Stress-based assessment of the lifetime extension for wind turbines

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Abstract. To assess of the lifetime extension (LTE) of wind turbines, the remaining fatigue budget of different turbine components is predicted. The state-of-the-art approach to predicting the LTE uses a comparison of damage-equivalent loads (DEL) under site conditions and design conditions. The DEL-based approach entails several simplifications, i.e., neglecting the load direction and the mean load. An analysis based on stresses can mitigate the above simplifications. In this work, the LTE of a 1.5 MW turbine is assessed on the basis of the DEL-based approach and compared to that of the stress-based approach. The assessment focuses on components which are critical for the lifetime, i.e., the blade bolts, the blade root laminate, and the main shaft. Generic models of these components are implemented to calculate stress histories for the stress-based assessment. In addition, the main assumptions that may have to be based on estimates are outlined. The analysis shows that, depending on the component, the results of the stress-based approach may differ notably from those of the DEL-based approach. The stress-based approach can be used to improve model fidelity in LTE assessments.

1. Introduction

Wind turbine operators are faced with a decision as to how to deal with their wind turbines once their certified lifetime has been reached. Common options are: decommissioning, repowering, or a lifetime extension (LTE) of the turbine. Both technical and economic aspects have to be taken into account when making this decision. The decision of repowering versus LTE not only depends on possible subsidies and legal restrictions, but also the extent to which the lifetime can be extended with manageable technical risk.

Older turbines were designed according to general wind conditions that were reflected by wind turbine classes according to IEC [1], or by local standards such as DIBt [2] which used even broader classifications. Classified turbines were placed at sites at which the wind conditions have been less severe than assumed during design. While these turbines have been exposed to lower loads, their energy yield has also been lower.

Ziegler et al. [3], Piel et al. [4], and Rubert et al. [5] investigated the economic options regarding end-of-life decisions for wind turbines. Rosemeier and Saathoff [6] assessed a rotor blade extension retrofit along with an LTE scenario to increase energy yield. Regarding the technical feasibility, Holzmüller [7] showed that an LTE assessment can often reveal more than 10 years of possible LTE. The state-of-the-art approach to the LTE assessment entails a comparison of damage-equivalent loads (DEL) for the design and site conditions as laid out in
the guidelines from BWE [8] and DNV GL [9]. Another approach is the use of visual inspections [10]. Finally, structural monitoring can assist the LTE analysis as shown by Loreaux and Brühwiler [11] and discussed by Thöns et al. [12]. An approach based on stress time series was chosen by Ziegler and Muskulus [13] in the LTE analysis of offshore substructures for wind turbines. To our knowledge, generic structural component models have not yet been investigated as a means of calculating the remaining useful life.

In the present study, a state-of-the-art DEL-based approach for the calculation of the remaining fatigue budget is compared to a more detailed stress-based approach. The use case investigated for this study is a 1.5 MW Südwind S70 wind turbine. The turbine was installed in 2003 in the Bremervörde-Iselelsheim wind farm located in Northern Germany [14].

The objectives of the comparison are to assess whether a stress-based approach can be used to increase the reliability of the results. To calculate stresses, generic structural models are set up for the most critical components of the turbine.

2. Methods
2.1. Use case turbine and site
The probability density distributions for the design wind conditions and at the site at Bremervörde-Iselelsheim are shown in Fig. 1. The turbulence intensity on site was found to be close to the design assumptions. The Südwind S70 is a pitch-controlled wind turbine. Other main characteristics of the wind turbine are summarized in Table 1.

![Figure 1. Probability density of wind speed of design condition and at actual site.](image)

| Parameter               | Symbol | Value | Unit  |
|-------------------------|--------|-------|-------|
| Wind turbine class      | –      | II    | –     |
| Turbulence category     | –      | A     | –     |
| Rotor radius            | $R$    | 35    | m     |
| Hub height              | $h$    | 65    | m     |
| Cut-in wind speed       | $v_{in}$ | 3.5  | m s$^{-1}$ |
| Cut-out wind speed      | $v_{out}$ | 25.0 | m s$^{-1}$ |
| Cut-in rotor speed      | $\Omega_{in}$ | 10.5 | min$^{-1}$ |
| Rated rotor speed       | $\Omega_r$ | 19.0 | min$^{-1}$ |
| Overspeed limit         | $\Omega_4$ | 20.9 | min$^{-1}$ |
| Design lifetime         | $T_d$  | 20    | years |

Table 1. Design parameters of 1.5 MW turbine. [15]
2.2. Load simulation
The LTE assessment of the turbine was performed by means of a relative comparison of site-specific loads to design loads. This assessment used the loads from an aeroelastic load simulation. To this end, the use case turbine was modeled in the multibody dynamics simulation software MSC ADAMS (Automated Dynamic Analysis of Mechanical Systems) [16]. For the fatigue limit state analysis, design load case (DLC) 1.2 according to IEC 61400-1 [17] was considered.

2.3. Components under investigation and generic models
The transfer functions that convert moments to stresses were obtained with generic component models. The generic models were set up for the critical components of the turbine, i.e., the blade bolts, the blade root laminate, and the main shaft (Fig. 2). The components were chosen because they usually have the shortest calculated remaining useful life out of all structural turbine components. The components under investigation were part of the rotating system of the turbine. The fatigue damage was determined to a large extent by the number of cycles of the gravity loads as the components were rotated through the gravitational force field. For most turbine types, the site conditions do not have a big effect on the number of rotations, hence the gravity loads on site do not differ greatly from the design loads. Since these components are often the limiting factor for the lifetime extension of the turbine, an improvement of the method to determine the remaining useful life may be an improvement of the overall lifetime extension assessment.

The generic models consisted of geometric and material properties that are explained in the following sections.

2.4. Damage-equivalent-load-based approach
In the simple state-of-the-art DEL-based approach, the load histories are rainflow-counted [18] to obtain Markov matrices (Fig. 3). The load set is reduced to the post-processed moments about the main axes of the component in cartesian coordinate systems. The Goodman correction for
the mean moment influence is usually neglected since it requires additional simulation of the ultimate DLCs to estimate ultimate moments. The DEL amplitude for each component with respect to each main axis of the coordinate system is obtained according to Hayman [19] as

\[ M_{a_{eq}} = \left( \frac{\sum_i (n_i \cdot (M_i^a)^m)}{N_{eq}} \right)^{\frac{1}{m}}, \]

where \( M_i^a \) denotes the moment amplitude of the \( i^{th} \) step of the load spectra, \( m \) the negative inverse S-N curve exponent, and \( N_{eq} \) the number of equivalent cycles to failure.

Assuming a linear relationship between moments and stresses, a relative comparison between the DEL under site conditions \( M_{eq,s} \) and under design conditions \( M_{eq,d} \) is possible. With (1), the relative fatigue damage can then be obtained as

\[ D_{LTE} = \frac{D^s}{D^d} = \left( \frac{M_{eq,s}^{a,s}}{M_{eq,d}^{a,d}} \right)^m = \frac{\sum_i (n_i^s \cdot (M_i^{a,s})^m)}{\sum_i (n_i^d \cdot (M_i^{a,d})^m)}. \]

Figure 3. Calculation workflow for the stress-based approach and the DEL-based approach.
The fatigue budget or remaining lifetime is then obtained with

\[ T_{LTE} = T_d \left( \frac{1}{D_{LTE}} - 1 \right) \]

where \( T_d \) denotes the design life of the turbine.

2.5. Stress-based approach

With the help of transfer functions, the moment histories are directly transferred into stress histories. The stress histories are calculated taking into account the directions in which the moments act. For all components, the stress calculation is based on axial stresses resulting from the bending moments. After rainflow-counting the stress histories, Markov matrices are generated around the circumference of the component under investigation. Assuming a symmetric constant life diagram [20], the allowable cycle number to failure \( N_i \), with a mean stress \( \sigma_{m,i} \), and a stress amplitude \( \sigma_{a,i} \), is derived from

\[ N_i = \left( \frac{R^i - M_\sigma |\sigma_{m,i}|}{|\sigma_{a,i}|} \right)^m, \]

where \( R^i \) denotes the tensile strength and \( M_\sigma \) denotes the mean stress sensitivity of the material of the component. By analogy with (2), the relative fatigue damage is obtained as

\[ D_{LTE} = \frac{D^s}{D^d} = \frac{\sum_i n^s_i \left( n^s_i \cdot \left( \frac{1}{R^i - M_\sigma |\sigma_{m,i}|} \right)^m \right)}{\sum_i n^d_i \left( n^d_i \cdot \left( \frac{1}{R^i - M_\sigma |\sigma_{m,i}|} \right)^m \right)} \]

It should be noted that geometric details such as cross sections or absolute values for the fatigue resistances of the materials have no effect on the outcome of the results. As the lifetime of the components is calculated by a relative comparison of the damage under design and site conditions, such factors cancel each other out, as can be taken from (5).

For the blade root, the laminate around the bushing was investigated (Fig. 2a). To this end, a one-dimensional bar model as proposed by Tsai et al. [21] calculated the shear stress in the matrix. A tensile strength of \( R^t = 45 \text{ MPa} \) of the matrix material, i.e., epoxy resin, was assumed.

For the bolts, the axial stresses resulting from the flap-wise and lead-lag blade root bending moments were considered. The stresses were calculated for each of the 54 bolts individually. The strength category was assumed to be 10.9. In accordance with common standards [22, 23], the mean stress sensitivity was assumed to be \( M_\sigma = 0 \).

For the main shaft, the bending stresses were evaluated in steps of 1° around the circumference of the cross section. Both bending moments in the directions lateral to the rotor axis were considered. The mean stress sensitivity \( M_\sigma \) was calculated for the shaft as a steel component according to [24]:

\[ M_\sigma = 0.35 \cdot 10^{-3} \cdot \frac{R^t}{\text{MPa}} - 0.1 \]

A common material for steel shafts is 34CrNiMo6 with a nominal tensile strength of \( R^t_n = 880 \text{ MPa} \). To determine the effective tensile strength \( R^t \), the technological size factor has to be determined. The diameter of the shaft at the critical cross section, which is often located at the front bearing seat, can be assumed to be \( d_o = 600 \text{ mm} \) (Fig. 2c). When the resulting technological size factor was taken into account, the effective tensile strength of the component was \( R^t = 812.8 \text{ MPa} \).
3. Results
Equation (3) was used to determine the remaining fatigue budget of the components using the two analytical methods. The results for the stress-based approach ($T_{\sigma}^{LTE}$) and for the DEL-based approach ($T_{\text{DEL}}^{LTE}$) are shown in Fig. 4. Table 2 summarizes the results for each component.

Table 2. Remaining fatigue budget of components.

| Turbine component       | $m$ | $T_{\text{DEL}}^{LTE}$ in year | $T_{\sigma}^{LTE}$ in year | $\Delta$ in % |
|-------------------------|-----|-------------------------------|---------------------------|--------------|
| Blade bolts             | 4   | 3.8                           | 4.7                       | +23.7        |
| Main shaft              | 4   | 8.8                           | 8.5                       | −3.4         |
| Blade root laminate     | 10  | 12.5                          | 22.9                      | +183.2       |
| Hub                     | 7   | $> 20.0$                      |                           | −            |
| Main frame              | 7   | $> 20.0$                      |                           | −            |
| Tower top               | 4   | $> 20.0$                      |                           | −            |
| Foundation              | 4   | $> 20.0$                      |                           | −            |

Considering the remaining budget of the laminate, the stress-based approach ($T_{\sigma}^{LTE}$) reveals far more optimistic results than the DEL-based approach ($T_{\text{DEL}}^{LTE}$). The stress-based approach estimates the lifetime to be 183.2% longer than that of the DEL-based approach.

The remaining budget of the blade bolt shows that the stress-based approach ($T_{\sigma}^{LTE}$) yields more optimistic results than the simplistic DEL-based approach ($T_{\text{DEL}}^{LTE}$). Using the stress-based approach, the calculated remaining useful life of the blade bolts is 23.7% longer than the value obtained with the DEL-based approach. As the mean stress sensitivity is zero, the difference arises solely from the directionality of the loads. The fatigue damage accumulates the fastest on those bolts that are most highly stressed, i.e., the pair of bolts in the direction of the largest bending moment. Which bolts are most highly loaded depends on the current aerodynamic loading on the blade, and the pitch angle. When using the DEL-based approach, all loads are projected onto a single pair of bolts, and the spread of the loading around the circumference is not considered.
For the main shaft, the calculated fatigue budgets obtained with the two methods are in good agreement, while the stress-based approach yields slightly more conservative results. The load spectrum of the main shaft is very similar to that of the DEL, and the mean stress sensitivity is of minor importance. Hence, the variation in damage around the circumference of the component is small when compared to the blade root bolts and laminate.

4. Discussion
The stress-based approach facilitates the consideration of the load direction over time as well as the mean stress sensitivity. The method yields results very similar to those obtained with the DEL-based approach when the loading can be characterized as deterministic rather than stochastic, as can be observed on the main shaft. The latter is easily explained by the fact that the actual load spectrum closely resembles a constant-amplitude spectrum. For the blade root bolts and laminate, the stochastic aerodynamic loading and the blade pitch lead to a significant variation in the location that is stressed the most. Hence, the fatigue damage is actually spread out around the circumference of the respective cross section, which is reflected in the stress-based approach. Conversely, the DEL-based approach projects the loads and thus the maximum stress onto a single location, leading to overestimated fatigue damage in that location in these cases. Since the components are evaluated by means of the maximum damage at any location, the estimated lifetime can be regarded as conservative for these components. For components subjected mainly to deterministic gravity loads, e.g., the main shaft, the stress-based approach does not offer significant benefit over the DEL-based approach.

When using the generic models, some assumptions and simplifications need to be made. The mean stress sensitivity of the components has to be obtained from relevant standards, guidelines or experiments. As is the case for the main shaft of the use case turbine, the application of a design guideline requires some knowledge about the geometry and material of the component. However, the results show that the uncertainty in determining the mean stress sensitivity is of little practical importance for this component. The applicability of the stress-based method thus depends on the ability of the user to obtain information of a quality that allows these assumptions to be made.

We suggest that the stress-based approach will prove useful when applied to other main structural components of the wind turbine as well. For instance, the tower and foundation are loaded by stochastic loads and the loading changes direction when wind direction and yaw angles are taken into account. Hence, the DEL-approach will show a similar disparity to the stress-based approach for the blade root bolts and laminate, and yield conservative results. In addition, to avoid excessively conservative assessments, the stress-based approach may also be used as a means of uncertainty analysis as a complement to the conventional DEL-based approach. The deviations between the results of the two approaches compared can be quantified for many models, and patterns may be found. In this case, an uncertainty or risk number can be derived for the results of the DEL-based approach. This additional information could help to determine the actions taken in the field, such as the maintenance plan, to ensure the safe continued operation of the turbine with a reasonable amount of effort.

5. Conclusions
The stress-based approach was conducted for three components critical for the LTE of the wind turbine, i.e., the blade root laminate, the blade bolts, and the main shaft. It was shown that generic models can be set up without detailed knowledge of the particular component, and the key assumptions were highlighted. Depending on the component analyzed, the results of the stress-based approach can be in agreement with the results of the DEL-based approach or differ significantly from the latter. In cases where the loading on the turbine is predominantly stochastic in nature, i.e., determined by the aerodynamics and controls, the stress-based
approach can be expected to yield more optimistic results than the DEL-based approach. In cases where the loading is predominantly deterministic in nature, i.e., determined by gravity loads, the two approaches are in good agreement with each other. The difference described is down to the fact that the stress-based approach takes account of the loading direction as a function of time and the resulting variation of the location with the greatest stress. It can be concluded that the stress-based approach thus yields more exact results, given that the objective of performing a relative comparison of loads is maintained. The stress-based approach is also applicable to turbine components other than those investigated. It can replace the conventional approach to decrease the uncertainty, or be used as a supplement by giving additional information about the uncertainty in the results.

**Supplemental material**

The data used for the figures are available at https://doi.org/10.5281/zenodo.3895649 [25].

**Acknowledgments**

We acknowledge the support of P. E. Concepts GmbH.

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