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Directional fatigue accumulation in wind turbine steel towers

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Abstract. Wind turbines are subject to fatigue loads during their entire lifetime of 20-25 years. A main source of the fatigue loads is the turbulence, which varies with direction due to the surrounding terrain and wake effects inside wind farms. A common approach to assess wind turbine fatigue loads is to simulate the structural response based on a site-specific wind climate, described in the IEC 61400-1 standard. To reduce the amount of needed simulations the standard introduces an “effective turbulence” approximation that integrates directional variation of turbulence, resulting in an omnidirectional value. This method implicitly assumes that all wind turbine components face the wind directly, which is a conservative simplification for components below the yaw bearing.

Using wind measurements from almost one hundred international sites, we show how this simplification leads to over-predictions of tower fatigue loads of up to 23% compared to directional fatigue accumulation. Three simplified models are developed to approximate the directional fatigue damage using various levels of information ranging from only the wind rose to full sector wise simulations. The first two recommended models may be used as proxies to decide if sector wise simulations are feasible, and the last model accurately predicts the full directional fatigue damage. The simplified models can contribute to a reduced material consumption of wind turbine towers, thereby reducing the cost of wind energy.

1. Introduction

Wind turbines experience fatigue loads during their lifetime of 20-25 years due to the fluctuating excitation from the turbulent wind field. An important task for engineers is therefore to verify that a given wind turbine design can withstand the site-specific fatigue loads in the entire design lifetime. For this purpose the design standard IEC 61400-1 ed. 3 [1] describes how a site-specific wind climate can be evaluated in terms of the windspeed distribution, windspeed standard deviation (turbulence), vertical windspeed variation (wind shear), air density, and flow inclination. Together, these parameters form the basis for simulating structural loads using aero-elastic codes, to check whether the site-specific fatigue loads are within the design loads of the considered wind turbine.

It is computationally expensive to simulate wind turbine loads, which makes it important to ensure that a site-specific wind climate is specified such that no excessive simulations are required. In the IEC standard¹ [1] this is addressed by adopting the “effective turbulence” approximation, first introduced by

¹ The design standard IEC 61400-1 ed. 3 is referred to as “IEC standard” in the remainder of the paper.



Frandsen [2], which integrates out the directional variation of the turbulence. The accuracy of the effective turbulence is beyond the scope of this paper but has been investigated in e.g. [3] using wind data from two existing wind farms, which showed good agreement between fatigue loads obtained by sector-wise and omnidirectional simulations. This was further confirmed in [4] where it was shown that combining the effective turbulence with bi-linear material fatigue strength models leads to accurate predictions of fatigue loads. However, neither [3] nor [4] investigated the consequence of neglecting directional variation of turbulence, which directly implies that fatigue damage is accumulated at the same point on a given component, regardless of the varying wind direction. This was shortly discussed in [5] stating that the rule of thumb in the industry was that neglecting directions overpredicted tower fatigue damage with 10%. As potential consequence wind turbine towers may have been over-designed for more than a decade, thereby increasing the cost of wind energy.

The aim of this work is to quantify the consequence of not taking wind direction into account when accumulating fatigue damage in a steel wind turbine tower. A modern multi-megawatt turbine is considered and wind measurements from 99 international sites are used to define real characteristic site-specific wind climates. The large number of sites is subsequently used to develop three simple models that approximate the directional fatigue damage based on different levels of information ranging from only the wind rose to full directional simulations. Together, these models form the basis for improved decision support when it is unclear if sector-wise simulations are worth the increased investment, compared to the expected material reduction by doing directional fatigue accumulation in the tower.

2. Wind measurements and site-specific wind climates

The site-specific wind climates used in this study are based on high quality 10 min. measurements of mean windspeed, mean wind direction, turbulence, and wind shear from 99 international sites. At all sites the measurements span exactly one year to account for seasonal variation and the surrounding terrain represent varying types of orography with and without nearby forest. Neither air density nor flow inclination has been measured and for consistency these parameters are fixed at all sites as 1.225 kg/m^3 and 0.0° , respectively. This is a simplification but these two parameters have insignificant influence on wind turbine tower fatigue loads [6,7]. This setup was also used in [6] where a more detailed description of the sites and the measurements is presented.

To determine the characteristic site-specific wind climates according to the IEC standard [1], the wind measurements are grouped into windspeed bins of 1 m/s and 12 sectors (θ) covering 30° each. The characteristic turbulence ($\sigma_{U,c}$) is determined as the 90% quantile according to Eq. (1) using the windspeed and sector-wise turbulence mean value ($\sigma_{U,\mu}$) and standard deviation ($\sigma_{U,\sigma}$).

$$\sigma_{U,c}(U, \theta) = \sigma_{U,\mu}(U, \theta) + 1.28\sigma_{U,\sigma}(U, \theta) \quad (1)$$

The characteristic wind shear (α_c) is derived from the wind measurements as the mean value, and the windspeed distribution and sector frequencies are taken directly from the measurements.

To reflect that most modern turbines are installed in wind farms, artificial wake added turbulence has been considered. Neighbouring wind turbines are assumed located 5 rotor diameters (RD) up and downwind in the main wind direction, and 3 RD perpendicular to that. The wake added turbulence is modelled by Eq. (2) according to [1], where C_T is the thrust coefficient. Note that the wakes are assumed to cover an entire sector independent of the distance to the assumed neighbouring turbine. This simplification is not unrealistic as the main purpose of introducing the wakes is to have a directional variation of the turbulence that reflects modern utility turbines.

$$\sigma_{U,T}(U, \theta) = \sqrt{\frac{U^2}{\left(1.5 + \frac{0.8RD}{\sqrt{C_T(U)}}\right)} + \sigma_{U,c}(U, \theta)^2} \quad (2)$$

Finally, the characteristic turbulence values including wake contributions are used to calculate the damage equivalent effective turbulence according to Eq. (3), taken from [1], where m is the “Wöhler exponent” related to material fatigue strength.

$$\sigma_{U,\text{eff}}(U, m) = \left(\int_0^{2\pi} \sigma_U^m(U, \theta) f_\theta(\theta|U) d\theta \right)^{1/m} \quad (3)$$

In table 1 the characteristic wind climate parameters are summarized.

Table 1. Characteristic wind climate parameters used for site-specific fatigue assessment.

Description	Measured	Characteristic value	Notation
Wind direction	Yes	Sector-wise frequency in 30° bins	f_θ
Windspeed	Yes	Windspeed frequency in 1m/s bins	f_U
Turbulence	Yes*	Windspeed and sector dependent 90% quantile including wake contribution	$\sigma_{U,T}$
Wind shear	Yes	Mean value	α_c
Air density	No	Fixed value (1.225 kg/m ³)	ρ_c
Flow inclination	No	Fixed value (0.0°)	φ_c

*only the ambient turbulence is measured.

3. Wind turbine simulation and fatigue assessment method

Fatigue damage is assessed by aero-elastic simulations of the 5MW reference wind turbine by NREL [8] during normal operation (design load case 1.2 in [1]). The turbine is simulated using FAST [9] and the turbulent wind fields are generated by TurbSIM [10], using 20 seeds for each combination of characteristic wind climate parameters.

The material fatigue strength of the steel tower is modelled by a linear SN -curve with a Wöhler exponent of 4, which relates a given stress range to the number of cycles to failure. To accumulate fatigue damage from varying stress ranges, linear summation by Miner’s rule [1] is performed based on Rainflow counting [11] of the output response from the simulations. This allows the fatigue damage to be expressed in terms of a “damage equivalent load” (DEL) as defined in Eq. (4), where N_{eq} is an equivalent number of cycles set to 10^7 and n_i is the number of cycles with moment range ΔM_i .

$$\text{DEL} = \left(\frac{1}{N_{\text{eq}}} \sum_i n_i \Delta M_i^m \right)^{1/m} \quad (4)$$

The combined equivalent fatigue load of the tower (F_{eq}) from different windspeeds and directions can be combined according to Eq. (5), where U_{in} and U_{out} represent the cut-in and cut-out windspeed of the turbine, respectively.

$$F_{\text{eq}}(f_\theta, f_U, U, \sigma_U, \alpha, \rho, \varphi, m) = \left(\int_0^{2\pi} f_\theta(\theta) \int_{U_{\text{in}}}^{U_{\text{out}}} f_U(U|\theta) \text{DEL}(U, \sigma_U, \alpha, \rho, \varphi)^m d\theta dU \right)^{1/m} \quad (5)$$

4. Quantification of the consequence of neglecting direction

This section quantifies the consequence of not explicitly accounting for wind direction in fatigue accumulation of wind turbine towers. First, the method used to fully account for direction directly in the time domain is presented followed by a short discussion of the results.

To assess the directional fatigue damage the tower cross-section is divided into 36 equidistant points as shown in figure 1. For the sake of simplicity, the cross-section is assumed to be circular symmetric, hence, no door is considered. This is not expected to influence the conclusion of this paper, as the effect of the door is handled by local re-enforcements whereas the scope of this paper is the entire tower.

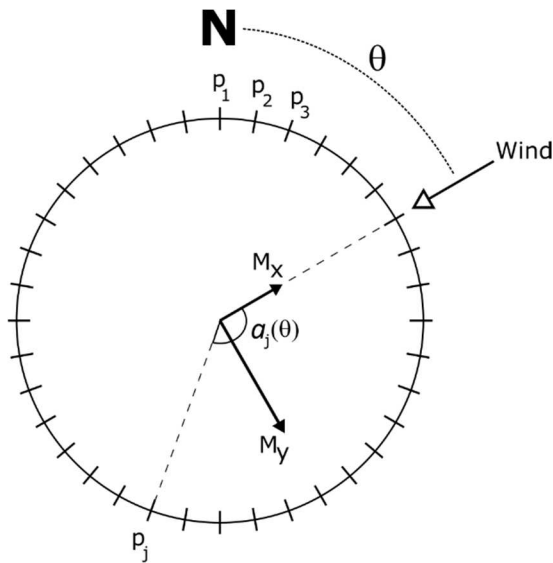


Figure 1: Sketch of the tower bottom cross-section (no door is considered).

For each simulated time step (t_s) the projected moment at each of the 36 points is evaluated by Eq. (6) where M_x is the tower side-side moment, M_y is the tower fore-aft moment, M_{p_j} is the projected moment at point p_j , and a_j is the angle between the wind direction and point p_j .

$$M_{p_j}(t_s, \theta) = M_x(t_s) \sin(a_j(\theta)) + M_y(t_s) \cos(a_j(\theta)) \quad (6)$$

Based on the projected moment time series the fatigue damage in the tower is evaluated at each point (F_{eq,p_j}) as outlined in Eq. (7).

$$F_{eq,p_j}(f_\theta, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, m, \theta) = \left(\int_0^{2\pi} f_\theta(\theta) \int_{U_{in}}^{U_{out}} f_U(U|\theta) \text{DEL}_{p_j}(U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta)^m d\theta dU \right)^{1/m} \quad (7)$$

The point-wise damage equivalent load for each wind climate combination (DEL_{p_j}) is given by Eq. (8) where $\Delta M_{p_j,i}$ are the projected point-wise moment ranges.

$$\text{DEL}_{p_j}(U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta) = \left(\frac{1}{N_{eq}} \sum_i n_i \Delta M_{p_j,i}^m \right)^{1/m} \quad (8)$$

The critical point with the maximum combined fatigue damage ($F_{eq,p_{max}}$) is then assumed representative for the tower design, and the consequence of not taking direction into account is quantified as the fatigue damage ratio defined by Eq. (9).

$$\Delta F_{\text{eq,eff}} = \frac{F_{\text{eq,eff},y}(f_U, U, \sigma_{U,\text{eff}}, \alpha_c, \rho_c, \varphi_c, m)}{F_{\text{eq,pmax}}(f_\theta, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, m, \theta)} \quad (9)$$

Where $F_{\text{eq,eff},y}$ is the site-specific tower fore-aft fatigue damage found by omnidirectional simulations, see Eq. (10).

$$F_{\text{eq,eff},y}(f_U, U, \sigma_{U,\text{eff}}, \alpha_c, \rho_c, \varphi_c, m) = \left(\int_{U_{\text{in}}}^{U_{\text{out}}} f_U(U) \text{DEL}_{\text{eff},y}(U, \sigma_{U,\text{eff}}, \alpha_c, \rho_c, \varphi_c)^m d\theta dU \right)^{1/m} \quad (10)$$

The damage equivalent load from the effective turbulence simulations at a given windspeed, $\text{DEL}_{\text{eff},y}$, is defined by Eq. (11) where $\Delta M_{\text{eff},y,i}$ is found by Rainflow counting the fore-aft moment response.

$$\text{DEL}_{\text{eff},y}(U, \sigma_{U,\text{eff}}, \alpha_c, \rho_c, \varphi_c) = \left(\frac{1}{N_{\text{eq}}} \sum_i n_i \Delta M_{\text{eff},y,i}^m \right)^{1/m} \quad (11)$$

Figure 2 shows the results of Eq. (9) across all 99 sites, where the average overprediction across the sites is 14% with a maximum of up to 23%. This documents that neglecting directional fatigue accumulation leads to unnecessary steel consumption at most real sites, but there is a significant variation from site to site. Since full sector-wise calculations require at least 12 times more simulations this motivates the need for simple approximate methods to assess the site specific overprediction, to provide decision support whether this increased computational cost is justified. Furthermore, the full method presented here requires postprocessing of the results from the aero-elastic simulations directly in the time domain (besides cycle counting), thereby introducing an extra step in the workflow from wind climate to wind turbine loads. To alleviate this effort, an accurate method is proposed that use traditional fore-aft and side-side fatigue loads from the sector-wise simulations, without losing any significant accuracy compared to the full method presented in this section.

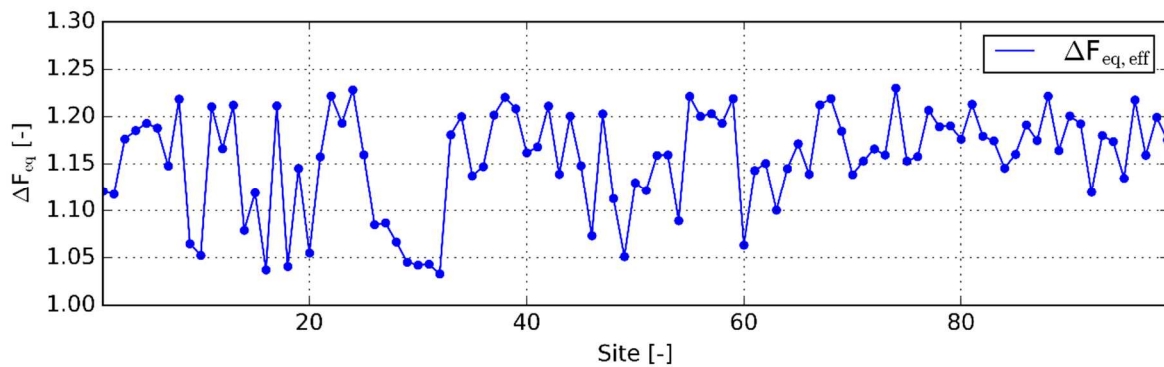


Figure 2: Overestimation of damage equivalent loads across all sites by doing omnidirectional fatigue assessment compared to explicitly accounting for direction.

5. Simplified framework to account for directional dependence of tower loads

In this section three models are developed to approximate the results of the full directional approach described in the previous section. Each model from one to three requires increased information and computational investment ranging from using the wind rose only to using sector-wise simulations.

5.1. Model 1: Spread of wind rose

A straightforward explanation for the large deviation of the overprediction of fatigue loads seen in figure 2 is the site-specific wind roses. When the wind is more unidirectional the overprediction is less

significant. This is illustrated in figure 3 where $F_{eq,eff}$ is plotted as function of the site-specific max frequency of the wind across the 12 sectors ($f_{\theta,max}$) for all 99 sites. Note that $f_{\theta,max}$ is a very simple metric to describe the spread of the wind rose and it contains no information of the windspeed or turbulence distribution in the sectors which are both governing factors for the fatigue damage. This results in significant scatter in the datapoints, but the tendency that lower overpredictions follow with higher $f_{\theta,max}$ is clear.

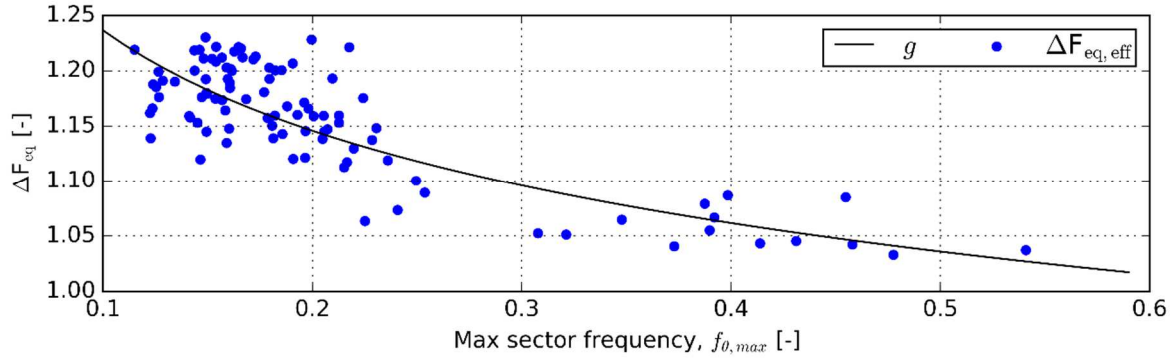


Figure 3: Overprediction of fatigue damage by not accounting for direction shown as function of the frequency of wind in the main direction.

By fitting a power function, g , to the observations a very simple tool for decision support is provided to predict if sector-wise simulations are feasible. The accuracy of this method is quantified by comparison to the full method as defined in Eq. (12), where the fitted function is given by Eq. (13).

$$\Delta F_{eq,M1} = \frac{g^{-1}(f_{\theta,max}) \cdot F_{eq,eff,y}(f_U, U, \sigma_{U,eff}, \alpha_c, \rho_c, \varphi_c)}{F_{eq,pmax}(f_{\theta}, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta)} \quad (12)$$

$$g(f_{\theta,max}) = 0.96 \cdot f_{\theta,max}^{0.11} \quad (13)$$

5.2. Model 2: Omnidirectional simulations

To approximate $F_{eq,pmax}$ directly based on fatigue load estimates from omnidirectional simulations, the simplified method described by Eq. (14) is proposed, where $f_{\theta}(\theta_k)$ is the frequency of wind measurements in sector k , a_j is the angle between sector k and point p_j , and $F_{eq,eff,x}$ describes the side-side bending fatigue damage from the omnidirectional simulations (estimated by the same procedure as $F_{eq,eff,y}$).

$$F_{eq,M2}(f_{\theta}, f_U, U, \sigma_{U,eff}, \alpha_c, \rho_c, \varphi_c, \theta) = \max_{p_j} \left(\sqrt[m]{\sum_{k=1}^{12} f_{\theta}(\theta_k) \cdot \left| \sin(a_j(\theta_k)) F_{eq,eff,x} + \cos(a_j(\theta_k)) F_{eq,eff,y} \right|^m} \right) \quad (14)$$

To quantify the accuracy of this method the predictions are compared to the full method as defined in Eq. (15).

$$\Delta F_{eq,M2} = \frac{F_{eq,M2}(f_{\theta}, f_U, U, \sigma_{U,eff}, \alpha_c, \rho_c, \varphi_c, \theta)}{F_{eq,pmax}(f_{\theta}, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta)} \quad (15)$$

5.3. Model 3: Sector-wise simulations

This last method is intended to accurately approximate the fatigue loads of the full method without explicitly accounting for the fore-aft and side-side moment interaction in the time domain. It is initially based on the assumption that the tower fore-aft and side-side moment accumulate fatigue damage fully independent, in which case the full method of assessing the fatigue damage boils down to the fatigue damage combination in Eq. (16).

$$F_{eq,indep}(f_\theta, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta) = \max_{p_j} \left(\sqrt[m]{\sum_{k=1}^{12} f_\theta(\theta_k) \cdot \left(\sqrt[m]{|\sin(a_j(\theta_k)) F_{eq,x,k}|^m + |\cos(a_j(\theta_k)) F_{eq,y,k}|^m} \right)^m} \right) \quad (16)$$

Where $F_{eq,x,k}$ represent the combined sector specific side-side fatigue damage as outlined in Eq. (17), with the side-side damage equivalent load ($DEL_{x,k}$) defined by Eq. (18), where $\Delta M_{x,k,i}^m$ is found by counting the side-side moment response.

$$F_{eq,x,k}(f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta_k) = \left(\int_{U_{in}}^{U_{out}} f_U(U|\theta_k) DEL_{x,k}(U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c)^m d\theta dU \right)^{1/m} \quad (17)$$

$$DEL_{x,k}(U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c) = \left(\frac{1}{N_{eq}} \sum_i n_i \Delta M_{x,k,i}^m \right)^{1/m} \quad (18)$$

Equations (17) and (18) describe the sector-wise side-side fatigue damage, but the procedure is the same for the fore-aft fatigue damage ($F_{eq,y,k}$).

By checking the accuracy of Eq. (16) it was found that the assumption of independence leads to a slight non-conservative bias compared to the full method of ~1%. To calibrate the final version of model 3 a site-specific offset is therefore introduced by weighting the side-side loads slightly higher in the load combination by using a power of 2 instead of m as shown in Eq. (19).

$$F_{eq,M3}(f_\theta, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta) = \max_{p_j} \left(\sqrt[m]{\sum_{k=1}^{12} f_\theta(\theta_k) \cdot \left(\sqrt[2]{|\sin(a_j(\theta_k)) F_{eq,x,k}|^2 + |\cos(a_j(\theta_k)) F_{eq,y,k}|^2} \right)^m} \right) \quad (19)$$

The accuracy of the calibrated model 3 is quantified by comparison to the full method as defined in Eq. (20)

$$\Delta F_{eq,M3} = \frac{F_{eq,M3}(f_\theta, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta)}{F_{eq,pmax}(f_\theta, f_U, U, \sigma_{U,T}, \alpha_c, \rho_c, \varphi_c, \theta)} \quad (20)$$

5.4. Summary of the developed models

In Table 2 an overview of the three simplified methods is presented. For comparison the computational time is specified in a relative sense (Relative cost), as the actual computational time is highly dependent on the aero-elastic code and specific turbine that is considered.

Table 2. Simplified methods to account for directional fatigue damage variation.

Simplified approach	Accuracy assessment*	Relative cost	Short description
Model 1 - Eq. (12)	$\Delta F_{eq,M1}$	0	Proxy to assess the overprediction with no information of actual loads.
Model 2 - Eq. (15)	$\Delta F_{eq,M2}$	1/12	Proxy to predict the fatigue damage of the full model by omnidirectional simulations.
Model 3 - Eq. (19)	$\Delta F_{eq,M3}$	1	Accurate model to evaluate the fatigue damage of the full model without projecting moment time series.

*The accuracy of all methods is evaluated with respect to the same fatigue damage obtained by the full model for comparison.

Note that model 3 requires the same amount of simulations as the full method making it very suitable for e.g. response surface methods to predict the fatigue loads based on pre-run simulations [12,13].

6. Results and recommendations

The results of applying the three developed models across all 99 sites are shown in figure 5 and summarized in Table 3. For comparison the results of using the omnidirectional effective turbulence are also presented, which show that the developed model results are more accurate at all sites. Care should be taken though, as both model 1 and 2 result in non-conservative fatigue assessments at some of the sites. Based on the observations the following recommendations are considered by the authors:

Model 1 – Spread of wind rose:

Using information of the wind rose only, this model provides an initial estimate of the consequence of neglecting direction when accumulating fatigue damage. A core benefit of this model is that it requires no expert knowledge of wind turbine simulation. The accuracy is comparable to the second method, but it cannot be used to predict fatigue loads directly. Instead, it may be used either to decide if omnidirectional simulations should be skipped entirely, or in conjunction with the results from the second method to assess whether directional simulations are feasible at the specific turbine location.

Model 2 – Omnidirectional simulations:

Using omnidirectional fatigue loads an estimate of the actual directional fatigue damage is obtained, but since the method may lead to non-conservative assessments it is only recommended as a proxy to decide if sector-wise simulations are justifiable. In contrast to the first approach, a clear benefit of this method is that it allows the designing engineer to compare the expected material savings in the fatigue limit state with the margins from other design load cases. The importance of this is illustrated by the following simple example: The initial simulations show that the ultimate limit state governs the tower design, hence, any expected reduction in material consumption in the fatigue limit state is irrelevant.

Model 3 – Sector-wise simulations:

This last model may be used directly to predict fatigue loads within 1% of the full method across all analysed sites. The computational cost is the same as for the full method, but it alleviates the designing engineers for the extra step in the workflow from wind climate to wind turbine loads of computing projected moments.

Table 3. Summarized results of all simplified methods.

Simplified approach	ΔF_{eq} minimum [-]	ΔF_{eq} Maximum [-]	ΔF_{eq} Average [-]	ΔF_{eq} Std.dev. [-]
Effective turbulence	1.033	1.230	1.156	0.053
Model 1	0.940	1.076	1.004	0.027
Model 2	0.938	1.097	1.013	0.029
Model 3	0.995	1.001	0.999	0.001

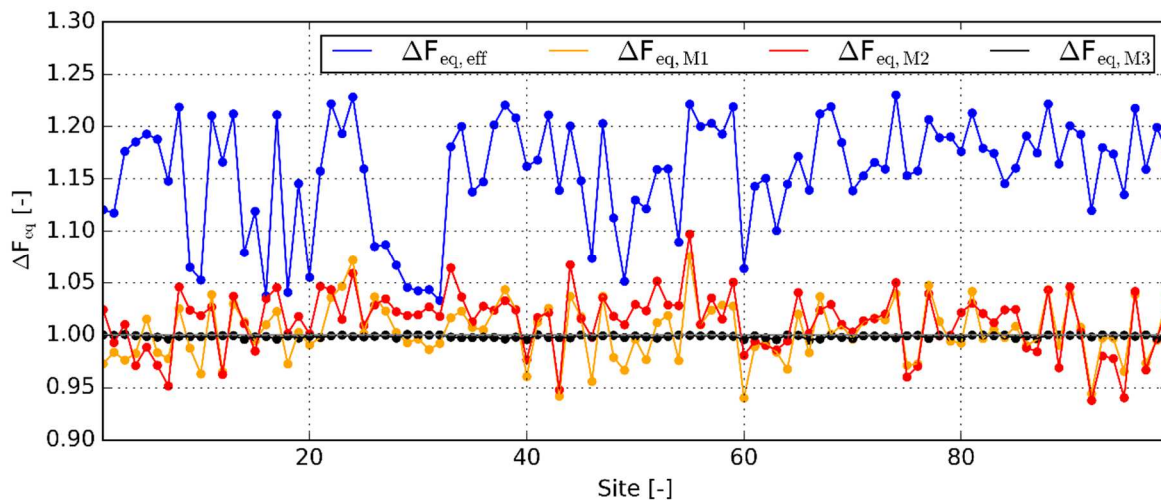


Figure 4: Results of analysing all 99 sites using the effective turbulence approximation (blue) and the three simplified models (yellow, red, and black) compared to the full directional approach.

7. Conclusions

Fatigue assessment of wind turbine components is commonly based on simulations using omnidirectional effective turbulence to limit computational time. This approach implicitly assumes that fatigue damage accumulates independently of the wind direction, which is a simplification for all components below the yaw bearing. Using wind measurements from 99 real sites this assumption has been shown to overestimate DELs by an average of 14% for wind turbine steel towers, compared to explicitly accounting for direction in the fatigue accumulation.

Utilizing the large number of available sites three simplified models have been developed to approximate the full sector-wise model. Model 1 is based only on wind measurements which makes it accessible to wind and site engineers without expert knowledge of wind turbine simulation. The method can predict the actual overprediction within 8% of the full model. Model 2 is based on results of omnidirectional simulations, making it possible to predict the actual fatigue loads of the full model within 10%. Both models 1 and 2 show promising results, but for some sites they are non-conservative, hence, they should only be used as proxies to decide if full sector-wise simulation are justified at the considered site and turbine location. The third method accurately predicts the directional fatigue damage using sector wise simulations, but without explicitly accounting for tower fore-aft and side-side bending in the time domain. This method captures the fatigue loads of the full model within 1% without any bias and is regarded as accurate as the time-based calculation.

The models and results that have been presented in this work may contribute to an overall reduction in the steel consumption of wind turbine towers, thereby reducing the cost of wind energy and the environmental impact of wind turbines when the entire life-cycle is considered.

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