Fatigue lifetime estimation of wind turbine blades in a wind farm using damage extrapolation

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Problem introduction and Necessity:

- Fatigue is common in blades
- Higher turbulence in windfarms: Higher fatigue probability
- Higher failure probability: Higher risk and financial loss

Needed:

- Computationally fast quantification of reliability levels of turbine components as compared to target design level

Outline:

Case 1:

- Using fitting to 10 minute interval damaging instead of linear damage assumption through lifetime.

Case 2:

- Using longtime simulations and their truncations for fatigue lifetime estimation and comparing the results with 10min simulations.

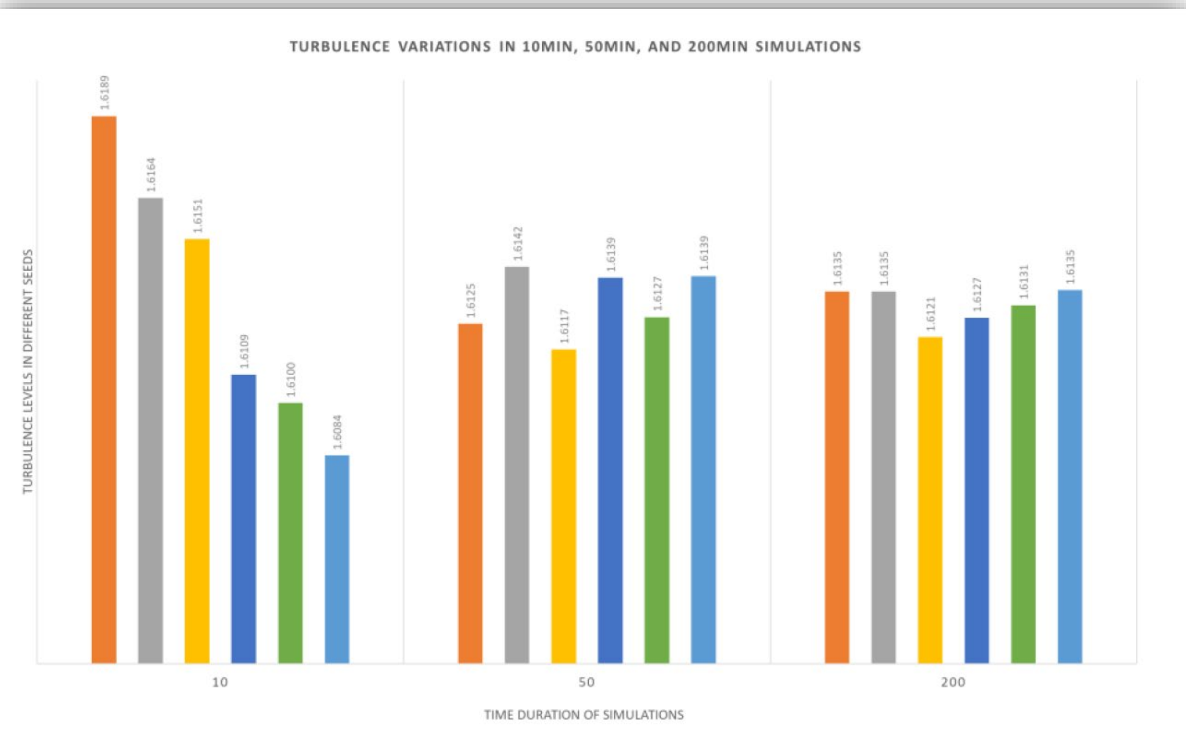
Case 3:

- Using SCADA data for deriving lognormal distribution of turbulence intensity (TI) and comparing the probability of failure in some mean wind speeds with the case of 90% quantile TI (by which the blade is designed based on)

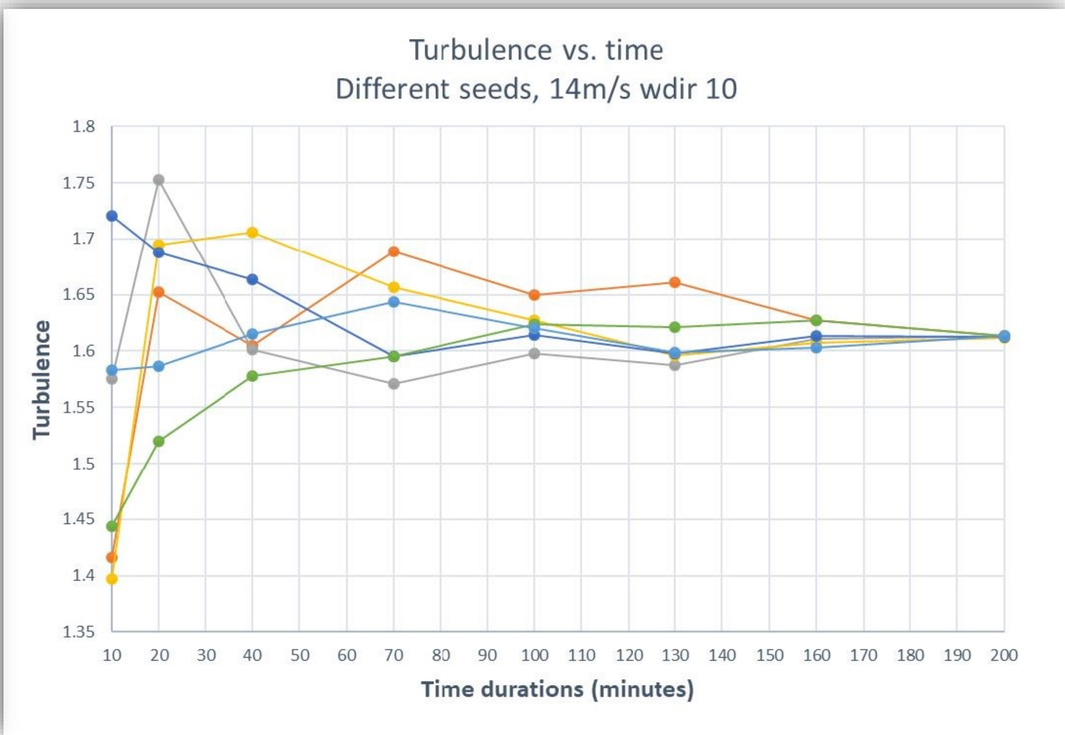
Case 1- Using statistical fitting for assessment of fatigue using long simulations

- 200min aeroelastic simulations of DTU10MW turbine in HAWC2 according to DLC1.2 with wind bins of 2 m/s.
- Finding the most critical section and point along the blade using MATLAB.
- Fatigue damage calculation using rainflow counting and Miner's rule for different mean wind conditions (using IEC standard).
- Tracking of fatigue damage accummulation over time.
- CDF fitting to the growth of damage in 10min intervals and extrapolation to assess the reliability.

Investigation of effects of turbulence convergence over time duration



Variations of turbulence levels for different simulation time durations at a fixed mean wind speed

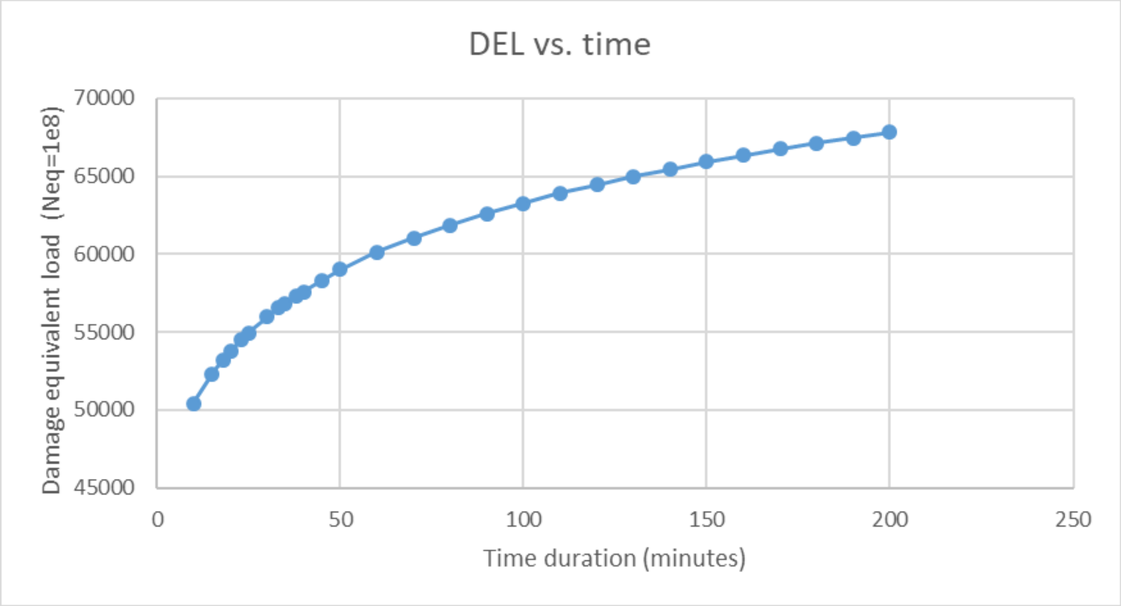


Actual turbulence magnitudes in different realizations (seeds) of wind time series with a given turbulence level input

Tracking Damage equivalent load (DEL) over time

- Damage equivalent load is calculated considering Neq=1e8 and tracked over time

- The changes of DEL with time is not linear over time



Change of DEL based on resultant moment with time

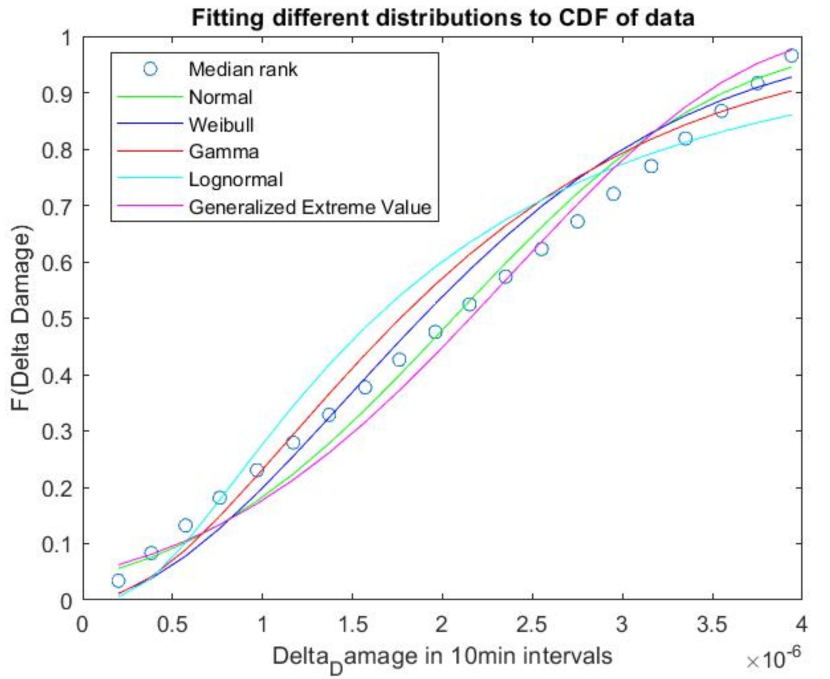
Fitting of CDF of damage data

- The variable is considered the change of dam... through time in 10 minute intervals
- G... l of the data is impo...

Parameters	Estimated magnitude
ξ	-0.3792
σ	2.8727e-9
μ	4.2654e-7

Parameters for GEV fitting on data at MWS of 10m/s

- Different fits are also investigated using ML...



Fitting of CDF of different distributions to the CDF of data.
(Sample from 10m/s is shown)

- The best fit for all the wind speeds is Generalized Extreme Value

Calculations of probability of failure

- Mean wind speed (v), Rayleigh distribution (considering class *l*, Vref=50)

CDF(v) = 1-exp(-π $\left(\frac{v}{20}\right)^2$), PDF(v) = $\frac{v}{100} * \exp\left(\frac{-v^2}{200}\right)$

- Reliability (R)=1-Probability of failure (P_f)
- $P_f = \sum(P_{v-1<v<v+1}) * (P_{D>D_{crtcl}})|v$
- $P_f = \sum(CDF_{v+1} - CDF_{v-1}) * (1 - CDF_{D=D\_crtcl24|v}) =$ 1.133e−05

- **D_crtcl is the threshold of damage in 10 minutes derived by iteration with the starting point as below:**
- Constant damage in 10min causing failure in 24 year ~ 2.52745e-07
- Constant damage in 10min causing failure in 25 years ~ 2.01035e-07

Methodology

- The fittings to GEV corresponds to type 2 and type 3 (Weibull and Frechet distribution)

- Once the distribution is known for 10 minute damage, we will start to find the critical damage in 10 minutes by below procedure:

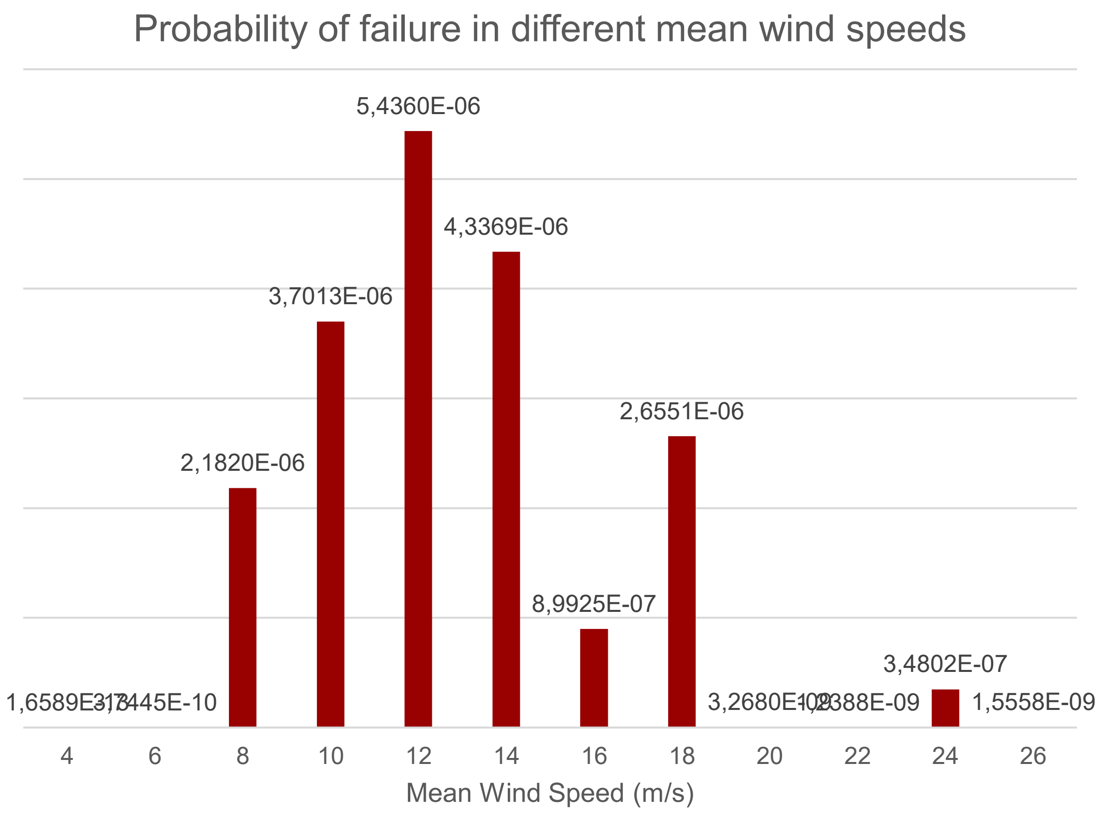
  - ❖Mean damage based on linear assumption is considered as the starting point of iterations

  - ❖Back calculating to perform iterations

  - ❖The first point on the fit starting from linear based critical point would be the new critical point on the fit

- Calculation of the probability of failure based on probability of the critical damage to happen

Calculation of Probability of failure in different wind bins



Probability of failure in 25yrs for each MWS considering joint probability in each wind bin

Overal P_f=sum (Pf in each MWS)

<u>Pf in year 24:</u>

$$\sum (CDF_{v+1} - CDF_{v-1}) * (1 - CDF_{D=\text{D\_crtcl24}|v})$$

$= 1.133e{-}05$

<u>Pf in year 25:</u>

$$\sum (CDF_{v+1} - CDF_{v-1}) * (1 - CDF_{D=\text{D\_crtcl25}|v})$$

= 1.960e-05

Reliability after 25 years of lifetime

- Target reliability index of β =3.3 (Pf=5e-4) is recommended by standards.

- Annual probability of failure in year 25th is calculated by calculation of probability of failure in year 24th and year 25th

- $\Delta Pf = \frac{Pf(t)-Pf(t-1)}{(1-Pf(t))}$ = 8.30016E−06< 5e-4 Accepted

Case 2- Comparison of the results of 10min and longer time simulations

- Number of 150 simulations of 10min duration for 10m/s and 14m/s
- Fatigue assessment for those wind speed
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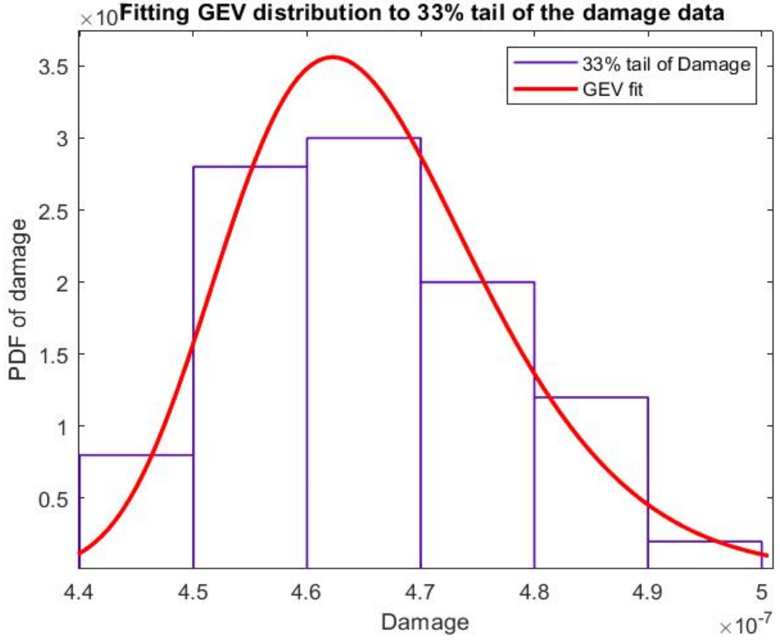
- comparing with the probability of failure

Difference between probabilities of failure

MWS (m/s)	Pf estimated using 10min simulations	Pf estimated using 200min simulations	Difference (%)
4	1.69E-13	1.66E-13	2.15%
10	4.01E-06	3.70E-06	8.28%
14	3.99E-06	4.34E-06	-7.95%
26	1.64E-09	1.56E-09	5.64%



Fitting generalized extreme value to the data from 150 simulations in mean wind speed of 10m/s

Case 3- Comparing the probability of failure using 90% percentile of turbulence with lognormal distribution

- 10 random turbulence Intensities from lognormal distribution in MWS of 10m/s

- Fatigue damage calculated and averaged over 15 seeds

- Comparing the fatigue assessment (averaged through different turbulences) with 90% percentile (used in IEC standard)

- Assumptions of lognormal distribution for turbulence
- μ_σ = from SCADA data
- σ_σ = 1.4*Iref (Iref = 0.1)

Changes of damage and probability of failure in 10m/s and 14m/s using turbulence distribution

Turbulence intensity	0.0962	0.0877	0.0948	0.0888	0.0942	0.1007	0.1015	0.0962	0.0971	0.0996
Changes in $D_{10\text{min}}$ (%) compared to Damage in 90% quantile TI for 10m/s	-1.86	-5.90	-2.64	-3.96	-7.64	-3.41	11.56	-3.03	0.16	0.02

Turbulence intensity	0.0727	0.0822	0.0876	0.1009	0.1003	0.0846	0.0945	0.0817	0.0916	0.1061
Changes in $D_{10\text{min}}$ (%) compared to Damage in 90% quantile TI for 10m/s	-0.98	-2.04	-3.02	2.18	2.29	-2.10	-0.98	-1.57	-1.04	1.02
Changes in P_f (%) compared to P_f in 90% quantile TI for 10m/s	-8.23	-6.19	-4.29	4.92	4.61	-7.75	-9.88	-6.26	-10.55	1.06

$$P_f = \iint (P_{v<v<v+1}) * (P_{IT-\delta<TI<TI+\delta})|v * (P_{D>D_{crtcl}})|v,TI \, .dv.\, dI$$

$$Pf = \iint (CDF_{v+1} - CDF_{V-1}) * (CDF_{TI+\delta} - CDF_{TI-\delta}) * (1 - CDF_{D=D\_crtcl25|v}) \, .dv.\, dI$$

Results and discussions:

- Maximum of 8% difference in probability of failure is seen in MWS of 10m/s when using simulations with different lengths.

- Maximum of 7.75% difference in P_f is seen in MWS of 14m/s when considering turbulence intensities from log normal distribution.

- Due to the standard error of 5% in estimated parameters for the fitting, the above percentages are not accountable.

- Maximum of 11.56% in fatigue damage is seen in mean wind speeds of 10m/s when considering turbulence intensities from log normal distribution.

Acknowledgement

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