

Dear Reviewer,

Thank you for taking the time and effort to review our article. We appreciate your valuable feedback and suggestions.

The authors present a very relevant and interesting analysis into quantifying the impact of low frequency cycles on fatigue damage.

While the subject is clearly presented, the results are not convincing. The following aspects are to be clarified or added before the article can be published.

1) The low cycle region of the SN curve for welded steel is conventionally taken with the slope $m = 3$ as given in Eurocode 3, DNV GL C 203 and IIW standards. The knee point is usually $2e6$ or higher cycles. Therefore the impact of LFFD would be limited to $m = 3$ or low slope portion of the bi-linear SN curve only and have a smaller contribution relative to the high slope segment of the SN curve. Reference Larsen, G C. Thomsen, K that you quote also states the impact with the small slope only has a 1% increase due to LFFD. In this light Figure 3 needs to be better explained as to how much impact to the Miner sum is obtained when including LFFD.

We understand the reviewer's perspective, and while there is definitely truth to their statement, our paper aims to provide a more generalized overview of the impact of LFFD. Meanwhile, we believe a similar conclusion can be derived from our current work. With just the minor consideration that most designs will keep loads low and therefore have the majority of the load cycles in the $m=5$ region, especially those associated with the first tower mode and waves.

As shown in Fig. 2. we covered very common S-N curves including the single-sloped S-N curves with slopes of 3, 4, and 5 which are usually used in the design to calculate DELs, and bi-linear S-N curves with the slopes of 3 and 5 which are the common curves for fatigue damage calculation. Note that even though $m=4$ is not linked to any design code, it is a commonly used compromise in design for DEL calculation. In Fig. 3, the full cycles before and after considering the low-frequency fatigue Dynamics (LFFD) are shown to illustrate the full cycles that are neglected in case of no LFFD consideration.

To show how much impact on the Miner sum is obtained when including LFFD, Fig. 5 is showing the increase in the damage before and after LFFD, by showing the ratio. There, we can see that after one year, for example, for $m=3, 4, \text{ or } 5$, how much percent increase we have on the damage, due to LFFD. In line with the reviewer's comment, the impact of LFFD for $m=3$ is almost negligible.

As explained in the paper, "It is noteworthy that the LFFD-factor for single gradient curves does not depend on the S-N curve intercept (a) but the slope (m) only."

Also mentioned in the paper: "The focus on the single gradient linear S-N curves is motivated by the desire to have a general LFFD-factor, independent of the fatigue spectra and multiplicative factors. On the other hand, bi-linear S-N curves will yield to a nongeneralizable LFFD-factor".

Therefore, concerning bi-linear curves, we showed in Figure 8 that the LFFD-factor is not fixed, as it is really site dependent, and based on the position of the stress ranges with respect to the knee point, the position of the knee point, and the Stress Concentration Factors (SCF), the LFFD-factor will change. Therefore, based on the place of the knee point, the contribution of the $m=3$ region and $m=5$ region can be different, but we cannot say that the higher slope region has no effect from the LFFD. While as the respected reviewer mentions, there might be sites with insignificant/significant LFFD-factor in the condition of using bi-linear curves. Indeed, when a higher SCF is used, the bigger fraction of the load spectrum moves into the $m=3$ region and the LFFD effect becomes more similar to $m=3$ (and therefore less). However, as most designs keep loads relatively low, the majority of loads will be in the $m=5$ region of the S-N curve (hence the common use of $m=5$ DELs in design). Note this might be counterintuitive, as with a larger SCF, the relative effect of LFFD becomes less.

Regarding the work of Larsen, G C. Thomsen, K, they studied a turbine of 150KW, and the insignificant contribution of LFFD is potentially due to the small size of the turbine. We think it is fair to assume that

conclusions of that generation need not necessarily translate to the current Multi-MW offshore wind turbines. The onshore example of a 2MW turbine from Pacheco et al. (2022) and an offshore example of a multi-MW turbine by Marsh et al. (2016), are more in line with our results, and they all showed that we might have a significant LFFD effect, but there can still be cases that the effect is negligible.

2) Figure 4: Can you show that the 0 load response of the strain sensors have no frequency components (that is noise)?

We suppose that the reviewer is concerned about the fact that cyclic noise in the strain measurements might change the result of LFFD. To show that the sensors have no frequency components under zero load conditions, we do not have a period of measurement with zero loading as the turbine is constantly under wind and wave load. So we cannot provide the reviewer with a plot that shows the Power Spectral Density (PSD) of sensors for a non-loaded period. But by looking at Fig. 4, we observe that the spectrum is dominated by the physical loads, and therefore, we do not doubt that the sensors might have unphysical frequency components.

3) If the stress cycle has a period of several hours or days, then the mean wind speed would have significant changes during that period and the conventional method of fatigue damage accumulation cannot be applied. How is fatigue damage accumulation to be made over different mean wind speeds considering LFFD? Does it require a non-stationary statistics process to compute this?

Although the low-frequency cycles are the results of gradual change in primarily the wind speed and wind direction, our methodology is data-based and the measured data is actually the result of all those loading variations over time. Thus, while the LFFD is a direct result of variation in the wind speed, we did not calculate LFFD based on an assumed wind speed distribution or any other probabilistic method that considers the wind speed variation in time. The only assumption we made for environmental conditions in the processing was that the yaw angle is fixed during 10min windows to calculate the fore-aft and side-side bending moments. This assumption was not made when calculating the damage based on one single strain sensor.

We acknowledge that because we made no assumptions about the wind speed and we merely used the measurement data, our results are site-specific. Therefore, based on the method used in our paper, if the measurement is from a hypothetical site with almost constant wind speed and direction, the LFFD effect would be negligible. However, the investigated sites are inside the most populated area for offshore wind (North Sea), so the results are representative of a sizable offshore capacity.

One should employ different techniques beyond the scope of this article if they want to connect LFFD to wind speed statistics. As far as we are aware, even selecting a Weibull distribution as a typical wind speed distribution does not give information about how wind speed and direction change over time. As a result, additional characteristics are required to demonstrate the randomness of the variation in wind speed over time. E.g. consider following the thought experiment, draw wind speed samples from a Weibull, but then sort them. While the data obtained still adheres to the Weibull distribution, only a very limited LFFD effect is present as just a single cycle in windspeed is experienced.

4) Usually for offshore structures, it is the welded joints that have the lowest fatigue life. It appears these are not considered at all in the present work and therefore is unclear if LFFD has any impact on design life. The stress at the welded joint is significantly increased due to local stress gradients in different directions. The impact of the stress gradients can be much higher than the increase in loading due to LFFD.

We agree with the reviewer that the critical points have higher damage. We usually calculate their damage from measured data by applying different SCF factors to the stress ranges from the sensors. Although we did not mention any specific weld on the substructure, the paper still covers all points. The majority of the paper is discussing the LFFD-factor with single-slope S-N curves. As mentioned in the article: "We chose three linear S-N curves with different slopes (3, 4, and 5) because these are normally used to calculate damage equivalent moments (DEM), as one of the applications of the desired LFFD-factor would be to consider the LFFD effect in the calculated DEM (refer to Appendix C). The focus on the single gradient linear S-N curves is motivated by the desire to have a general LFFD-factor, independent of the fatigue spectra and multiplicative factors.

As mentioned before, the share of LFFD on the damage on any point of the substructure would be the same, in the case of single-slope S-N curves. As shown in Eq. 1, the applied SCF is canceled out and the LFFD-factor would be fixed for different SCF and therefore different welds.

$$\text{LFFD_factor} = D_{\text{LT}}/D_{\text{ST}} = \frac{1/a \cdot \sum_{j=1}^{N_{\text{blocks}}} n_{\text{LT},j} (\text{SCF} \times \Delta\sigma_{\text{LT},j})^m}{1/a \cdot \sum_{j=1}^{N_{\text{blocks}}} n_{\text{ST},j} (\text{SCF} \times \Delta\sigma_{\text{ST},j})^m} = \frac{\sum_{j=1}^{N_{\text{blocks}}} n_{\text{LT},j} (\Delta\sigma_{\text{LT},j})^m}{\sum_{j=1}^{N_{\text{blocks}}} n_{\text{ST},j} (\Delta\sigma_{\text{ST},j})^m} \quad \text{Eq. 1}$$

Where (m, a) are the S-N curve slope and intercept, respectively, n_j is the number of cycles in the j-th load block, N_j are the cycles to failure at the load level $\Delta\sigma_j$, and D_{LT} , D_{ST} are the long-term and short-term fatigue damages.

On the other hand, bi-linear S-N curves will yield to a nongeneralizable LFFD-factor". Since often bi-linear S-N curves are applicable for welded joints, we included these in the paper too. As already mentioned above, the LFFD-factor cannot be generalized in this case and will depend on the SCF applied and the knee point of the required S-N curve.

Can an analysis be shown as to how much reduction in lifetime is present at a welded joint due to LFFD ?

As an example, if we consider the yearly damage in the critical welded joint as D, which is calculated by using a single slope S-N curve with $m=3$, a linear extrapolation of the lifetime without LFFD is $\frac{1}{D}$ years, while the lifetime considering LFFD would be $\frac{1}{D \times \text{LFFD_factor}}$ years. If we read the LFFD_factor for $m=3$ as 1.09, it means that the lifetime with LFFD is $\frac{1}{1.09} = 91\%$ of lifetime without LFFD, so almost 9% reduction in the lifetime is due to considering the LFFD effect in any weld on the substructure.

In case of bi-linear curve, as the reviewer correctly mentioned, it is not generalizable, since it depends on the position of the stress ranges with respect to the knee point, the position of the knee point, the exact geometry of the detail, and the SCF (as discussed in Section 4.3 of the paper). Therefore, although we showed that with the increase in the SCF, the LFFD effect decreases (for bi-linear S-N curves), yet, we did not claim that the results are generalizable for any specific weld.

5) In figure 5, is the $m = 5$ slope also at cycles less than $2e06$, that is, the minimum slope $m = 5$?

Yes, in Fig. 5, we assumed linear S-N curves. We did not consider the Haibach rule, as it will introduce a bi-linear curve.

If this is the case, the using Haibach rule, the higher slope of the SN curve would be 9 and would result in higher partial safety factors. Can you quantify what is the impact of the LFFD in the usage of partial safety factors (PSF) in the fatigue life assessment? Does the inclusion of uncertainty due to LFFD result in a significant increase in the PSFs? This assessment is needed to understand its impact in the design process.

We appreciate the question, while we need to ask the reviewer to clarify it to us. At this stage, we do not know what you would like us to undertake. Without more information from the design background, we are unable to establish any connection between the LFFD-factor and the Partial Safety Factors (PSF), since we do not know the precise justifications for the partial safety factors, how they were chosen throughout the design process, or what uncertainties they are intended to cover.

In this work, we quantified the effect of LFFD from a deterministic point of view for a data-driven method. We do not know how the LFFD would change the PSF in the design and as far as we know LFFD is not considered in design by default. It is worth highlighting that the LFFD-factor is applied on the damage while the PSF are applied on the stress ranges. So, translating LFFD-factor to a PSF should be done cautiously, as LFFD-factor is dependent on the used S-N curve.

We might be able to research the relationship between LFFD and PSF if the reviewer can provide some details regarding how the PSF have been defined. The authors believe that for including the LFFD effect in design, further discussion between designers and authors would be necessary. Therefore, if there are any recommendations, we would be happy to consider them.

6) Figure 6 is unclear. How is this damage presented to be considered over the lifetime of the structure as the mean wind speed is not a constant over a day or a week

The objective of Fig. 6 is to show the origin of LFFD. So we showed that for example for $m=3$, 90% of the damages are from 10min cycles, and the rest of the damage is due to LFFD (that majority of them happen as daily cycles). As already answered in question 3, we did not actively use wind speed in the calculation of damage,

although by having the measured strains, we included the gradual change in the mean wind speed and direction, indirectly.

and therefore it is unclear how the lifetime of the structure can be evaluated without actually measuring the damage until failure.

We showed in Fig. 5, that these LFFD-factors converge to a fixed value and are constant for the lifetime of the wind turbine if we have enough measurement (one year). So by calculating the LFFD-factor from one year of measurement, we can apply the factor directly to the final damage without LFFD (10min-based) and have the final damage with LFFD.

Clarifications to the above are required before the article can be accepted.

We appreciate the valuable comments of the respected reviewer, and we hope that our answers are clear.