Introduction to probabilistic design guidelines and the IEC standards system

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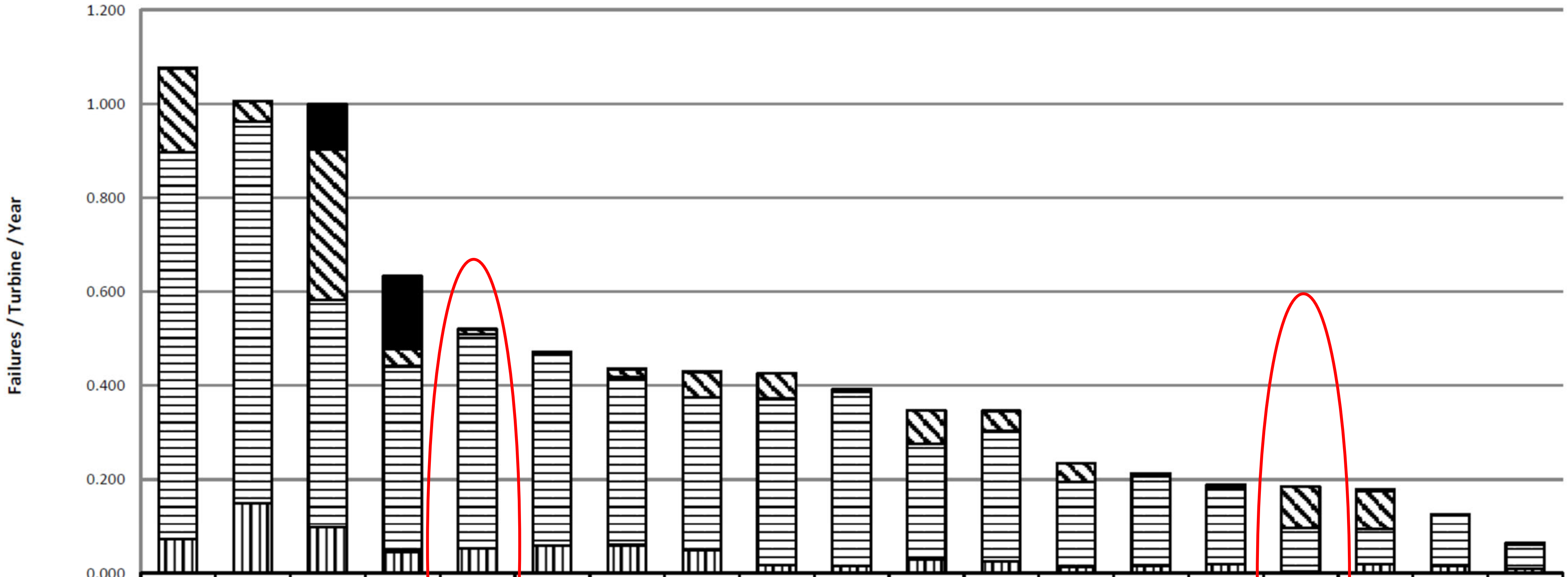
Content:

- Introduction
- Reliability level for structural components and systems
- Probabilistic design of wind turbines
- Uncertainty modelling
- Structural reliability
- IEC standards – Reliability modelling

Introduction

Failure rates based on ~350 offshore wind turbines from a leading manufacturer



	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
■ Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
□ Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.054	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
□ Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
▥ No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

Caroll et al. 2015

Introduction

Mechanical / electrical components

Data: Observed failure rates
Classical reliability theory

Structural components

Data: loads, strengths, models
Probabilistic models for failure events
Structural Reliability Theory

Introduction

- ISO 2394:2015: General principles for reliability of structures
  1. **Semi-probababilistic** method – partial safety factor method
     - ➢ EN1990, IEC 61400-1
  2. **Reliability-based** decision making – **probabilistic design**
     - ➢ IEC TS 61400-9
     - → **calibration of partial safety factors for design**
  3. **Risk-informed** decision making
     - → acceptable and target reliability level for **probabilistic design**
     - Basis for O&M planning

- JCSS: Joint Committee on Structural Safety: Probabilistic Model Code

Introduction – Probabilistic Design of Wind Turbines

- Components are designed to satisfy requirements to minimum reliability

  $$\beta_i(z) \geq \beta_i^{min}$$

  β_i^{min} depend on consequence / component class

- Calibration of partial safety factors to target reliability

  $$\min_{(\gamma_1 . \gamma_2, \dots)} \sum \left(\beta_i(\gamma_1 . \gamma_2, \dots) - \beta^{target} \right)^2$$

  β^{target} depend on consequence / component class

Additional aspects to be considered:

- Consequence of failure: type of failure; component classes and consequence classes
- System reliability
- Application area

Reliability level – ISO 2394

- Risk-based decision making involves

  - Optimization

    Maximization of utility function (e.g. cost-benefit function)

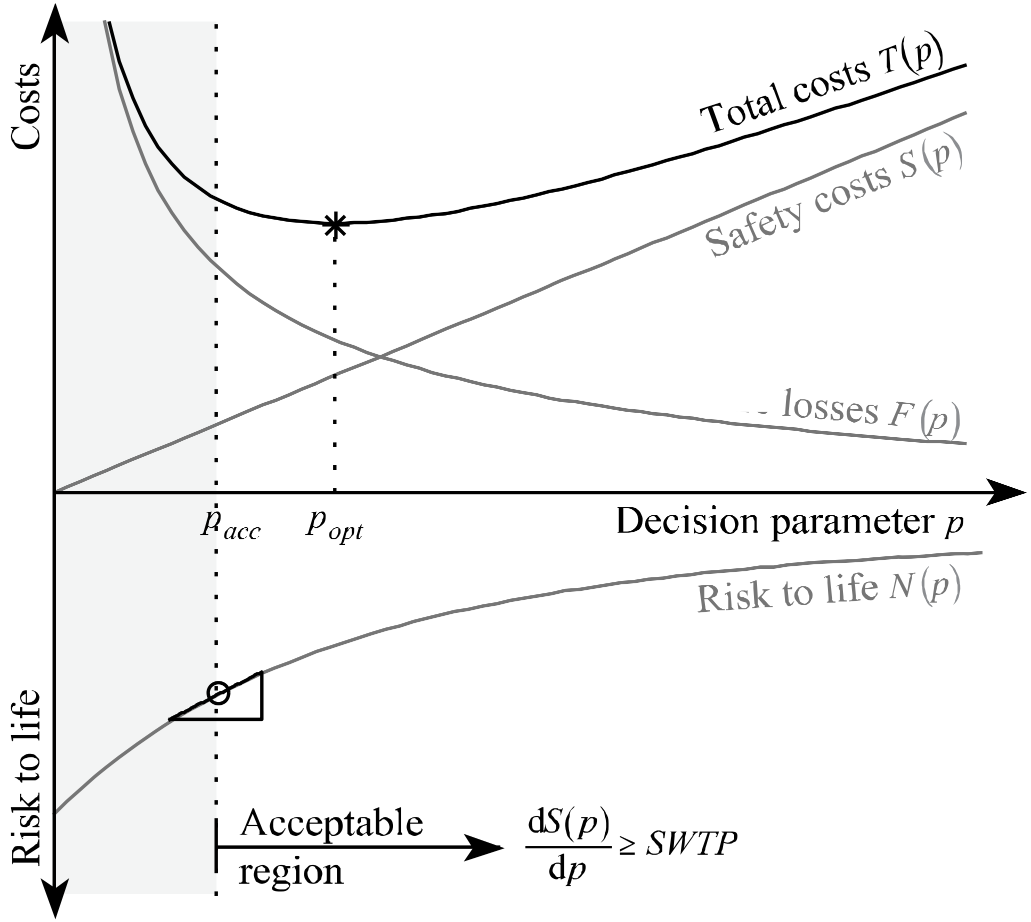
    → target (nominal) reliability level, P_{opt}

  - Assessment of Acceptability

    Is the decision acceptable from a societal perspective?

    Marginal Life Saving Cost - MLSC

    → minimum acceptable reliability level, P_{acc} (wrt. risk to life)



Reliability level – ISO 2394

Annual minimum reliability index (based on MLSC principle)

Relative lifesaving cost	LQI target reliability
Large	$\beta = 3.1\left(P_f = 10^{-3}\right)$
Medium	$\beta = 3.7\left(P_f = 10^{-4}\right)$
Small	$\beta = 4.2\left(P_f = 10^{-5}\right)$

Wind turbines

Annual target reliability index (based on optimization)

Relative cost of safety measure	Consequences of failure		
	Minor	Moderate	Large
Large (A)	$\beta = 3.1\left(P_f \approx 10^{-3}\right)$	$\beta = 3.3\left(P_f \approx 5 \cdot 10^{-4}\right)$	$\beta = 3.7\left(P_f \approx 10^{-4}\right)$
Normal (B)	$\beta = 3.7\left(P_f \approx 10^{-4}\right)$	$\beta = 4.2\left(P_f \approx 10^{-5}\right)$	$\beta = 4.4\left(P_f \approx 5 \cdot 10^{-6}\right)$
Small (C)	$\beta = 4.2\left(P_f \approx 10^{-5}\right)$	$\beta = 4.4\left(P_f \approx 5 \cdot 10^{-6}\right)$	$\beta = 4.7\left(P_f \approx 10^{-6}\right)$

Reliability level

- Building codes: e.g. Eurocode EN1990:2002:
  annual $P_F = 10^{-6}$ or $\beta = 4.7$
  Danish National Annex for buildings: annual $P_F = 10^{-5}$ or $\beta = 4.3$

- Fixed steel offshore structures: ISO19902:2002:
  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 (older wind turbines)
  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 – IEC 61400-1 ed. 4

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)

Reliability level

- Risk of human injuries / nearby houses, roads, …
  - → risk analysis

- Existing wind turbines / farms
  - Relative cost of safety measure changes → target reliability level changes ?
  - IEC TS 61400-31

Probabilistic Design of Wind Turbines

www.lmwindpower.com

Overall design approach:

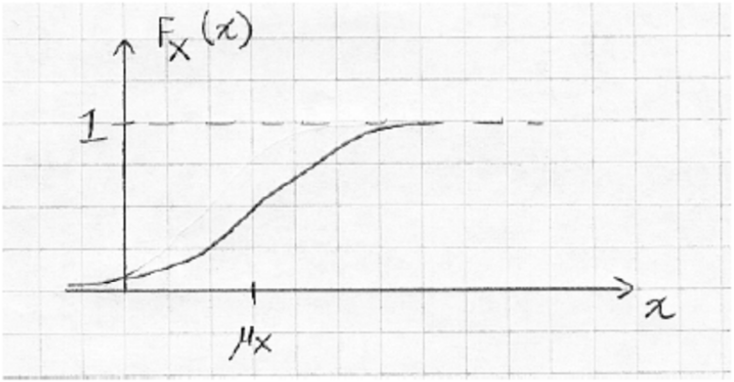
- Combination of
  - Theoretical computational models
  - Test of components / materials
  - Measurements of climatic conditions
  - Full-scale tests / measurements

- Information are subject to physical, model, statistical and measurement uncertainties

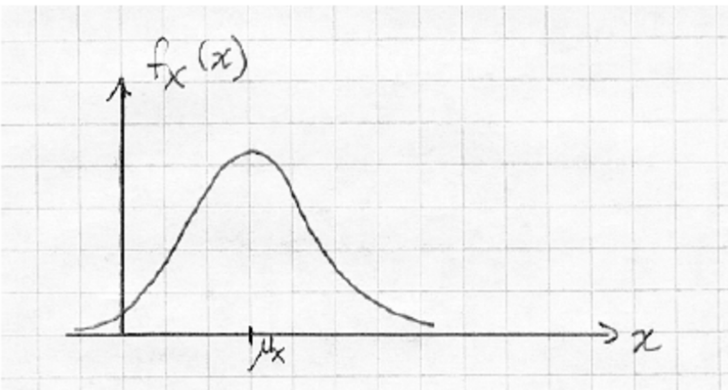
- Uncertainties can be assessed and combined by use of Bayesian statistical methods for use in probabilistic design

Uncertainty modelling

Distribution function: $F_X(x) = P(X \leq x)$



Density function $f_X(x) = \dfrac{d}{dx} F_X(x)$



Uncertainty modelling

Extreme loads:

- Gumbel distribution: Extreme wind-, snow- and temperature loads
- Weibull distribution: Significant wave heights

Fatigue loads:

- LogNormal distribution
- Weibull distribution

Material strengths:

- Normal distribution: if strength
    - can be modelled as a sum of single contributions – e.g. ductile materials
- LogNormal distribution: if strength
    - can be modelled as a product of single contributions
- Weibull distribution: if strength
    - depends of the largest defect in material

Uncertainty modelling

Estimation of statistical parameters

- Maximum Likelihood method
- Moment method
- Least squares method
- Bayesian statistics

Maximum Likelihood method

Log-Likelihood function gives the probability that the actual data are outcomes of a given distribution with given statistical parameters.

It is assumed that the data are statistically independent!

Uncertainty modelling

Statistical parameters: e.g. in a Weibull distribution (α,β,γ)

$x_i \quad : i = 1,\ldots,n$ data values

Optimal parameters (α, β, γ) determined from optimization problem:

$$\max_{\alpha,\beta,\gamma} \ln L(\alpha, \beta, \gamma)$$

Statistical uncertainty: if the number of data is larger than 25-30 α, β, γ can be assumed asymptotically normal distributed with expected values equal to the solution of the optimization problem and with covariance matrix:

$$\mathbf{C}_{\alpha,\beta,\gamma} = -\left[\mathbf{H}_{\alpha,\beta,\gamma}\right]^{-1} = \begin{bmatrix} \sigma_\alpha^2 & \rho_{\alpha\beta}\sigma_\alpha\sigma_\beta & \rho_{\alpha\gamma}\sigma_\alpha\sigma_\gamma \\ \rho_{\alpha\beta}\sigma_\alpha\sigma_\beta & \sigma_\beta^2 & \rho_{\beta\gamma}\sigma_\beta\sigma_\gamma \\ \rho_{\alpha\gamma}\sigma_\alpha\sigma_\gamma & \rho_{\beta\gamma}\sigma_\beta\sigma_\gamma & \sigma_\gamma^2 \end{bmatrix}$$

where $\mathbf{H}_{\alpha,\beta,\gamma}$ is the Hessian matrix with second derivatives of the Log-Likelihood function.

Uncertainty modelling

Uncertain parameters for buildings, bridges, towers, off-shore structures, wind turbines, …:

- Loads
- Strengths – load bearing capacity
- Models

Modelled by $\mathbf{X} = (X_1, \ldots, X_n)$: stochastic variables

Types of uncertainty:

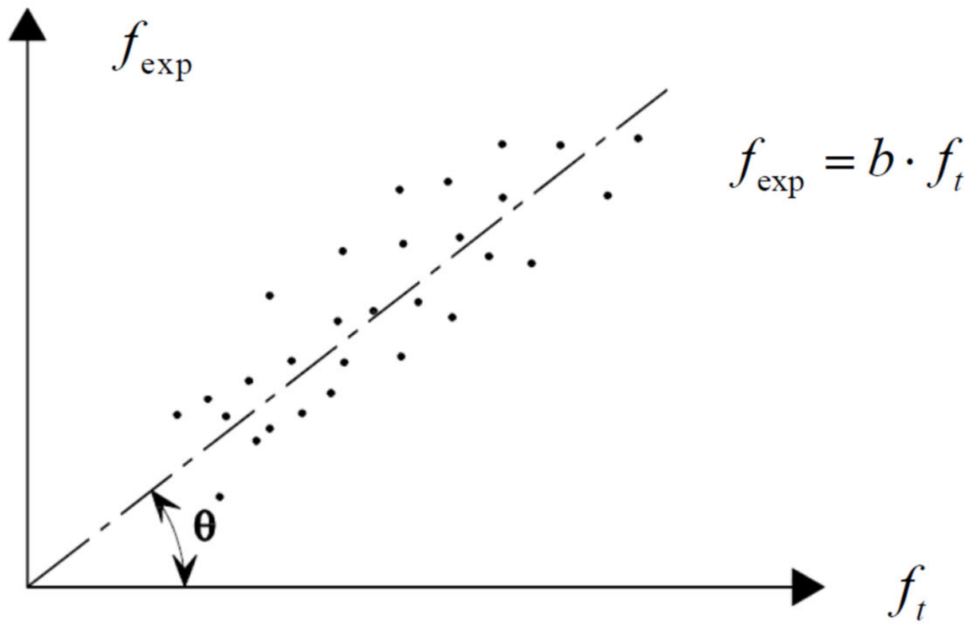
- **Physical uncertainty**
- **Measurement uncertainty**
- **Statistical uncertainty**: due to limited number of observations
- **Model uncertainty**

Aleatory

Epistemic

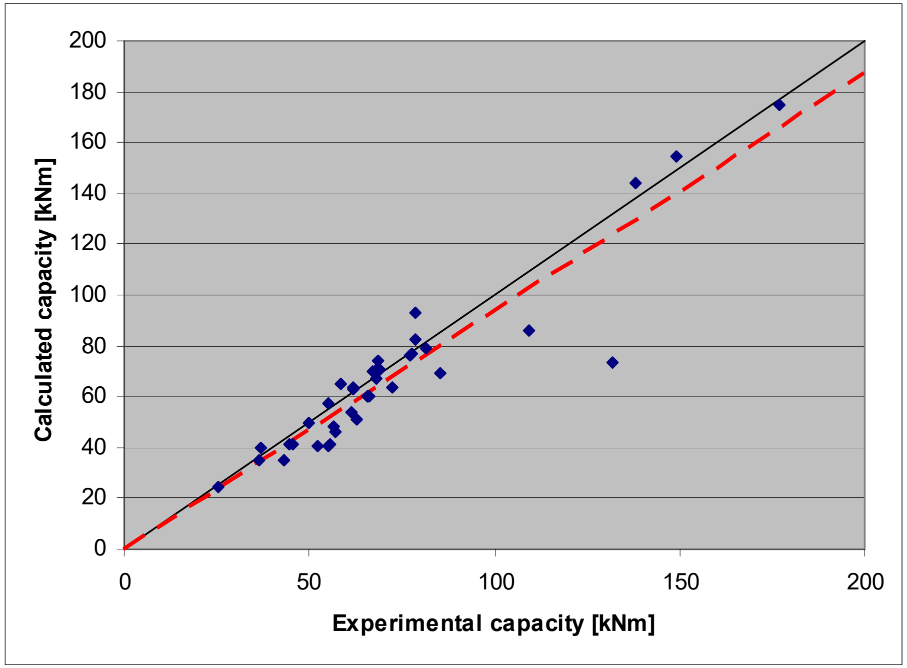
Not covered: gross errors / human errors

Uncertainty modelling



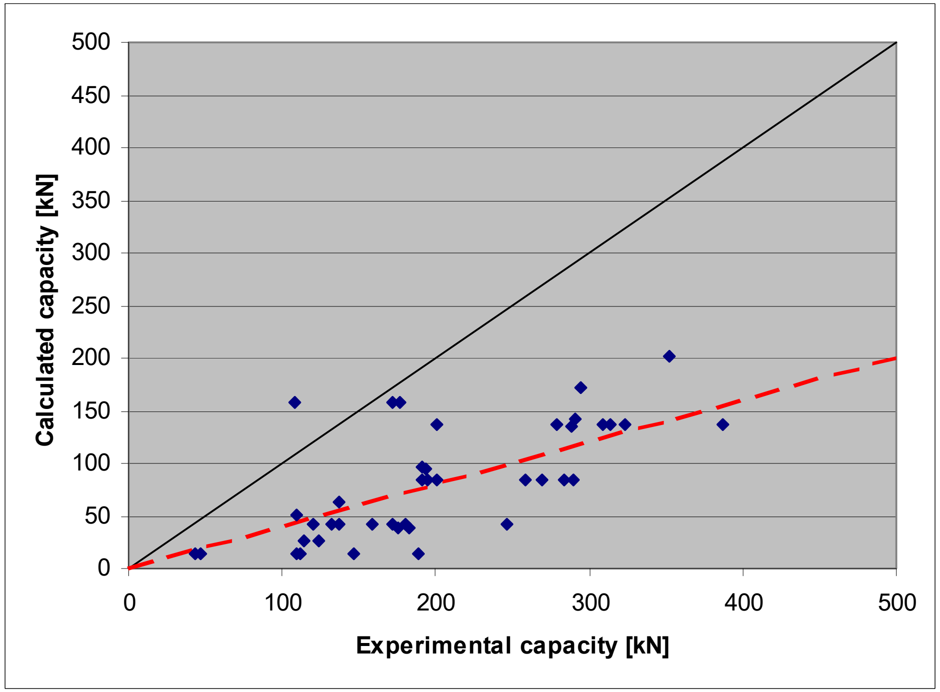
Experimental results $f_{\exp}$ versus theoretical values f_t.

Uncertainty modelling



small bias: 1.06

small COV: V_{20} =12%



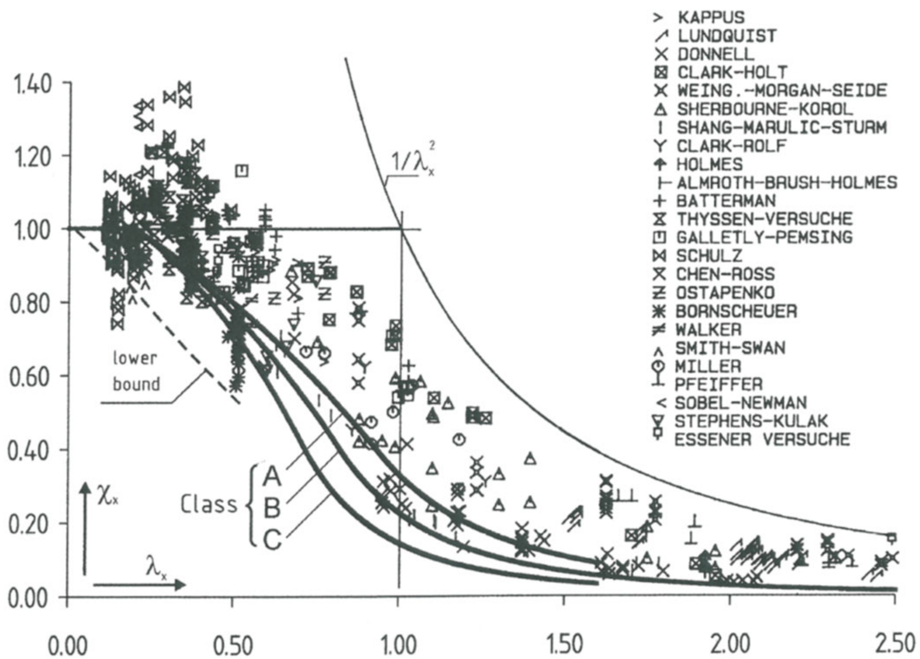
large bias: 2.5

large COV: V_{20} =25%

Probabilistic Design of Wind Turbines (Tower)

Failure modes for wind turbine towers:

- Fatigue
- …
- Buckling



ECCS 2008

www.bladt.dk

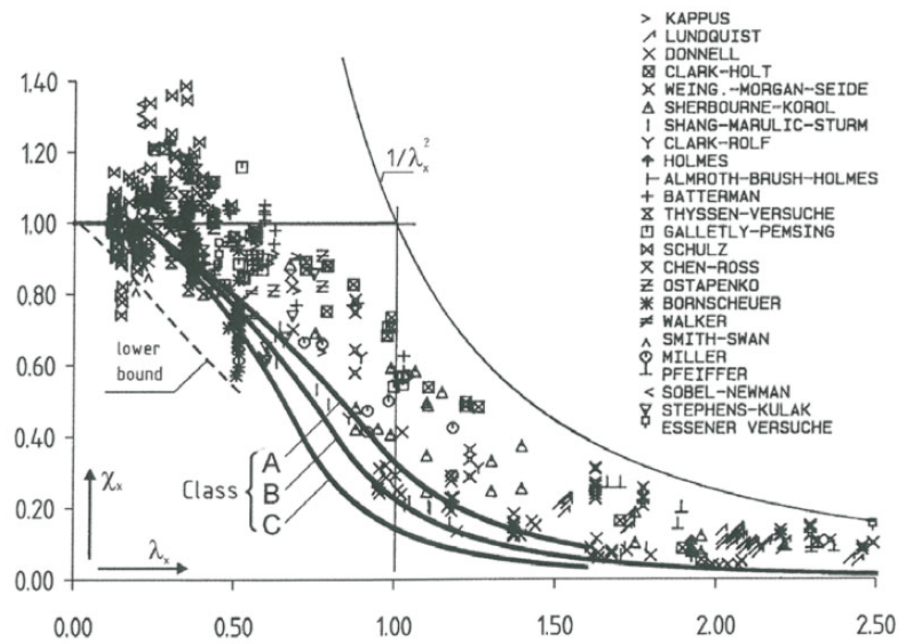
Probabilistic Design of Wind Turbines (Tower)

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 and f_y = 265MPa (COV=5%)
- E-modulus: 210.000MPa

- Model uncertainty:
  Test results only based on axial loading. EN 1993 calculation model: COV=13%, *bias* = 0,85



Uncertainty modelling

Uncertain parameters for buildings, bridges, towers, off-shore structures, wind turbines, …:

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Modelled by $\mathbf{X} = (X_1, \ldots, X_n)$: stochastic variables

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Aleatory

Epistemic

Not covered: gross errors / human errors

Structural reliability

Limit state equation:

$\{g(\mathbf{x}) \leq 0\}$

$\mathbf{X} = (X_1, X_2, ..., X_n)$ basic stochastic variables

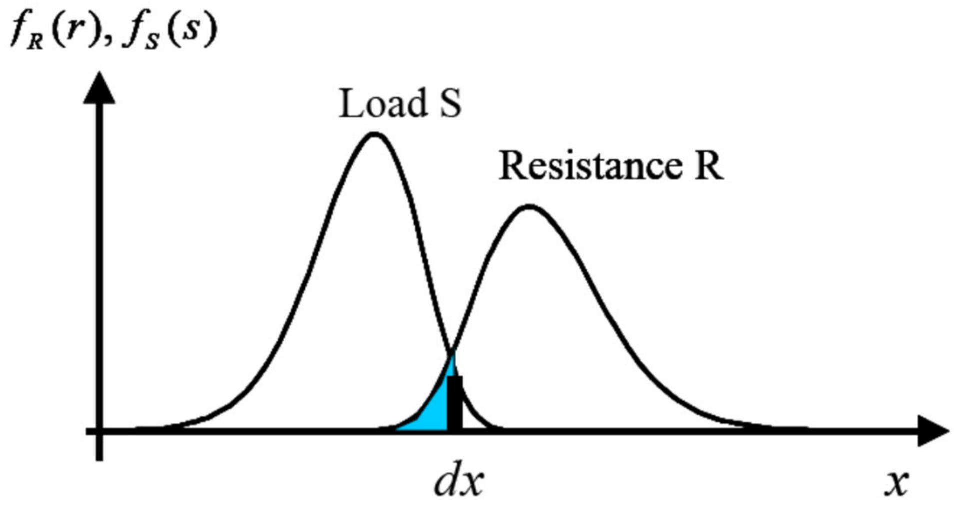
Fundamental case:

Limit state function:

$g(x) = R - S$

R resistance with distribution function $F_R(r)$

S load with probability density function $f_S(s)$



Probability of failure (independence):

$$P_F = P(R \leq S) = P(R - S \leq 0) = \int^{\infty} F_R(x) f_S(x) dx$$

Structural reliability

Special case:

R Normal distributed $N(\mu_R, \sigma_R)$

S Normal distributed $N(\mu_S, \sigma_S)$

Safety margin: *M*=*R*-*S*

Probability of failure

$$P_F = P(g(\mathbf{X}) \leq 0) = P(R - S \leq 0) = \Phi\left(\frac{0 - \mu_M}{\sigma_M}\right) = \Phi(-\beta)$$

$$\mu_M = \mu_R - \mu_S$$

$$\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2}$$

β **reliability index**

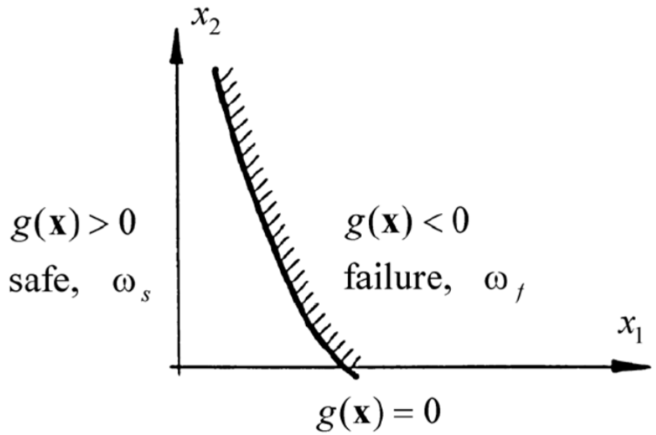
Reliability index β	Probability of failure P_F
3,1	10^{-3}
3,7	10^{-4}
4,3	10^{-5}
4,7	10^{-6}
5,2	10^{-7}

Structural reliability

- Limit state function, $g(\mathbf{x})$, divides the sample space for $\mathbf{X}$ in two parts, ω_f (failure) and ω_s (safe)

- $g(\mathbf{x})$ is defined such that:

$$g(\mathbf{x})\begin{cases} >0 & , \quad \mathbf{x}\in\omega_s \\ \leq 0 & , \quad \mathbf{x}\in\omega_f \end{cases}$$



- If $\mathbf{x}$ is exchanged with the basic stochastic variables $\mathbf{X}$, the safety margin is obtained: $M=g(\mathbf{X})$

- Probability of failure:

$$P_f = P(M\leq 0) = P(g(\mathbf{X})\leq 0) = \int_{\omega_f} f_{\mathbf{X}}(\mathbf{x})d\mathbf{x}$$

Structural reliability

HASHOFER & LIND'S RELIABILITY INDEX

Hashofer & Lind reliability index:

- invariant with respect to mathematical formulation of failure function

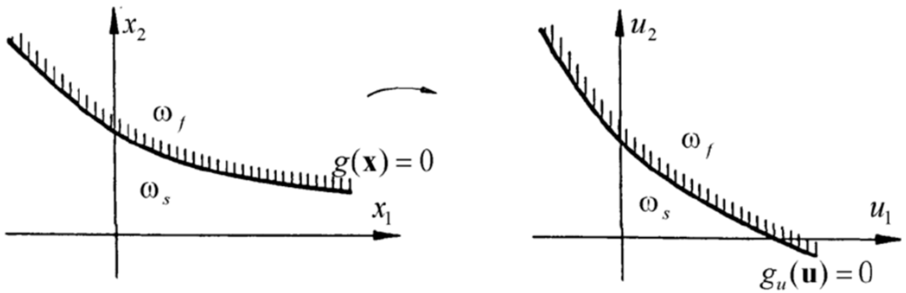
- Basic variables, **X:** Normal distributed and independent

- Normalised variables, $U_i \sim N(0,1)$:

$$U_i = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}} \quad i = 1, 2, \ldots, n$$

- Failure function in u-space:

$$g_u(\mathbf{u}) = g(\mu_{X_1} + \sigma_{X_1} u_1, \ldots, \mu_{X_n} + \sigma_{X_n} u_n)$$



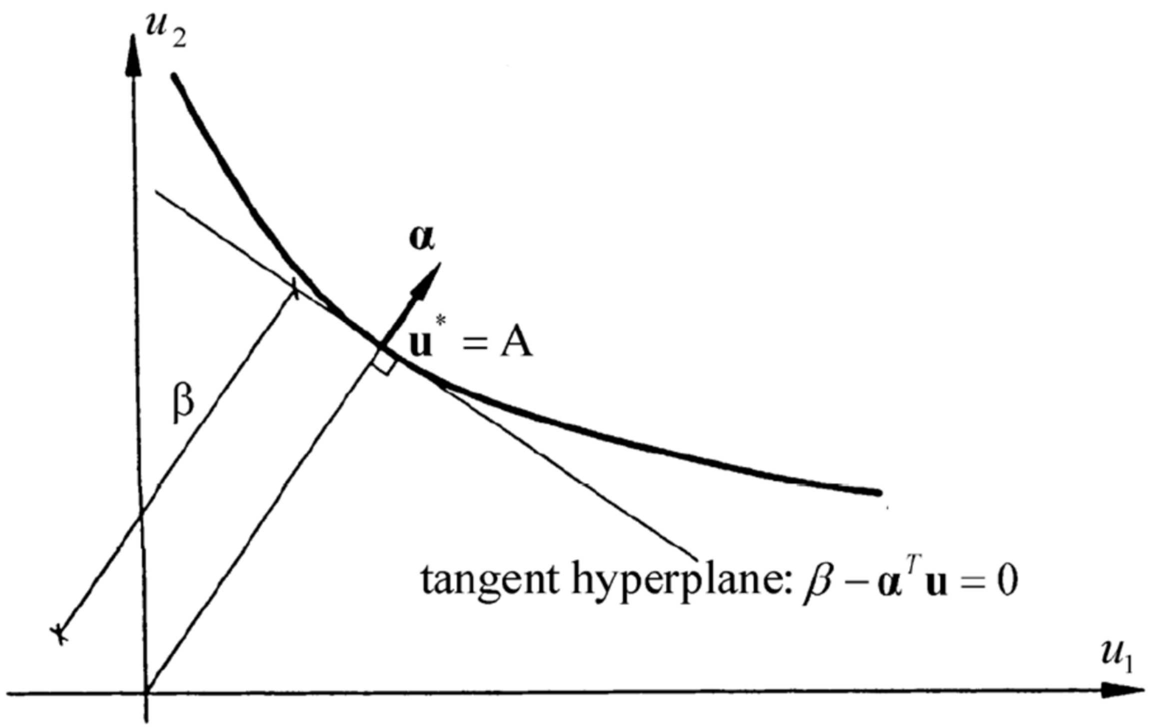
Structural reliability

The reliability index is defined as the shortest distance from origo to failure surface in u-space:

$$\beta = \min_{g_u(\mathbf{u})=0} \sqrt{\sum_{i=1}^{n} u_i^2}$$

Solution point in u-space:

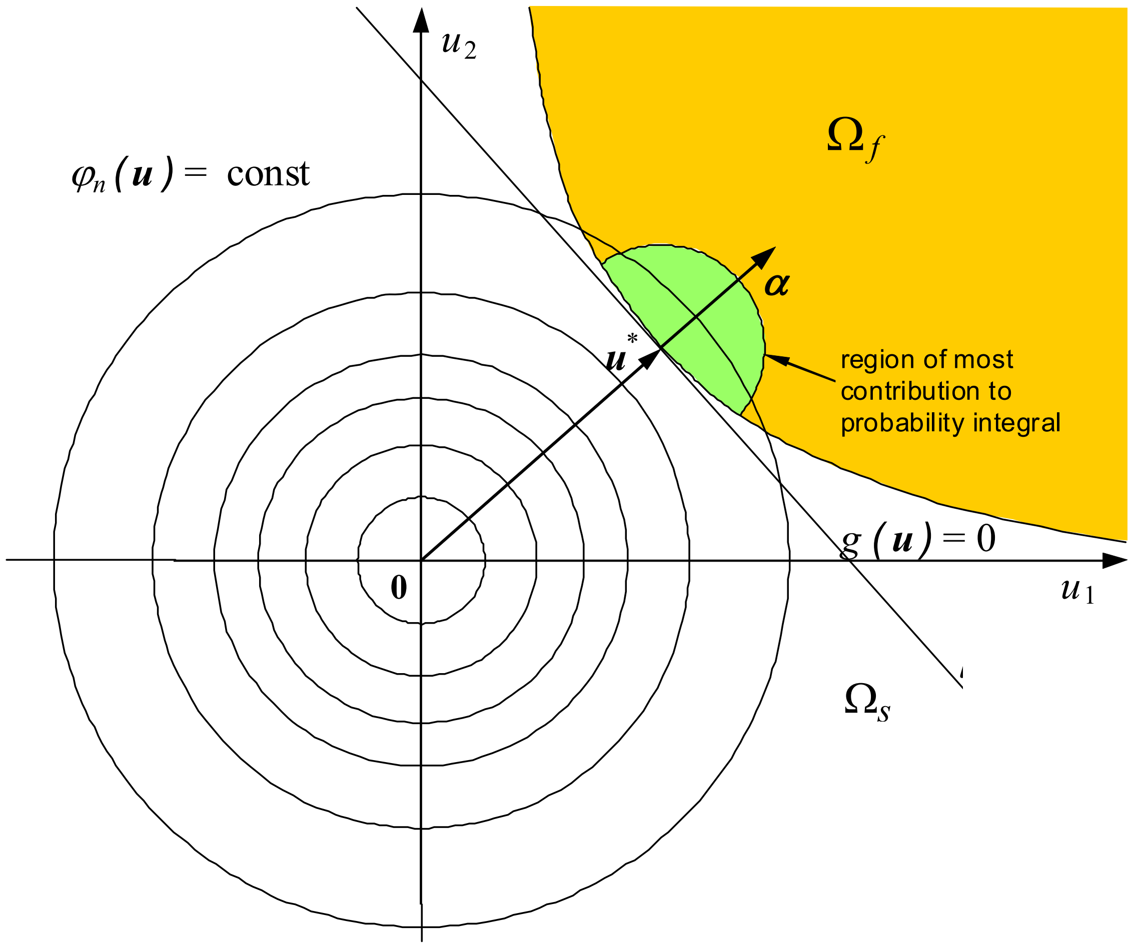
β-point *or* design point, $\mathbf{u}^*$



Probability of failure:

$$
\begin{aligned}
P_f &= P(M \le 0) \\
&= P\big(g(\mathbf{X}) \le 0\big) \\
&= P\Big(g\big(\mathbf{T}(\mathbf{U})\big) \le 0\Big) \\
&\approx P(\beta - \boldsymbol{\alpha}^T \mathbf{U} \le 0) \\
&= \Phi(-\beta)
\end{aligned}
$$

Structural reliability



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\end{aligned}
$$

Structural reliability

MONTE CARLO SIMULATION

Application of simulation to estimate probability of failure
$P_f = P\left(g(\mathbf{U})\right) \le 0$

Crude Monte Carlo Simulation

P_f is estimated by:

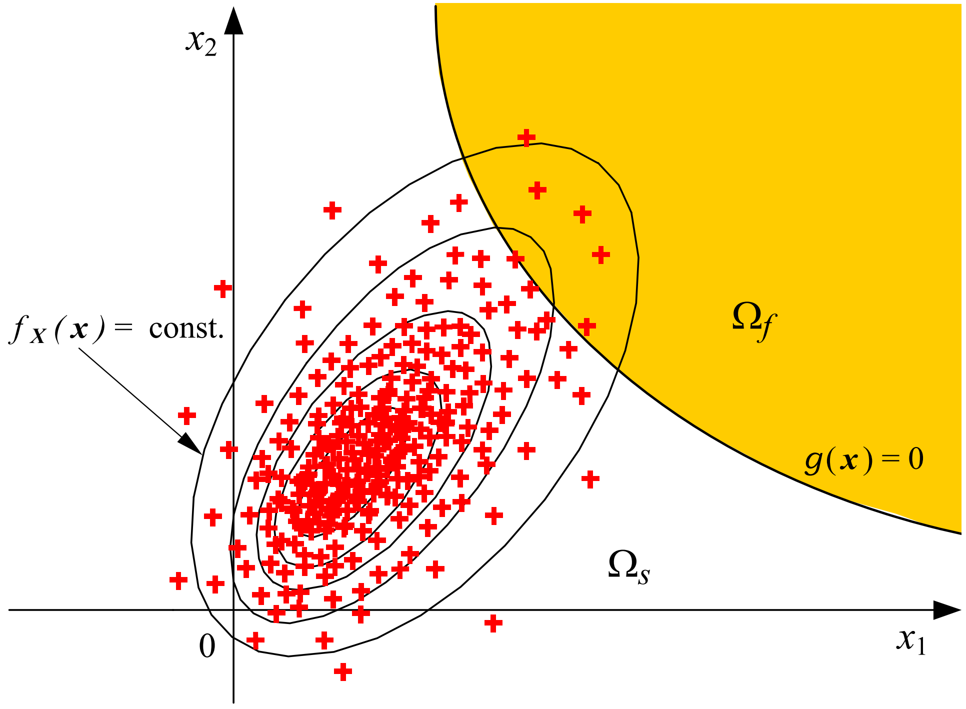
$$\hat{P}_f = \frac{1}{N}\sum_{j=1}^{N} I[g(\hat{\mathbf{u}}_j)]$$

N number of simulations
$\hat{\mathbf{u}}_j$ outcome no j of standard normal vector $\mathbf{U}$
$I[g(\mathbf{u})]$ indicator function:

$$I[g(\mathbf{u})] = \begin{cases} 0 & \text{if} \quad g(\mathbf{u}) > 0 \quad \text{(safe)} \\ 1 & \text{if} \quad g(\mathbf{u}) \le 0 \quad \text{(failure)} \end{cases}$$

Standard deviation of $\hat{P}_f$ (error):

$$s = \sqrt{\frac{\hat{P}_f(1-\hat{P}_f)}{N}}$$



Wind Turbine Standardization - IEC

• IEC 61400-1	Design requirements
• IEC 61400-2	Design requirements for small wind turbines
• IEC 61400-3-1	Design requirements for offshore wind turbines
• IEC 61400-3-2	Design requirements … Floating wind turbines
• IEC 61400-4	Design and specification of gearboxes
• IEC 61400-5	Wind turbine rotor blades
• IEC 61400-6	Tower and foundation design
• *IEC 61400-8*	*Structural components*
• ***IEC TS 61400-9***	***Probabilistic design***
• IEC 61400-11	Acoustic noise measurement techniques
• IEC 61400-12-1	Power performance measurements
• IEC/TS 61400-13	Measurement of mechanical loads
• IEC/TS 61400-14	Declaration of apparent sound power level and tonality
• IEC 61400-15	Site suitability …
• IEC 61400-21	Measurement and assessment of power quality
• IEC/TS 61400-23	Full-scale structural testing of rotor blades
• IEC 61400-24	Lightning protection
• IEC 61400-25-(1-5)	Communication
• IEC/TS 61400-26	Availability
• *IEC TS 61400-28*	*Lifetime extension*
• *IEC 61400-30*	*Safety of Wind Turbine Generator Systems (WTGs)*
• *IEC TS 61400-31*	*Siting Risk Assessment*
• *IEC 61400-101*	*General requirements for wind turbine plants*

Reliability modeling of structural components

Design load cases in IEC 61400-1 and -3:

- 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)

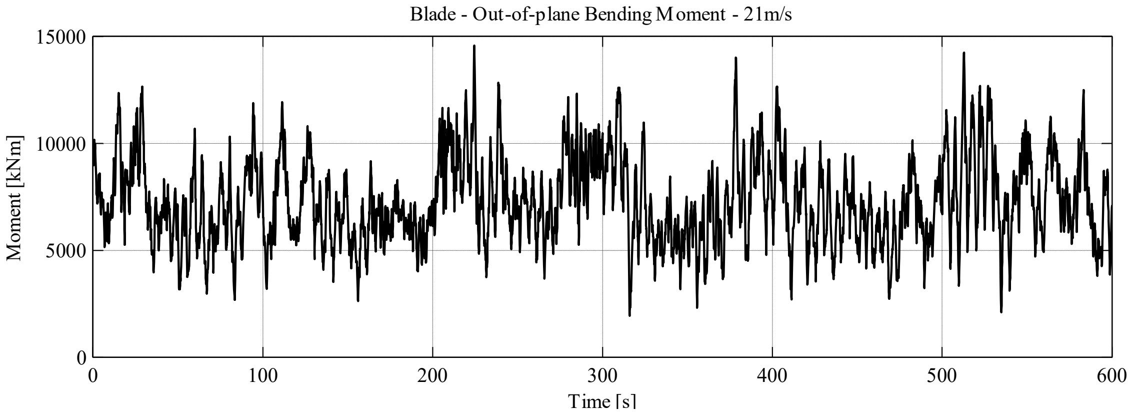
Reliability assessment in normal operation (DLC 1)

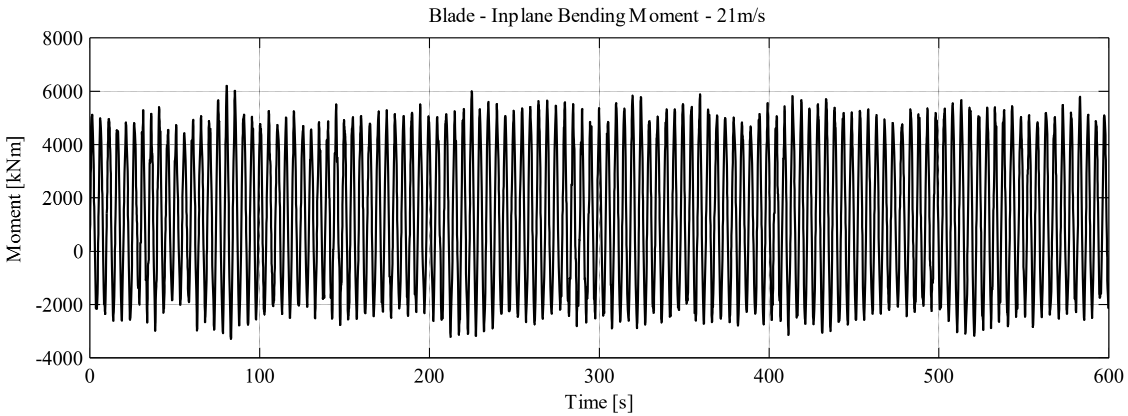
Loads on wind turbines depends on:

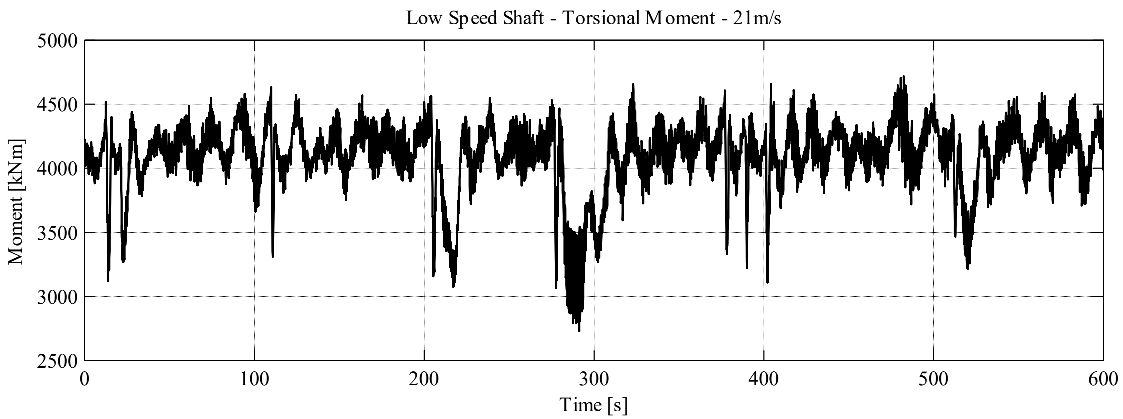
- Structural dynamics
- Aerodynamics
- Control system
- Wind climate
- Wake effects
- …

www.dongenergy.dk

Reliability assessment in normal operation (DLC 1)







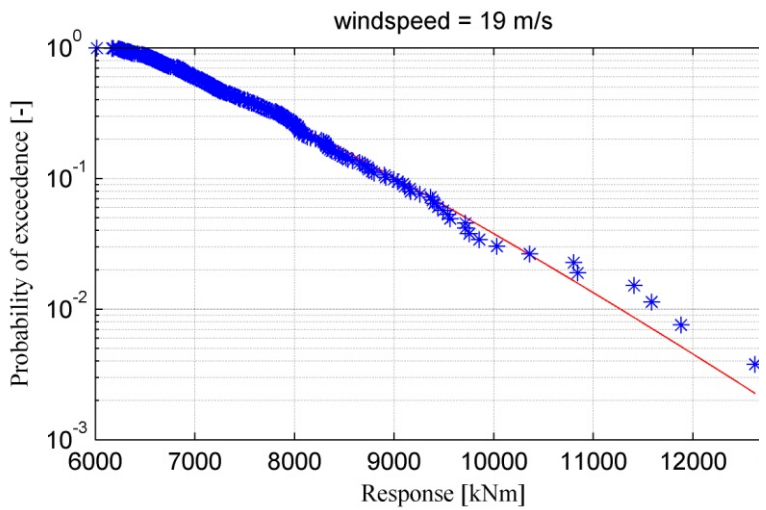
Reliability assessment in normal operation (DLC 1)

Stochastic model for annual maximum load:

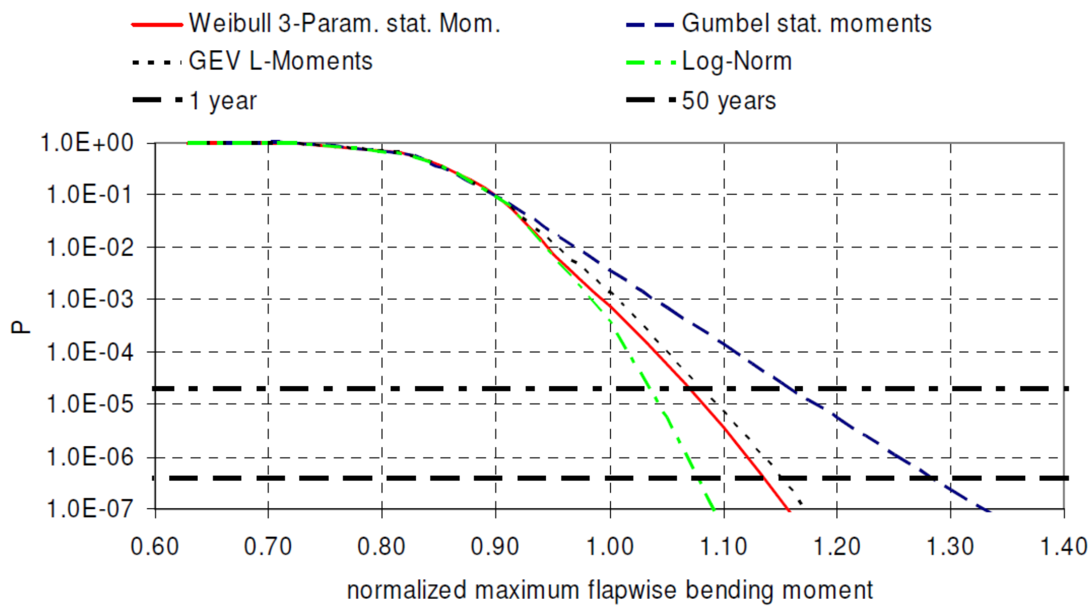
$$P = X_{dyn} X_{\exp} X_{aero} X_{str} L$$

L extreme load effect based on ‘Load extrapolation’: typically assumed Weibull distributed

Fit of load effect for each wind speed:



Aggregated fit of load effect for all wind speeds:



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:

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

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:

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

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

Example - Structural Reliability (DLC 1.1)

Reliability analysis for a wind turbine component – extreme load

Limit state equation:

$$g_1 = z\, X_R R - P\, X_{\exp}\, X_{st}\, X_{aero}$$

Variable		Distribution	Mean	COV
z	Design parameter	Deterministic	781	
R	Strength	Lognormal	330 MPa	0.15
X_R	Model uncertainty – strength	Lognormal	1.0	0.05
P	Annual maximum load effect	Weibull	$1.0\ 10^5$ MN	0.15
X_{exp}	Model uncertainty – site assessment	Lognormal	1.0	0.15
X_{st}	Model uncertainty – limited wind data	Lognormal	1.0	0.10
X_{aero}	Model uncertainty – lift and drag coefficients	Gumbel	1.0	0.10

Example - Structural Reliability (DLC 1.1)

Comrel:

Job Control

Symbolic Expressions | Stochastic Model | Correlations | Results | Plots

```
FLIM(1){g1}=z*Xr*R-P*Xexp*Xst*Xaero
```

Job Control

Symbolic Expressions | Stochastic Model | Correlations | Results | Plots

Ident...	Comment	Distribution	.	.	.	.	Value	.	.	Value	.	.	...
R Xr	Model uncertaincy	Lognormal	M	✓	x̄	c	1	σ	c	0.05			
R R	Strength	Lognormal	M	✓	x̄	c	330	σ	c	49.5			
R Xexp	model uncer - site	Lognormal	M	✓	x̄	c	1	σ	c	0.15			
R Xst	model uncer- wind data	Lognormal	M	✓	x̄	c	1	σ	c	0.1			
R Xaero	model uncer - drag coff	Gumbel (max)	M	✓	x̄	c	1	σ	c	0.1			
R P	Annual max load	Weibull (min)	M	✓	x̄	c	100000	σ	c	15000	τ	c	0
P z	design parameter	Constant	P	✓	c	c	781						

Example - Structural Reliability (DLC 1.1)

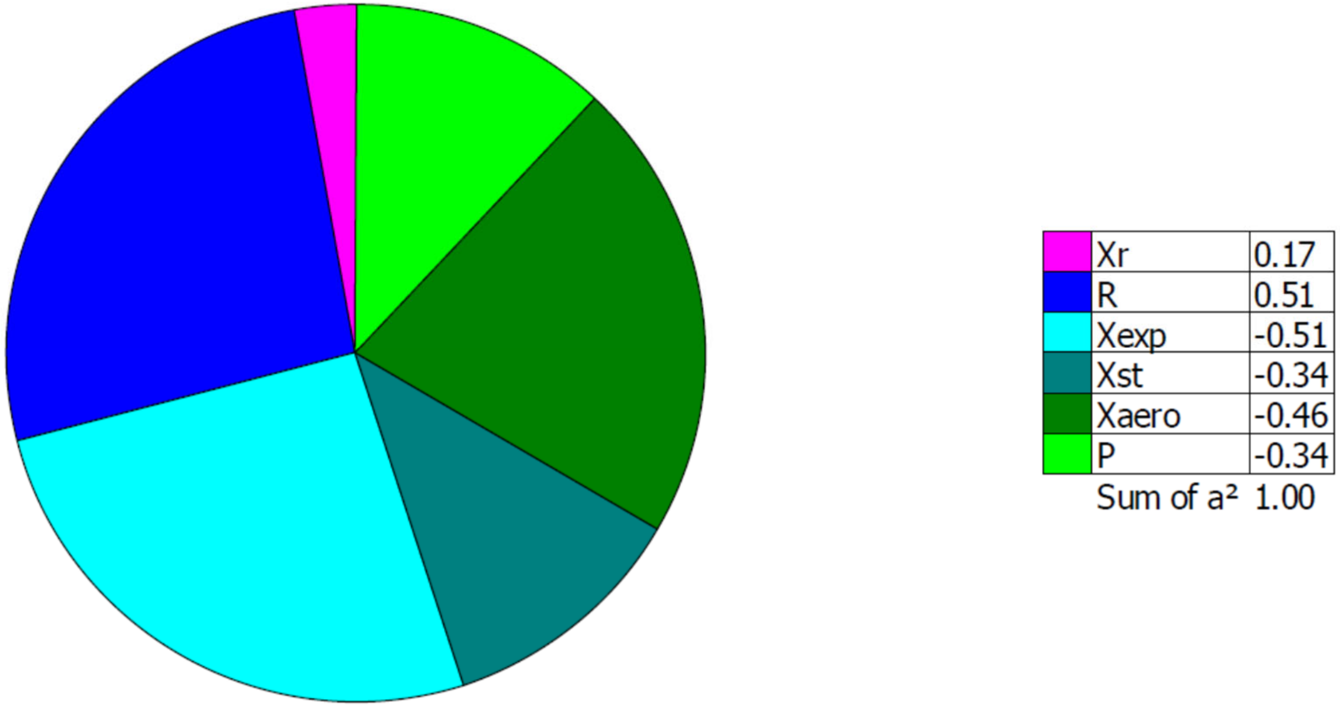
Symbolic Expressions | Stochastic Model | Correlations | Results | Plots

Varia...	Xr	R	Xexp	Xst	Xaero	P
Xr		0	0	0		
R	0		0	0		
Xexp	0	0		0		
Xst	0	0	0			
Xaero						
P						

```
FORM-beta=    3.301; SORM-beta=    --    ; beta(Sampling)=   --     (IER=   0)
FORM-Pf=  4.82E-04; SORM-Pf=    --      ; Pf(Sampling)=    --
```

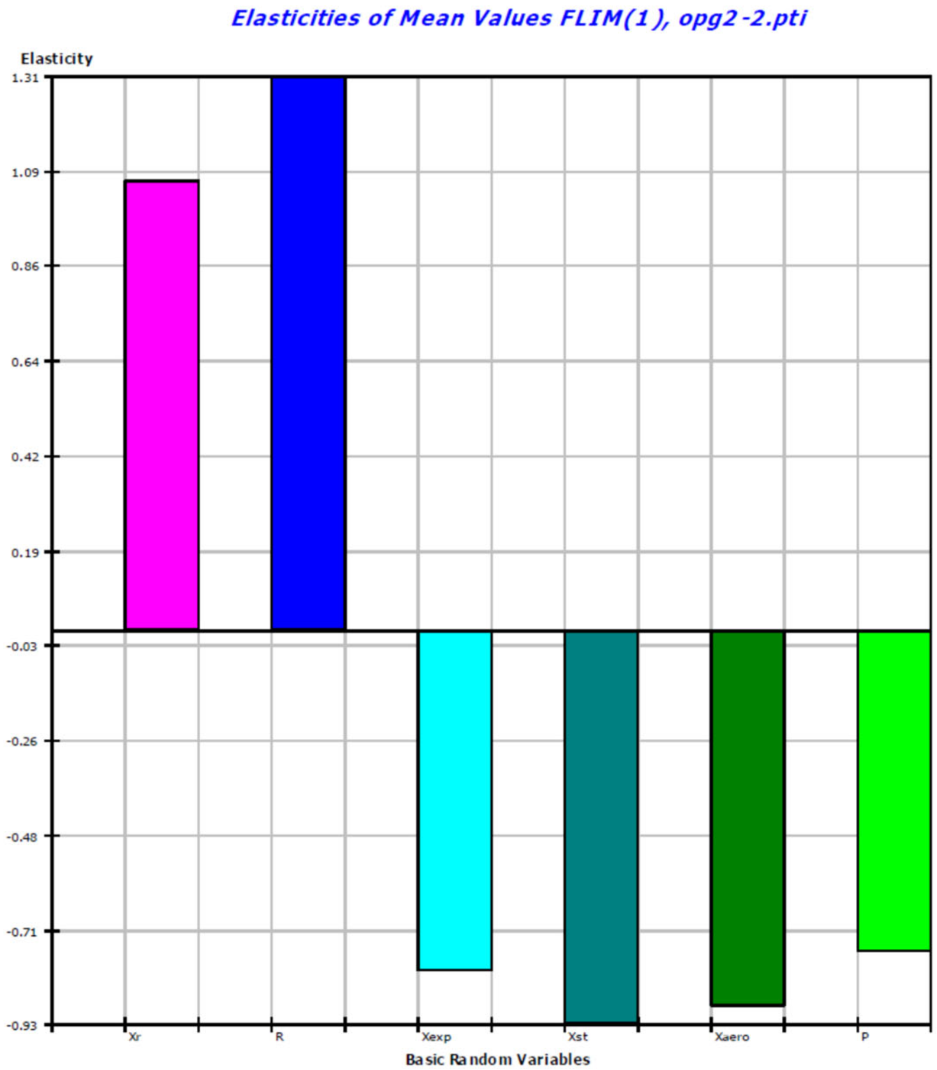
Example - Structural Reliability (DLC 1.1)

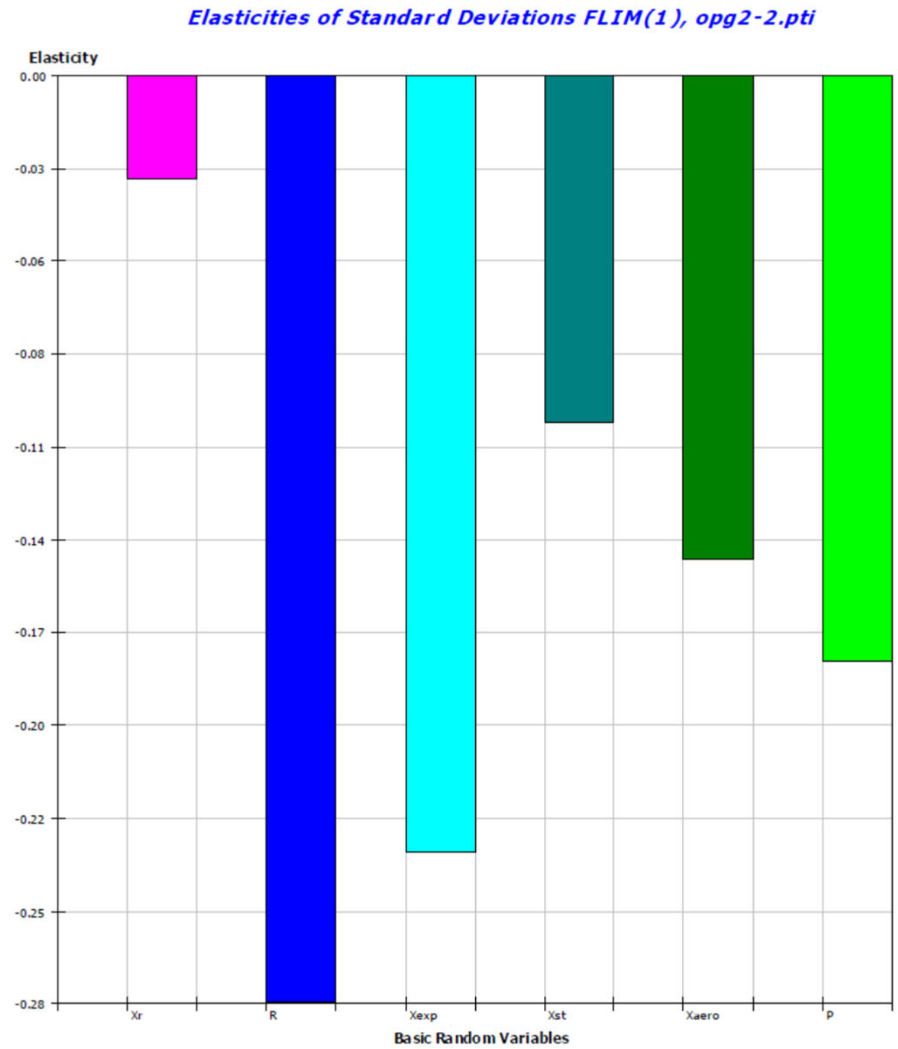
Alpha values:



Example - Structural Reliability (DLC 1.1)

Elasticity values:





Applications of reliability to probabilistic design of wind turbines

- Potential gains and design optimizations ….
  - More uniform reliability level
  - Cost savings
  - Rational use of knowledge (data)
  - May be used in a relative way e.g. in site suitability
- Potential pitfalls ….
  - Modelling of uncertainties, especially model uncertainties
- Questions and discussion

Thank you for your attention!

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