Main Bearing Replacement and Damage – A Field Data Study on 15 Gigawatts of Wind Energy Capacity

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James Brasseur,[4] and Fraser Tough[5]

1 The University of Strathclyde
2 National Renewable Energy Laboratory
3 The University of Sheffield
4 The University of Colorado
5 The University of Glasgow

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
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Disclaimer

The results and discussions contained within this report are intended to support an improved understanding of wind turbine main bearing replacements and damage. Although the results and associated data have been reviewed for accuracy and completeness, the authors do not assume liability for any decisions or actions made in light of the presented information.

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Table of Contents

List of Figures

List of Tables

1 Introduction

The Advancing Main BEaRing Science for wind and tidal turbines (AMBERS) project seeks to improve the scientific understanding of main bearings in wind and tidal turbines through a program of research and innovation. One of the AMBERS work packages was initiated to establish a comprehensive baseline of knowledge for the replacement and damage of main bearings in wind turbines. Additionally, it has allowed for the implementation of established best-practice statistical methods for handling such data.

Through working with industrial partners, the authors compiled and analyzed an extensive data set. We emphasize that we maintained the anonymity of the contributing industrial partners throughout, and that only anonymized and aggregated results from the various analyses were made available to contributing experts for comment.

The purpose of this report is to provide a high-level summary of the data set, methodology, and results of this work. Full technical details and an extended analysis will be made available separately, in a journal publication.

1.1 The Data Set

We collected data on main bearing replacements and reported damage from a number of industrial partners based in Europe and the United States. These data included the dates of turbine/main bearing commissioning for all wind turbines, the date of replacement for each main bearing that was exchanged, turbine rated-power levels, and, where possible, the reported main bearing damage. In total, we obtained data for 167 wind power plants (7,707 wind turbines), with a combined capacity of 15.3 gigawatts (GW). Within this data set were 689 instances of main bearing replacement. Multiple main bearing replacements for the same wind turbine were found to be relatively uncommon in the data, with replacements occurring for different turbines in the vast majority of cases. Table 1 and Figure 1 provide breakdowns of the overall data set. Note, turbines of power rating less than 1 MW only comprise 1% of the overall data set. As shown in the table, complete information was not available regarding various characteristics of individual wind turbines and/or drivetrains. Therefore, we conducted the analysis without differentiating between land-based versus offshore, spherical roller bearings (SRBs) versus tapered roller bearings (TRBs), and three-point versus four-point mounts[1]. Most of the data set was comprised of land-based, three-point mount, SRB main bearings. The vast majority of main bearing failures in the data set occurred for the downwind row of the locating bearing. Additionally, the vast majority of turbines were geared, rather than direct-drive, machines.

Table 1. Data Summary

Data set summary information									
Total num. wind farms	167	Breakdown by category							
Total num. turbines	7707	Onshore turbs.	76%	SRB	77%	3-pt. mount	56%	Replacements with date	94%
Total represented capacity	15.3 GW	Offshore turbs.	2%	TRB	1%	4-pt. mount	15%	Replacements with damage info	91%
Total num. MB replacements	689	Unknown	22%	Unknown	22%	Unknown	29%		

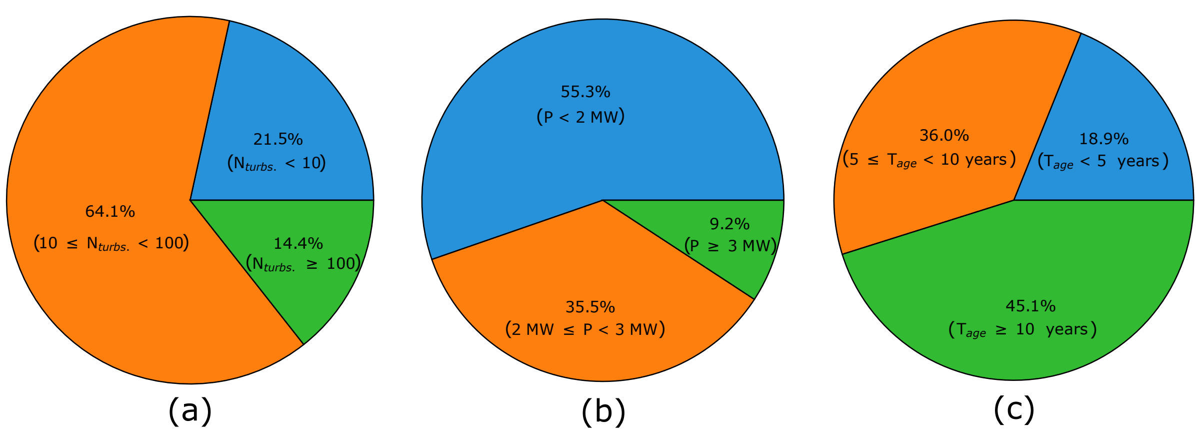

Figure 1. Data set breakdown by a) wind plant size, b) wind turbine power rating, and c) turbine age

[1]In the four-point case, the locating (thrust supporting) bearing is a SRB or TRB, whereas the nonlocating bearing can be a SRB, TRB, or cylindrical roller bearing

Note, some levels of uncertainty are present in the data. This uncertainty is due, in part, to some operators having access to the exact date of main bearing replacement, whereas others were only able to share the date of turbine stoppage prior to main bearing replacement. Furthermore, time to replacement for any component will be influenced by external considerations (operator- and wind-plant specific), which drive both planned and opportunistic maintenance decisions. These considerations introduce further uncertainty as to the specific drivers behind the replacement times that were analysed. Results should therefore be interpreted with this in mind.

2 Methodology

The analysis was undertaken in two parts:

1. Statistical analysis of the main bearing time-to-replacement data
2. Quantitative and qualitative analysis of collected damage information.

The statistical analysis in Part 1 used techniques from survival analysis, a field of statistics specifically developed to analyze time-to-event data. The analysis utilized information on both the replaced and nonreplaced main bearings while also accounting for the new main bearings that are installed as a result of replacements. In Part 2, reported damage information was put into a standardised form to allow the proportions of different damage types and damage locations to be scrutinised and interpreted. Implications for possible drivers of observed damage types were then considered.

We established the methodology to consider the following key questions:

- How does the proportion of main bearing replacements progress over time?
- How does the risk of replacement for a main bearing change over time?
- What are the most prevalent reported damage types and locations and what do they indicate with respect to possible and/or probable drivers of main bearing replacements?
- Related to the previous question, what do the answers imply with respect to the role (or not) of rolling contact fatigue (RCF) in main bearing replacements?

3 Results

3.1 Time-to-Replacement Results

A power-plant-level summary of the collected data is provided in Figure 2. For each wind plant, age is plotted against the total number of main bearing replacements expressed as a proportion of the number of turbines. While this figure provides only a crude representation of the data, a number of pertinent observations can still be made. First, the proportional number of replacements appears only weakly correlated with wind plant age. There is also no

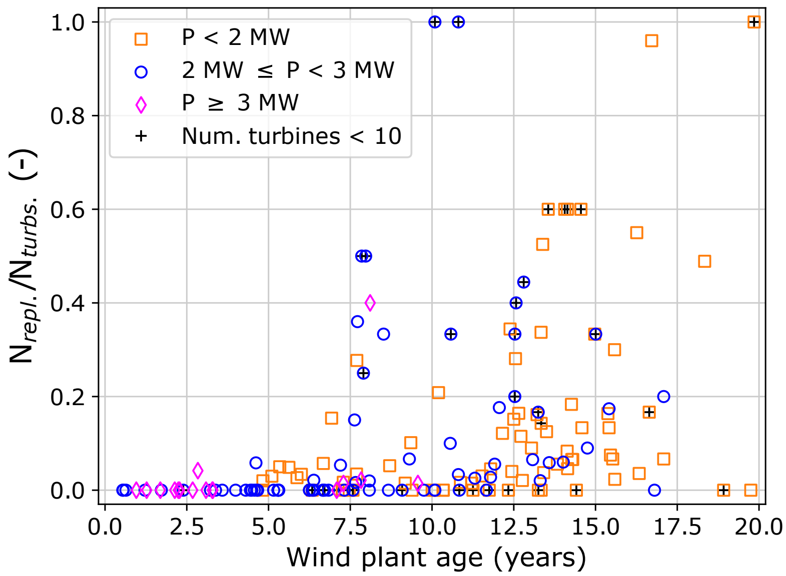

Figure 2. For each wind plant, age is plotted here against the total number of main bearing replacements, $N_{repl.}$, expressed as a proportion of the number of turbines at that plant, $N_{turbs.}$.

immediately obvious relationship with turbine rated power levels. Together, these results indicate that other factors (e.g., site conditions, maintenance practices, and technological changes) are driving variability in the number of replacements occurring for a given age of wind plant. Second, this figure indicates that main bearing replacement numbers appear not to be strongly driven by "infant mortality" effects. Third, the modified reference rating life of the main bearing is such that no more than 10% should need replacing, due to rolling contact fatigue, within the specified design life of the wind turbine—typically 20 years or more. From the figure, it is clear that this threshold is being passed before 20 years in many cases, and in some instances as early as 7–7.5 years. This result indicates that one of two scenarios must hold: either rolling contact fatigue is not a principal driver of premature main bearing replacements (meaning other damage mechanisms dominate); or rolling contact fatigue does contribute to observed replacements, but current rating life assessment methods do not capture it sufficiently; hence, they are unable to provide realistic rating life predictions. Finally, while some sites see high proportions of main bearing replacements, others have no or very low proportions replaced even after 12–20 years.

We then undertook a more formal statistical analysis by combining data from all sites into a single, large, time-to-replacement data set. From this data set the survival curve, $S(t)$, for main bearing replacements was obtained using the Kaplan-Meier estimator. In the current context, $S(t)$ describes the proportion of main bearings "surviving" (*i.e.,* those that have not been replaced) until or beyond time t in a fixed population over time. At any time, t, the proportion that has been replaced is therefore $U(t) = 1 - S(t)$, which is sometimes referred to as the unreliability curve. Figure 3 shows the survival curve for the collected main bearing replacement data, including 95% confidence intervals[2].

[2] Confidence intervals in this figure are based on data quantities alone. However, as described earlier, other uncertainties are present in the analysis that are not accounted for directly here. True confidence intervals are therefore wider than those shown here, although the additional uncertainty is understood to only be on the order of around ± 1 month.

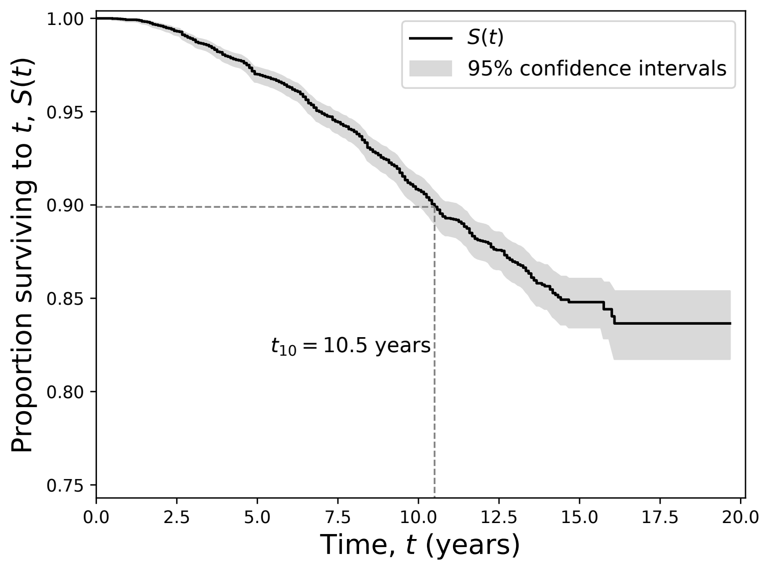

Figure 3. Survival curve, $S(t)$, of main bearing replacement data, obtained using the Kaplan-Meier estimator.

Defining t_{10} to be the time at which 10% of main bearings in the population have been replaced (so $S(t_{10}) = 0.9$), this value may be directly compared to the desired design value of 20 years. For this population of 7,707 wind turbines, $t_{10} = 10.5$ years, which is close to half of the design value.

It is also of interest to consider the proportion of the main bearing population, $S(20)$, which would be expected to survive the 20-year design life. Since the data set itself does not reach 20 years, and only a small proportion of turbines are > 15 years of age, parametric fitting is necessary to estimate $S(20)$. A number of common survival/reliability distributions were therefore fitted to the data, with goodness-of-fit determined via the Bayesian Information Criterion (BIC) score. The best-fitting distribution was the 2-parameter log-normal, followed by the gamma, log-logistic, and Weibull distributions (in that order). Fitted distributions are shown in Figure 4.

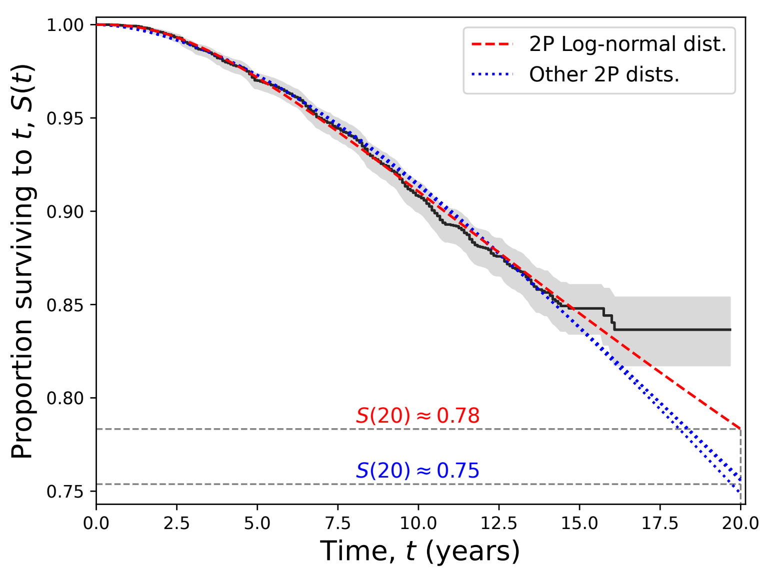

Figure 4. Survival curves obtained from the parametric distribution fitting

The log-normal distribution predicts $S(20) = 0.78$, equivalent to 22% of the main bearing population having been replaced by year 20. The other fitted distribution $S(20)$ predictions are all lower than that of the log-normal distribution. The mean of these other predictions is $S(20) = 0.75$, equivalent to 25% having been replaced by year 20. This is similar to the 15–30% main bearing replacement rates at year 20 for three- and four-point mounted wind turbines in the 1 to 3 megawatt (MW) range reported in Hart et al. (2019) and less than those obtained by extrapolating the data reported in Chovan (2018).

Related to the survival function is the hazard rate, $h(t)$, also referred to as the conditional failure rate. In the current context, $h(t)$ estimates the probability of a main bearing being replaced in the next month, given that it has survived to time, t (for t in years). The hazard rate is generally considered to be more informative than the survival function when considering underlying mechanisms of failure. $h(t)$ may be estimated[3] directly from $S(t)$, and a hazard rate curve can also be obtained for each fitted distribution. These various forms are shown in Figure 5 for the analyzed main bearing replacement data set. Both the empirical- and distribution-based hazard rate curves are shown to

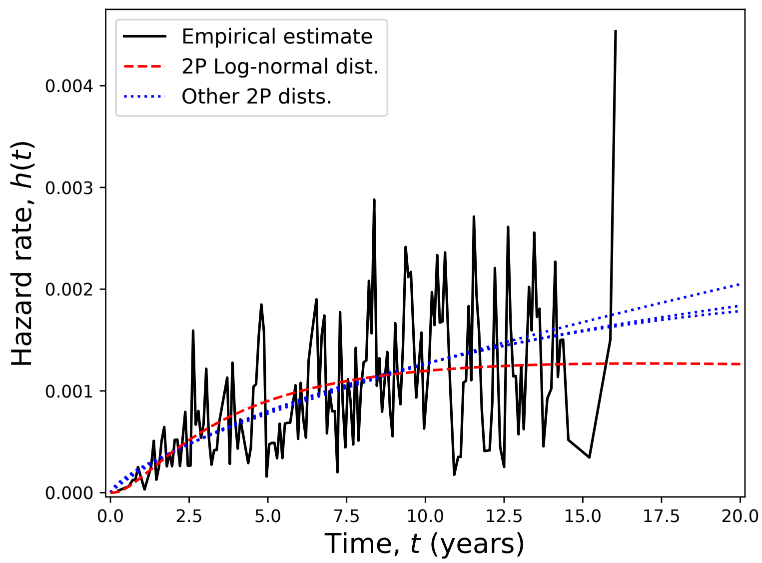

Figure 5. Monthly hazard rate, $h(t)$, for main bearing replacements obtained empirically and from fitted parametric distributions.

increase from zero in the early years, with a roughly monotonic increase continuing until around $t = 8.5$. Thereafter, the trend is less certain, with the empirical estimate being very noisy[4], the log-normal fitted distribution predicting a leveling of $h(t)$ as t increases further, and the remaining fitted distributions predicting a continuing monotonic increase in $h(t)$.

In the current case, the Weibull fit results in the smallest $S(20)$ value in Figure 4 and, correspondingly, the largest hazard rates in Figure 5. It is notable that the Weibull distribution, often the default distribution fitted during reliability analysis, provided the poorest fit (as determined by the Bayesian Information Criterion score) of the four distributions for which results have been shown. Other distributions may therefore provide a better characterization of reliability data in some instances. It is therefore recommended that, in general, a number of distributions are fitted and goodness-of-fit checks performed. Caution is advised when extrapolating beyond the data. This is due to a) possible later features of a parametric distribution that are not justified by the data, and b) the possibility of new mechanisms becoming important later in a component's life.

We conducted a further statistical analysis, Cox proportional-hazard modeling, to ascertain if a relationship between wind turbine power and main bearing time-to-replacement values could be detected. However, no statistically significant relationship was found to be present for this data set.

[3]Hazard rate estimates obtained this way tend to be quite "noisy" because of the stepped nature of $S(t)$.
[4]The final spike in the empirical, $h(t)$, estimate may appear significant, but, considering the final flat, $S(t)$, segment, the next value, $h(t)$, will likely be small.

3.2 Damage Results

As outlined in Section 2, we processed damage reports into standard categories of listed damage types and damage locations. Damage types included: indents (I), microspalling (MiSp)[5], pitting (P), spalling (Sp), chipping (Ch), wear (W), fracture (Fr), particles/debris in grease (GP), axial cracking (AC), and heat damage (HD). Damage locations included: inner raceway (IR), outer raceway (OR), roller (R), cage (C), and housing (H). Figure 6 shows occurrence distributions for damage and location (separately) from collected main bearing damage reports. In these figures, the diagonal elements indicate the proportion of damage reports listing that damage/location type. Off-diagonal elements indicate the proportion of damage reports listing both corresponding types of damage or location. A single damage report may include multiple damage types and/or locations.

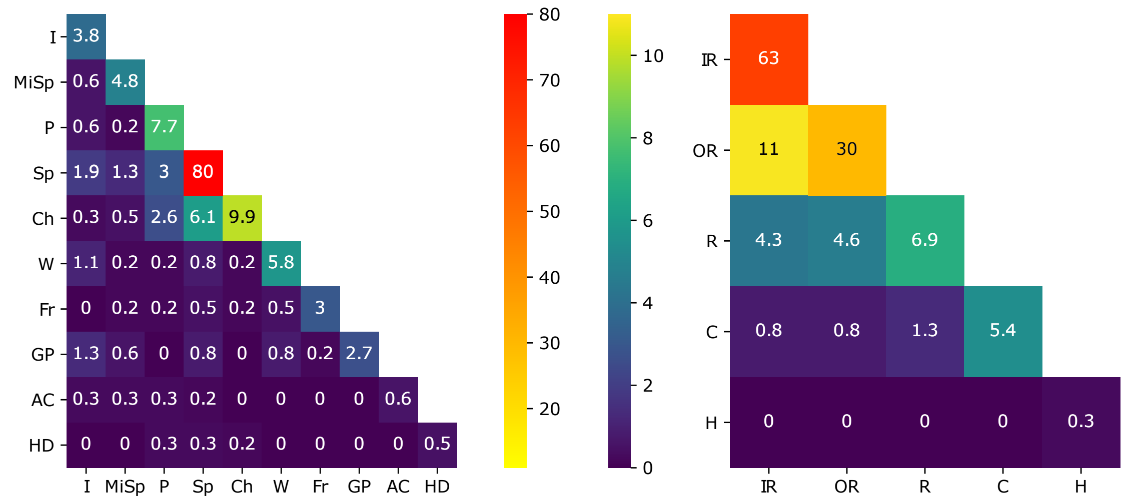

Figure 6. Occurrence distributions for a) damage type and b) damage location. Diagonal elements indicate the proportion of damage reports listing that type of damage or location. Off-diagonal elements indicate the proportion of damage reports listing both corresponding types of damage or location.

Note, the different damage types and locations are not independent of one another. For example, indents can precipitate microspalling, which leads to spalling. Similarly, all observable damage is likely not listed in every damage report (for example, in cases of Sp there will always be GP, but GP tends to only be listed when it is the main type of damage observed). Spalling, which can result from both subsurface- and surface-initiated RCF, is mentioned in a significant proportion of damage reports. Subsurface-initiated RCF can therefore not be ruled out as possibly contributing to main bearing damage. The presence of surface damage (I, MiSP, P) in around 16% of cases indicates that some proportion of replacements are likely the result of surface-initiated RCF. This type of damage is typically caused by surface distress (due to deformation of asperities) and may be an indication of insufficient lubrication. The risk of surface-initiated RCF is significantly increased if slip is present in combination with abrasive particles or poor lubrication conditions. In such cases, there are non-trivial interactions occurring between wear and RCF mechanisms which can increase the likelihood of surface-fatigue damage initiation. For cases where fatigue has been precipitated by wear, RCF should be considered a secondary damage mode. Unfortunately, the information in the current dataset alone does not allow for easy differentiation between instances of "wear induced" surface-initiated RCF, surface-initiated RCF and subsurface-initiated RCF since widespread spalling is the eventual result in all cases. Wear, fracture, and heat damage are all indicative of non-RCF mechanisms, possibly associated with abrasion, smearing, or impact/excessive loads. Fracture of rings and cages can also result from classical fatigue (not RCF) initiated at a stress riser. With respect to damage locations, the inner raceway is most commonly listed in the collected data, followed by the outer raceway, rollers, the cage and, finally, the housing.

Figure 7 shows the occurrence distribution between damage type and location for the subset of data in which specific damage types are linked with specific locations in the main bearing. Note that chipping was only listed as occurring on the outer raceway, where spalling is the most common form of damage. These results may be linked, because

[5] Micropitting is the most commonly applied name for this damage, but the term microspalling is used here to ensure consistency with ISO 15243.

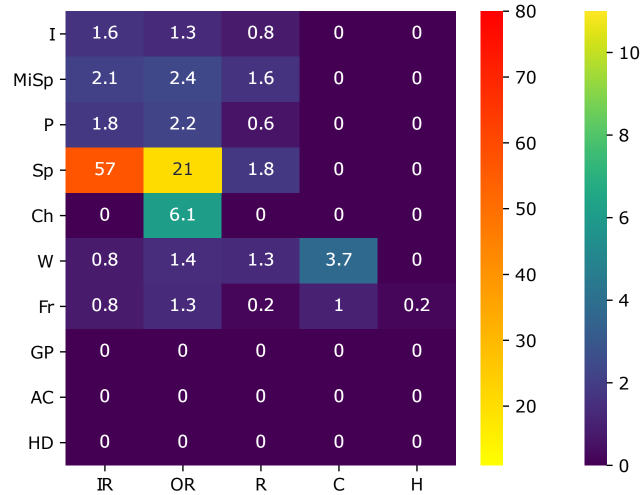

Figure 7. Occurrence distribution between damage type and location. Each entry indicates the proportion of damage reports listing both the corresponding damage type and location.

excessive spalling could lead to increased freedom of movement within the main bearing, allowing the load zone to shift toward the edge of the outer raceway. Under such circumstances edge stresses may occur that exceed the material strength, resulting in a local forced fracture (chip) on the edge of the outer raceway.

4 Conclusions

This report summarizes the analyses and findings of a field-data-focused project AMBERS work package. With respect to the questions posed in Section 2:

- We analyzed the proportions of main bearing replacements occurring over time using survival analysis techniques. Results indicated that 10% of a fixed population would be expected to have been replaced by 10.5 years. This is close to half of the 20-year design value. Fitted distributions then indicated that by year 20, between 22% and 25% of main bearings are expected to have been replaced. No statistically significant relationship between wind turbine power and main bearing replacement times was detected for this data set.
- The probability of replacement at time $t+1$ *month* (having survived to time t) was also explored via hazard rate curves. The best-fitting distribution indicated a monotonic increase between years 0 and 8.5, followed by an approximately constant value thereafter. Other distributions predicted a continuing monotonic increase.
- The damage report analysis revealed spalling to be the main type of damage listed. Spalling results from both surface- and subsurface-initiated rolling contact fatigue. The presence of surface damage in the collected data indicates that at least part of the spalling cases are likely due to surface-initiated rolling contact fatigue. This type of damage is typically caused by surface distress and may be an indication of insufficient lubrication. Other (nonrolling contact fatigue) mechanisms were also evident, possibly linked to abrasion, smearing, or impact/excessive loads. Some of these latter effects are associated with time-varying operating conditions and bearing internal dynamics.
- The dominance of spalling as a reported damage mode indicates that rolling contact fatigue plays an important role in main bearing damage and replacements. However, as discussed, it is not clear at this time what proportion of spalling cases result from "wear induced", surface-initiated and subsurface-initiated rolling contact fatigue. Certainly, additional evidence is present for the first two (described in the previous item), but, at this stage subsurface-initiated rolling contact fatigue should not be discounted as a possible contributor to early main bearing damage.

This work provides important insights into the current state of main bearing replacements and damage. However, much remains unanswered. Therefore, there is clear value in expanding the current data set while improving the information available. In particular, identifying additional variables that might allow for the variability present in Figure 2 to be better explained. We propose that information relating to site conditions (e.g., International Electrotechnical Commission wind class, site turbulence intensity, annual temperature range) and maintenance scheduling (relubrication and/or grease flushing activities in particular) are good places to start in this regard. With respect to damage modes, more data of the same type will be important. Additionally, procuring physical samples of damaged main bearing subcomponents would provide further insights via sectioning and detailed metallurgical analyses. In general, it is important to obtain damage information and samples prior to the later stages of widespread internal damage, because by this stage any evidence of root cause has likely been lost.

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