We would like to thank the reviewer for the valuable feedback. Below, we respond to each comment and explain the changes made to the manuscript.

In this paper, the authors present a methodology for calculation of the probability of failure of a wind turbine pitch bearing due to static overload – specifically based on exceedance of the static safety factor as determine by the recently published pitch bearing design guide (Stammler et al 2024). The presented methodology also includes treatment of a variety of design uncertainties, which is especially interesting, and examines specific wind sites. Having said that, I have a number of technical and editorial comments. My most significant question pertains to the interrelationship of terms R and S as described in the comments. Maybe there is no issue, but I seek clarification and comment from the authors.

Title

- The phrase "reliability design" is applied very broadly in the title and "reliability analysis" similarly in the text. This is a little misleading, as what has been examined is the risk of static overload resulting in plastic deformation damage, which is just one aspect of the design. Obviously, rolling contact fatigue and wear prevention are other essential aspects in the design.
- Answer: The paper has employed the classical "structural reliability" approach to estimate the reliability of the design under a certain failure mode – static overload in this case. We therefore used this term "reliability design" to emphasize the level of reliability one can expect under different design assumptions. We have now updated the text to make this to be more clear.

- Other than in the Title, "code calibration" is not used in the manuscript. What did the authors intend with this phrase? I have the feeling it has something to do with comparison of IEC wind classes to actual wind sites, but I would not describe this as "code calibration". Please reconsider your meaning.
- Answer: In reliability engineering, "code calibration" often refers to checking whether the partial-safety factors or load factors in a design code achieve a target reliability when confronted with real stochastic input data. Our study compares IEC 61400-1 wind classes against measured site-specific wind regimes and quantifies the resulting probability of failure—an exercise that resembles a pre-calibration check of the code's implicit safety margin. We agree that we do not perform a formal statistical calibration of IEC partial factors, nor do we propose new calibrated factors. To avoid over-promising, we have deleted the term and replaced it with "code–site comparison." In sections 4.3-4.4.
- The title changed to the following:

  "On reliability assessment of wind turbine blade bearings under extreme wind conditions"

Abstract

- Lines 1-5: The Abstract says the manuscript presents and describes "*the* reliability analysis" in several places. As commented on the Title, this manuscript examines the risk of static overload resulting in plastic deformation damage. This is one or "a" aspect of the design, not "the" aspect. Additionally, the abstract mentions "probability of failure" very broadly without specifying that it is limited to risk of static overload resulting in plastic deformation damage. In terms of the importance of ball diameter and the conclusion on IEC vs. actual wind sites, please see later comments.
- Answer: We agree that the opening sentence should state the specific failure mechanism that is analyzed. We now introduce the study as an "*analysis under static overload ".*
- Lines 3-6: The phrase "sensitivity in the dimension aspect of reliability" is unclear. That is, it is not clear if "dimension" refers to a physical dimension (ball diameter, pitch diameter) assessed in the reliability analysis, or if it refers to one element or an aspect of the analysis. Further, lines 3-6 all say similar things, but in slightly different manners – so, it is not clear if key differences are being communicated or not. My sense is not, so for greater clarity, I recommend lines 3-6 be combined and simplified to something like "The sensitivity of the probability of failure to uncertainties in turbulence intensity, material properties, and bearing dimensions is evaluated. Within the bounds examined, the pitch bearing conformity and ball diameter have the largest effect on the probability of failure."
- Answer: We have adopted the reviewer's suggested wording in full. The text has been revised as below:

  "*The sensitivity of the probability of failure to uncertainties in turbulence intensity, material properties, and bearing dimensions is evaluated. Within the bounds examined, the blade bearing conformity has the largest effect on the probability of failure, and ball diameter is next.*"

- Lines 6-7: Here too the sentence is a bit hard to understand, especially "IEC standards…are studied…". I recommend more simply and directly "The probability of failure for some example wind sites around the world is assessed and is higher at those sites than for wind conditions described by IEC 61400-1."
- Answer: The sentence has been shortened and clarified as recommended. The text has been revised as below:

  "The probability of damage for case-study wind sites around the world is assessed, and it is observed that the probability of failure is higher in some cases than for wind conditions described by IEC 61400-1."

1 Introduction

- Lines 14-15: I believe a more accurate representation of the cost in Stehly et al 2023 is that "Although the entire pitch system assembly costs less than one percent of the wind turbine Stehly et al. (2023), changing a blade bearing is costly due to the need for lowering of the blade with a large crane." That is, Stehly lists the full system assembly cost (for all 3 blades, including the bearings, motors, controls, batteries, etc.) rather than only the bearing and I recommend emphasizing that an individual bearing is vanishingly cheap but can have a costly failure ramification.

- Answer: Thank you for the clarification. We have revised the sentence to state explicitly that the < 1 % figure applies to the *whole* pitch-system assembly, while replacing one failed bearing is costly because it requires blade removal with a large crane and results in significant downtime. The text has been revised as below:

  "Although the entire pitch system assembly costs less than one percent of the wind turbine (Stehly et al., 2023), changing a blade bearing is costly due to the need to lower the blade with a large crane."

- Lines 17-18: This sentence, especially "perform the calculation of the ultimate limit state" is a bit garbled and incomplete. I believe a better statement of its intent is "As part of the design and certification process, the blade bearing static safety factor must be assessed in the ultimate limit state (ULS) (IEC 61400-1 2019; DNV-ST-0437 2016; Harris et al. 2009; Germanischer Lloyd 2010; Stammler et al. 2024)."

- Answer: We agree, and the text has been revised as below:

  "*As a part of the design and certification process in a blade bearing, the static safety factor of the blade bearing in the ultimate limit state (ULS) must be assessed, as mentioned in IEC 61400-1 (2019); DNV-ST-0437 (2016); Harris et al. (2009); Germanischer Lloyd (2010);* Stammler et al. (2024)."

- Line 20: I recommend deleting the sentence "There are numerous studies on the fatigue of the bearings; however, the studies about the blade bearing are not many." It provides no information, is entirely subjective, and as time moves on, is less and less accurate. My personal opinion is that it is not accurate even today, as I have a library of 6 dozen technical papers and journal articles regarding blade bearings.

- Answer: We agree. The sentence has been deleted, and the text has been revised as below:

  "Several studies have analyzed blade bearings. Among them"

- Line 26-27: Although I myself was a co-author on Rezai et al (2023) and the paper does speak to "seed number", the phrase "...shows the importance of seed number in the turbulence wind model at bearing's life" is not the best description of the work and likely to confuse many readers. I believe a better description of Rezai et al (2023) is that it "...assessed the variation in blade bearing fatigue with shear power law exponent, turbulence intensity, and even resulting from each individual turbulent wind time series."

- Answer: Thank you for the suggestion. We have adopted the reviewer's proposed wording, which more accurately summarizes Rezaei et al. (2023). The text has been revised as below:

“Rezaei et al. (2023) studied the blade bearing of the 5 MW NREL reference wind turbine and assessed the variation in blade bearing fatigue with shear power law exponent, turbulence intensity, and even resulting from each individual turbulent wind time series.”

- Line 32-33: I recommend deleting the phrase “…blade bearing reliability is not studied thoroughly…”. Similar to line 20, this phrase provides no information and is entirely subjective. I also recommend the phrase “…it is not clear what level of reliability one can obtain with the current design process” also be revised. Although true to some extent, a more informative statement would be to refer to the statistics in Haus, Sheng, and Pulikollu (2024) at https://app.box.com/s/ktjzjdxn77omu1cjoy9znymbrynlsw0d. The statistics therein from 55+ GW of wind plant data show that pitch bearings installed pre-2016 perform fairly well, only reaching a 10% replacement rate in 15 years. However, pitch bearings installed post-2016 on larger wind turbines are projected to have a 10% replacement rate in only 7.5 years.
- Answer: We have removed the subjective clause and replaced the following sentence with an evidence-based statement. The text has been revised as below:

  “Haus et al. from 55+ GW of wind plant data show that blade bearings installed pre-2016 perform fairly well, only reaching a 10% replacement rate in 15 years. However, blade bearings installed post-2016 on larger wind turbines are projected to have a 10% replacement rate in only 7.5 years.”

- Line 34: It isn’t clear that ISO 19902 and ISO 19904-1 standards for oil and gas industries are relevant to offshore wind. More broadly, it seems like IEC 61400-3-1 and -3-2 are better references here. Additionally, IEC 61400-8, titled “Design of wind turbine structural components”, seems better suited for a general reference than ISO 2394 for general principles on reliability for structures. Do the authors have a particular meaning in mind with the references to oil and gas standards? In what situations would these standards apply to offshore wind?
- Answer: Thank you for the questions. The reliability targets for offshore wind-turbine support structures are still those in the ISO 19900 series; IEC 61400-3-1 (fixed-bottom, 2023) and IEC 61400-3-2 (floating, 2019) adopt those targets by normative reference. IEC 61400-8 (2024) focuses on nacelle- and hub-level structural components and guidance on external conditions. We have therefore rephrased the sentence both in the introduction and the results to cite:

  “*IEC 61400-1:2019 for on-shore component-level reliability, ISO 19902:2020 and ISO 19904-1:2019 (as invoked by IEC 61400-3-1:2019 / -3-2:2019) for offshore support-structure reliability, and IEC 61400-8:2024 for nacelle/hub structural design guidance.*”

- Line 39: I think most readers will find the sentences “ISO 76 (2006) stated that experience shows that a total permanent deformation of 0,0001 of the rolling element diameter at the center of the most heavily loaded rolling element/raceway contact can be tolerated in most bearing applications without the subsequent bearing operation being impaired. The bearing static failure corresponds to such a permanent deformation" conflicting. That is, "without operation being impaired" and "corresponds to bearing static failure" are conflicting. I recommend changing the second sentence to "In this work, it is proposed that ball-raceway contact stresses approaching the limits corresponding to ISO 76 increase the probability of failure of the bearing."

- Answer: We agree that the wording was contradictory. We have replaced the second sentence with a statement that makes our modelling assumption explicit:

  "ISO 76 (2006) stated that experience shows that a total permanent deformation of 0.0001 of the ball diameters at the most heavily loaded contact without the subsequent operation being impaired. In the present study, we treat contact stresses that reach this deformation limit as attaining the ultimate limit state, i.e., stresses approaching the ISO 76 threshold are assumed to represent the onset of static failure and therefore increase the probability of bearing failure."

- Line 42: The phrase "and the formation of cavities in the raceways" was curious to me. Does this refer to the core crushing phenomenon described in Harris et al. 2009 and Stammler et al 2024?
- Answer: The phrase is extracted from [Harris and Kotzalas (2006)], and when the cavities formed in the core of the raceway, it leads to core crushing as it is described in [Harris et al. 2009] and [Stammler et al 2024].

3.2 Safety factor and failure function

- Lines 76-84: Although somewhat relevant, I don't believe the ISO 76 static safety factor S0 = C0a/P0a mentioned here or shown in Step 5 of Figure 1 is used in the remainder of the manuscript. If this is the case, I recommend deleting these lines as not to distract the reader.
- Answer: The method is referenced in IEC 61400-1 section 9.8.4, and that's the reason it is presented in the paper; however, it is not used in the paper. The ISO 76 static-factor paragraph and the associated "Step 5" box in Fig. 1 have been removed. A short bridging sentence now guides the reader directly to the Hertz-stress-based limit-state formulation used in the remainder of the paper.

  "For the reliability model, the static limit state is formulated with the Hertzian contact-stress criterion."

- Equations 6-8: I am curious how it is handled and might be worth discussing in the manuscript that the contact area parameters a and b in Equation 6 and within the variable R in Equation 8 are dependent on the maximum ball load Qmax in Equation 6 which is the variable S in Equation 8. That is, R = R(S). Is this automatically accounted for in the described methodology? If so, how? This appears to me acknowledged to some extent in line 135.

- Answer: It is correct that a and b are functions of Q_{max} and R=R(S), and it is accounted for in the calculation. In every Monte-Carlo realization, Q_{max} is calculated first, and then a and b are evaluated with consideration of the uncertainty in dimensions and Q_{max}. Finally, R is calculated based on a and b. The following texts are added:

  "a and b in the R are functions of the applied maximum ball load Qmax; therefore, R is implicitly a function of S."

  "In every Monte-Carlo realization, therefore, Qmax is computed first, then evaluated a, b, and finally R, ensuring that the dependency R(S) is fully captured"

- Line 102: It appears the text here has the opposite sense of Equation 8. Shouldn't the text here say "If the failure function value is less than or equal to the static safety ratio, the bearing is safe; otherwise, the bearing is in a failure state"?
- Answer: When the failure function value is equal to or less than the safety ratio, the bearing is in a failure state. Let's consider value 1 for the safety ratio. When the function value is less than 1, it means that R is smaller than S and the bearing is in a failure condition. In order to clear it for the readers, the text was revised as follows:

  "If the failure function value is equal to or smaller than the static safety ratio, the bearing is in a failure state; otherwise, the bearing is in a safe state."

- Lines 107 – 115: Although I don't disagree, the math here seems a little longer than necessary. I think one can simply take the cube root of Equation 9 and get to Equation 12 quite directly.
- Answer: Replaced the multi-step derivation with:

  "Taking the cube root of Equation 6 yields the failure function directly as"

- Line 126: Here R and S are described as resistance and stress. Hearkening back to Equation 6, these are meant to be R = 4200*pi*a*b/1.5 and S = Qmax I believe. I don't disagree that the load S = Qmax partially represents the stress, but so do the terms pi*a*b (contact ellipse area) which is part of what is called R (resistance) if I understand correctly. As commented earlier, a and b are dependent on Qmax, that is, R = R(S). I do agree that the stress of 4200 MPa can be thought of as resistance here.
- Answer: The following text is added to the paper:

  "These randomnesses can appear in the R representation of the load-capacity term and S the representation of the applied maximum ball load."

- Figure 2: Two boxes here are "Uncertainty on aerodynamic" and "Uncertainty on wind". I'm not entirely sure I understand the distinction.

- Answer: We agree that a clearer distinction between different types of uncertainties would help the reader better understand the structure of the reliability model. Therefore, we have updated Figure 2 to clarify the sources and types of uncertainty involved in the loads. In particular, we now distinguish between:
  Aleatory uncertainty represents inherent variability, such as the stochastic nature of short-term wind conditions (e.g., turbulence and seed number variability).
  Epistemic uncertainty, which we further divide into:
    Model uncertainty — including simplifications in aerodynamic load modeling, and structural response
    Measurement and parameter uncertainty
    Statistical uncertainty — arising from finite sampling periods.

  To make this clearer, we drew a light dotted rectangle around them, labelled "*combined → uncertainty on wind-induced loads*", and the following text is added right after the figure:

  "The dashed box represents uncertainty on loads that have distinct uncertainty sources -(i) external wind variability and (ii) Epistemic uncertainty arises from model, measurement, and stochastic uncertainties, which are sampled separately and then combined to generate the stochastic wind-induced loads. The uncertainties of the measurement and statistics are not considered in this study."

3.2.1 Uncertainty in material

- In addition to the given citations, I recommend the authors consider adding Lai, J. 2011. "A New Model for the Static Load Rating of Surface-Induction Hardened Bearings." *Evolution* 2:27– 32 and Lai, J., P. Ovize, H. Kuijpers, A. Bacchetto, and S. Ioannides. 2009. "Case Depth and Static Capacity of Surface Induction-Hardened Rings." *Journal of ASTM International* 6 (10): 1–16. http://doi.org/10.1520/JAI102630.

- Answer: The following text is added to include Lai works.

  "Lai et al. (2009) presented a model for plastic indentation, and they tested it on 42CrMo4 steel. Their model predicted that the contact pressure for causing plastic indentation of 10^{-4}D in the through-hard raceway is 4260 MPa, as well as good validation results. In the extended work, Lai (2011) predicted the contact pressure to be 4270 MPa."

3.2.3 Uncertainty in loads

- Lines 174-176: Here again, the focus on "seed number" still feels odd to me, as though this number has a much more important meaning than it really does. It seems much more straightforward to say that "Different realizations of the turbulence produce a Gaussian distribution of TI in the longitudinal wind component due to spatial coherence (Jonkman 2009)" and "Each simulation leads to a time series of distributions… Different simulations result in a series of…" Similarly in lines 193 to 197, different numbers simulations are considered.

- Answer: The text has been revised as follows:

“Different realizations of the turbulence, called "seed number," produce a Gaussian distribution of TI in the longitudinal wind component due to spatial coherence Jonkman (2009).”

4.2 Sensitivity analysis and Conclusions

- Lines 237-239: I’m not sure I understand why this discussion of raceway conformity is here compared to Section 4.2.3?
- Answer: The authors intended to emphasize the importance of raceway conformity; however, the comment is correct, and the text moved to section 4.2.3.

- Comparing sections 4.2.1 through 4.2.4 and Figures 5a-d, the discussion here feels like it is missing the major point: That changes in failure probability for groove conformity are 10^3 greater than those for ball diameter, pitch diameter, and contact angle. Isn’t this a very important part of the discussion, or am I missing something? That is, the Pf for a groove conformity of 0.545 is like 10-3 and rapidly decreases to 10-5 for 0.525 – a similar level for ball diameter, pitch diameter, and contact angle. Or maybe that’s the point of the vertical lines – that outside this range these conformities aren’t realistic? In the Abstract and Conclusions, is it then fair to compare that “Ball diameter and raceway conformity in this aspect have the highest contribution to the reliability of the blade bearing”? From the plots in 5a-d all with different y-scales, it is really hard for a reader to really see this. Why can’t all 4 be put on the same plot? It still feels to me that the effect of the groove conformity is far larger effect than the ball diameter, even within the range of vertical lines in Figure 5c.
- Answer: The vertical lines refer to using fine tolerance for ball diameter and calculating the groove conformity as described in section 4.2.3 with lower and higher tolerance in the ball diameter. The effect of groove conformity is dominant, and therefore, the related section in the abstract and conclusion is modified. Another figure is added to show all parameters together.

4.2.1 Ball diameter

- In this section, how are the differences in ball diameter applied? Are all balls equal in diameter and a range of diameters studied, or are these differences in diameter present in the bearing for a given simulation? I wonder what inspection methods might be applied by suppliers during assembly – I believe it is typical to make an effort to select balls of similar diameter.
- Answer: The balls assumed equal in diameter and a range of diameters according to ISO 2768 were studied. The text has been modified as below to clear the subject:

  “Although the balls are usually manufactured and sorted in a batch with fine tolerances in diameters, it is assumed that the ball diameter can change from fine to very coarse machining according to ISO 2768-1 ISO 2768-1 (1989). In every analysis, the balls’ diameters are assumed to be the same, and a range of diameters was studied. However,

the extreme tolerances are not realistic; they can help to observe the trend of changes in reliability. The assumption leads to a 0.15 to 1.5 mm variation in the ball diameter."

4.3 IEC wind conditions and 5 Conclusions

- In this section, I'm not sure a "fair" comparison is being made between results from say 15 seeds to many, many seeds. The design guideline suggests using load factors as described in Section 7.6.2.2 of IEC 61400-1. Although it is buried in the Appendix A of the design guideline, a safety factor of 1.35 and a partial load factor of 1.25 are applied to the average of the highest loads from each of the DLC turbulent seed time series to determine the maximum stress and static safety factor. Can the authors comment on this? That is, these load factors are purposefully applied knowing that only a few simulations aren't enough to represent the maximum loads and thus the maximum stress and risk of exceeding 4200 MPa. Greater importance is placed on this matter in the Conclusions, where it is stated "It is observed that by considering 15 seed numbers, as proposed in the standards and guidelines, the effect of different turbulence conditions cannot be achieved."
- Answer: A safety factor of 1.35 applied to DLC 1.1, which is a normal turbulence model. The studied DLC is 1.3, which is an extreme turbulence model; therefore, only Partial safety factors for loads of 1.35 according to Table 3 of IEC 61400-1 will apply. It should be that the IEC factors are intended to create a single conservative design load when only 15 turbulent seeds are simulated. Our probabilistic study, in contrast, seeks the full failure-probability distribution, so we use many seeds. The text is revised as follows:

  "It is observed that by considering 15 seed numbers, as proposed in the standards and guidelines, the distribution of the loads is not represented."

Table 3, Section 4.4 Wind sites and Conclusions

- I am both interested in and curious about the wind site characteristics of the real sites presented in this study compared to IEC classes. I don't think I saw it anywhere: what are Vave and TI for the real sites compared to the IEC classes? Are they appreciably different? If so, how? Is TI much higher? If they're appreciably different, then it should be no surprise that putting a turbine with a pitch bearing designed even for say IEC 1A is a bad idea. Isn't that an important part of the discussion? Without this information, is it really fair to say "The probability of failure for the selected onshore and offshore wind sites are mostly worse than those of IEC sites"?
- Answer: The average wind speed is the same in both wind sites and IEC classes, and it is mentioned in the descriptions of the DLC section. A new table has been added to present the extreme TIs for the real sites. They were different than IEC classes and both higher and lower. The TIs were higher for those two wind sites with a high probability of failure. The conclusion part is changed as below:

  "The probabilities of failure for the selected onshore and offshore wind sites are mostly worse than those of IEC sites, which indicates that IEC-designed turbines may result in

lower blade bearing reliability, and it shows the necessity of assessing the blade bearing in every wind site condition according to extreme turbulence wind."

References

- The citation for Harris, Rumbarger, and Butterfield 2009 leaves Butterfield's name incomplete. That is, it is only "C.P. B.".
- Answer: The incomplete name was corrected

- The doi for Stehly et al 2023 actually takes one to Harris, Rumbarger, and Butterfield 2009. Since I stumbled on this, I also recommend that this citation be updated to the Stehly 2024 edition at doi 10.2172/2479271.
- Answer: The reference doi was corrected and updated.

Minor grammatical comments:

- Line 14: Please ensure consistency in citation style throughout the manuscript, here "Stehly et al. (2023)", in line 17, "(Andreasaen et al., 2022)" (parenthesis w/ comma), and line 42 "[Harris and Kotzalas (2006)]" (square-bracketed w/out comma). Each citation is used in the same manner and thus should have the same style, which in Latex would be \citep for example.
- Answer: Citation was revised to ensure consistency throughout the manuscript.

- Line 27: Should be "...wind turbine and showed the..."
- Answer: The text in the section has been revised.

- Lines 28-29, 169, and 310: I recommend that "fatigue life" be used here instead of just simply "life" (4 places).
- Answer: The text was corrected.

- Line 40: Change "...can cause possibly stress..." to more simply "...can cause stress..." or "...can possibly cause stress...", although "can possibly" is redundant.
- Answer: The text was corrected.

- Line 42: Please add "also" to "can also lead to" to help distinguish the risk of static failure from surface-initiated fatigue failure.
- Answer: The text was corrected.

- Line 43: Single sentences rarely constitute a paragraph. Please combine with the previous paragraph. Additionally, this sentence refers to "main parameter" (singular), when multiple parameters (plural) are examined.
- Answer: The text was corrected.

- Line 85: I don't believe the acronym SF is used elsewhere in the manuscript. If so, please replace with variable S0.
- Answer: The SF changed to S_0.

- Line 86 and 90: MPa is used in 86 while megapascals is used in 90. Please define on first use.
- Answer: The text was corrected.

- Line 94: Please italicize parameters a and b in the text.
- Answer: The text was corrected.

- Line 96: The number of balls is listed previously as z, whereas in equation 7 the variable Z is used.
- Answer: The number of balls was changed to "*Z*" in the whole text.

- Line 98: Variables Dpw, z, and alpha are previously defined in Table 2, so do not need to be defined here.
- Answer: The sentence was removed from the text.

- Line 161: I'm not sure I understand "spherical roller bearings" and "ball diameter". Shouldn't this be roller diameter?
- Answer: The rolling diameter is correct, and the text has changed.

- Line 163: Should be "sensitivity".
- Answer: It was corrected to "sensitivity".

- Line 168: I think simply “turbulence” or “atmospheric turbulence” makes more sense than “turbulence of the wind turbine”. I suppose one could say “turbulence acting on the wind turbine” here.
- Answer: the text changed to “*turbulence acting on the wind turbine*”

- Lines 216 and 236: here this should be “IEC 61400-1”.
- Answer: The standard changed to IEC 61400-1.

- Line 239: Should be “0.5%”
- Answer: It changed to “*0.5%*”.

- Line 306: Should be “Pf”.
- Answer: It changed to “*Pf*”.

- Line 310: “if are used” should be simply “if used”.
- Answer: It changed to “*if used*”.