UNCERTAINTY MODELLING FOR CALIBRATION OF PARTIAL SAFETY FACTORS FOR DESIGN OF WIND TURBINE COMPONENTS

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Outline

- Introduction
- Probabilistic design of wind turbines
- Calibration of partial safety factors in CD IEC 61400-1 ed 4
- Fatigue reliability analysis of wind turbine cast components
- Assessment of extreme design loads for modern wind turbines using the probabilistic approach Aspects of uncertainty quantification and probabilistic methods
- Some ongoing projects
  - From wind climate to wind turbine loads - Efficient and accurate decision support and risk analysis
  - Probabilistic design
- Concluding remarks

Introduction

Minimize the Total Expected Life-Cycle Costs

↓

Minimize Levelized Cost Of Energy (LCOE)

Initial Costs	• Dependent on *Reliability* Level
Operation & Maintenance Costs	• Dependent on O&M Strategy, Availability and *Reliability*
Failure Costs	• Dependent on *Reliability*

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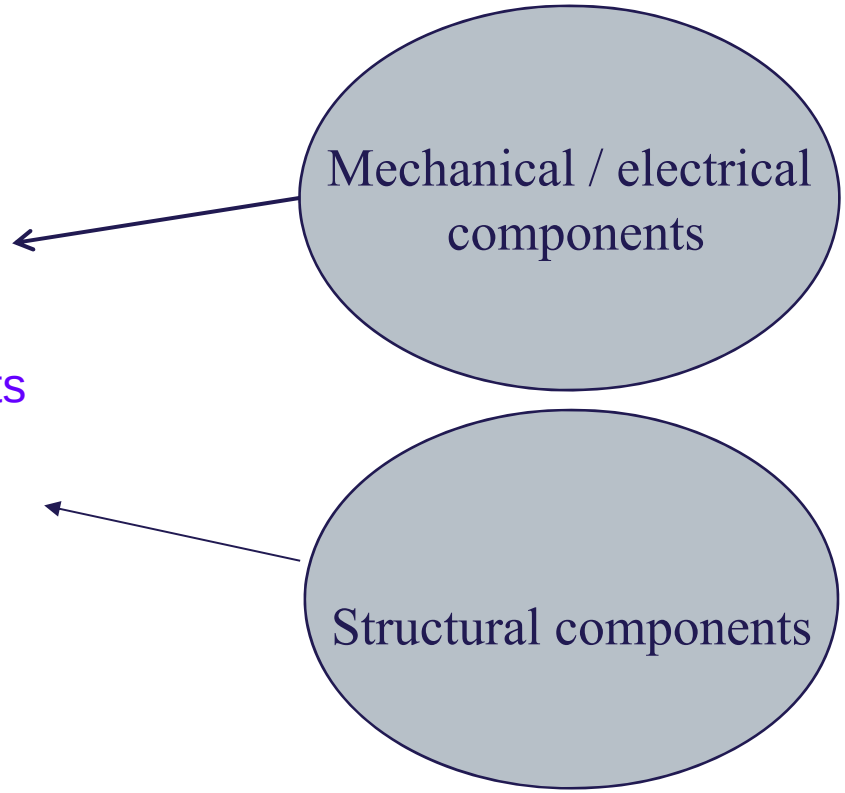
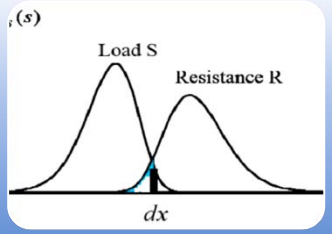
Introduction

Observed failure rates
Classical reliability theory

Probabilistic models for failure events
Structural Reliability Theory

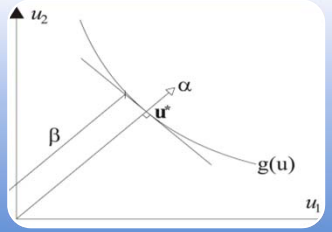


Introduction



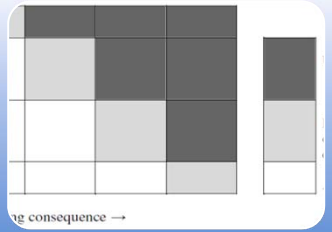
Uncertainty Modelling

- Resistance
- Loads
- Models



Reliability Assessment

- Probability of failure
- Calibration of safety factors



Risk Analysis

- Consequences
- Rational decision making

- Using models and principles by JCSS (Joint Committee on Structural Safety)

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Introduction

Some standards and guidelines :

- ISO 2394:2015: General principles for reliability of structures
  - Performance modelling
  - Uncertainty representation and modelling
  1. Risk-informed decision making
  2. Reliability-based decision making – probabilistic design
  3. Semi-probabilistic method – partial safety factor (LRFD) method

- IEC 61400-1 (ed. 4):2014: Wind turbines – Design requirements

- JCSS: Joint Committee on Structural Safety: Probabilistic Model Code
  - Part 1: Basis of design
  - Part 2: Load models
  - Part 3: Material properties

Introduction

Stochastic modeling of loads:

- Wind
- Waves
- Currents

Influenced by:

- o Control system
- o Aerodynamics
- o Structural dynamics

Stochastic modeling of resistances / material parameters:

- Blades: composite materials
- Hub, …: cast steel
- Tower: structural steel
- Foundation: soil

Probabilistic Design of Wind Turbines

www.lmwindpower.com

Overall design approach:

- Combination of
  - Theoretical computational models
  - Test of components / materials
  - Measurements of climatic conditions
  - Full-scale tests / measurements
- Information are subject to physical, model, statistical and measurement uncertainties
- Uncertainties can be assessed and combined by use of Bayesian statistical methods for use in probabilistic design

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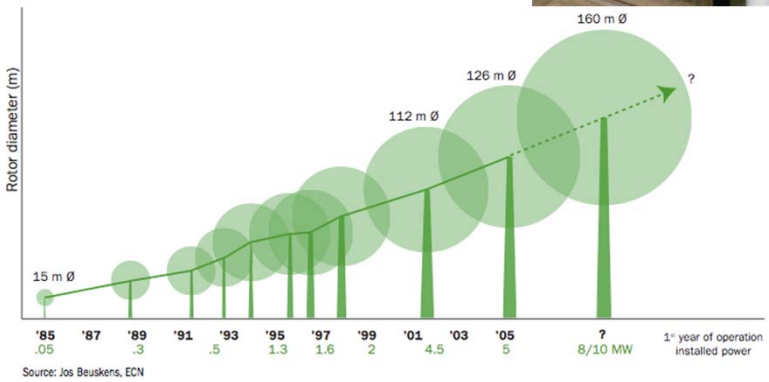
Probabilistic Design of Wind Turbines

6-8 MW - www.siemens.com

8 MW - www.vestas.com



Testcenter: Østerild

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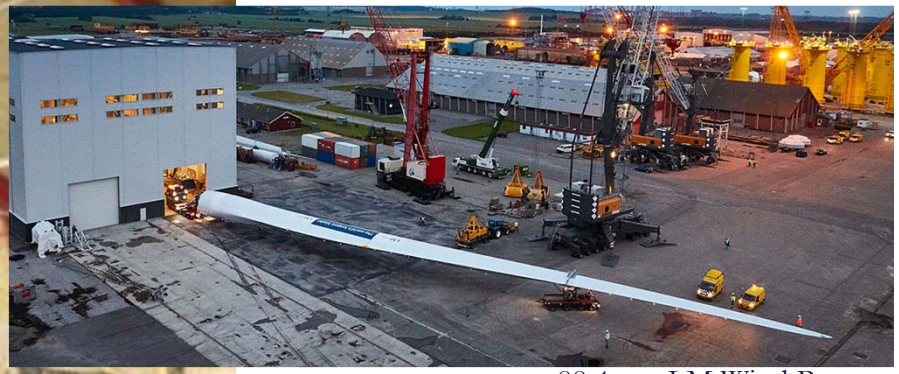
Probabilistic Design of Wind Turbines

Test and research infrastructure – Denmark

Nacelle test:

www.LORC.com

Blade test:



88.4 m - LM Wind Power

www.blaest.com

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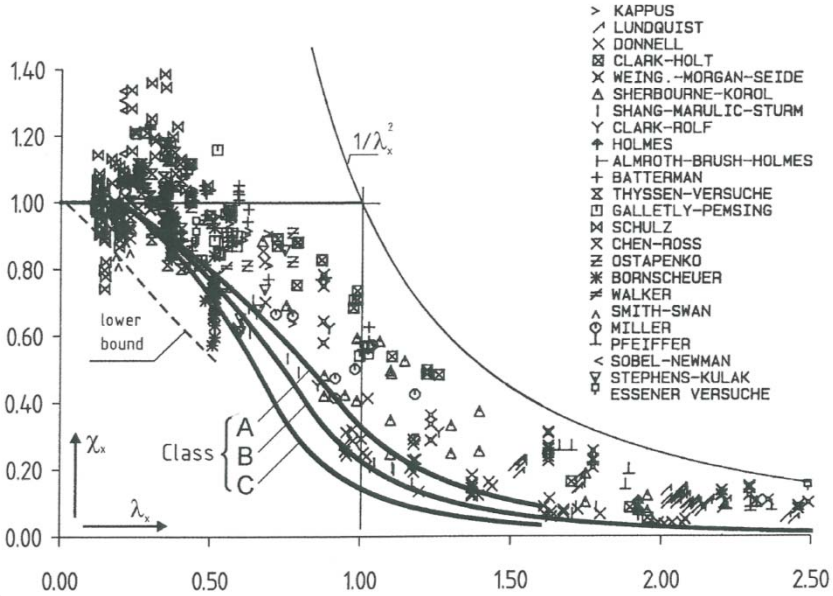
Probabilistic Design of Wind Turbines (Tower)

Failure modes for wind turbine towers:

- Buckling failure
- Yield strength
- Fatigue properties
- Bolted/welded connections



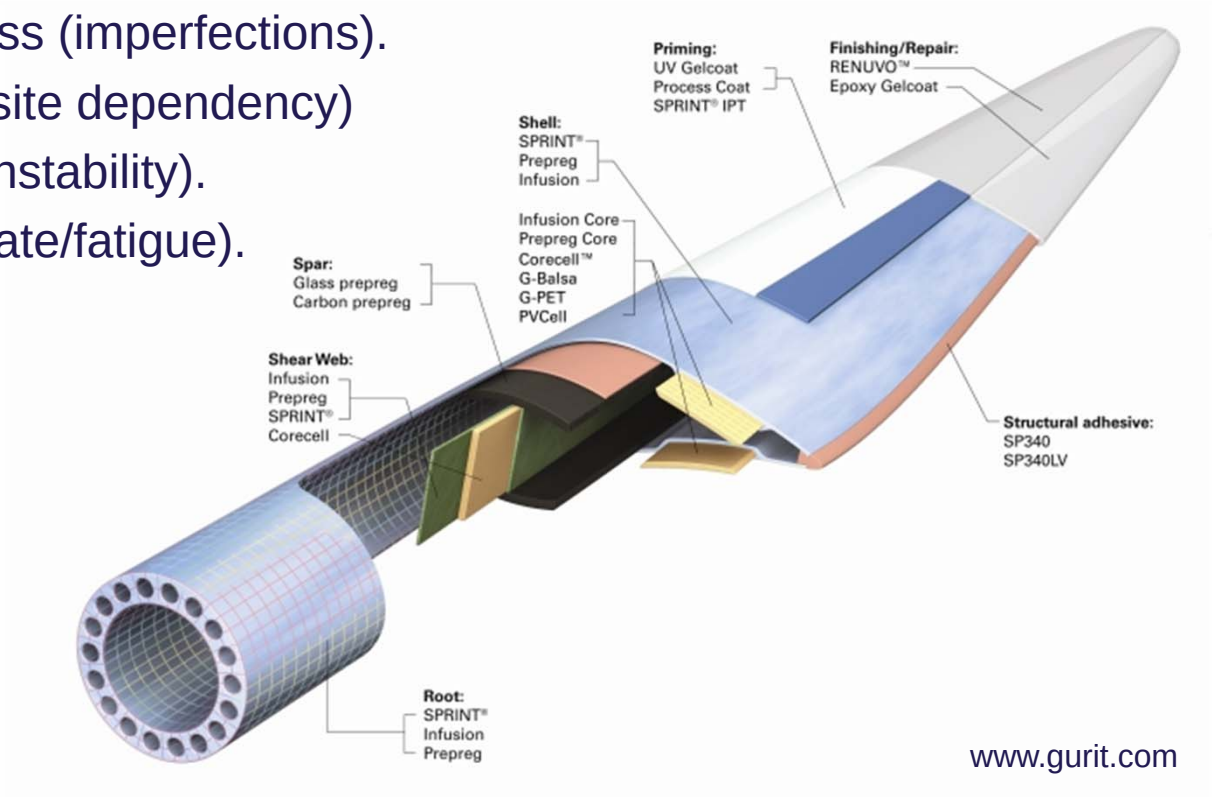
ECCS 2008

www.bladt.dk

Probabilistic Design of Wind Turbines (Blades)

Uncertainties for wind turbine blades:

- Aerodynamics, damping,…
- Complex material structure (damage tolerance).
- Manufacturing process (imperfections).
- Loading conditions (site dependency)
- Structural analysis (instability).
- Failure criteria (ultimate/fatigue).



www.gurit.com

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Reliability-based calibration of partial safety factors

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Reliability modeling of structural components

Design load cases in IEC 61400:

- Normal operation – power production (DLC 1)
- Power production plus occurrence of fault (DLC 2)
- Start up (DLC 3)
- Normal shut down (DLC 4)
- Emergency shut Down (DLC 5)
- Parked (standing still or idling) (DLC 6)
- Parked and fault Conditions (DLC 7)
- Transport, assembly, maintenance and Repair (DLC 8)

Reliability assessment in normal operation (DLC 1)

Stochastic model for annual maximum load based on ‘Load extrapolation’:

$$P = X_{dyn} X_{\exp} X_{aero} X_{str} L$$

X_{dyn} uncertainty related to modeling of the dynamic response, including uncertainty in damping ratios and eigenfrequencies

X_{exp} uncertainty related to the modeling of the exposure (site assessment) - such as the terrain roughness and the landscape topography

X_{aero} uncertainty in assessment of lift and drag coefficients and additionally utilization of BEM, dynamic stall models, etc

X_{str} uncertainty related to the computation of the load-effects given external load

Limit state equation for structural component:

$$g = z\,\delta\,R - X_{dyn} X_{\exp} X_{aero} X_{str} L$$

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Reliability assessment in parked position (DLC 6)

Stochastic model for annual maximum load based on ‘Load extrapolation’:

$$P = X_{dyn} X_{\exp} X_{aero} X_{str} L$$

L extreme load effect from wind pressure: Gumbel distributed

Limit state equation for structural component:

$$g = z\,\delta\,R - X_{dyn} X_{\exp} X_{aero} X_{str} L$$

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Reliability assessment with faults (DLC 2)

Annual frequency of failure of structural component *i* considering faults (e.g. electrical component):

$$\nu_{F,i} = P\left(F_i \middle| \text{fault}\right) \nu_{annual}\left(\text{fault}\right)$$

probability of failure of structural component *i* given fault

annual frequency of fault

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Reliability assessment with fault - example

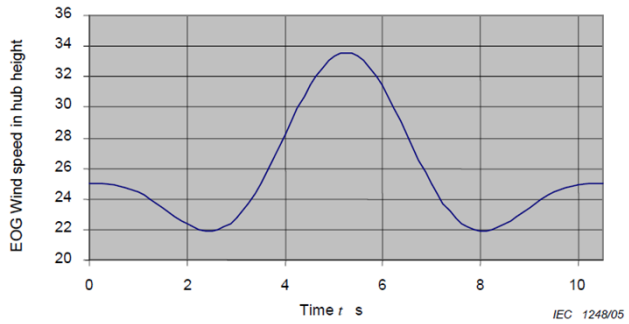
Annual failure rate for structural component *i* when grid loss and occurrence of an EOG (Extreme Operating Gust) – DLC 2.3:

$$\lambda_{F_1} = \{P(F_i | V \in I_1 \cap \text{grid loss} \cap \text{EOG}) P(V \in I_1) + P(F_i | V \in I_2 \cap \text{grid loss} \cap \text{EOG}) P(V \in I_2)\} \cdot P(\text{EOG}) \cdot \nu_{\text{grid loss}}$$

$P(F | V \in I_1 \cap \text{grid loss} \cap \text{EOG})$ probability of failure for a specific structural failure mode given a mean wind speed in the range I_1 , e.g. [8-15 m/s] and occurrence of an EOG

$\nu_{\text{gridd loss}}$ mean annual rate of occurrence of grid loss

Extreme Operating Gust:



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Reliability level

- Building codes: e.g. Eurocode EN1990:2002:
  annual $P_F = 10^{-6}$ or $\beta = 4.7$

- Fixed steel offshore structures:
  manned: annual $P_F \sim 3\ 10^{-5}$ or $\beta = 4.0$
  unmanned: annual $P_F \sim 5\ 10^{-4}$ or $\beta = 3.3$

- Observation of failure rates for wind turbines 1984 – 2000
  Failure of blades: approx. $2.0 \cdot 10^{-3}$ per year (decreasing)
  Wind turbine collapse: approx. $0.8 \cdot 10^{-3}$ per year (decreasing)

Reliability level

Assumptions:

- A systematic reconstruction policy is used (a new wind turbine is erected in case of failure or expiry of lifetime).
- Consequences of a failure are ‘only’ economic (no fatalities and no pollution).
- Wind turbines are designed to a certain wind turbine class, i.e. not all wind turbines are ‘designed to the limit’.

→ Target reliability level corresponding to an *annual nominal probability of failure*:

$5\ 10^{-4}$ (annual reliability index equal to 3.3)

Application of this target value assumes that the risk of human lives is negligible in case of failure of a structural element.

Corresponds to minor / moderate consequences of failure and moderate / high cost of safety measure (JCSS)

Calibration of safety partial factors - materials

The load bearing capacity, R is assumed to be estimated by:

$$R = b\,\delta\,R(\mathbf{X}, a)$$

$\mathbf{X}$	strength parameters
a	geometrical parameters, …
$R(\ )$	model for resistance
δ	model uncertainty (mean value = 1)
b	bias in resistance model

Model 1: Design value:

$$R_d = b\frac{R(X_{1,d},\ldots,X_{n,d},a_d)}{\gamma_\delta} \qquad X_{j,d} = \eta_1 \frac{X_{j,k}}{\gamma_{m,j}}$$

Model 2: Design value:

$$R_d = b\frac{R(\eta_1 X_{1,k},\ldots,\eta_n X_{n,k},a_d)}{\gamma_\delta \gamma_R}$$

Model 3: Design value obtained from tests:

$$R_d = \frac{R_k}{\gamma_M}$$

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Calibration of safety partial factors – materials

For calibration it is assumed that

- no bias (hidden safety) in calculation of load effects
- no bias (hidden safety) in calculation of load bearing capacities
- no scale effects, time duration effects,…

i.e. η = 1 and b = 1

Limit state equation:

Design equation:

$$g = z\,\delta\,R - X_{dyn} X_{\exp} X_{aero} X_{str} L$$

$$\frac{z\,R_k}{\gamma_R} - \gamma_f L_k \geq 0$$

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Partial safety factors – materials

Variable	Distribution	Mean	COV	Quantile	Comment
R	Lognormal	-	V_R	5%	Strength
δ	Lognormal	-	V_δ	Mean	Model uncertainty
L – DLC 1.1	Weibull	-	0.15	0.98	Annual maximum load effect obtained by load extrapolation
L – DLC 6.1	Gumbel	-	0.2	0.98	Annual maximum wind pressure – European wind conditions
X_{dyn}	Lognormal	1.00	0.05	Mean	
X_{exp}	Lognormal	1.00	0.15	Mean	
X_{aero}	Gumbel	1.00	0.10	Mean	
X_{str}	Lognormal	1.00	0.03	Mean	

Characteristic value for R: 5% quantile
Characteristic value of model uncertainty: mean value

Partial factor for loads: $\gamma_f = 1.35$

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Partial safety factors – materials

Model 1: γ_m and $\gamma_\Delta = \dfrac{\gamma_\delta}{b}$ approximately: $\gamma_M = \dfrac{\gamma_\delta \gamma_R}{b}$

Model 2: $\gamma_M = \dfrac{\gamma_\delta \gamma_R}{b}$

Model 3: $\gamma_M = \gamma_\delta$

Coefficient of variation for strength parameter in model 1, V_X or resistance in model 2 and 3, V_R	≤5 %	10 %	15 %	20 %	25 %
γ_m in model 1 or γ_R in model 2 and 3	1,0	1,0	1,0	1,0	1,0

Coefficient of variation for model uncertainty for resistance model in model 1, V_δ	0 %	5 %	10 %	15 %	20 %
γ_δ	1,15	1,20	1,25	1,35	1,45

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Partial safety factors – loads

Reduction factor on load partial safety factor, γ_f.

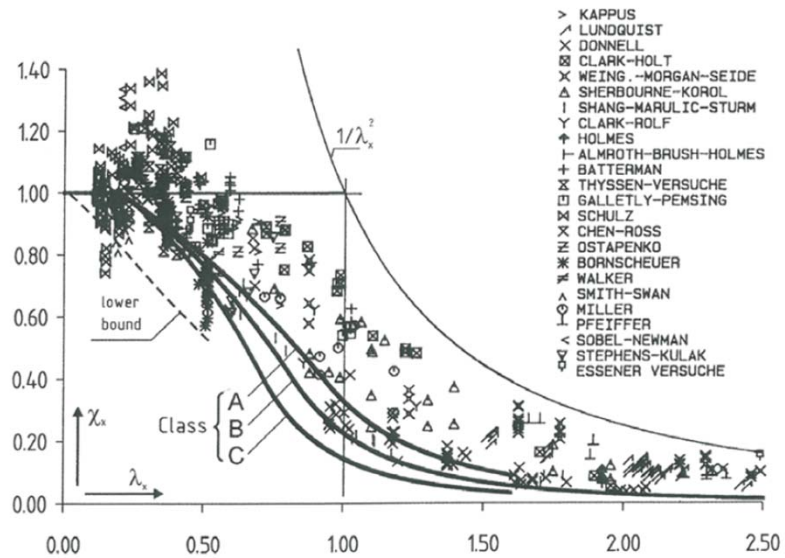
	Reduction factor
COV (X_{dyn}) = 0.05 → 0.03	0.99
COV (X_{exp}) = 0.15 → 0.10	0.93
COV (X_{aero}) = 0.10 → 0.05	0.93
COV (X_{str}) = 0.03 → 0.00	0.99

Example: Reliability-based calibration of material partial safety factors

Example: Buckling - EN1993 calculation model

Assumptions:

- No internal stiffners in the cylinder
- Boundary conditions BC 2
- Bending moment applied – No axial force
- Quality class B in EN 1993-1-6
- Yield strength: f_{yk} = 235MPa (COV=5%)
- E-module: 210.000MPa



- Test results only based on axial loading. EN COV=13%, b = 1 / 0,85
- The bias is normally slightly less for bending. The COV for bending is unknown.
- → γ_R = 1,31
- → γ_M = 1,31 * 0,85 ~ 1,1

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Partial safety factors – fatigue – welded details

- SN approach: linear or bi-linear
- Miner's rule

Variable	Distribution	Expected value	Standard deviation / Coefficient Of variation	Comment
Δ	N	1	$COV_{\Delta} = 0.30$	Model uncertainty Miner's rule
X_{Wind}	LN	1	COV_{Wind}	Model uncertainty wind load
X_{SCF}	LN	1	COV_{SCF}	Model uncertainty stress concentration factor
m_1	D	3		Slope SN curve
$\log K_1$	N	determined from $\Delta\sigma_D$	$\sigma_{\log K_1} = 0.2$	Parameter SN curve
m_2	D	5		Slope SN curve
$\log K_2$	N	determined from $\Delta\sigma_D$	$\sigma_{\log K_2} = 0.2$	Parameter SN curve
$\Delta\sigma_F$	D	71 MPa		Fatigue strength
$\log K_1$ and $\log K_2$ are fully correlated				

Partial safety factors – fatigue – welded details

Partial safety factors are introduced:

γ_f a fatigue load partial safety factor multiplied to the fatigue stress ranges obtained by e.g. Rainflow counting.

γ_m a fatigue strength partial safety factor. The design value of the fatigue strength is obtained by dividing the characteristic fatigue strength by .

Total coefficient of variation of the fatigue load: $COV_{load} = \sqrt{COV_{Wind}^2 + COV_{SCF}^2}$

Partial safety factors fo $\gamma_m = 1.25$

Coefficient of variation, COV_{load}	0-5 %	5-10 %	10-15 %	15-20 %	20-25 %	25-30 %
γ_f	0.85	0.90	0.95	1.00	1.10	1.20

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Partial safety factors - fatigue - welded details

Table C5. Examples of COV_{SCF} .

COV_{SCF}	Fatigue critical detail
0.00	Statically determinate systems with simple fatigue critical details (e.g. girth welds) where FEM analyses are performed
0.05	Statically determinate systems with complex fatigue critical details (e.g. multi-planar joints) where FEM analyses are performed
0.10	Statically in-determinate systems with complex fatigue critical details (e.g. doubler plates) where FEM analyses are performed
0.15	2 dimensional tubular joints using SCF parametric equations
0.20	Tubular joints in structures where tubular stiffness is modeled by Local Joint Flexibility (LJF) models and SCF parametric equations are used

Partial safety factors – fatigue - welded details

Table C6. Examples of COV_{Wind} .

COV_{Wind}	Uncertainty is assessment of fatigue wind load
0.10-0.15	More than 2 years of climatic data, corrected with MCP techniques. Wind measurements above and below wind turbine hub height. Flat terrain with low roughness
0.15-0.20	Minimum 1 year of climatic data. Wind measurements at hub height and below. Non-complex site with medium roughness.
0.20-0.25	Less than 1 year of data, not corrected with MCP techniques Wind measurements below hub height. Complex terrain.

Fatigue reliability analysis of wind turbine cast components

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Fatigue reliability analysis of wind turbine cast components

Objectives:

- Formulate stochastic models for initial damage/defect sizes and distribution in time and space
- Reliability assessment for fatigue failure using the SN-curve approach and the fracture mechanics approach

- PhD students: Hesam Mirzaei Rafsanjani and Arvydas Beržonskis

- Rafsanjani, H.M., J.D. Sørensen, K. Mukherjee, S. Fæster and A. Sturlason: Statistical analysis of manufacturing defects on fatigue life of wind turbine casted Component. Proc. ASRANET. 2014.
- Rafsanjani, H.M. & J.D. Sørensen: Reliability Analysis of Fatigue Failure of Cast Components for Wind Turbines. Energies, 2015, Vol. 8, pp. 2908-2923.

- The work is supported by the Strategic Research Center “REWIND – Knowledge based engineering for improved reliability of critical wind turbine components”, Danish Research Council for Strategic Research, grant no. 10-093966. Fatigue test data is provided by Vestas Wind Systems A/S, Denmark.

Stochastic modelling of fatigue life of cast components

Models for fatigue life

- LogNormal model

$$\log N(\sigma_a) = m\log\sigma_f - m\log\sigma_{a0} + \frac{1}{b_n}\log s_V - \log(\ell) + \varepsilon$$

- Weibull model

$$F_N(n) = 1 - \exp\left[-\left(\frac{n}{N(\sigma_{a0})}\right)^{b_n}\right]$$

The Maximum Likelihood Method is used to estimate the parameters

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Reliability assessment of cast component

- Limit state equation based on Miners rule for fatigue failure

Stochastic variables:

N number of cycles to failure given stress range and mean stress

X_{SCF} model uncertainty related to determination of stresses given fatigue loads

X_w model uncertainty related to determination of fatigue loads.

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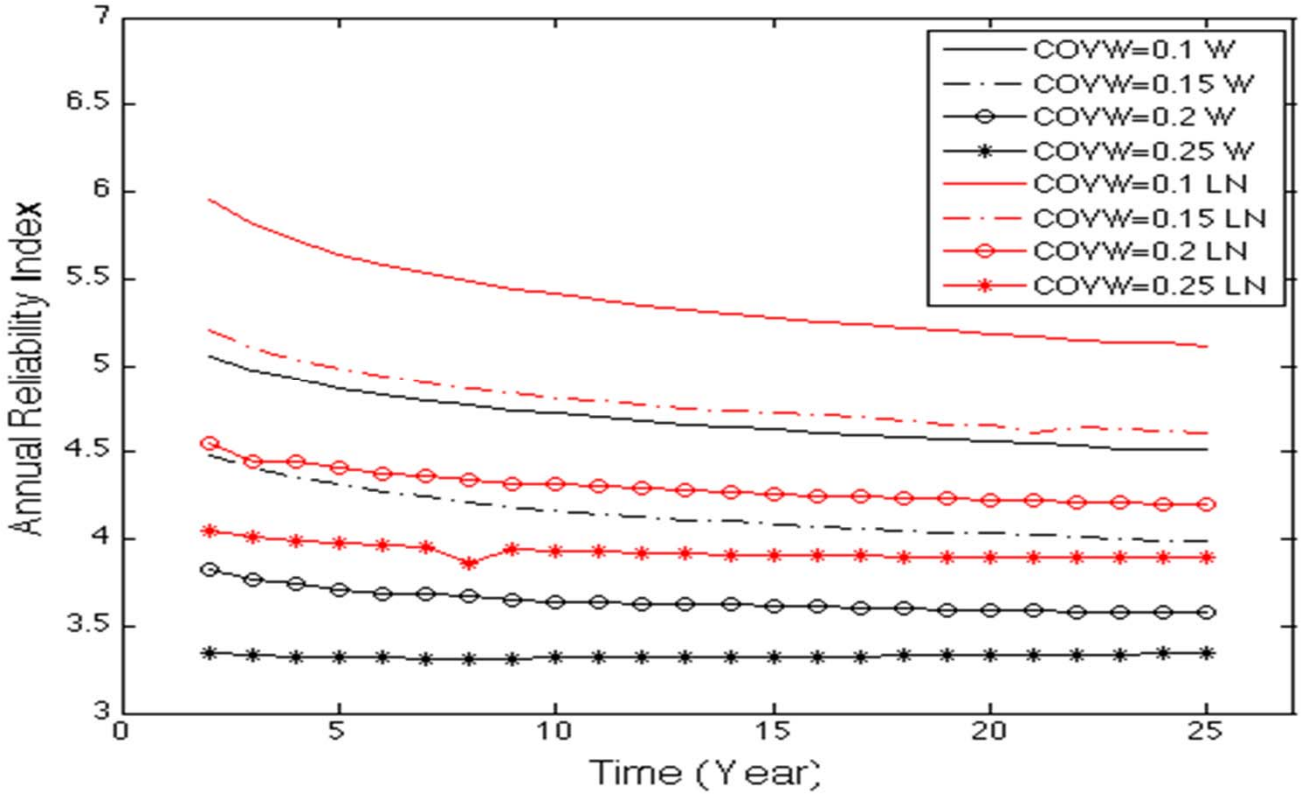
Reliability assessment of cast component

Sample of Sensitivity analysis (for X_W fatigue load uncertainty)



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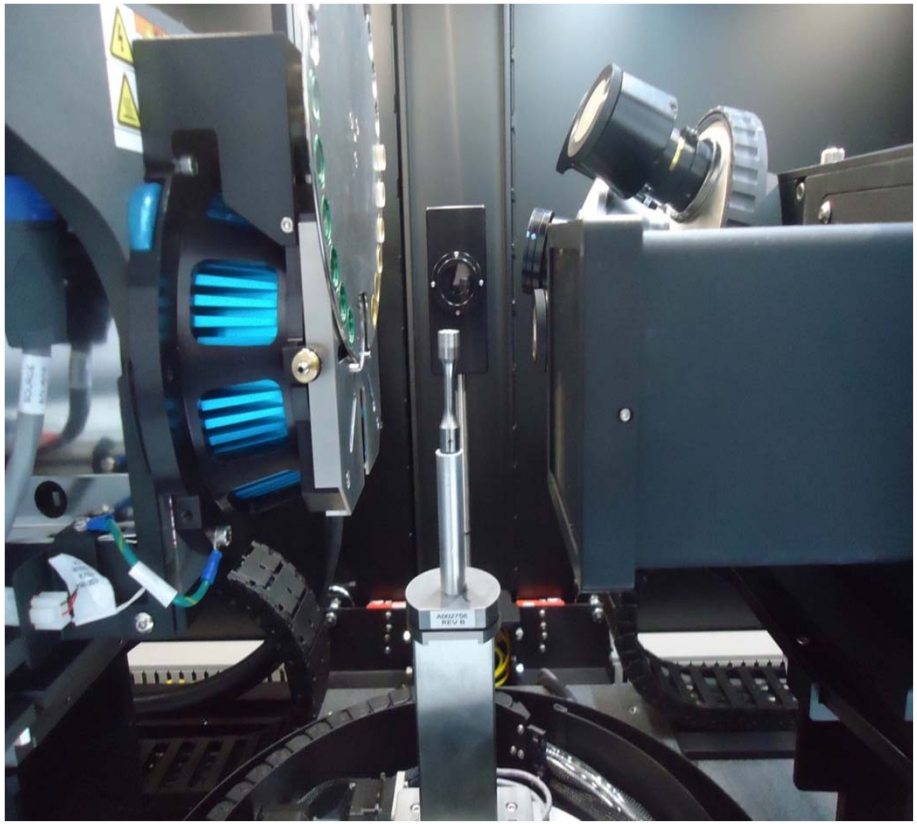
Stochastic modelling of defects

- 3D scan of cast iron fatigue samples



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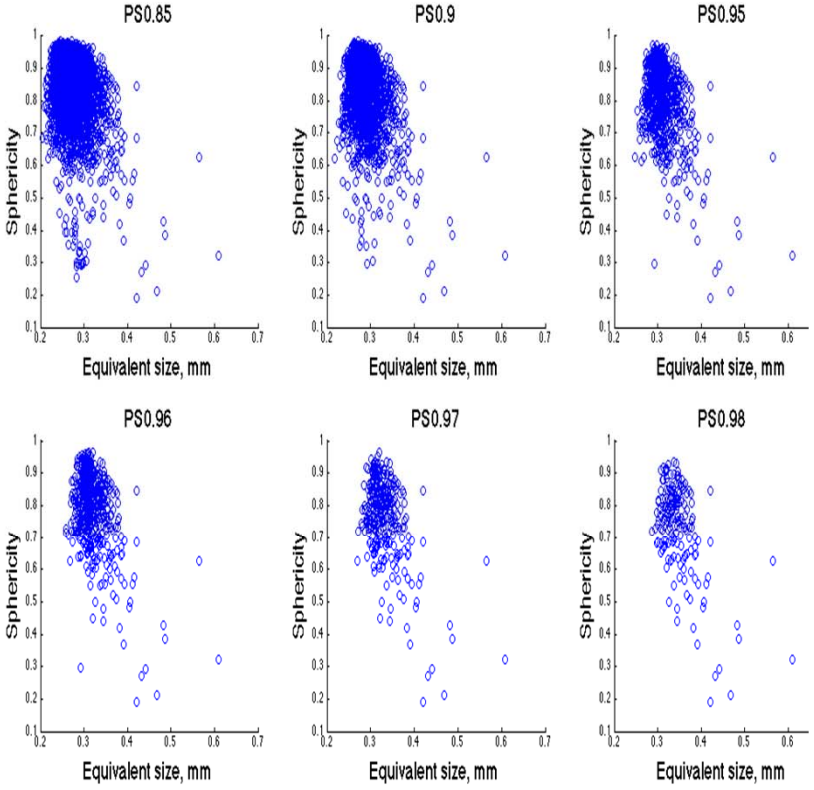
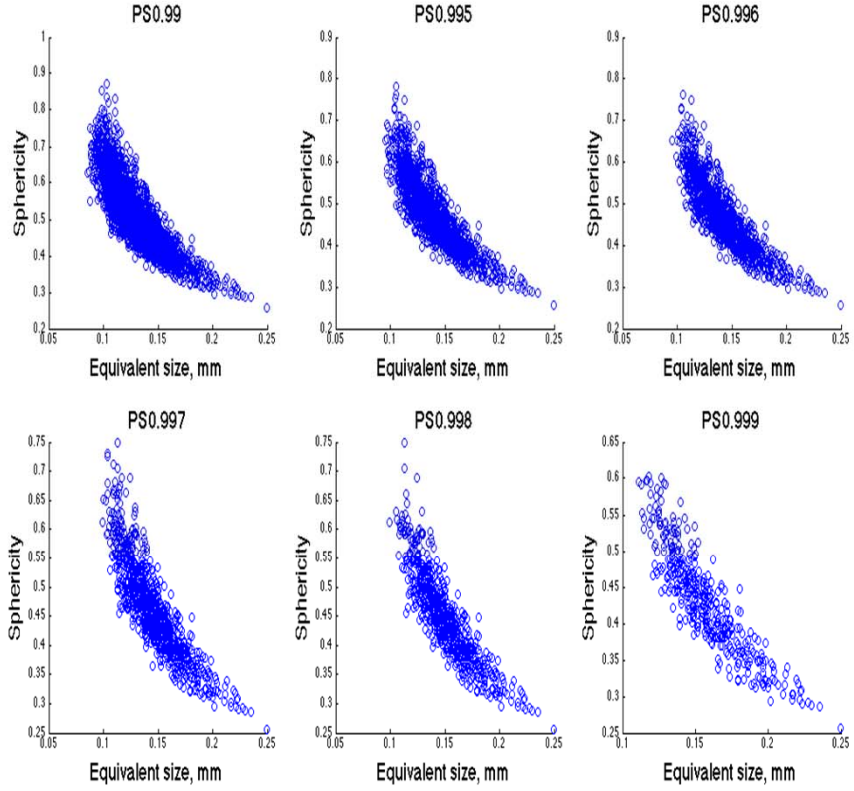
Stochastic modelling of defects

Sand casting



Chill casting



Sphericity vs Equivalent size for each nodules, in sand casting and chill casting samples

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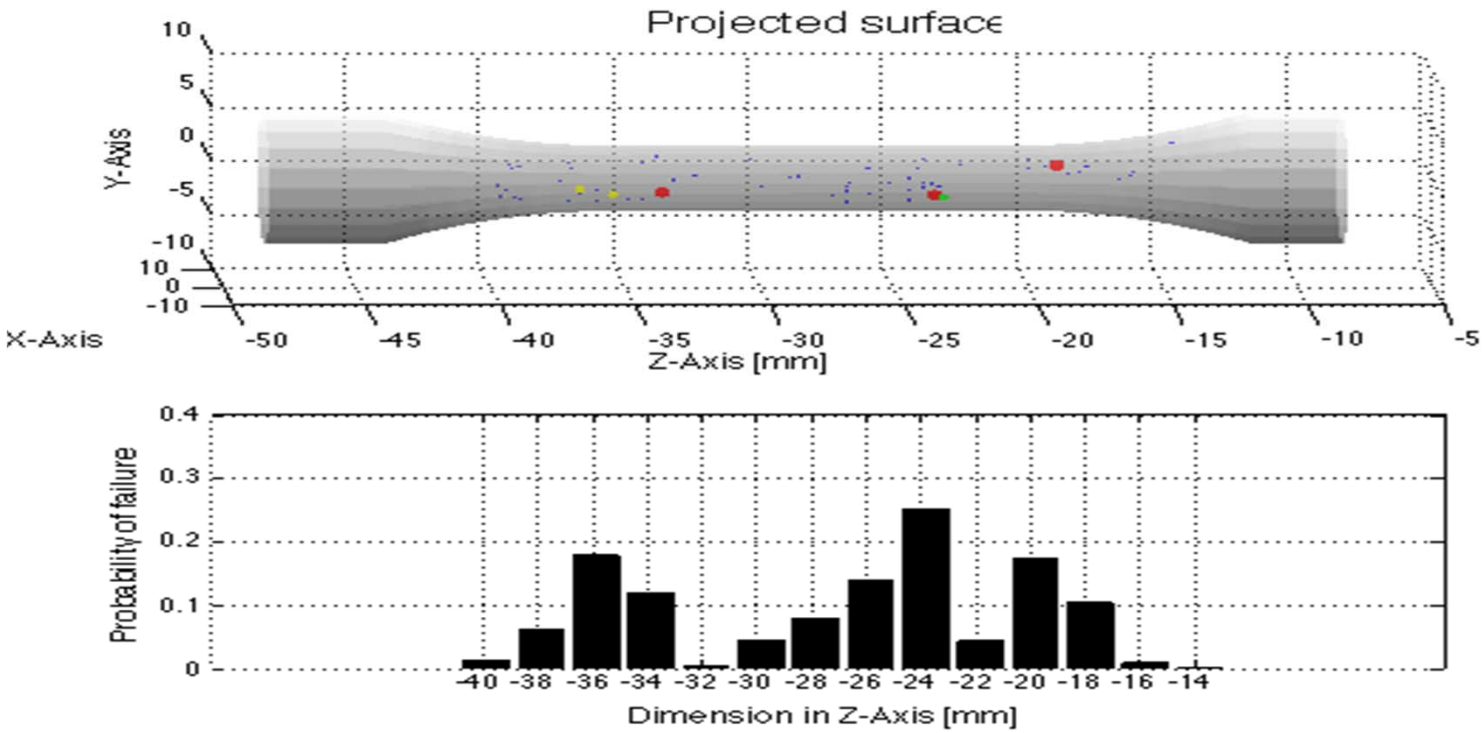
Effects of defects

- Probability of fatigue failure for sub-volumes



- Next: Probability of fatigue failure for whole component

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Assessment of extreme design loads for modern wind turbines using the probabilistic approach Aspects of uncertainty quantification and probabilistic methods

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Examples from: Assessment of extreme design loads for modern wind turbines using the probabilistic approach Aspects of uncertainty quantification and probabilistic methods

Industrial PhD thesis by Imad Abdallah

Supervisors: Anand Natarajan & John Dalsgaard Sørensen

- Impact of uncertainty in airfoil characteristics on extreme loads
- Influence of the control system: structural reliability and safety factors
- …

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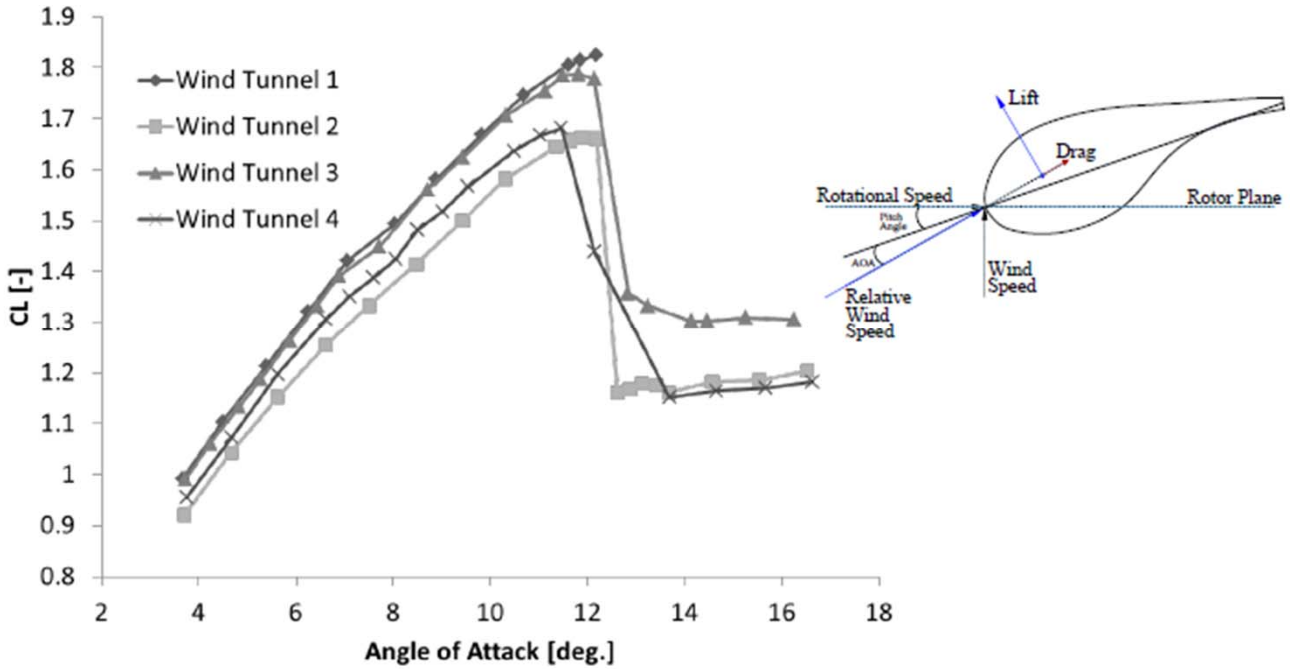
Impact of uncertainty in airfoil characteristics on extreme loads

Abdallah, I., Natarajan, A. and J.D. Sørensen. Impact of Uncertainty in Airfoil Characteristics on Wind Turbine Extreme Loads. Renewable Energy, Vol. 75, 2015, pp. 283-300.

- variations of *CL* in wind tunnels



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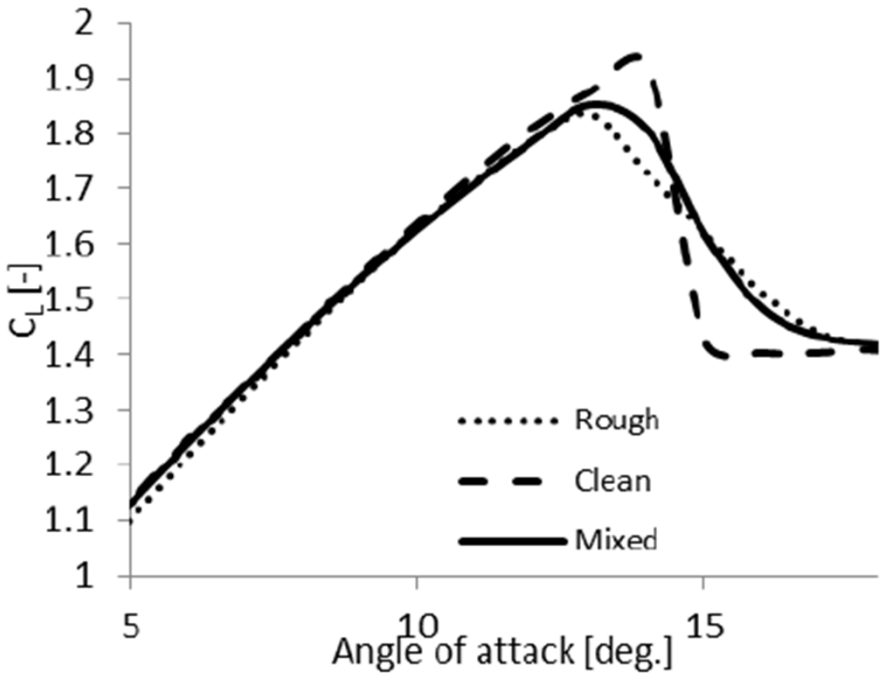
Impact of uncertainty in airfoil characteristics on extreme loads

- Sources of uncertainty - surface roughness



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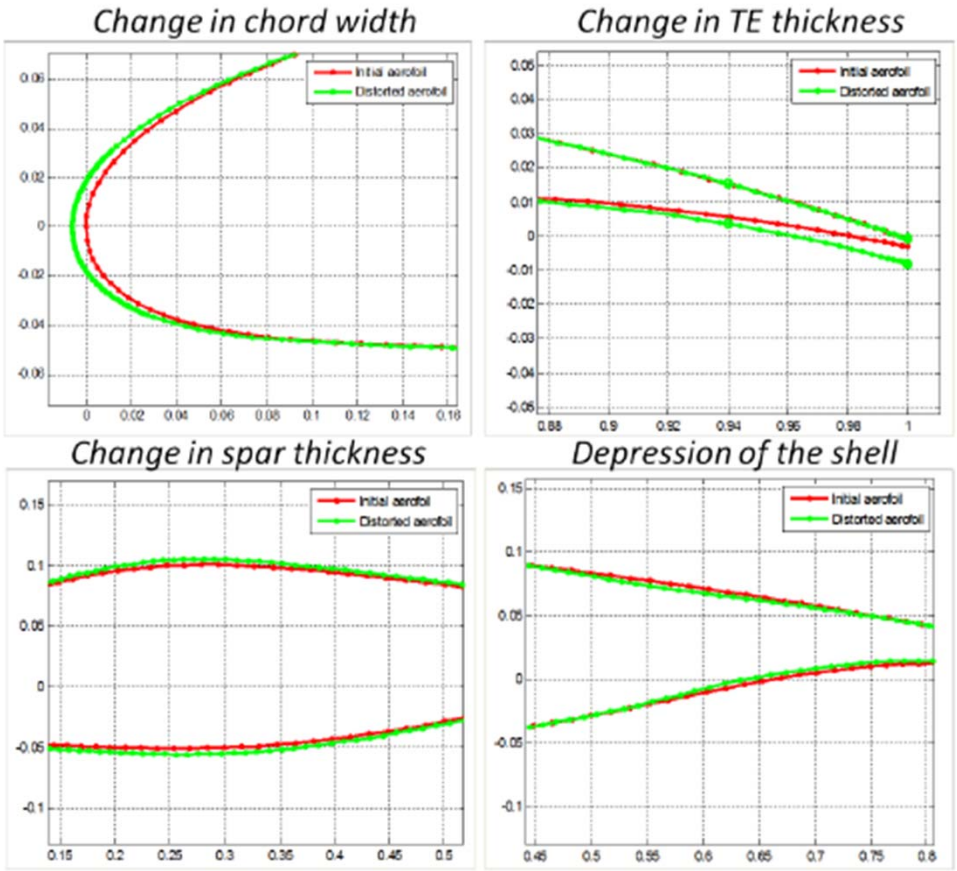
Impact of uncertainty in airfoil characteristics on extreme loads

- Sources of uncertainty - Geometric uncertainty



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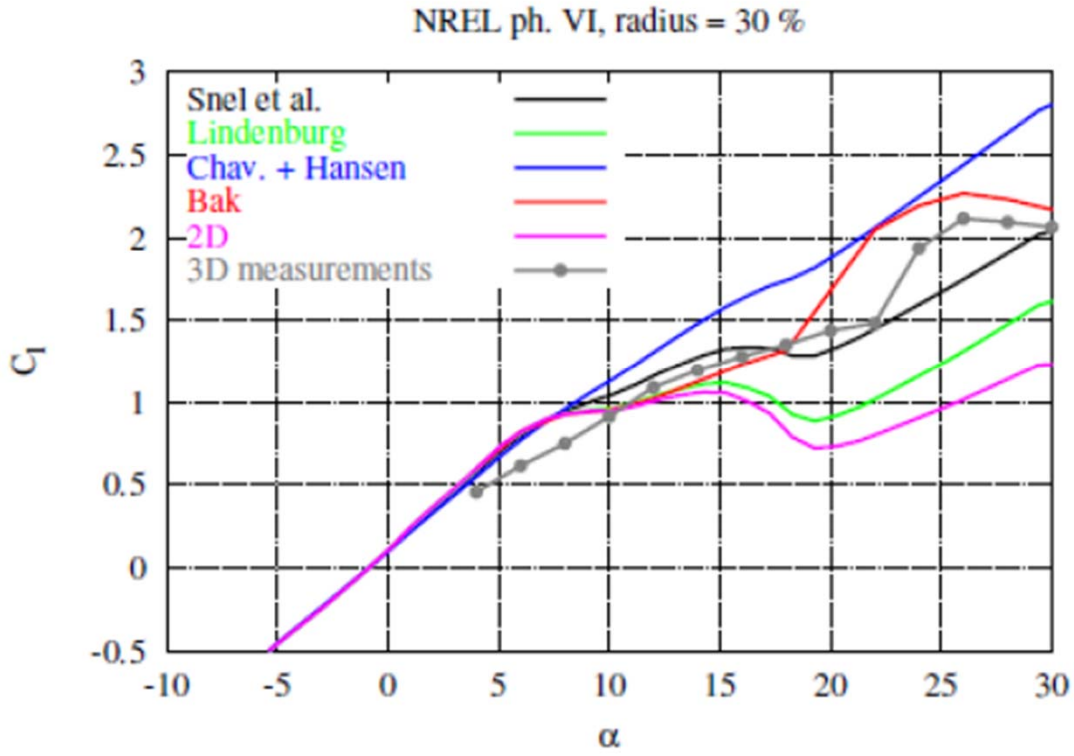
Impact of uncertainty in airfoil characteristics on extreme loads

- Sources of uncertainty - 3D correction models



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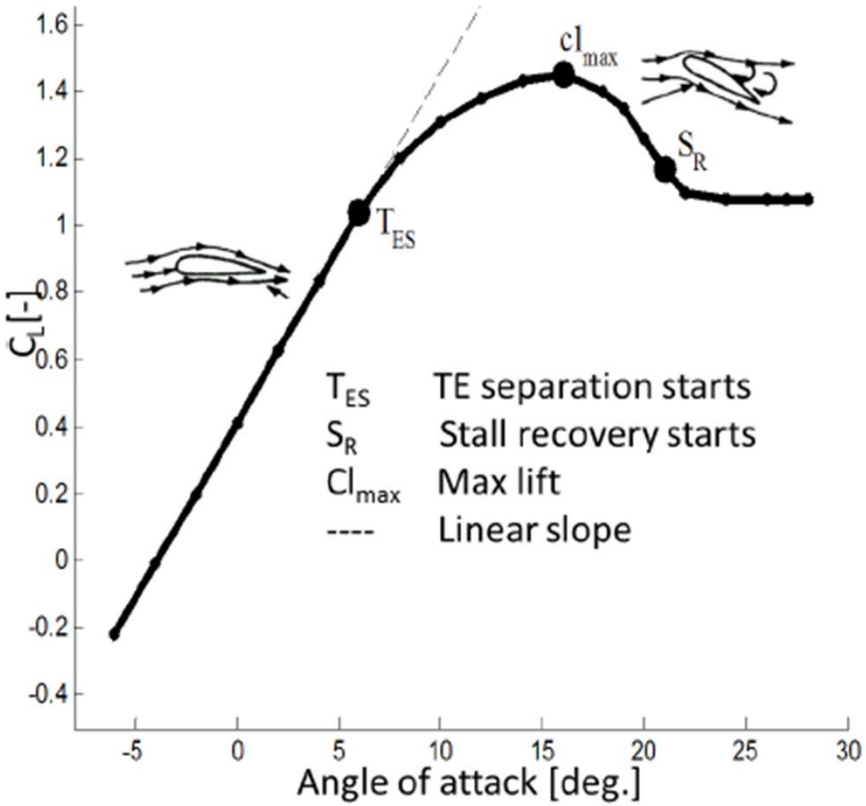
Impact of uncertainty in airfoil characteristics on extreme loads

- Stochastic model



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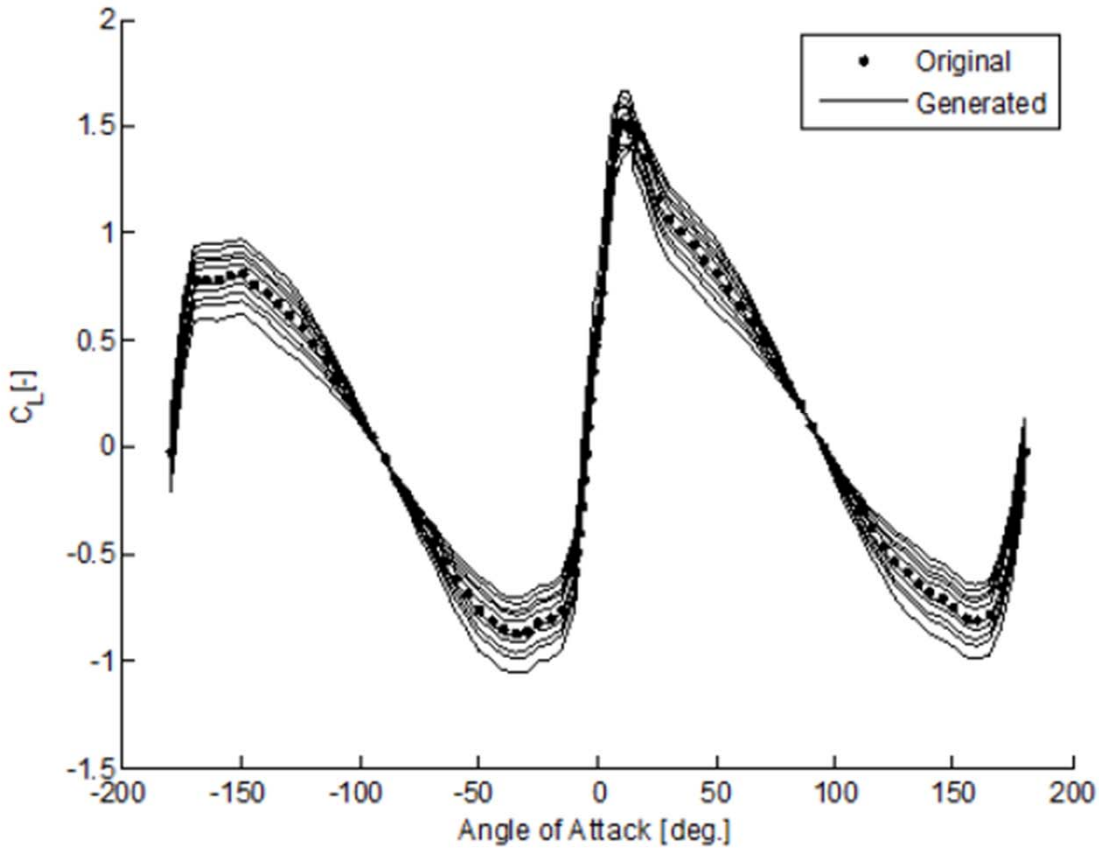
Impact of uncertainty in airfoil characteristics on extreme loads

- Stochastic model - example of synthetically generated C_L



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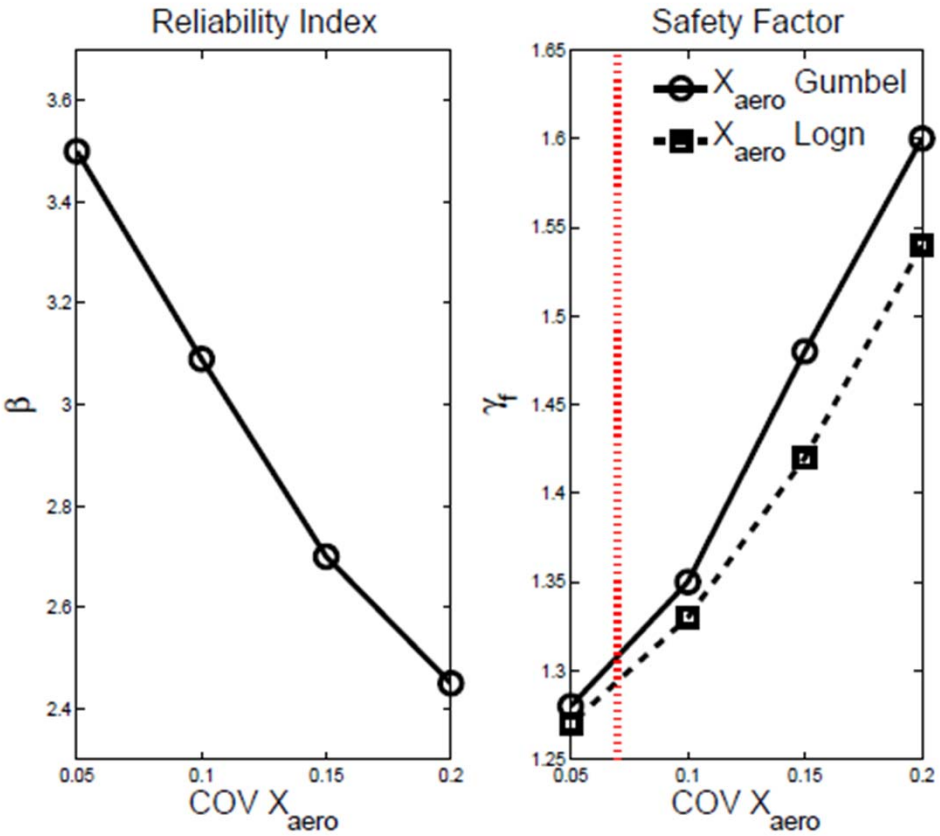
Impact of uncertainty in airfoil characteristics on extreme loads

- Uncertainty propagation to extreme loads by Monte Carlo simulation
- Results: COV for extreme loads

Load Component	Most likely COV
Blade root flapwise bending moment	7%
Blade root edgewise bending moment	2%
Blade flapwise bending moment at 3/4 span	11%
Blade edgewise bending moment at 3/4 span	5%
Tilt and yaw moments at the main shaft	12%
Tower base fore-aft bending moment	7%

Impact of uncertainty in airfoil characteristics on extreme loads

- Application: Effect on loads safety factors of a blade



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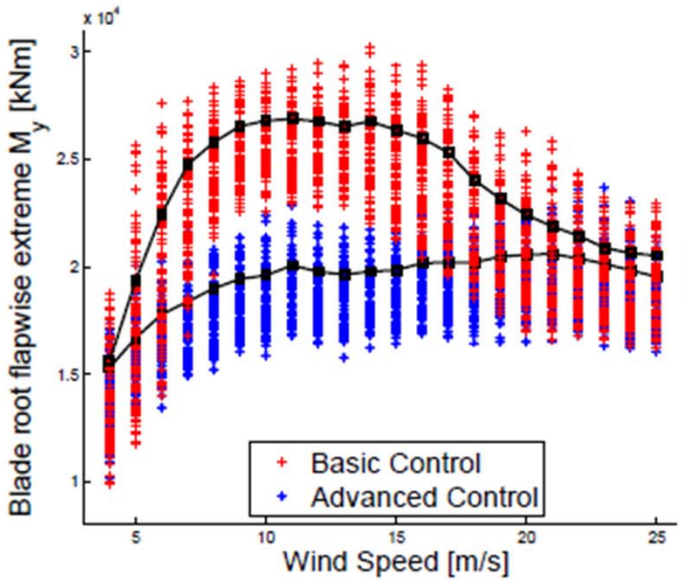
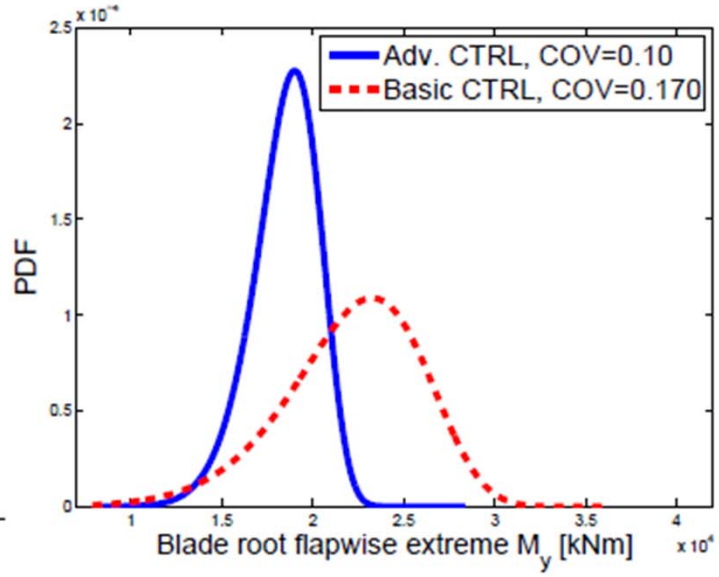
Influence of the control system: structural reliability and safety factors

Abdallah, I., Natarajan, A. and J.D. Sørensen: Influence of the control system on wind turbine loads during power production in extreme turbulence: structural reliability. Renewable Energy, Vol. 87, 2016, pp. 464-477.

- Performance of advanced load controllers





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Examples - ongoing projects

1. From wind climate to wind turbine loads
Efficient and accurate decision support and risk analysis

Industrial PhD

EMD International & Aalborg Unversity - Cooperation with: Nordex and Vattenfall

COMMERCIAL CHALLENGES:

1. A full site-specific aeroelastic load evaluation/optimization requires specialist knowledge.

2. Significant multidisciplinary co-operations between wind analysts and structural engineers are needed to do a proper site-specific load evaluation and optimization.

3. Aeroelastic models on wind turbines are not available for the general wind energy community – they are held as internal models at the wind turbine manufacturers.

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1. From wind climate to wind turbine loads
Efficient and accurate decision support and risk analysis

- Site assessment using IEC61400-1 is a deterministic approach
  - Characteristic values for the design and environmental conditions
  - Partial Safety factors applied
  - A ‘nominal’ reliability level is assumed
- The actual reliability of the turbine depends on site specific factors…
  - … Quality and amount of wind data
  - Mean wind speed, turbulence, shear, air density, …

    …
- Taking into account the site specific uncertainties, is the actual more or less reliable than the “standard design site”?

1. From wind climate to wind turbine loads
Efficient and accurate decision support and risk analysis

Goals:

- To develop a decision support tool for site suitability analysis based on reliability assessment, considering the specific uncertainties of each site.
- To allow wind analysts to do site specific load evaluations (without help from a load expert).
- To allow wind analysts to do site specific load evaluations by use of generic turbines, representative for the main commercially available turbines on the market today
    - Using ‘generic’ response surface models for loads.

1. From wind climate to wind turbine loads
Efficient and accurate decision support and risk analysis

Papers from a previous related Industrial PostDoc project:

- Toft, H.S., L. Svenningsen, W. Moser, J.D. Sørensen and M.L. Thøgersen: Assessment of Wind Turbine Structural Integrity using Response Surface Methodology. Engineering Structures, Vol. 106, 2016, pp. 471–483.
- Toft, H.S., L. Svenningsen, J.D. Sørensen, W. Moser & M.L. Thøgersen: Uncertainty in Wind Climate Parameters and their Influence on Wind Turbine Fatigue Loads. Renewable Energy, Vol. 90, 2016, pp. 352-361.
- Toft, H.S., L. Svenningsen, W. Moser J.D. Sørensen, & M.L. Thøgersen: Wind Climate Parameters for Wind Turbine Fatigue Load Assessment. Journal of Solar Energy Engineering, Vol. 138, 2016.

2. Probabilistic design

Goal: to perform reliability-based design of wind turbine components

1. Identify failure modes
2. Uncertainty modelling:
   - Physical uncertainty - Aleatory
   - Model, Measurement and Statistical uncertainties - Epistemic
3. Estimation of reliability / probability of failure

4. Design components such that reliability requirements are satisfied: absolute or relative?

Concluding remarks

- Reliability assessment of wind turbine components is important for decreasing Cost Of Energy (LCOE)
- Reliability level are generally **10^{-4} - 10^{-3}** per year
- Many complex design load cases to be considered accounting for aerodynamics, control, structural dynamics. …

- Compared to e.g. civil engineering much more information about uncertainties is available – making probabilistic design for specific applications possible, e.g. in connection with site assessment, planning of OM, inspections, ….
- But a systematic approach is needed for the uncertainty modelling taking into account the specific application

Thank you for your attention!

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