Comparison of extreme load extrapolations using measured and calculated loads of a MW wind turbine

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1 Abstract

Since edition 3 of the standard IEC 61400-1 "Wind Turbines-Part 1; Design requirements" has been issued extreme load extrapolation during normal production is an important part of the wind turbine design and certification.

At the ECN test site 'ECN Windturbine Testpark Wieringermeer' (EWTW) five in line 2.5 MW turbines are used for research purposes. A data base with about 4 years of high quality load and meteorological measurements for a 2.5 MW wind turbine in free stream and wake conditions is available for research. This gives ECN the unique opportunity to compare extreme loads using extreme value statistics based on load simulations and load measurements for both free stream and wake conditions. Extreme load extrapolation will be applied on the flat blade root bending moment and the for aft tower bottom bending moment. Attention will be paid to the selection of the extreme value probability distribution and the amount of data needed.

2 Introduction

During the last ten years the estimation of extreme wind turbine loads using extreme value statistics has been an important research topic [14, 4, 1, 15]. Due to a lack of long term load measurements on wind turbines focus was on load extrapolation using the results of aeroelastic calculations. Pandey [16] and Ragen [17] present extreme load extrapolation using measurements.

Until now research comparing the results of the extreme load extrapolation using load measurements and load simulations was based on a limited amount of load measurements. Genz et. al [6] present results for a Siemens 3.6 MW pitch regulated, variable speed wind turbine.

Since edition 3 of the standard IEC 61400-1 "Wind Turbines-Part 1; Design requirements" [10] has been issued, the extreme load extrapolation in wind turbine design also is of interest for wind turbine designers [6] and certification bodies [5].

At the ECN test site 'ECN Windturbine Testpark Wieringermeer' (EWTW) five in line 2.5 MW turbines are used for research purposes. One of the turbines is instrumented for load measurements. The wind conditions are measured at three different heights on a well equipped meteo mast. At this moment ECN has a data base available with about 4 years of high quality load and meteorological measurements for a 2.5 MW wind turbine in free stream and wake conditions. This gives ECN the unique opportunity to compare extreme loads based on extreme load extrapolation using load calculations simulations and load measurements.

In this paper results will be shown of the comparison between measurements and simulations for free stream and wake conditions paying attention to the selection of the extreme value distribution and the amount of data needed.

3 'ECN Windturbine Testpark Wieringermeer' (EWTW)

The ECN test site 'ECN Windturbine Testpark Wieringermeer' (EWTW) is located in the Wieringermeer, a polder in the North East of the province 'Noord-Holland'. The EWTW has a prototype site and a research wind farm. The research wind farm consists of five in line 2.5 MW wind turbines, numbered from 5 to 9 from West to East, see Figure 1. The topography and obstacles at the ECN test site are discussed by Eecen [3]. The wind turbines have a hub height $h = 80$ [m] and a rotor diameter $D = 80$ [m]. The spacing S between the wind turbines is 3.8 D.

The mechanical loads are measured on wind turbine N6. This it the second research turbine from the left (West). The loads are measured continuously at high

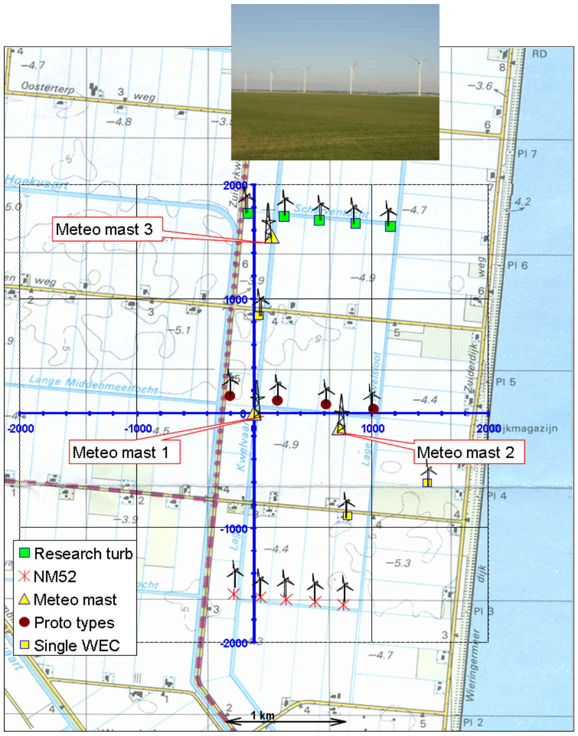

Figure 1: *Detailed map of the ECN Wind Turbine Test Site Wieringermeer, including the location of surrounding wind turbines and meteorological masts 1,2 and 3. Directly West of the Zuiderkwelweg the row of trees is located.*

sample rates.

3.1 Data selection

A wind turbine located in a wind farm can be exposed to free stream, partial wake, single wake and multiple wake wind conditions. The data base contains about four years of load measurements. For the data selection of wind turbine N6 westerly winds are considered from sectors where the meteorological mast 3 is not influenced by the wake of a wind turbine. For the extreme load extrapolation three wind sectors are considered (Figure 2):

1. Free stream, no disturbance of wind turbine N6, sector from $225°$ to $245°$
2. Partial wake, sector from $245°$ to $265°$. Bordered by the full wake and full recovery of the relative power production of wind turbine N6.
3. Full wake, sector from $265°$ to $285°$.

It is assumed that the borders are marked by the abrupt changes in yaw angle differences (corresponding to wind direction changes). See Figure 2. The wind direction measured at hub height on the southwest boom is used as reference. It should be noted that only the partial wake sector from $245°$ to $265°$ at the southwest side of the full wake sector is used for analysis. The reason is that for the partial wake sector from $285°$ to $305°$, the meteorological mast 3 may be influenced by the wake of wind turbine 5.

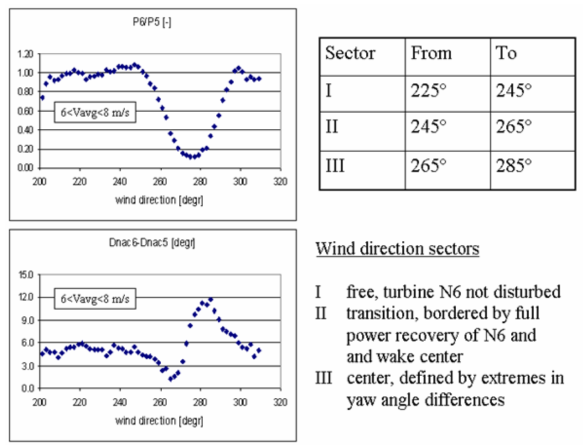

Figure 2: *Definition of the sectors for free stream, partial wake and full wake.*

For each wind sector the loads on wind turbine N6 are captured in scatter diagram with a bin width of 1.0 m/s for the mean wind speed v_{10} and 0.5 m/s for the standard deviation t of the wind speed. The data is selected based on the following assumptions:

- Normal power production of wind turbine N5 and N6, no starts and stops, thus the generator speed of the turbines is chosen above the minimum value for normal operation. The minimum power production during 10-minute records is above 5 kW.
- The minimum time difference between the time stamps of two measurements is chosen 30 minutes.

In the 'European Wind Standards Turbine Standards II' [2] the number of independent 10-minute events is determined to be 23037 in a year. The total number of 10-minutes in a year is 52596. This means that for 10-minute wind events there is no correlation after about 30 minutes. This criterion is applied for the selection of load time series in a bin. The selected bins for further analysis are given in Table 1.

Table 1: *Selected wind bins for extreme value analysis for the mean wind speed v_{10} and the standard deviation t of the wind speed.*

	v_{10} [m/s]	t [m/s]	number
Free stream	15.5	1.75	157
Partial wake	15.5	1.75	38
Full wake	15.5	1.75	37

4 Set up of aeroelastic computations

Aim of the research project on extreme load extrapolation is to compare the extreme loads based on measurements with the extreme loads based on aeroelastic calculations. The calculations should reflect the measured conditions as good as possible. To model every measured load case the following steps are necessary:

- Collect the measured wind conditions;
- Perform single wake calculations for the measured wind condition;
- Generate a stochastic wind field taking the wake effect into account;
- Perform aeroelastic time domain calculation.

For the selected load measurement the 10-minute mean wind speed at 52 m, 80 m (hub height) and 108 m are retrieved from the wind data base together with the mean wind direction and the turbulence at hub height. The mean wind speeds and the turbulence are used to estimate the surface roughness length z_0, the friction velocity u_* and the Monin-Obukhov Length MOL.

The partial and full wakes are calculated with the ECNWakeFarm program. The modeling of the wake behind a turbine is described by Schepers et. al [18]. ECNWakeFarm uses the mean wind direction, the surface roughness length z_0, the friction velocity u_* and the Monin-Obukhov Length MOL as an input. The output of ECNWakeFarm are four files with the mean wind speed u_w, v_w and w_w in longitudinal, lateral and vertical direction and the turbulence intensity for a 23 (horizontal) by 24 (vertical) grid.

For the calculation of the stochastic wake wind field the program SwiftWake is used. SwiftWake uses the four output files of ECNWakeFarm together with an additional file containing the turbulence length scale L_w of the wake. The turbulence length scale of the wake is determined using an engineering model [12, 2].

$$L_w = L_a(1 + min(\frac{12.2(1 - \frac{D}{L_a})}{v_{10} S_r^{0.6}}, 0.9)) \qquad (1)$$

with L_a the ambient turbulence length scale, v_{10} the ambient mean wind speed and D the rotor diameter. The reduced spacing is given by S_r

$$S_r = 2^{0.8} + (S - 2)^{0.8} \qquad \text{for } S \geq 2 \qquad (2)$$

where S is the wind turbine spacing expressed in rotor diameter D.

The stochastic wind field for the free stream condition is calculated using the program SwiftIEC. The wind input parameters in this case are the surface roughness length z_0 for the vertical wind shear and the mean wind speed and turbulence at hub height. For both the free stream and wake conditions the Kaimal wind spectrum was selected in SwiftIEC and SwiftWake.

The 2.5 MW research wind turbine was modeled in the ECN's aeroelastic code PHATAS [13] according to the local situation. Finally the loads are calculated with PHATAS for the selected measurements taking into account the measured yaw misalignment.

5 Statistical models of extreme load

5.1 Basic approach

According to the IEC 64100-1 standard [10] edition 3 the calculated extreme loads of a wind turbine should have a 50-year return period. In order to calculate the 50-year extreme load L_{50} a long-term extreme load distribution is needed.

To obtain the long-term load distribution the short-term distribution $F_{short}(L|v_{10})$ that is conditional on the mean wind speed, should be integrated over the probability density function of the mean wind speed $f(v_{10})$:

$$F_{long}(L) = \int_{v_{10}} F_{short}(L|v_{10}) f(v_{10})\, \mathrm{d}v_{10} \qquad (3)$$

The probability density function of the mean wind speed $f(v_{10})$ in equation 3 is described by the Weibull distribution.

In wind energy it is common practice to consider a 10-minute period for measurements and load calculations. This means that the probability level associated with a 50-year return period should be based on the number of 10-minute periods during 50 year

$$F_{long}(L_{50}) = \frac{10}{50 \times 365 \times 24 \times 60} = 3.8 \times 10^{-7} \quad (4)$$

The focus will be on the short-term distribution $F_{short}(L|v_{10})$

5.2 Probability distributions

For the extreme load extrapolation the maxima extracted from the load time series are modeled using different probability distributions. To see how well the probability distributions fit with the extracted maxima the probability distributions are plotted together with the so called empirical distribution.

The empirical distribution is determined as follows. First the maxima of the time series are ordered is ascending order. The smallest maxima will have a value $i = 1$. The largest maximum will be $i = N$. Now every maximum is given a probability according to the plotting position in equation 5.

$$F(L|v_{10}) = \frac{i}{N+1} \tag{5}$$

Looking at the occurrence of a certain wind speed bin the probability of exceedance of the short-term distribution $F_{short}(L|v_{10})$ is in the order of 10-4 to 10-6 in order to contribute to the long-term response distribution $F_{long}(L_{50}) = 3.8 \times 10^{-7}$. The total number of maxima N has to be very large for these probabilities of exceedance. Therefore extreme value distributions are needed for the extreme load extrapolations beyond the observations.

For the short-term extreme load distribution $F_{short}(L|v_{10})$ the however different distributions are used:
- The Generalized Extreme Value (GEV) distribution;
- The Gumbel distribution;
- The Lognormal distribution;
- The Weibull distribution.

The distributions are defined for a load L with α as the scale parameter, ξ as the location parameter and in case of a three parameter distribution with k as the shape parameter.

Theoretically the extreme loads can be modeled using the Generalized Extreme Value (GEV) distribution only. The GEV distribution contains the classical Gumbel distribution ($k = 0$), the Frechet distribution ($k < 0$) and the reverse Weibull distribution ($k > 0$). See equation 6

$$F_{GEV}(L|v_{10}) = \begin{cases} \exp(-(1 - \frac{k(L-\xi)}{\alpha})^{\frac{1}{k}}) & k \neq 0 \\ \exp(-\exp\left(-\frac{(L-\xi)}{\alpha})\right) & k = 0 \end{cases} \tag{6}$$

Since the GEV distribution only asymptotically reaches $k = 0$, the Gumbel distribution is defined separately.

$$F_{Gumbel}(L|v_{10}) = \exp(-\exp\left(-\frac{(L-\xi)}{\alpha})\right) \tag{7}$$

In practice the Lognormal and three parameter Weibull distribution show good results [5, 1, 17] and are therefore included for the extreme load extrapolation here.

$$F_{Lognormal}(L|v_{10}) = \begin{cases} \Phi\left(-\frac{\log\left(1-\frac{k(L-\xi)}{\alpha}\right)}{k}\right) & k \neq 0 \\ \Phi\left(\frac{(L-\xi)}{\alpha}\right) & k = 0 \end{cases} \tag{8}$$

with Φ the standard Normal distribution.

$$F_{Weibull}(L|v_{10}) = 1 - \left[\exp\left(\frac{L-\xi}{\alpha}\right)^k\right] \qquad L-\xi, \alpha, k > 0 \tag{9}$$

5.3 L-moments

For the selected distributions the scale parameter α, the location parameter ξ and the shape parameter k are estimated using the L-moment method introduced by Hosking and Wallis [8, 9]. L-moments are linear combination of probability weighted moments PWM. Greenwood [7] defined the probability weighted moment PWM for a distribution function $F(x) = P(X \leq x)$ as:

$$M_{p,r,s} = E[X^p F(X)^r (1 - F(X))^s] \tag{10}$$

where $E[]$ is the expectation.

Useful probability weighted moments are $\alpha_r = M_{1,0,r}$ and $\beta_r = M_{1,r,0}$, where α_r is related to minima and β_r to maxima. For a distribution that has a quantile function $x(u)$ α_r and β_r are given by:

$$\alpha_r = \int_0^1 x(u)(1-u)^r \, \mathrm{d}u \qquad \beta_r = \int_0^1 x(u)u^r \, \mathrm{d}u \tag{11}$$

Unbiased estimators of the PWM α_r and β_r are defined by Landwehr [11]:

$$a_r = \frac{1}{n}\binom{n-1}{r}^{-1} \sum_{j=r+1}^{n} \binom{n-j}{r} x_{j:n} \tag{12}$$

$$b_r = \frac{1}{n}\binom{n-1}{r}^{-1} \sum_{j=r+1}^{n} \binom{j-1}{r} x_{j:n} \tag{13}$$

where $x_{j:n}$ is the j^{th} order statistics in a sample of size n

Hosking and Wallis [9] gives the L-moments λ_r as:

$$\begin{aligned}
\lambda_1 &= \alpha_0 && = \beta_0 \\
\lambda_2 &= \alpha_0 - 2\alpha_1 && = 2\beta_1 - \beta_0 \\
\lambda_3 &= \alpha_0 - 6\alpha_2 + 6\alpha_2 && = 6\beta_2 - 6\beta_1 + \beta_0 \\
\lambda_4 &= \alpha_0 - 12\alpha_1 + 30\alpha_2 - 20\alpha_3 \\
\lambda_4 &= 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0
\end{aligned} \tag{14}$$

Beside L-moments λ_r, L-moment ratios are defined:

$$\tau_r = \frac{\lambda_r}{\lambda_2} \qquad r > 2 \tag{15}$$

where τ_3 is called the L-skewness and τ_4 the L-kurtosis.

The expression of the probability distribution parameters in L-moments λ_1, λ_2, τ_3 and τ_4 is given by Hosking and Wallis [9] for the GEV, the Gumbel and the Lognormal distribution. For the Weibull distribution the definitions in the appendix are used.

6 Results and Discussion

Having described the EWTW test site and the calculation procedure an extreme load extrapolation is performed for the flat blade root bending moments and the for aft tower bottom bending moments.

For each load the global data approach is applied. This means that from every 10-minute load time series only one maximum value is used. Other approaches are known like the peak over threshold (POT) method or the block maxima method [15, 5] These methods use more data from each time series.

Here the extreme load extrapolation concentrates on:

- The sample size i.e. the number of data (maxima) needed for an load extrapolation,
- The load comparison between the wake conditions.

The sample size is discussed for the free stream condition.The loads are made dimensionless by the mean of the measured maxima for the free stream condition at rated wind speed.

6.1 Sample size

For the wind turbine designer it is important to know how many data is needed for a good fit of the short-term probability distributions keeping the number of calculations to a minimum. For the free stream condition at 15.5 [m/s] wind speed 150 measured and calculated time series are available. The sample size is compared for a probability of exceedance of 10^{-6}. Since this probability is expected to contribute to the long-term extreme load.

Flat blade root bending moment Figure 3 shows the distributions for the measured flat blade root bending moment for the free stream condition at 15.5 [m/s] wind speed. In total 150 maxima are used. It can be seen that the GEV, Lognormal and Weibull distribution follow the empirical distribution well. The Gumbel distribution overestimates the flat blade root bending moments. The Gumbel distribution is only valid when the GEV distribution and the Gumbel distribution have the same shape. Table 2 shows the measured flat blade root bending moment for a probability of exceedance 10^{-6}. For a number of maxima $n = 50$ or larger the difference is between 2% for the Gumbel distribution and 6% for the Lognormal distribution.

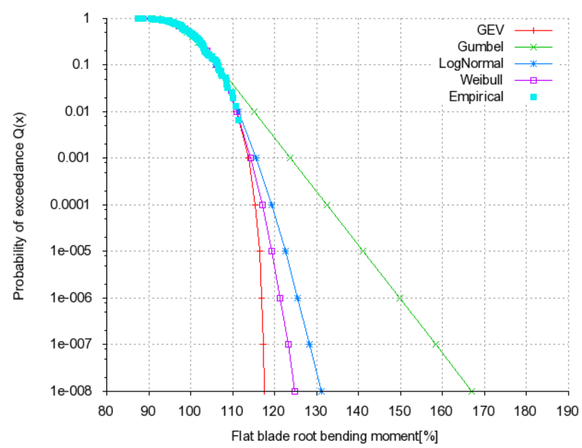

Figure 3: *Measured flat blade root bending moment for the free stream condition at 15.5 [m/s] wind speed.*

It is interesting to compare the measured extreme flat blade root bending moments with the calculated ones. Figure 3 shows the distributions for $n = 150$ maxima at the free stream condition with 15.5 [m/s] wind speed. The largest maxima in the sample follow the Gumbel distribution. However the Gumbel distribution has a different shape compared to the GEV distritbution. For the calculated case, Table 3, the mimimum difference is 4% for the Gumbel and Weibull distribution, the maximum difference is 11% for the Lognormal distribution.

For aft tower bottom bending moment The behavior for the extreme for aft tower bottom bending moment load are comparable with the flat blade root bending moments. In Figure 5 and Figure 6 the measured and calculated distribution are shown for $n = 150$ maxima. In this case for both measured and calculated maxima the largest values follow the Gumbel distribution best. Again the Gumbel distribution can only be a valid model when maxima are modeled the same with the GEV distribution.

Table 2: *Measured flat blade root bending moment for the free stream condition at 15.5 [m/s] wind speed for a probability of exceedance* 10^{-6}

n	GEV	Gumbel	Lognormal	Weibull
150	117%	158%	128%	123%
100	115%	159%	125%	121%
75	113%	160%	123%	120%
50	113%	159%	122%	119%
35	115%	159%	126%	120%
20	112%	162%	122%	118%
10	114%	176%	125%	124%

Table 3: *Calculated flat blade root bending moment for the free stream condition at 15.5 [m/s] wind speed for a probability of exceedance* 10^{-6}

n	GEV	Gumbel	Lognormal	Weibull
150	108%	128%	116%	109%
100	116%	127%	123%	112%
75	116%	128%	123%	111%
50	110%	128%	118%	109%
35	109%	129%	117%	108%
20	184%	124%	153%	114%
10	92%	105%	92%	0%

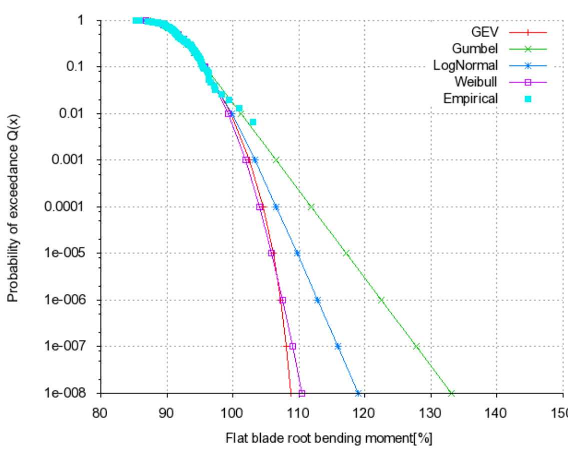

Figure 4: *Calculated flat blade root bending moment for the free stream condition at 15.5 [m/s] wind speed.*

Table 4 and Table 5 show the for aft tower bending moments for a probability of exceedance 10^{-6} and different sample sizes. It can be seen that for a sample size $n = 50$ or larger the difference in load estimation is between 4% and 11%.

6.2 Comparison of wake conditions

For the comparison of the extreme loads in free stream, partial wake and full wake condition the a bin with 15.5 [m/s] wind speed is selected from the scatter diagrams. Plotting only the empirical distribution of the measured and calculated loads the differ-

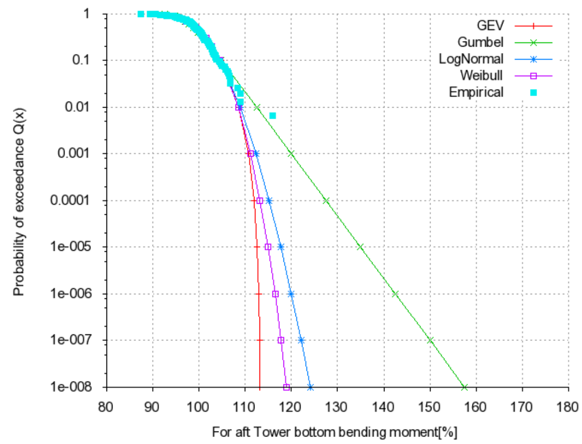

Figure 5: *Measured for aft tower bottom bending moment for the free stream condition at 15.5 [m/s] wind speed.*

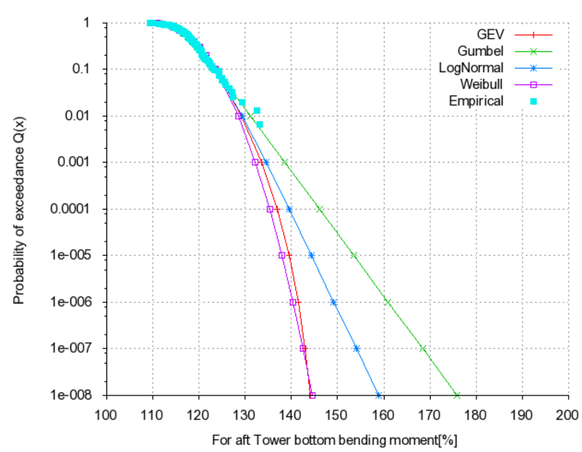

Figure 6: *Calculated for aft tower bottom bending moment for the free stream condition at 15.5 [m/s] wind speed.*

Table 4: *Measured for aft tower bottom bending moment for the free stream condition at 15.5 [m/s] wind speed for a probability of exceedance* 10^{-6}

n	GEV	Gumbel	Lognormal	Weibull
150	113%	150%	122%	118%
100	116%	150%	126%	119%
75	114%	151%	123%	118%
50	117%	155%	129%	128%
35	137%	153%	147%	128%
20	165%	162%	170%	137%
10	108%	150%	114%	114%

Table 5: *Calculated for aft tower bottom bending moment for the free stream condition at 15.5 [m/s] wind speed for a probability of exceedance* 10^{-6}

n	GEV	Gumbel	Lognormal	Weibull
150	143%	168%	154%	142%
100	136%	165%	146%	138%
75	134%	167%	143%	137%
50	133%	169%	143%	138%
35	124%	158%	128%	128%
20	122%	158%	125%	126%
10	135%	163%	146%	139%

ences become clearly visible. The empirical distributions are determined for $N = 35$ maxima. The empirical distribution for the flat blade root bending moment in Figure 7 shows that the calculated flat blade root bending moment maxima are smaller than the measured maxima. For the calculated blade root bending moments the free stream condition shows the smallest values followed by the full wake condition and the partial wake condition. In case of the measured loads the increasing order is free stream, partial wake, full wake condition.

Figure 8 shows the opposite behavior. For the for aft tower bottom bending moment the calculated loads are larger than the measured loads. It can also be seen that the measured tower bottom bending moments are more or less independent of the wake conditions, while for the calculated tower bottom bending moments the free stream loads are smaller than the loads in partial wake and full wake condition. The difference between the calculated partial wake loads and the full wake loads is negligible.

The measured and calculated flat blade root bending moments for a probability of exceedance 10^{-6} are given in Table 6 and Table 7. The calculated partial wake loads are overestimated compared with the measured partial wake load. The curve of the calculated distributions in Figure 10 is completely different from the measured ones in Figure 9.

Table 6: *Comparison of measured flat blade root bending moment for the free stream, partial wake and full wake condition at 15.5 [m/s] wind speed.*

	GEV	Gumbel	Lognormal	Weibull
Free	115%	159%	126%	120%
Partial	110%	154%	117%	115%
Full	128%	158%	139%	129%

Table 7: *Comparison of calculated flat blade root bending moment for the free stream, partial wake and full wake condition at 15.5 [m/s] wind speed.*

	GEV	Gumbel	Lognormal	Weibull
Free	109%	129%	117%	108%
Partial	254%	151%	200%	147%
Full	109%	130%	116%	111%

To the same extent the measured partial wake loads differ from the calculated for aft tower bottom bending moments. See Table 8 and Table 9. Also in this case the curve of the calculated distributions in Figure 12 is different from the measured one in Figure 11.

Table 8: *Comparison of measured for aft tower bottom bending moment for the free stream, partial wake and full wake condition at 15.5 [m/s] wind speed.*

	GEV	Gumbel	Lognormal	Weibull
Free	137%	153%	147%	128%
Partial	113%	149%	122%	118%
Full	117%	149%	128%	121%

Both for the flat blade root bending moment and the tower bottom bending moment there is a clear difference between the measured and calculated loads. It is difficult to say what causes the difference. Three models are used in the extreme load extrapolation procedure ECNWakeFarm, SWIFT and PHATAS. These models have to be be studied carefully to explain the differences between calculations and measurements. The large differences for the partial wake condition may be caused by the modeling in ECNWakeFarm. At the EWTW test site the spacing S between the turbines is relative small. However the free stream condition also shows the difference, may be caused by the use of the theoretical Kaimal wind spectrum instead of the measured wind spectrum.

7 Acknowledgments

Erik Korterink is thanked for his support in developing the PHATAS model of the 2.5 MW research wind turbine and for selecting the measured data from the ECN wind data base. We@Sea is thanked for the financial support of the We@Sea-project 2007-015.

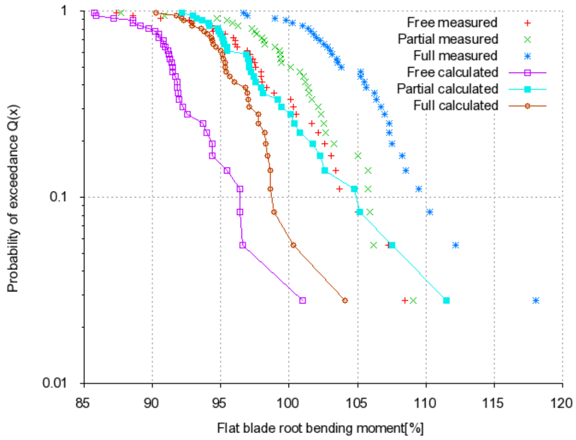

Figure 7: *Comparison of flat blade root bending moment for the free stream, partial wake and full wake condition at 15.5 [m/s] wind speed.*

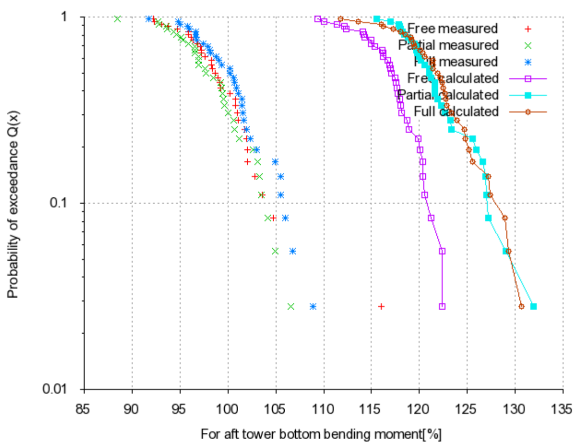

Figure 8: *Comparison of for aft tower bottom bending moment for the free stream, partial wake and full wake condition at 15.5 [m/s] wind speed.*

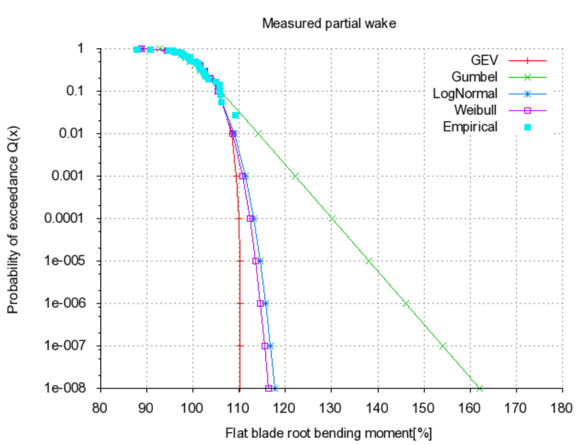

Figure 9: *Measured flat blade root bending moment for the partial wake condition at 15.5 [m/s] wind speed.*

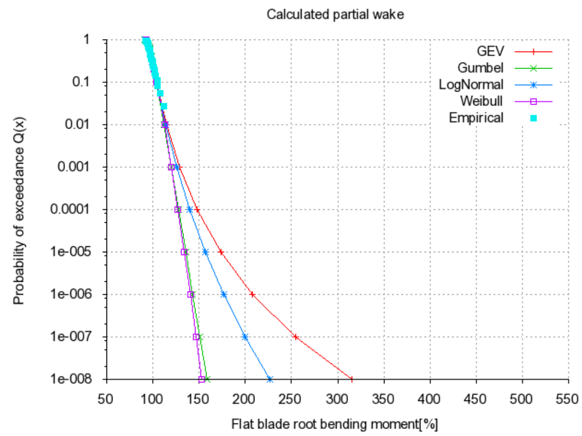

Figure 10: *Calculated flat blade root bending moment for the partial wake condition at 15.5 [m/s] wind speed.*

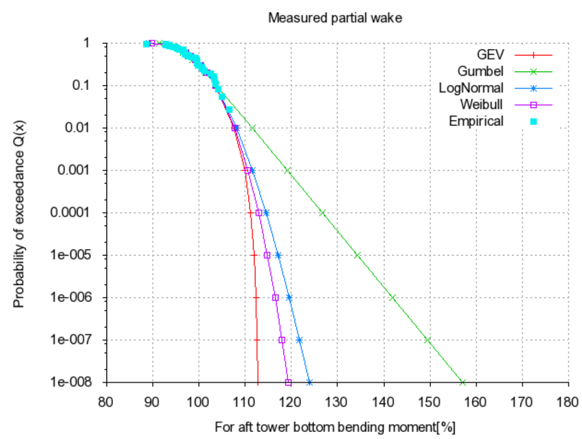

Figure 11: *Measured for aft tower bottom bending moment for the partial wake condition at 15.5 [m/s] wind speed.*

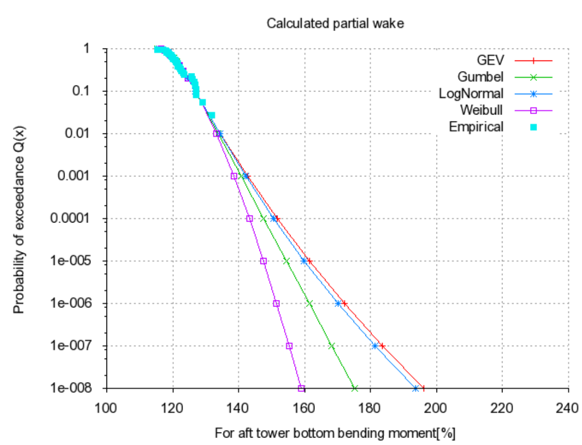

Figure 12: *Calculated for aft tower bottom bending moment for the partial wake condition at 15.5 [m/s] wind speed.*

Table 9: *Comparison of calculated for aft tower bottom bending moment for the free stream, partial wake and full wake condition at 15.5 [m/s] wind speed.*

	GEV	Gumbel	Lognormal	Weibull
Free	124%	158%	128%	128%
Partial	184%	168%	181%	155%
Full	135%	175%	144%	140%

8 Conclusions

An extreme load extrapolation is performed on calculated and measured loads from one of the research turbine at the EWTW test site. Based on the study the following can be conclude:

- For the global data approach, using one maxima from every time series, fifty maxima are sufficient to estimate the extreme load distribution conditional on the wind speed,
- There is quite a difference between the calculated and measured loads for the free stream, partial wake and full wake condition. The calculated flat blade root bending moment is smaller compared with the measurements, while the calculated for aft tower bottom bending moment is larger than the measured values.
- Wind models, wake models and aeroelastic models should be studied carefully to explain the differences between calculations and measurements.

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A Weibull L-moment

Greenwood [7] gave an expression of the Weibull distribution parameters in PWM's α_r. In L-moments the scale parameter α, the location parameter ξ and the shape parameter k can be expressed as follows:

$$\xi = \lambda_1 + \frac{5\lambda_2}{\tau_4 - 5\tau_3 - 1} \tag{16}$$

$$\alpha = \frac{\lambda_1 - \xi}{\Gamma\left[\frac{\log\left(\frac{10}{\tau_4 - 5\tau_3 + 4}\right)}{\log(2)}\right]} \tag{17}$$

$$k = \frac{\log(2)}{\log\left(\frac{5}{\tau_4 - 5\tau_3 + 4}\right)} \tag{18}$$