Mitigation of Wind Turbine Design Load Uncertainties

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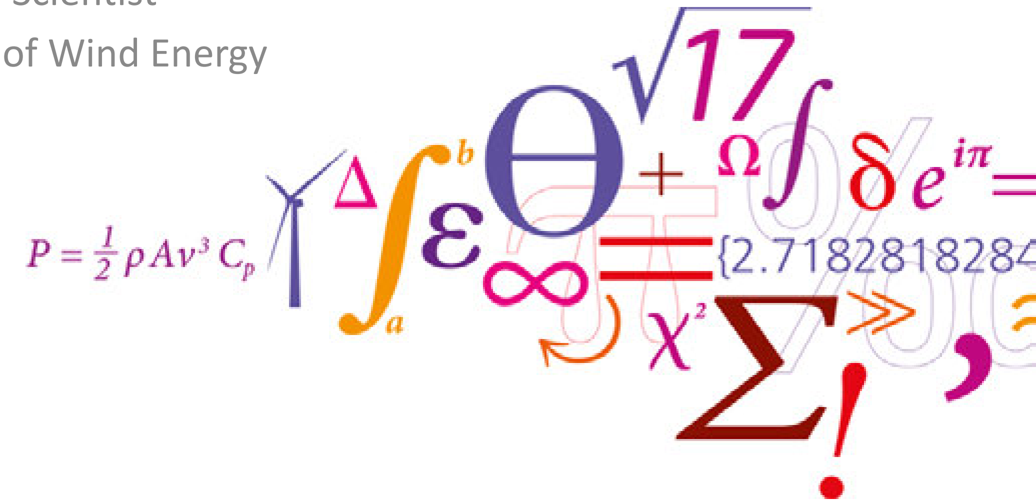


Design Loads on Wind Turbines

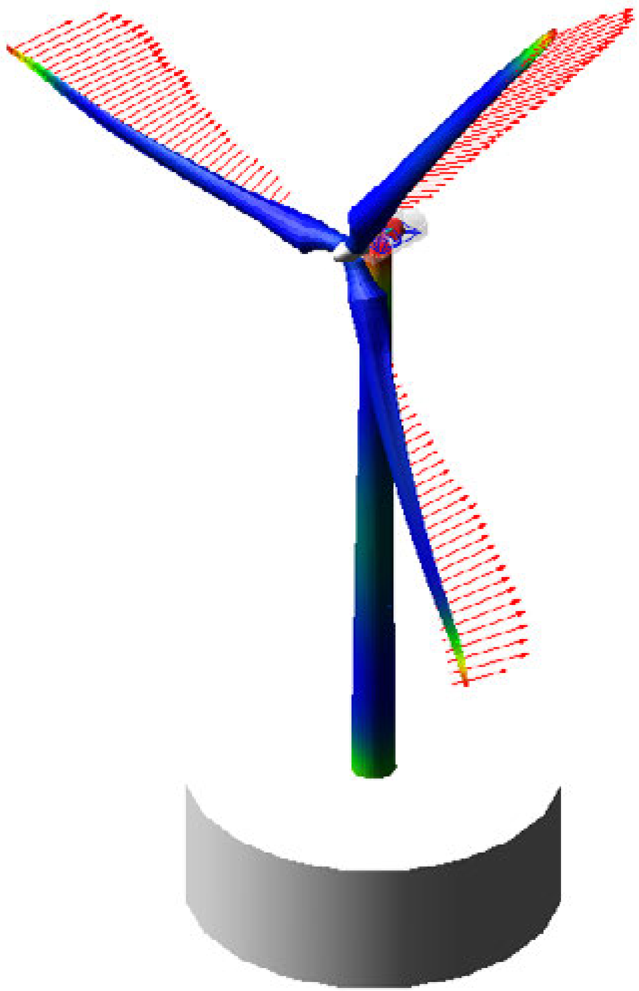
IEC 61400-1 prescribes several load cases required for assessing wind turbine structural integrity

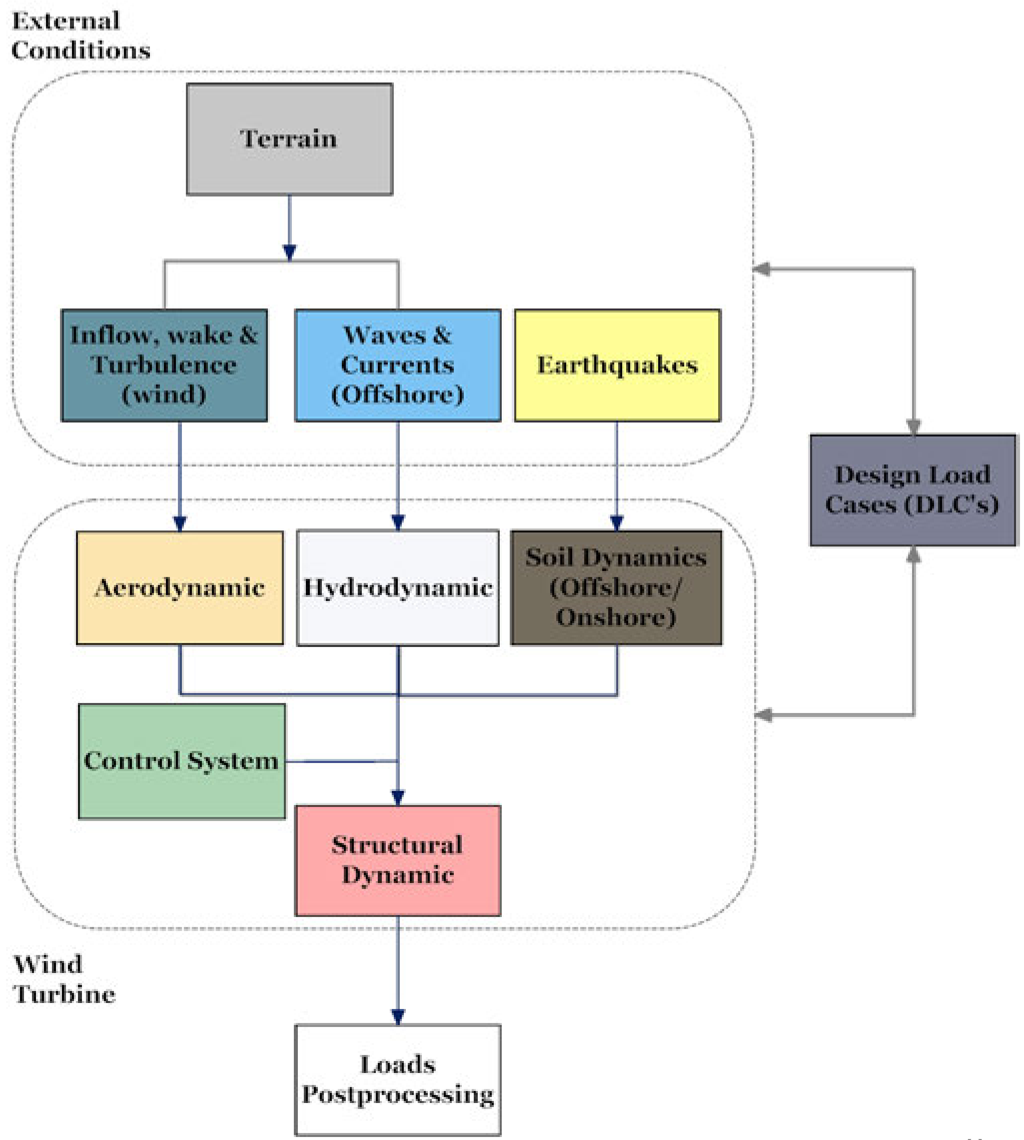
1. Normal turbulence operating and stand still loads
2. Extreme turbulence
3. Operating gusts, stand still gusts
4. Occurrences of events such as grid loss
5. High wind shear, direction change
6. Storms

- These load cases are simulated used aeroelastic codes and the design envelope of turbine components is determined by these loads.

- The process is stochastic and the bounds of load variation need to be quantified

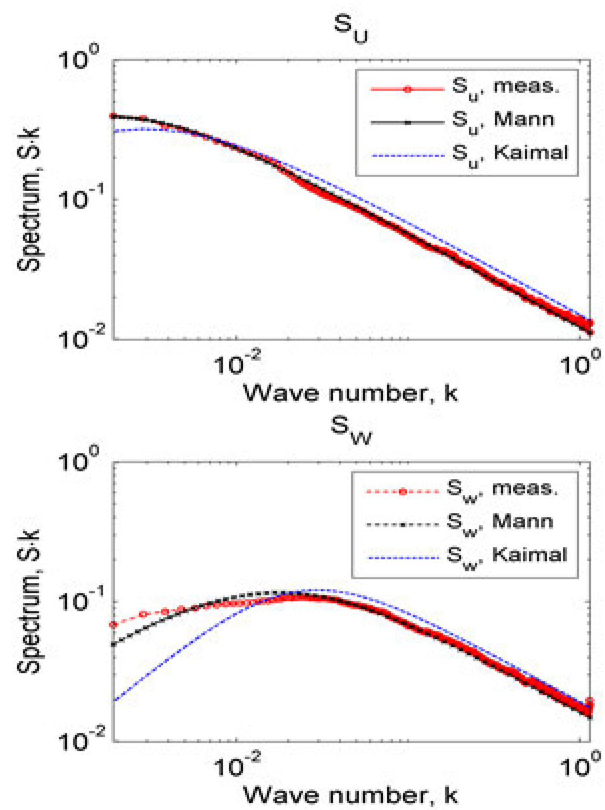
Sources of Design Load Uncertainities





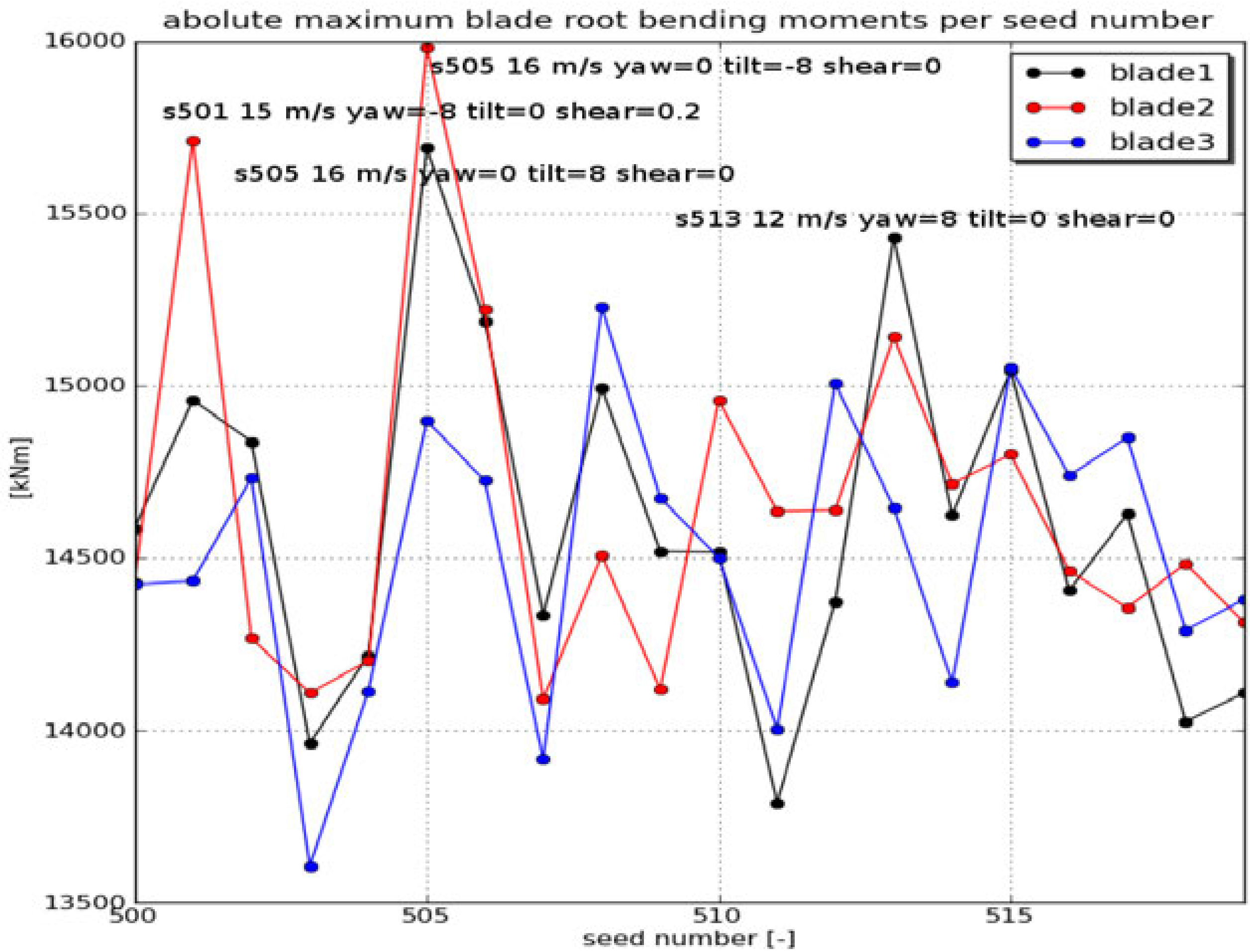
Inflow Uncertainties

- IEC 61400-1 Ed. 3 recommends Mann model or Veers (Kaimal spectrum) for wind turbulence.
- Parameters of the model ($\Gamma, L, \alpha\varepsilon^{2/3}$) are usually site dependent, causing load variations.
- Other inflow variations
  - Trends (de-trending)
  - Non-Gaussian/In-homogeneities
  - Shear
  - Veer
  - Gusts
  - Storms



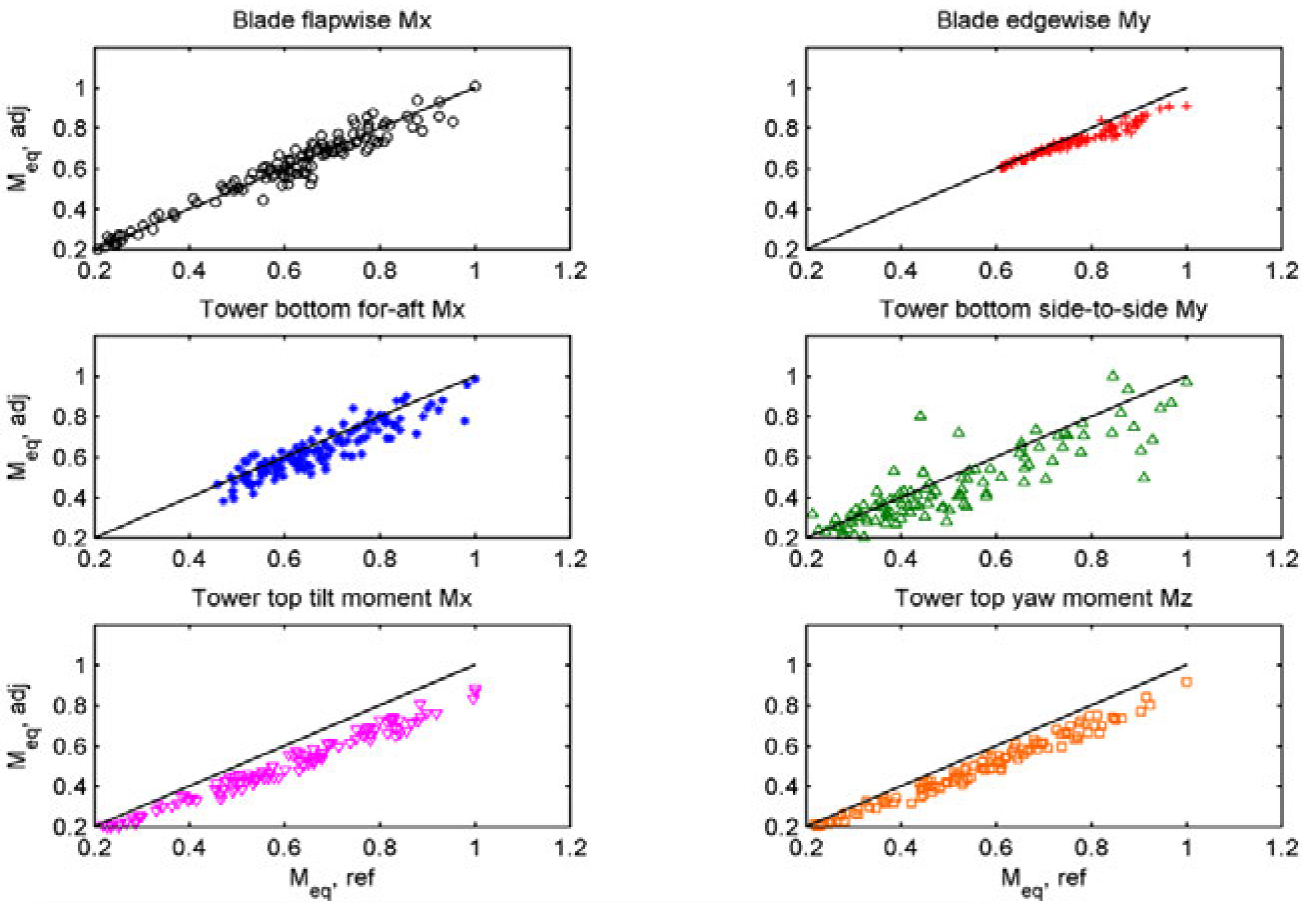
Example: Variation in inflow parameters

- Multiple seeds of wind turbulence run at each mean wind speed and with varying shear, slope and yaw directions



~20% variation in extreme loads for the same load case with 20 seeds at each mean wind speed

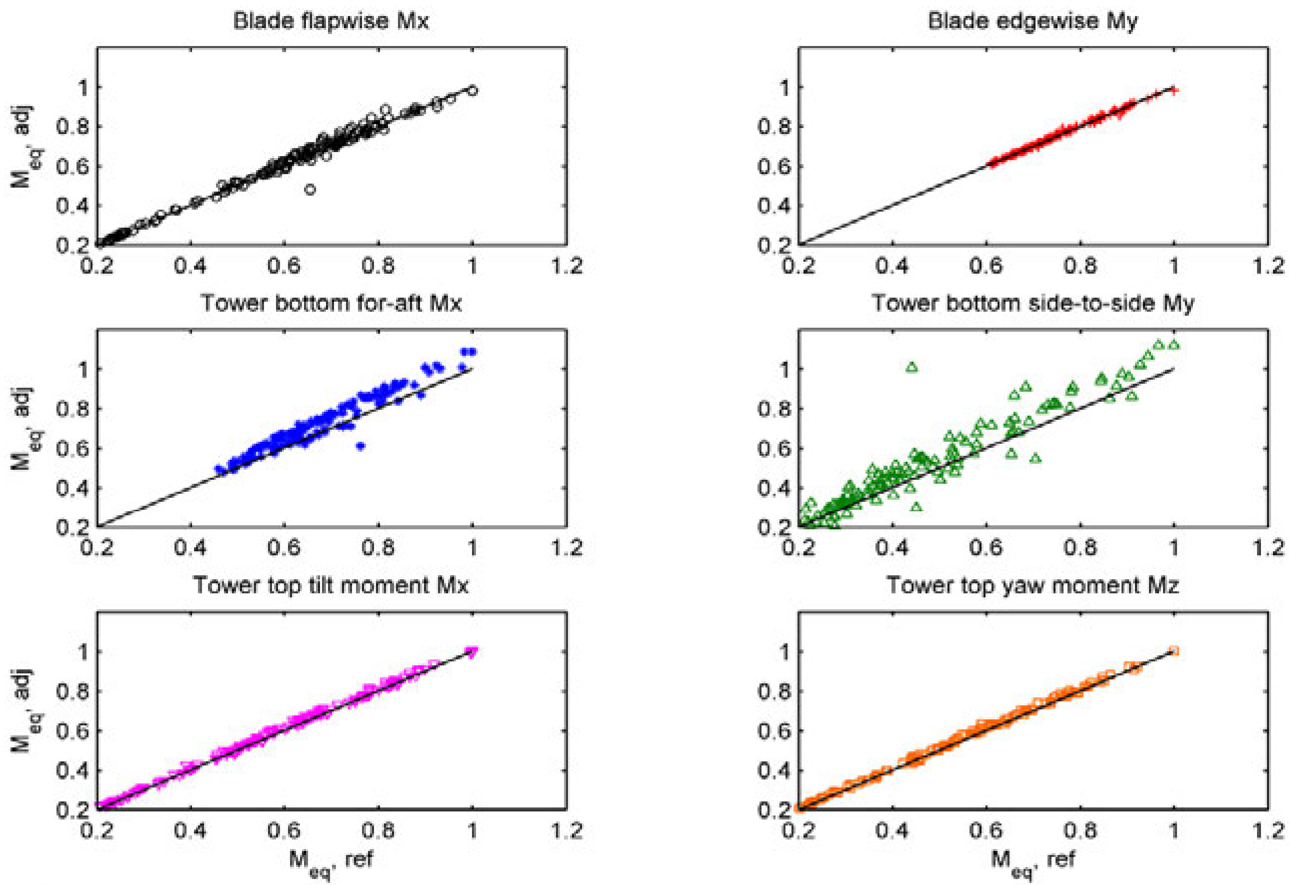
Influence of turbulence length scale L on fatigue loads (DTU 10MW turbine, DLC 1.1)



M_{eq},ref = f[M(Γ = 3.9, L = 29.4, $\alpha\varepsilon^{2/3}$ = 1, σ_U scaled to match target TI)]
M_{eq},adj = f[M(Γ = 3.9, L = 0.6z, $\alpha\varepsilon^{2/3}$ = 1, σ_U scaled to match target TI)]

Natarajan A, Dimitrov NK, Madsen PH, Berg J, Kelly MC, Larsen GC et al. Demonstration of a Basis for Tall Wind Turbine Design, EUDP Project Final Report. DTU Wind Energy, 2016, DTU Wind Energy Report (E); No. 0108).

Influence of parameter Γ on fatigue loads (DTU 10MW turbine, DLC 1.1)



M_{eq},ref = f[M(Γ = 3.9, L = 29.4, $\alpha\varepsilon^{2/3}$ = 1, σ_U scaled to match target TI)]
M_{eq},adj = f[M(Γ = 3.16, L = 29.4, $\alpha\varepsilon^{2/3}$ = 1, σ_U scaled to match target TI)]

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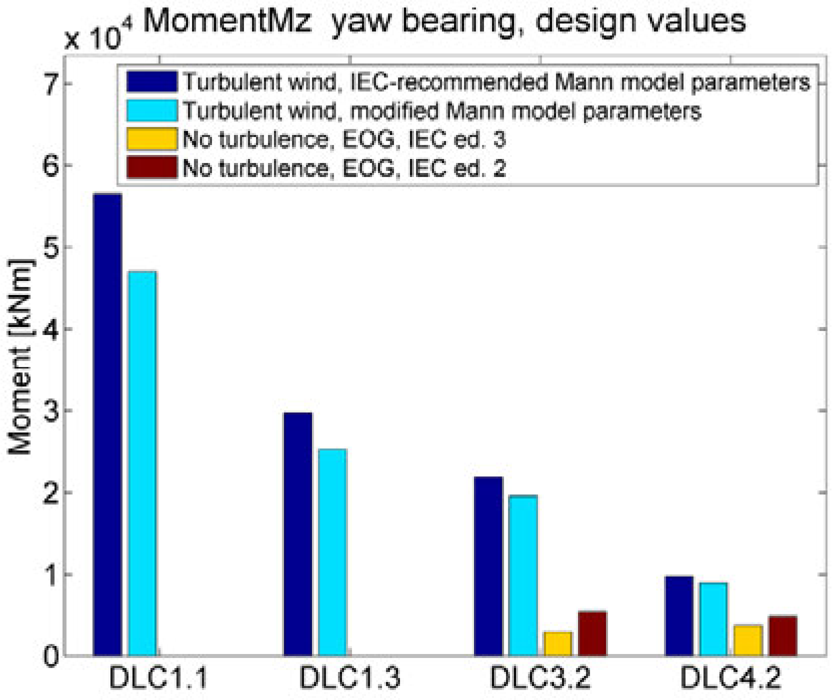
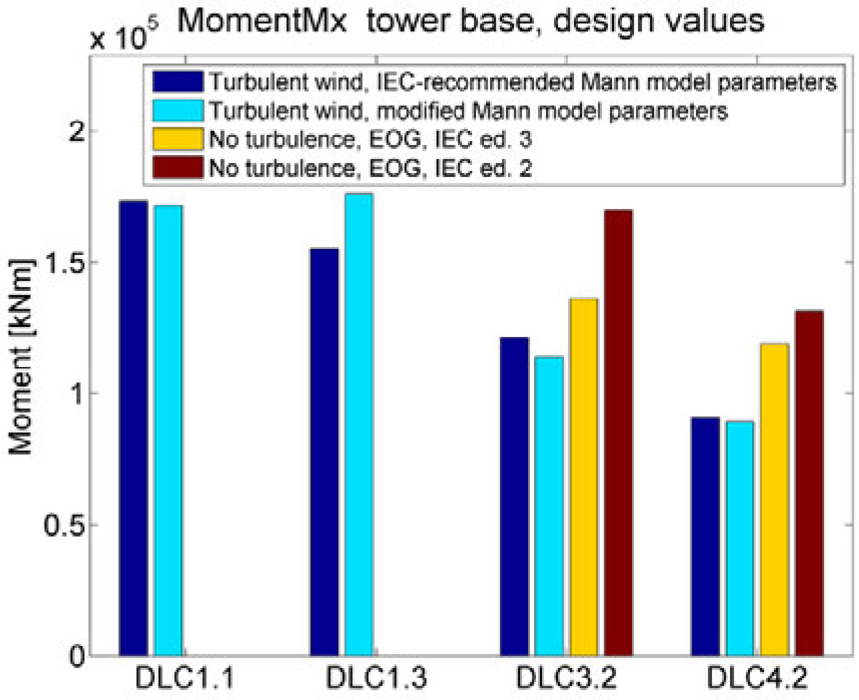
Effect of different IEC model parameters, Extreme Loads

- The Tower base extreme moments increase using the calibrated Mann model parameters under normal operation.
- This may also be amplified by the turbulence seeds that are used and the variation in loads due to turbulence seeds needs to also be ascertained.





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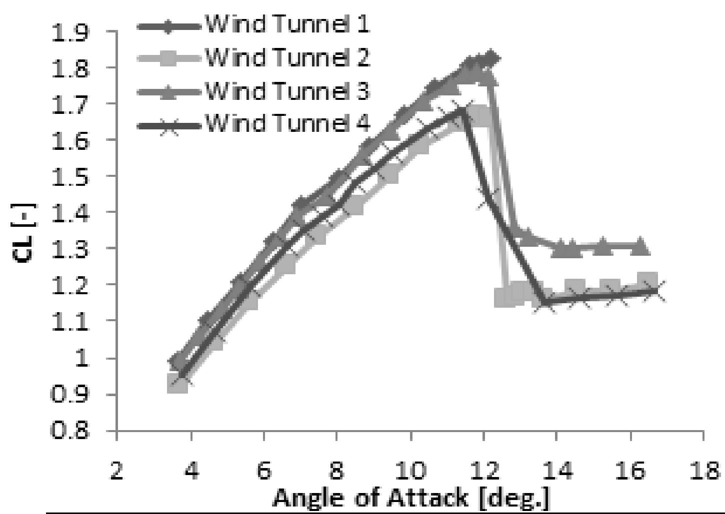
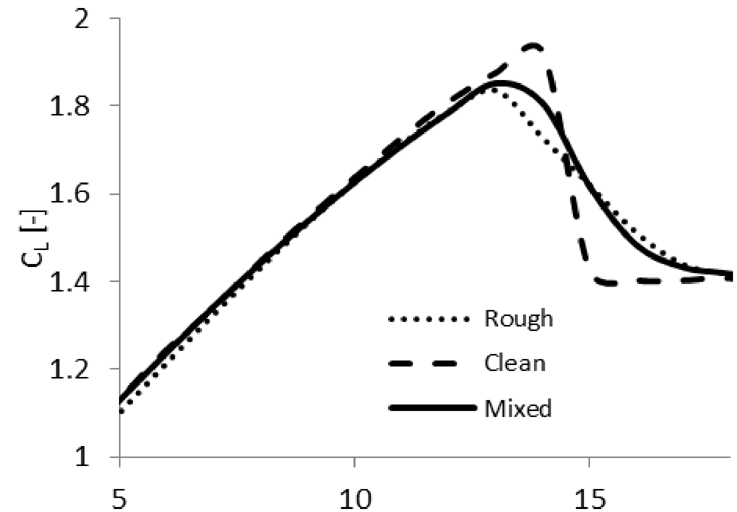
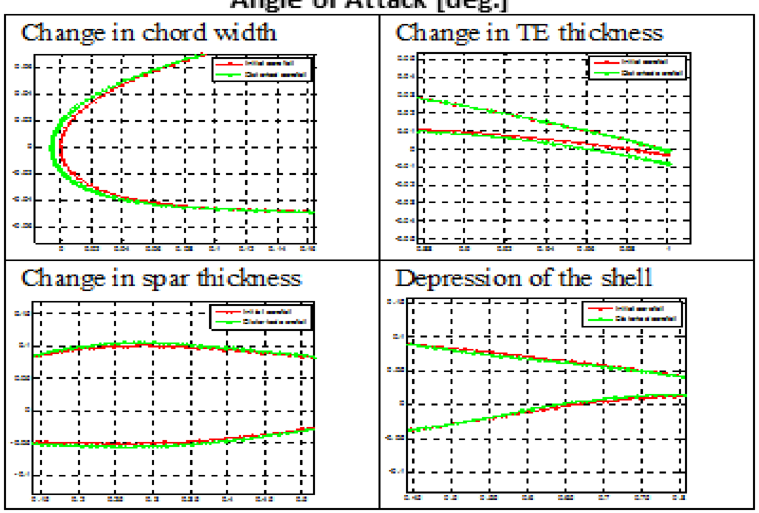
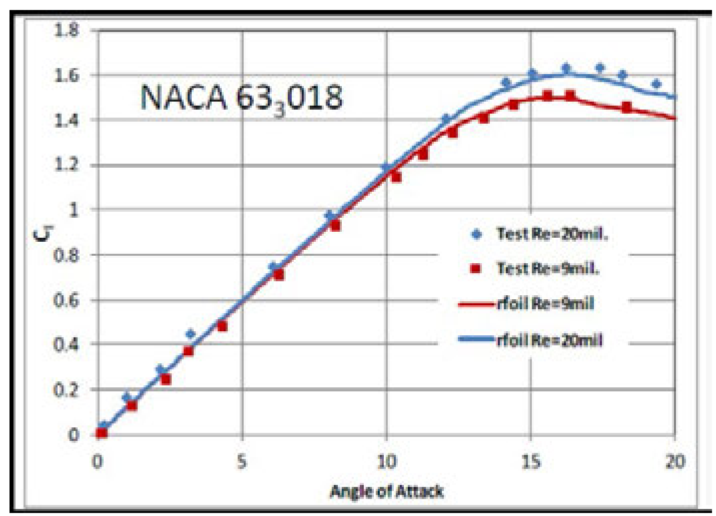
Aerodynamic Uncertainties

Uncertainities in measured lift coefficients



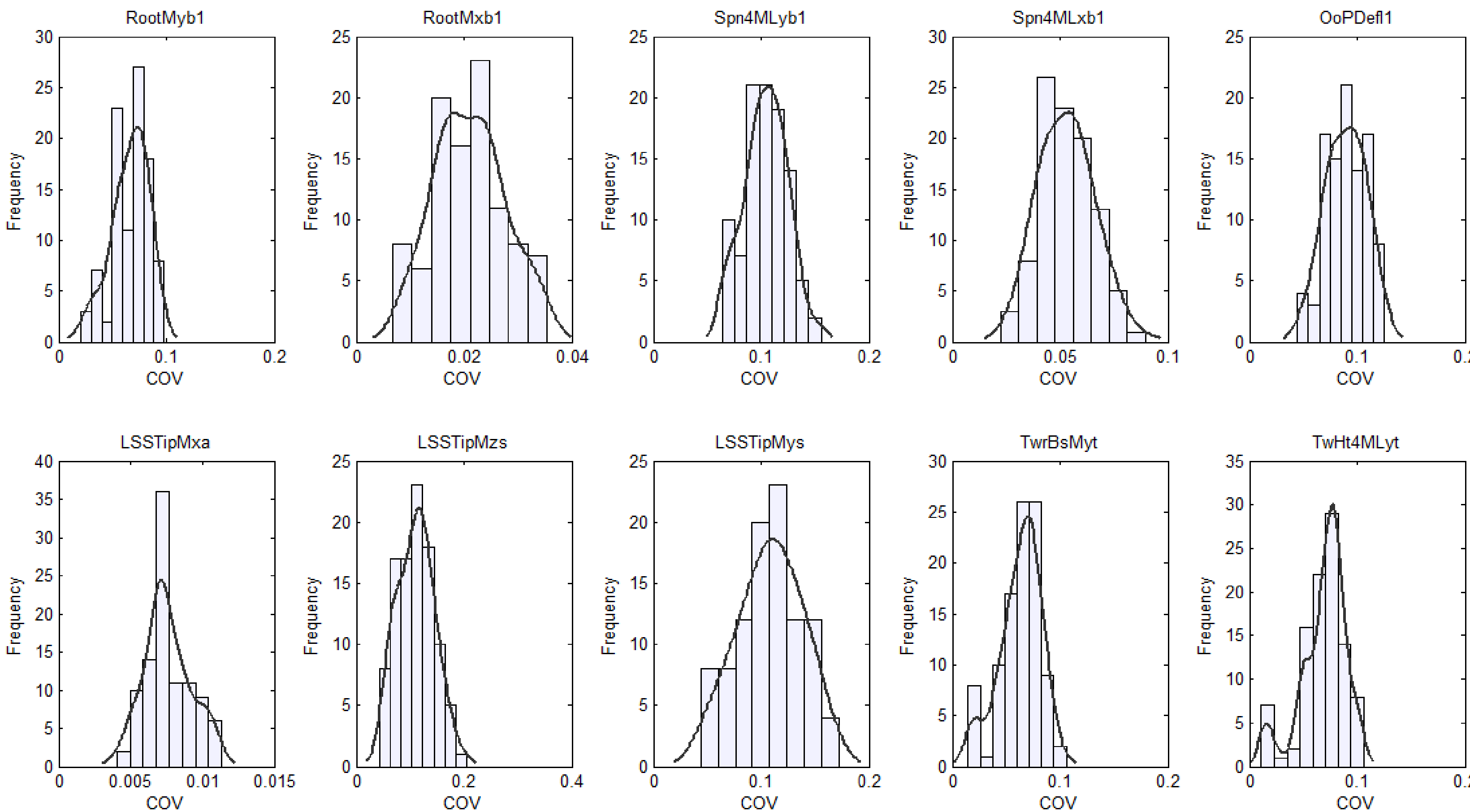






Abdallah, I., Natarajan, A. and Sørensen, J.D.," Impact of uncertainty in airfoil characteristics on wind turbine extreme loads", *Renewable Energy*, Vol. 75, 2015, 283-300

Uncertainty in extreme loads from aerodynamics



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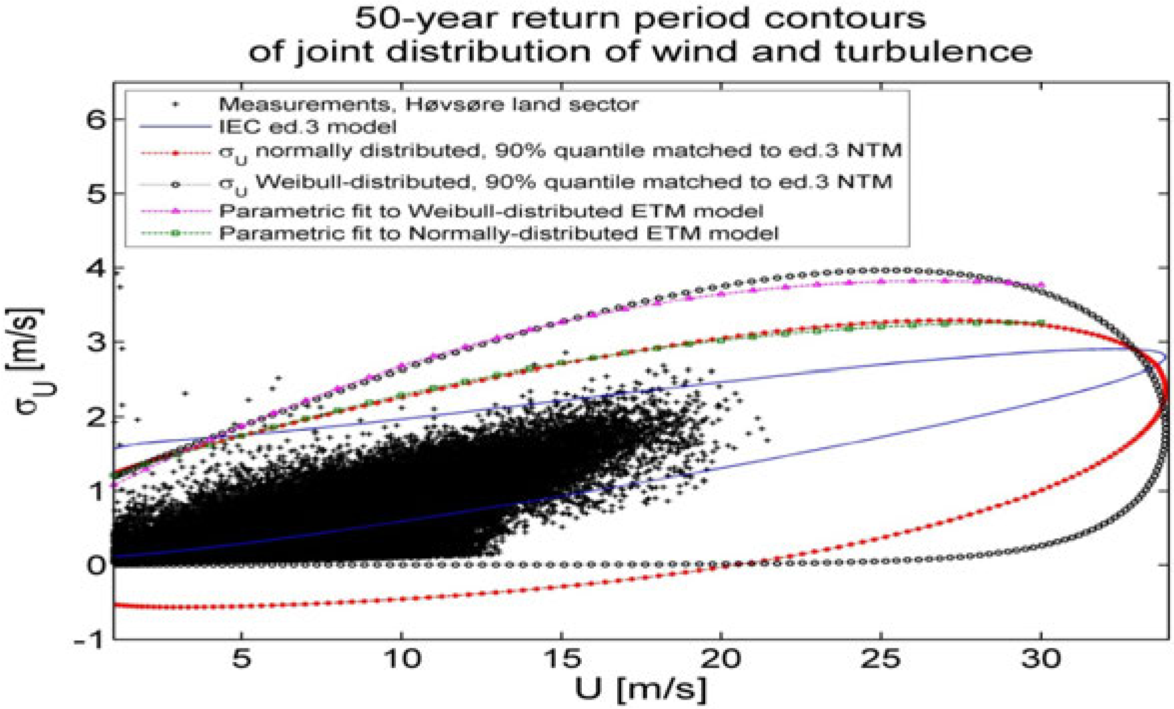
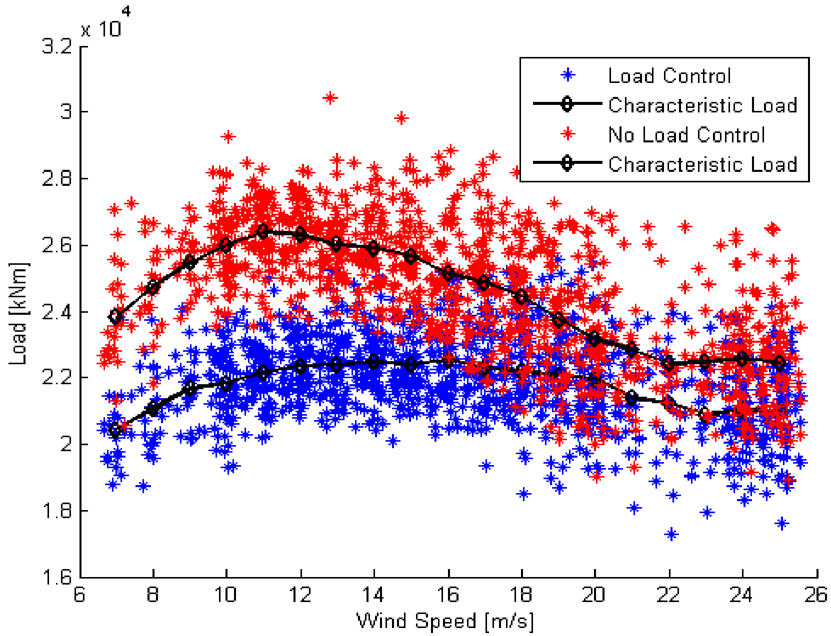
Extreme Turbulence Models Vs. Measurements

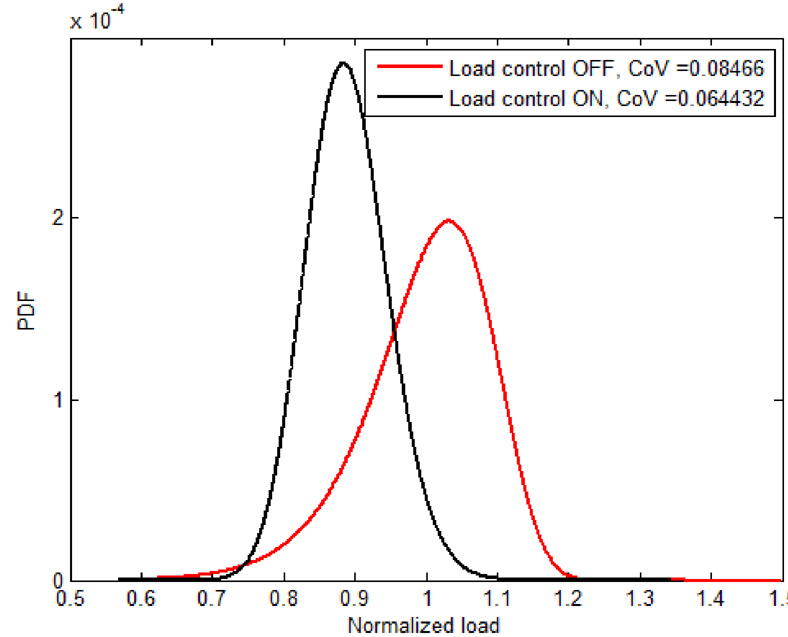
1. The IEC 61400-1 Ed. 3 uses a Log Normal distribution of turbulence with a std. deviation of 1.4I_ref.
2. A fit of the 50-year extreme turbulence can be made using measurements and with several probability distributions: Log Normal, Weibull, Normal etc.
3. All of the 50-year return contours typically exceed the IEC ETM model. Is that a problem for the turbine?



Dimitrov NK, Natarajan A, Mann J. Effects of normal and extreme turbulence spectral parameters on wind turbine loads. Renewable Energy, 2017,101:1180-1193

Effect of load control in maintaining load levels under extreme turbulence





1. Load based control such as IPC leads to satisfactory reliability levels under ultimate limit states
2. While the controller may be beneficial for operational cases, it may not have an effect on fault load cases.
3. The designer needs to verify that the uncertainties in the net response is within the partial safety factor limits.

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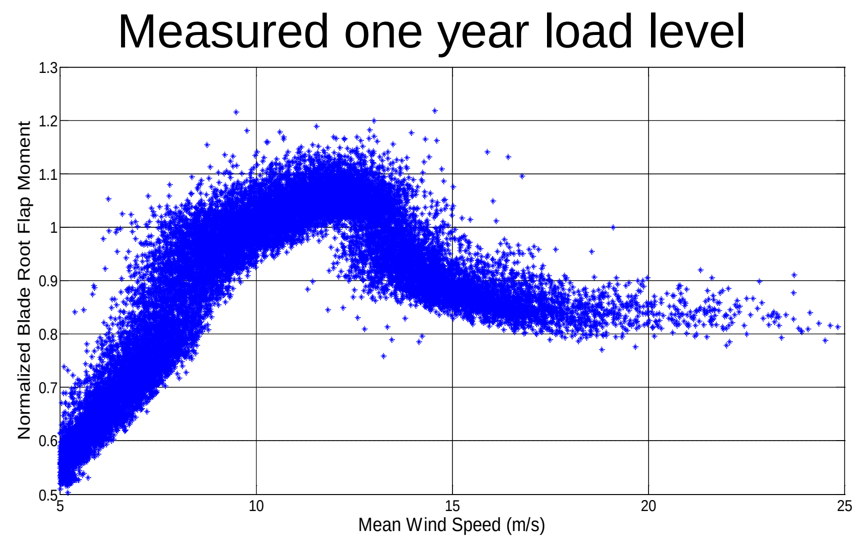
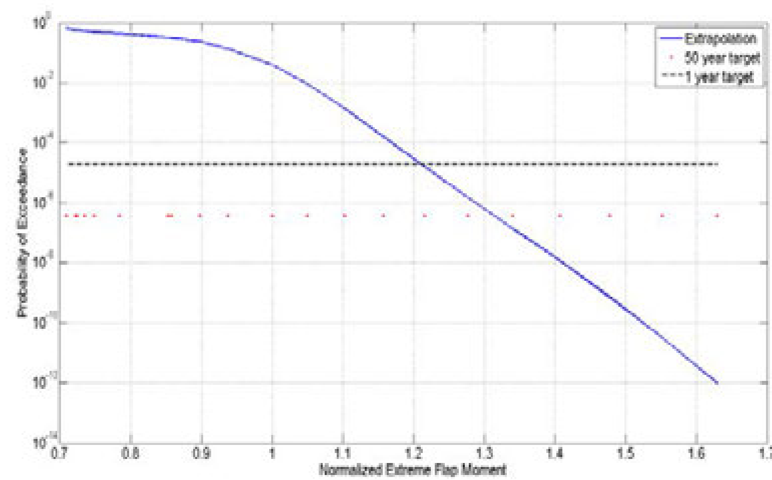
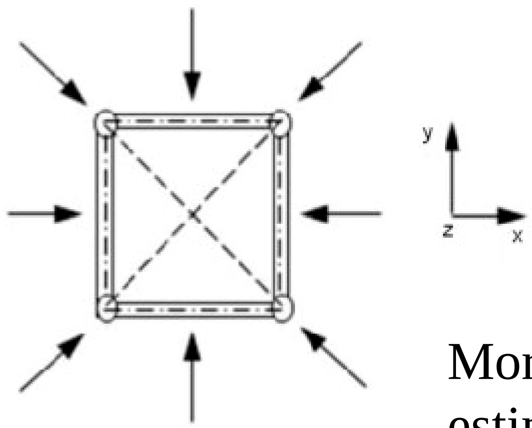
Blade design – Validate extreme load level

- 1 year measured data of blade root moments taken from Walney offshore wind farm.
- A subset of 30 extremes per mean wind speed bin is extrapolated to the one year probability of exceedance and compared with the 1 year meaured data,.
- ”A” computed extreme 1 year load level matches with measured extreme load level.
- Boot strapping over all samples in the one year load set can provide an expected one year extreme load level.





Fatigue of Offshore Jacket Welded Joints



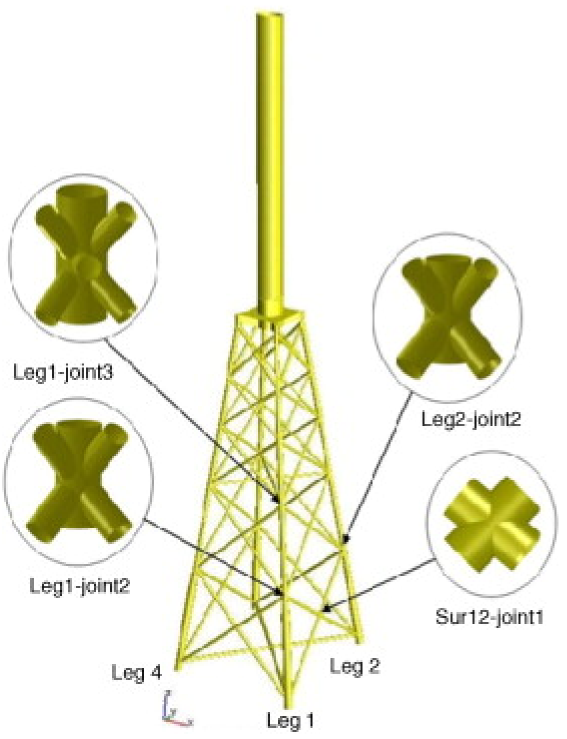
Dong, Moan, Gao 2011

Effect of wind and wave directionality

Fatigue analysis should include 8 wave directions for a reliable design.

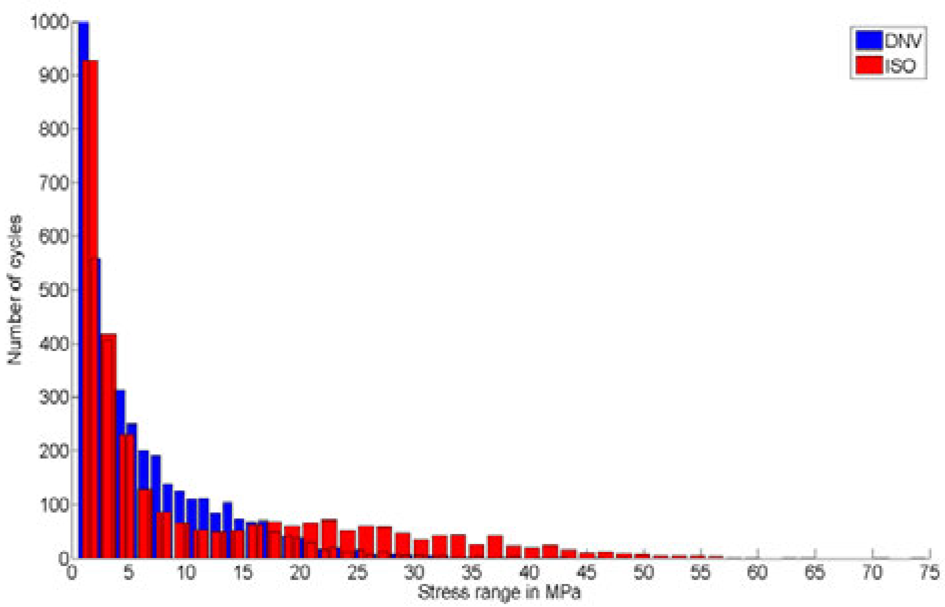
Morison C_D and C_M estimated by adding the contribution from all slender members.

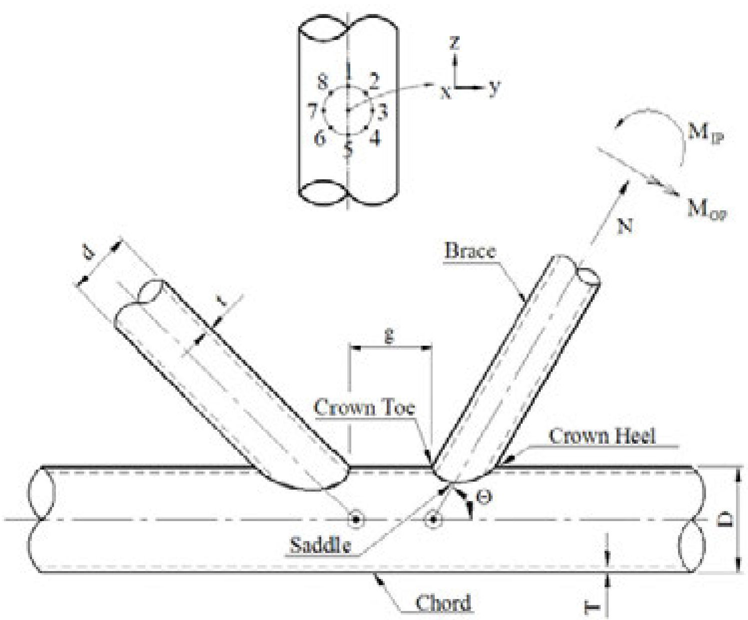
Fatigue lives at the nodes evaluated with SN curves with appropriate stress concentration factors



Comparison of ISO Vs. DNV Approaches on Fatigue Life

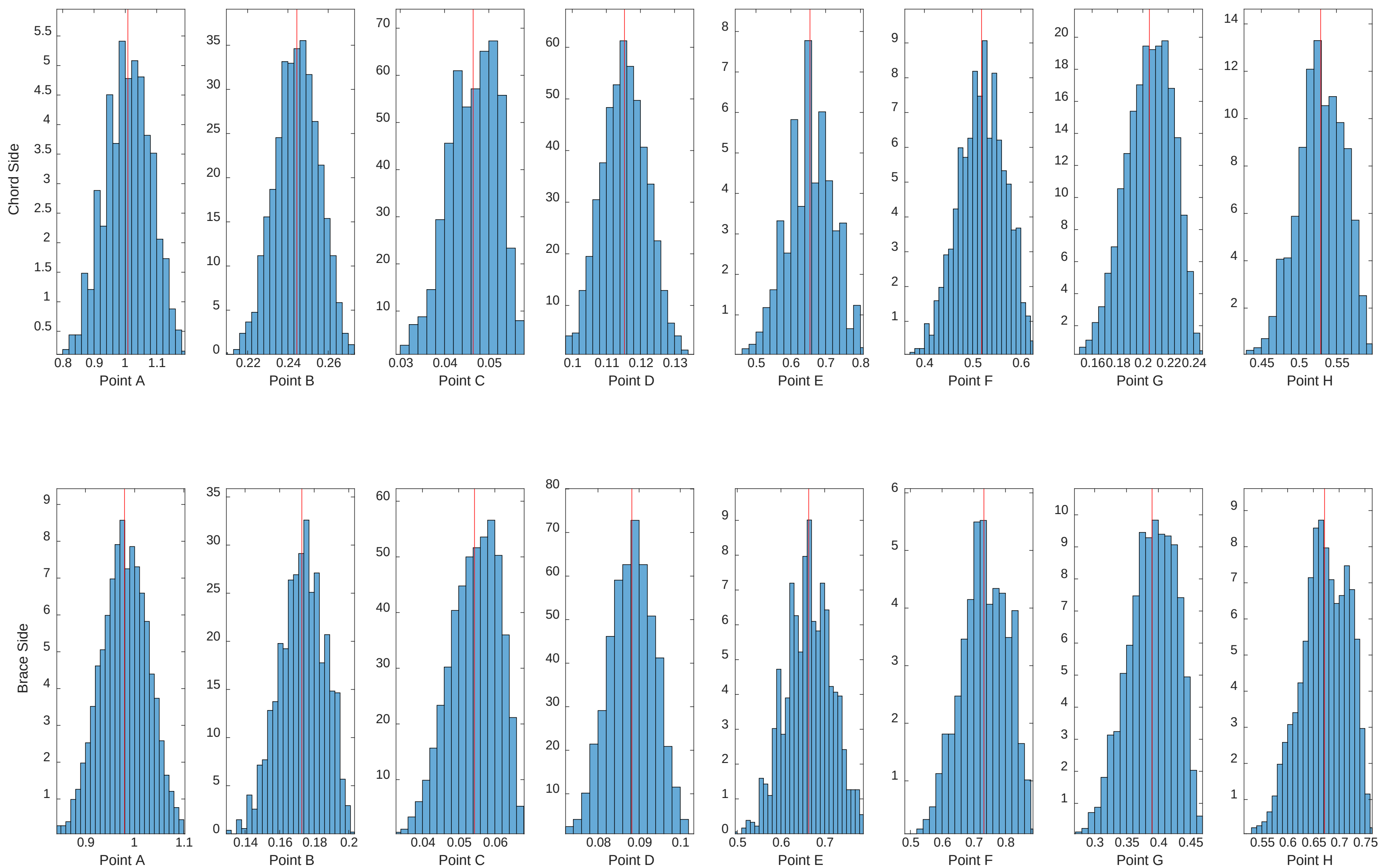
- Estimated stress ranges and number of cycles for position 1 (upper crown heel point) and mean wind speed of 25m/s.
- The method used in ISO 19902 differs in the number of cycles than the method used in DNV. The stress ranges using ISO 19902 may be higher for which reason larger fatigue damage is estimated.





Branner, K., Toft, H.S., Haselbach, P., Natarajan, A. and Sørensen, J.D., "Reliability Assessment of Fatigue Critical Welded Details in Wind Turbine Jacket Support Structures ",Proceedings of 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), 2013, ASME

Variation of Damage at a Joint



Reliability based design of a Jacket

- Determine lifetime, T_L considering uncertainities in the miners rule sum, load amplitude, stress concentration factors and material properties.

$$g = \Delta - \sum_{i,1} \frac{t\, n_i}{K_1 \left(X_{SCF} X_L \Delta\sigma_i \right)^{-m_1}} - \sum_{i,2} \frac{t\, n_i}{K_2 \left(X_{SCF} X_L \Delta\sigma_i \right)^{m_2}} \geq 0$$

- Assuming distribution functions for Δ X_L and X_{SCF} and DNV specified K and m parameters, the probability of failure or reliability index is estimated for different jacket design parameters.

- Given stress cycles, ν, damage, D

Wall thickness increase, z can be computed to maintain target reliabilty levels

No.	ISO 19902 γ_{FD}=10			DNV γ_{FD}=3		
	ν	D	z	ν	D	z
1	$1.68 \cdot 10^7$	1.13	1.025	$2.07 \cdot 10^7$	0.05	0.544
2				$2.07 \cdot 10^7$	0.14	0.674
3	$2.03 \cdot 10^7$	0.48	0.864	$2.03 \cdot 10^7$	0.20	0.727
4				$2.05 \cdot 10^7$	0.11	0.639
5	$2.04 \cdot 10^7$	0.08	0.600	$2.04 \cdot 10^7$	0.04	0.513
6				$1.87 \cdot 10^7$	0.03	0.482
7	$1.78 \cdot 10^7$	0.08	0.597	$1.78 \cdot 10^7$	0.03	0.501
8				$1.95 \cdot 10^7$	0.03	0.485

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Summary

- The turbulence model parameters including length scale and Mann anisotropy parameter affect the tower top and tower base damage equivalent moments and extreme moments more than blade root loads.

- The blade aerodynamic uncertainty results in extreme load variations between 10%-20% on the tower top, tower base and blade tip deflection.

- Advanced load alleviation control on a wind turbine, such as individual pitch control yield both a reduction in the mean of the annual maximum load distribution and its scatter (COV) which in turn translates into higher structural reliability level in the face of uncertainty in turbulence.

- Due to the wide variation of fatigue damage predictions on offshore jacket substructures, a reliability based approach is required to design the jacket to a satisfactory annual probability of failure and expected lifetime.