Response to referee #2 (Manuscript number: wes-2024-68):

We would like to truly thank the reviewer for the detailed and very relevant comments that helped us improve the work to a high extent.

The reviewer notes and comments are presented in black, and the responses are presented in blue.

Lifetime extension of wind turbines is a very important topic of high industrial relevance. Using a probabilistic approach is also very relevant. Therefore, the paper is of interest to be published. However, there are a number of unclear sections and missing explanations, see below. A major revision is recommended.

Detailed Comments:

Line 79

' One must consider that the material properties are calibrated such that the target reliability level of 3.7 ISO-2394 (2015) is reached': this is an annual reliability index? And why 3.7? which components are considered?

Here, only the blade is considered. Assuming a moderate consequence of failure, a target reliability index of 3.7 can be assumed based on ISO 2394. However, looking at your later comment, referring to Section 2.4.4, we agree that we must stay aligned with IEC 61400-1 basis for calibration of safety factors for the results of all probabilistic assessments to be comparable. We would like to thank you for your important comment. The modifications are added now to the text. Considerations of the offshore version (25years of design lifetime for the type) of SWT-3.2MW, which was missing previously, is also added.

Line 80

'the levels are not': unclear – reformulate

Reworded to 'magnitudes' to make it clearer.

Line 161

Which 'exponent'? wind shear?

Yes- changed to 'shear exponent' in the text for clarification.

Table 2

Is full (Weibull) distribution n of turbulence used as specified in IEC 61400-1:2019? And if not add a comment on the potential influence.

No, only the 90% quantile is used as in Ed.1. This is a good point. Thank you for your suggestion. Explanation added now as below:

'It shall be noted that group one is based on Edition 1 of the IEC standard and in case a full Lognormal or Weibull distribution are used (as in Editions 3 and 4, respectively), the results of the study differ (See (Mozafari et al., 2024) for differences). The following section includes the mathematical relations and procedures used in the study.'

Line 174

Rayleigh

Corrected. Thank you.

Line 174 + 178

Why use two different editions. Use ed 4 in order to obtain up-to-date comparisons?

The study shows the results based on Ed. 1 normal turbulence model (90% quantile as the representative value of turbulence in each wind speed bin). However, the difference that using Ed. 4 can make is shown in another research and the possible effect on the current study is discussed (see response to comment above regarding table 2).

Line 190

Explain equation

Explanations added now with a reference to IEC 61400-1 for further details.

Eq (4)

Missing m in eq?

Corrected now and fortunately it was only a mistake in the text not in the procedure. Thank you.

Eq (6)

k?

Explanation for 'k' is added now.

M to power m?

Clarified with addition cross sign and parentheses.

for composites the mean stress level is important. How is that accounted for?

1:

The mean stress level correction is not applied in calculations of DELs. However, since the aim of the work is to compare different approaches of obtaining DEL (all without correction), the effect on the results is low.

Line 213-215

Unclear – reformulate

Edited as:

'In Eq. (2), σ is the turbulence standard deviation (turbulence) of the free stream wind (ambient flow) considered as a random variable. In addition, μ_σ and σ_σ refer to the mean and standard deviation of the turbulence, respectively'

Eq (8)

How is lifetime damage obtained from 10-min damage?

By taking the weighted mean (by probabilities) of values of DEL_10min^m. Here the estimated value of (DEL_lifetime) was a mistake and has been omitted from the left side of the equation.

Line 218

'Probability of turbulence': which turbulence (ambient, effective, ...) is the probability linked to?

The word 'directional' is added for clarity.

Line 221

Conditional probabilities?

Yes! Reworded with 'conditional'. Thank you!

Line 235

Explain why 'log' is used

We refer to usage in equation 14 which is in form of log. A text is added.

Line 240

Describe what is 30-year return loads'. Is it 30-year extreme loads to account for the extreme loads being important due to the high Wohler exponent?

A reference is added to the relevant equations (and explanations) for return load in step 2.

Yes. The return load is used to extrapolate the tail of the distribution; description in the updated document:

1:

'The extrapolation is used to complete the tail of the DEL10min distribution to account for highest values that might change the weighted mean value (DEL_lifetime) if included. These values can have high effect due to the high fatigue exponent of the composite ((Mozafari et al., 2023b))'

Line 240

'Forming a database based on the distribution': unclear – explain which distribution. If the realizations follow the distribution function how is new information obtained?

Rewording is done now in step 2 with added reference to the corresponding explanations as below:

'2- Forming a database based on the distribution found in step 1 and extrapolating to 30-year return loads (Eq. 10 to 12)'

(previous reference in the next paragraph was a typo and now is corrected from 'Step 1' to 'Step 2')

Eq (10) +(11) +(12)

Explain the probabilistic assumption behind eq (10)

Explanation and reference added now as below as below:

*'Equation 10 is extracted from formula of probability of exceedance a threshold level (here the load which happens once every 30s) assuming a Poisson process for describing the peaks over threshold problem (for further information see (de Oliveira JT, 2013)). In the current case, the frequency of exceedance is 1/*T_LR'. *It has to be noted that Eq. 10 is correct when* T_LR *is relatively large (here, equal to the number of 10 minutes in 30 years).'*

Eq (1): Lr is not included in the right-hand side of the equation?

We assume you are referring to equation 10. A modification in Eq. 10 is made as follows:

T-> T_LR

In addition, explanations added as mentioned above describe how 'T_LR' is related to the LR.

Probabilities in eq (11) always between 0 and 1?

Yes, the 'log' sign is now omitted to make the formula correct (only text mistake and not the applications).

Explain reference times for the probabilities

Explanations added as mentioned above.

Are the loads obtained 'random point in time' loads or maximum loads with a certain reference period?

First, the maximum loads with a certain reference return period are defined, and the frequency of lower loads is derived accordingly.

1:

Above statement is added to the text for clarification (line 290 in the updated document).

Section 2.4.4

The Frandsen and IEC turbulence models together with partial safety factors are intended for deterministic design and not for probabilistic design and reliability analysis. This link should be included in the probabilistic formulations.

We very much appreciate your relevant and helpful comment.
Below paragraph is added to the end of section 2.4.4:
'It must be noted that the Frandsen and IEC turbulence models together with partial safety factors are intended for semi-deterministic design and not for probabilistic design and reliability analysis. However, since the partial safety factors are calibrated based on achieving certain reliability level (to which we are also setting the values for) at the end of the design lifetime, the results are comparable. Such comparisons are presented in the next section.'

Line 268

'Probability of failure at time t and can be stated as the probability of exceeding a certain level': this probability is the probability of failure at time t and not the accumulated probability of failure up to time t and also not the annual probability of failure?

Thank you for noting. To avoid misleading, the paragraph is reworded as below to stay as general as possible in terms of expressions and explanations:

'In Eq. 13, P_f (t) is the probability of failure at time t. Commonly, this problem is referred to with a function named limit state function (g (x, t)), and the safe region is where this function is positive. Thus, the probability of failure would be the'

Figure 2

The uncertainty of DEL is modelled by log(DELlifetime) ? add description of the uncertainty modelled by DELlifetime . How is this uncertainty quantified and does it include model uncertainty in estimating the stress ranges (obtained from a validation process)? This stochastic modelling assumes that strain gauge measurements are available for the fatigue detail considered?

We believe the reference to is figure '2' incorrect and thus, our answer is according to the general approach with assumption of reference to figure 6. The answer to all questions is 'yes'. An explanation is now added to the descriptions of figure 6 (lines 401– 404) as below:

'The uncertainty of log(DELlifetime) in the site is modelled by a frequentist approach (Maximum likelihood) based on observations in the measurements and includes all sources of uncertainty. However, in the case of the other two approaches, the uncertainty of this parameter is assessed based on bootstrapping and thus, it only includes epistemic uncertainty. The data in Fig. 6 are normalized by the converged mean of DEL_lifetime obtained above using site measurements.'

Eq (14)

Where does the time t enter in the limit state equation?

1:

Below statement is added before Eq. 14 for clarity:

'The time is omitted from Eq. 14 for simplicity with the assumption that all variables are referring to a certain time.'

Line 288

Explain how R=10 is used and why R=10 to account for mean stress level?

The SN curve is derived for that kind of loading; thus, the mean stress effect is already included. This explanation is added now to the same line for clarity:

'We consider R = 10 for fatigue properties (SN curve) of the composite Mikkelsen (2020). Although the variability of data is included as the CoV of such curve, a calibration is added at the end to set the mean value of material strength to a certain level at which target level of reliability is obtained at year 20.'

In addition, on the load side, we believe that in the flapwise direction, the ratio of mean to ultimate strength of the material is low compared to the relatively higher cycle range values making the effects of mean stress correction negligible in computation of DEL mean and standard deviation (as shown in [1]).

Table 3

How is the mean value calibrated?

As mentioned in the last paragraphs of introduction: '… the material properties are calibrated such that the target reliability level of 3.3 is reached after 25 years based on design class. ' A brief explanation is also added to the table 3 and the introduction as well as beginning of section 3.3 explaning that a factor is multiplied to the mean level of K.

Mean and standard deviation of log (DELlifetime) are missing in the table?

CoVs of all random variables are included now. However, the mean cannot be presented due to confidentiality.

Line 295

'Based on survival in the year before': not correct – reformulate

Rephrased to 'conditional on survival in the year before'

Figure 2

Add explanation of all symbols in the figure

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[1] Veers, P. S., "Fatigue Loading of Wind Turbines," Wind energy systems: Optimising design and construction for safe and reliable operation, Woodhead Publishing Ltd., Cambridge, UK, 2011.

1:

Added now.

Explanation of the symbols are added now to the figure

Figure 3

Could a Weibull distribution (as used in IEC 61400-1:20+29) fitted to the upper tail be as representative as the distributions considered?

Weibull is used in IEC 61400-1 for 'loads'. We do use the extreme value theory to model the tail of the 'DEL' data (Eq. 10 to 12). However, in general, we need to fit a full distribution as well since after all it is the weighted mean of DEL_10min that is of interest and not the tail. In the current case the Weibull distribution was not the best fit to DEL data.

Line 336

'Extrapolate the distribution to a 30-year return load': figure 3 shows random point in time observations of the turbulence level. Is this distribution used to estimate the load with a return period of 30 years? Or is the load with a return period of 30 years estimated using e.g. a peak-over-threshold technique considering the extreme, statistical independent loads observed during the measurement period (as in DLC 1.1 load extrapolation)? More explanation is needed.

Thank you for your comment. The latter is correct. More detailed explanations are now added in the methodology (section 2.4.3).

And how to use the load with a return period of 30 years for fatigue assessment?

More detailed explanations are now added in the methodology (section 2.4.3).

Line 357

The target annual reliability index in IEC 61400-1 Annex K is 3.3 (and not 3.7 as indicated in some DNV standards – assuming a ductile failure mode)

This is correct- We also keep the same level as the annex to get a fair comparison when using a reliability-based approach. However, the offshore version of the turbine being used here was neglected before and fortunately, the 25 years of lifetime is giving almost 3.3 in the current curves. Corrections are made now to aim for annual reliability index of 3.3 after 25 years.

Figure 7

As mentioned above the IEC and Frandsen models are intended for deterministic design with safety factors, not for reliability analyses. Recommendation: use the same approach for reliability analysis as in papers and reports related to fatigue of welded steel details in wind turbines.

Thank you again for the comment about the deterministic design versus reliability analyses.

Kindly see the below explanation:

1:

'It must be noted that the Frandsen and IEC turbulence models together with partial safety factors are intended for semi-deterministic design and not for probabilistic design and reliability analysis. However, since the partial safety factors are calibrated based on achieving certain reliability level (to which we are also setting the values for) at the end of the design lifetime, the results are comparable. Such comparisons are presented in the next section.'

Regarding the second comment:

Because this study focuses on blade-root moments, which are composite materials, it is not clear to us why we should use the same approach as those for fatigue of welded steel details.

Table 4

How is sensitivity defined?

As mentioned in the table description, they are '*importance rank of the random variables'* . Explanation and reference are added in the methodology now for more clarity (lines 322-324).

1: