in Figure 8.

It is seen from Figure 8 that the blade damage due to lightning is the most often reason for downtimes. The next most important failure type is blade surface damage at the root section followed by pitch bearing failure. Downtimes as long as more than 200 days have been observed for lightning cracks while for surface damage at root downtime was as high as 130 days. Outliers were observed for these popular types: lightning damage, surface damage at root, pitch bearing failure, and blade surface damage due to erosion.

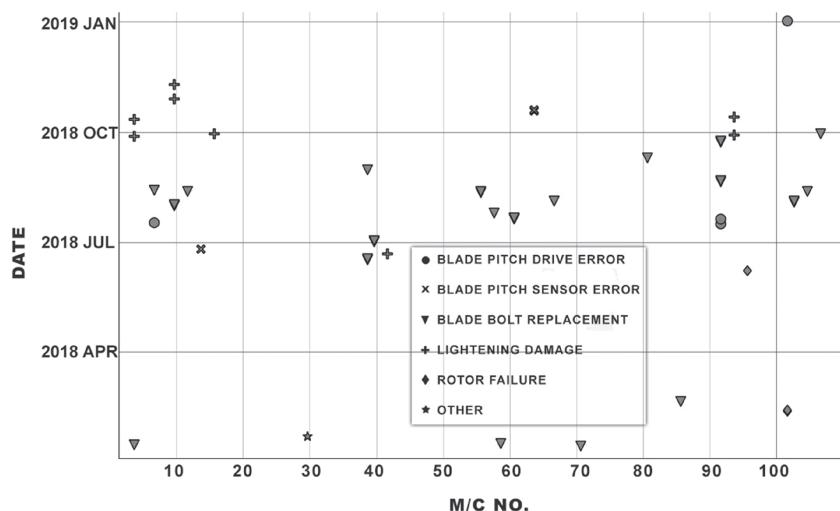
With large increase of wind turbine installations in 2021, four Indian states ensured largest quarterly additions of new turbines in operation. Gujarat is the leader, with 369.3 MW of new turbines, followed by Tamil Nadu (179 MW), then Karnataka (69.8 MW) and Andhra Pradesh (4.2 MW). The largest portions of the cumulative installed wind capacity are located in Tamil Nadu (9.6 GW of wind farms, market share of 25%) and Gujarat (8.5 GW, 22% share).<sup>3</sup>

Here, the downtime reasons are analyzed by states. The focus is on four states, namely, Tamil Nadu (south of India, tropical climate, partially humid subtropical), Rajasthan (Northern India, arid or semi-arid, extreme temperature variations), Gujarat (North-West, dry climate, hot in summer, cold in winter), and Maharashtra (West India, typical monsoon climate).

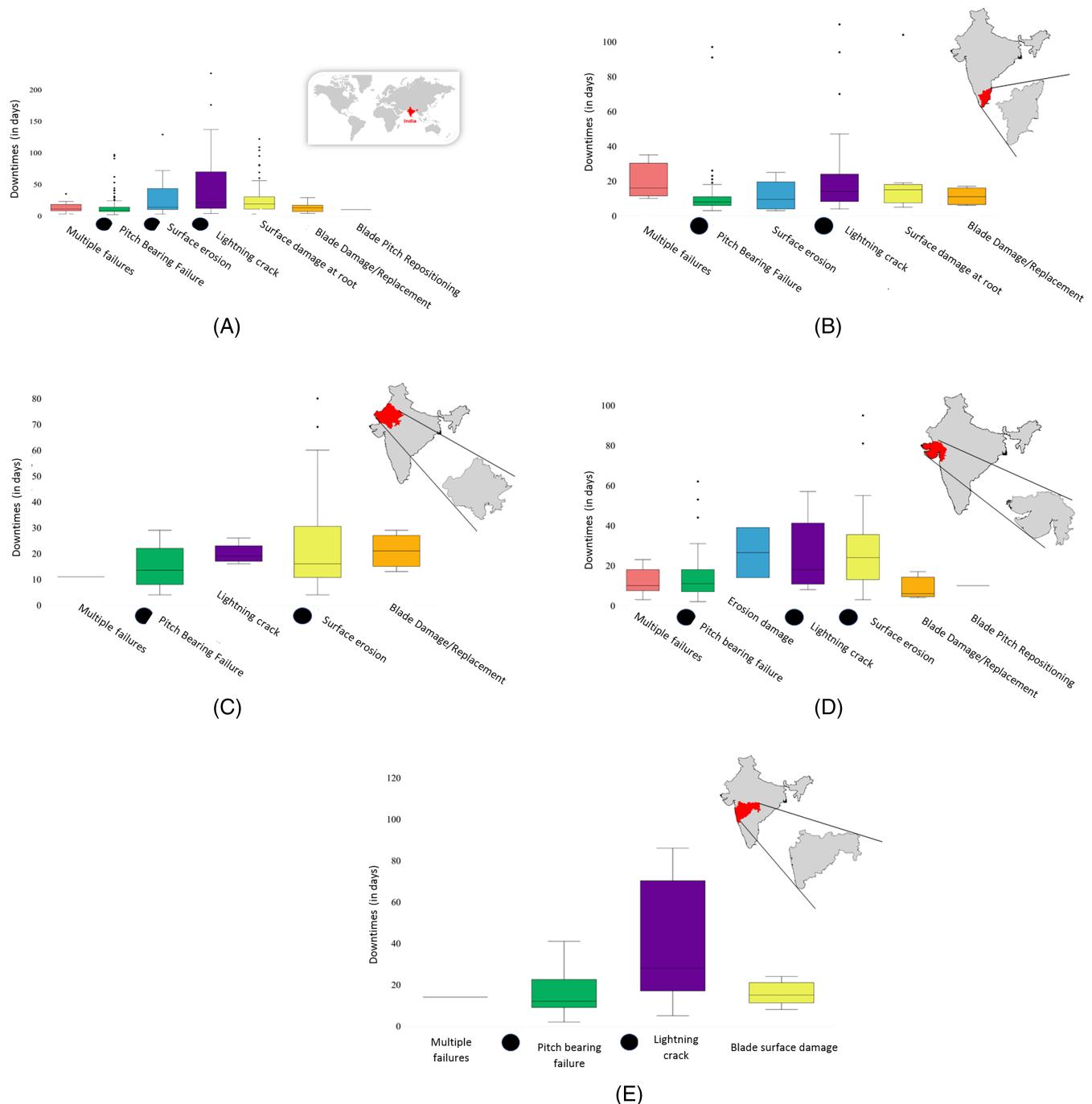
In Tamil Nadu, a graphical representation of downtime vs. failure type is shown in Figure 8. It was observed that blade tip damage due to lightning is again the dominating mechanism, as observed in the overall failures observed throughout the Indian region. Outliers were found with downtime more than 60 days for lightning damage. Pitch bearing failure had outliers with downtime more than 80 days. The downtime for blade damage at root and blade replacements was found to be less than 20 days.

Figure 9 shows photos of heavily eroded wind turbine blades. The erosion of blades can reduce the energy production of wind turbines by 5%–20%, and ultimately, lead to the cracking in laminates.<sup>20</sup>

Figure 10 shows wind turbine blade, damaged by lightning strike. It is worth to note that after a blade repair has been carried out, the same kind of repair can be needed again in only 2–5 years, depending on the site conditions.



**FIGURE 7** Overview of wind turbine repair reasons for considered wind turbines. X-axis shows the number of wind turbine (machine number)



**FIGURE 8** Downtime in days against the type of failure observed in different regions of India: (A) India as whole and four states, namely, (B) Tamilnadu, (C) Rajasthan, (D) Gujarat, and (E) Maharashtra

In Rajasthan, blade surface damage at the root and erosion dominate among the failure type. In fact, surface damage due to erosion dominates among the failure type. The state Rajasthan is known for frequent dust storms. The scale of the dust storms stretches in kilometers in height and width. Figure 11 shows dust storm by Cyclone Vayu in June 2019 in Sanu site near Jaisalmer (Rajasthan, India).

Specifications of wind farm site play an important role in the accumulation and build-up of dust on the blade surface of wind turbines. Whereas, the height of nacelle and rotor RPM in pitch regulated turbine were higher than stall-regulated ones, the effect of dust on the performance of pitch-regulated wind turbine is low. With growing dust on the surface of wind turbine blades, the drag force of the airfoil increases, but the lift force decreases diminishing the power output of the turbine. Also, the dusting on the rotor's blades of horizontal axis stall-regulated wind turbines may lead among others to a long time stops without no production due to heavy accumulated dust and safety demands.



**FIGURE 9** Eroded wind turbine blades



**FIGURE 10** Wind turbine blade damaged by lightning strike: (A) tip, (B) other side, and (C) splitting blade. Photos are made by Windcare employees

Comparing Figure 8A–D, one can see that lightning strikes cause most wind turbine downtimes in Maharashtra (monsoon region) and still play a very important role in Tamil Nadu and Gujarat (other monsoon regions).

## 5 | REPAIR AND MAINTENANCE: EXPERIENCE FROM INDIA

In this section, practical experiences of wind turbine service providers in India are summarized. The blade failure is the most common failure in India wind turbines. In Indian wind industry service providers, OEM's and blade manufacturers are presently involved to performing and specially focused on the blade maintenance and repairs of wind turbines. The repairing of wind turbines blades creates challenges due to the remote locations of wind farms, the size and height of the turbines, difficult to access the massive rotor blades, evaluate the blade materials and the



**FIGURE 11** Dust storm by cyclone Vayu in June 2019 in Sanu site near Jaisalmer (Rajasthan, India)

complex surface areas. Some of the technologies like using of rope access, Skylift method, and large platform for minor blade repair, using of winch method (craneless) and crane for major blade repair or replacement are being used, which aids in the rectification process.

Minor repairs are carried out using rope access, Skylift (cable-suspended), large platforms (cable-suspended), or lower capacity of crane (man basket). Major Repairs are carried out by using heavy duty crane, or using winch method (craneless). The advantages of rope access repair are faster and efficient service, appropriate for various height and size of wind turbine, less complicated equipment, lower design load effects on existing structures. However, it requires highly skilled rope professionals, possible only at wind speeds of less than 10 m/s, practical limits to rope access. Skylift (cable-suspended platform) leads to reduced overall costs and increased turbine production for the asset owner, is a cost efficient solution, allows to transport tools and materials up and down, less weight; however, it is difficult to access in all sides, and requires qualified electrical technician. Large cable-suspended platforms represent a best possible tailored solution, with full access to the blade, without necessity of highly specialized training, includes safety construction, allows working on the blade at wind speeds of up to 12.5 m/s, and gives stable access, however, it requires separate large vehicle for shifting the platform.

Lower capacity crane (man basket) allows technicians to safely carry out blade-repair work in wind speeds of up to 12.5 m/s, efficiently repair in tip portion failures, has suitable storage for required material and equipment and allows access to repair easily if the distance between blade and tower is large. However, if wind speeds are too high, the technician cannot be accessed, for safety reasons, the technology requires high initial investment. Cranes allow render both the assembly and replacement process faster, remote online diagnosis to be carried out, flexible operation, steady performance, exact positioning of loads. However, assembly taking more time, costs increase for higher tower, several trucks required for shifting, and high emission require well-trained competent person. Craneless technology, used by Windcare, allows less intensive technician requirements, reduced cost of transporting and mobilizing equipment, and requires only single truck for transportation.

The estimated repair costs vary for different damage types, for example, for a wind turbine of the order of 1.5–2 MW, the costs are 3.9 k€ for surface erosion, 11–16 k€ for structural cracks in blade, 28.1 k€ for broken blade, 3–10 k€ for blade retrofit, 16–20 k€ for blade repair after lightning strike if the blade is taken from wind turbine and the lightning cable connectivity inside is checked; 13 k€ for replacing one pitch bearing, including de-erection of the blade.

## 6 | CONCLUSIONS

Results of a survey of failure mechanisms of wind turbine blades in India, observed by service companies, are presented. Leading edge erosion can be observed even 1–2 years after wind turbine installation, while structural cracks are observed most often only 5–8 years after installation of the wind turbines.

Comparing the often observed damage mechanisms in Europe and in India, it was observed that leading edge erosion plays a critical role in both regions, starting from the installation and growing over 5 years. In India, also operational errors and manufacturing defects are among main failure mechanism of recently installed wind turbines, even after installation or 1–3 years old, leading to structural failure even in recently installed wind turbines. In Europe, manufacturing defects, fire and even operational errors determine the failure of wind turbines, reaching 5–10 years and more. Lightning strikes are registered relatively often, every 1–2 years, depending on climate and are especially often observed in monsoon regions of India. Analyzing the states and regions, one can state that lightning strikes are the main reasons for downtimes in southern regions, tropics, while blade surface damage at the root and erosion dominate in arid, North India climate, with extreme temperature variations. The most

widely used maintenance technologies are still time-based maintenance, with large part of emergency-based maintenance. Therefore, there remains a large potential for the transition from time-based maintenance (regular inspections) or emergency maintenance to the condition based maintenance.

## ACKNOWLEDGEMENTS

The authors kindly acknowledge the financial support of the Ministry of Foreign Affairs of Denmark, in the framework of Danida grant 19-M02-DTU “Maintenance and Repair Strategy for Wind Energy Development”.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**How to cite this article:** Boopathi K, Mishnaevsky L Jr, Sumantraa B, Premkumar SA, Thamodharan K, Balaraman K. Failure mechanisms of wind turbine blades in India: Climatic, regional, and seasonal variability. *Wind Energy*. 2022;25(5):968-979. doi:10.1002/we.2706