RELIABILITY OF WIND TURBINES AND WAVE ENERGY DEVICES

JOHN DALSGAARD SØRENSEN
Outline

• Introduction
• Reliability modeling of wind turbine and wave energy device components
• Structural reliability theory (FORM) - introduction
• Probabilistic design of wind turbines, OM and Risk assessment
• Example: Reliability-based calibration of material partial factors
• Example: Reliability-based calibration of safety factors for fatigue design of welded details in offshore wind turbines
• Example: Grouted connections
• Summary / Conclusions
Introduction – wind energy

Figure 2: The size of wind turbines at market introduction.
Introduction – wave energy devices

- Oscillating water column dev.
- Overtopping dev.
- Point absorbers
- Wave turbines
- And many others ...
Introduction

Development / qualification phases:

From Carbon Trust (DnV) 2005
Reliability assessment – WED vs WT

Wave energy devices (WED): ratio between structural loadings in extreme and production conditions is in most cases very high

Wind turbines (WT): ratio is significantly smaller, as wind turbine blades are pitched out of the wind in extreme conditions, making extreme loadings of the same order of magnitude as production loads.

As extreme loadings and survivability drive the costs of the devices, and as income is only generated in everyday production conditions, it is of tremendous importance for WED to increase reliability and reduce cost.
Introduction

Minimize the Total Expected Life-Cycle Costs

\[\downarrow\]

Minimize Cost Of Energy (COE)

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

Failure rates and downtime (examples – onshore wind turbines):

![Graph showing annual failure frequency and downtime per failure for different components of onshore wind turbines.](image-url)
Introduction

Observed failure rates
Classical reliability theory

Probabilistic models for failure events
Structural Reliability Theory

Mechanical / electrical components

Structural components
Reliability – elec. / mech. components

Bath tub curve

Failure Rate

‘Burn-in’ failures
Improve quality control

Random failure
Improve reliability

Wear out
Inspections
Robustness

Constant failure rate
= 1 / Mean Time Between Failure

Time
Reliability – structural components

• Use Structural Reliability Methods
  • ULS: Extreme loads
    • Stand-still
    • Operation
  • FAT: Fatigue
  • ALS: Accidental situations
  • SLS: Serviceability

• Damage tolerant / robustness

• Calibration of ‘Partial safety factors’
Reliability – structural components – **time invariant**

Limit state equation: 
\[ g(x) = 0 \]

Probability of failure: 
\[ P_F = P(g(X) \leq 0) \approx \Phi(-\beta) \]

<table>
<thead>
<tr>
<th>Probability of failure, ( P_F )</th>
<th>10^{-2}</th>
<th>10^{-3}</th>
<th>10^{-4}</th>
<th>10^{-5}</th>
<th>10^{-6}</th>
<th>10^{-7}</th>
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<tbody>
<tr>
<td>Reliability index, ( \beta )</td>
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<td>3,1</td>
<td>3,7</td>
<td>4,3</td>
<td>4,8</td>
<td>5,2</td>
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Requirements:
- Formulation of limit state equation
- Stochastic modeling of uncertain parameters
  - Physical uncertainties
  - Statistical uncertainties
  - Model uncertainties
  - Measurement uncertainties
Structural Reliability - introduction

Uncertainties:
• physical uncertainty
• statistical uncertainty
• model uncertainty

Bayesian statistical interpretation of uncertainties:
• can incorporate statistical evidence about uncertain parameters
• subjectively assessed uncertainties

Probabilistic model code: JCSS:
http://www.jcss.ethz.ch/
Structural Reliability

Limit state equation:
\[ \{ g(x) \leq 0 \} \]

\[ \mathbf{X} = (X_1, X_2, \ldots, X_n) \] 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 \( f_S(s) \)
Structural Reliability

Probability of failure (independence):

\[ P_F = P(R \leq S) = P(R - S \leq 0) = \int_0^\infty F_R(x)f_S(x)dx \]
Structural Reliability

Special case:
- $R$ Normal distributed $N(\mu_R, \sigma_R)$
- $S$ Normal distributed $N(\mu_S, \sigma_S)$

Probability of failure

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

$$\mu_M = \mu_R - \mu_S$$
$$\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2}$$

$\beta$ reliability index

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**Structural Reliability**

**General case**

\[ P_F = P(g(X) \leq 0) = \int_{g(x) \leq 0} f_X(x) \, dx \]

Solution of integral:
- numerical integration
- Simulation
- First and Second Order Reliability Methods (FORM/SORM)
FORM – First Order Reliability Method

- Limit state function, $g(x)$, divides the sample space for $X$ in two parts, $\omega_f$ (failure) and $\omega_s$ (safe)

- $g(x)$ is defined such that:

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

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

- Probability of failure:

$$P_f = P(M \leq 0) = P(g(X) \leq 0) = \int_{\omega_f} f_X(x) dx$$
FORM – First Order Reliability Method

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:
  \[ g_u(u) = g(\mu_{X_1} + \sigma_{X_1} u_1, \ldots, \mu_{X_n} + \sigma_{X_n} u_n) \]
FORM – First Order Reliability Method

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

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

Solution point in \( u \)-space:

\( \beta \)-point or design point, \( u^* \)

tangent hyperplane: \( \beta - \alpha^T u = 0 \)
Summary: FORM – First Order Reliability Method

\[ \varphi_n(u) = \text{const} \]

\[ \Omega_s \]

region of most contribution to probability integral

\[ g(u) = 0 \]

\[ l(u) = 0 \]

\[ \Omega_f \]

\[ \alpha = -\frac{\nabla G(U)}{\|\nabla G(U)\|} \bigg|_{u=u^*} \]

\[ l(U) = -\alpha^T U + \beta \]

\[ P_{f1} = \Phi(-\beta) \]
FORM – General transformation

Rosenblatt Transformation

\[ x_1 = F_{X_1}^{-1}(\Phi(u_1)) \]
\[ x_2 = F_{X_2|X_1}(\Phi(u_2) \mid X_1 = x_1) \]
\[ \vdots \]
\[ x_n = F_{X_n|X_1\cdots X_{n-1}}^{-1}(\Phi(u_n) \mid X_1 = x_1, \ldots, X_{n-1} = x_{n-1}) \]

where
\[ F_{X_i|X_1\cdots X_{i-1}}(x_i \mid X_1 = x_1, \ldots, X_{i-1} = x_{i-1}) \]
Conditional distribution function for \( X_i \) given \( X_1 = x_1, \ldots, X_{i-1} = x_{i-1} \)

Inverse transformation:

\[ u_1 = \Phi^{-1}(F_{X_1}(x_1)) \]
\[ u_2 = \Phi^{-1}(F_{X_2|X_1}(x_2 \mid X_1 = x_1)) \]
\[ \vdots \]
\[ u_n = \Phi^{-1}(F_{X_n|X_1\cdots X_{n-1}}(x_n \mid X_1 = x_1, \ldots, X_{n-1} = x_{n-1})) \]
Structural Reliability

• Reliability index – FORM (First Order Reliability Method)
• Reliability index – SORM (Second Order Reliability Method)

• Simulation methods
  • Crude Monte Carlo simulation
  • Importance sampling
  • Directional simulation
  • Asymptotic sampling
  • Subset simulation
  • …
Crude Monte Carlo simulation

\[ f_X(x) = \text{const.} \]

\[ g(x) = 0 \]

\[ \Omega_f \]

\[ \Omega_s \]
Importance sampling

$$\varphi_n(u) = \text{const}$$

$$f_U(u) = \varphi(u_1) \cdots \varphi(u_n)$$

$$\Omega_f$$

$$\Omega_s$$

$$f_S(u)$$

$$G_g(u) =$$
Other simulation techniques

• Asymptotic sampling

• Subset Simulation
Structural Reliability – computer programs

- rcp, Munich: STRUREL: STATREL, COMREL & SYSREL
- DnV: Proban
- FERUM (Matlab)
- ...

AALBORG UNIVERSITY
DENMARK
Reliability – WED structural components

ULS limit states:
- Fatigue failure of welded details
- Mooring failure by sliding of anchor
- Mooring failure by breaking of mooring line(s)
- Failure of structural element, leading to disintegration/change of geometry/loss of part(s)
- Local structural failure due to wave impact (slamming) (potentially leading to capsizing/sinking)
- Wear out of hinged connections
Reliability – WT structural components

Blades

Gearbox, …

Power electronics:
Reliability – WT structural components

Tower & Substructures:

Foundation:
Reliability – Uncertainty modelling / Reliability / Risk

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)
Reliability – WT structural components

Stochastic modeling of loads:
• Wind
• Waves
• Currents
  o Control system / aerodynamics

Stochastic modeling of resistances / material parameters:
• Blades: composite materials
• Hub: cast steel
• Tower: structural steel
• Foundation: soil
Probabilistic Design of Wind Turbines

Overall design approach:

• Combination of
  • Theoretical computational models
  • Test of components / materials
  • Measurements of climatic conditions
  • Full-scale 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
Probabilistic Design of Wind Turbines

- Blade flap: extreme (defl. and buckling)
- Blade edge: fatigue
- Shaft: fatigue
- Yaw system: extreme
- Main bearing: fatigue
- Gear: fatigue
- Nacelle weldings: fatigue
- Tower (pitch): fatigue
- Tower (no pitch): extreme (buckling)
- Tower weldings: fatigue
- Tower flanges: extreme

[Image of wind turbine]
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:
• Complex material structure (damage tolerance).
• Manufacturing process (imperfections).
• Loading conditions (site dependency).
• Structural analysis (instability).
• Failure criteria (ultimate/fatigue).

www.gurit.com
Probabilistic Design of Wind Turbines (Blades)

Design of wind turbine blades can typically be characterized by a combination / sequence of tests:

- Coupon tests
- Computational / numerical calculations
- One full-scale test – proof loading
Probabilistic Design of Wind Turbines (Blades)

Uncertainties related to fatigue design of composite structures:
• Linear SN-curve
• Constant life diagram
• Miners rule

Miners sum at failure

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Tests n</th>
<th>Mean $\mu_\Delta$</th>
<th>Std. $\sigma_\Delta$</th>
<th>$COV_\Delta$</th>
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<td>0.54</td>
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<td>Wisperx</td>
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<td>Reverse Wisperx</td>
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<td>All</td>
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<td>All values ≤ 1</td>
<td>31</td>
<td>0.33</td>
<td>0.21</td>
<td>0.64</td>
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</table>
Probabilistic Design of Wind Turbines (Foundations)

Design of foundations for offshore wind farms:

• Geotechnical field measurements are carried out at the location of each turbine (usually as CPT)
• Characteristic values of the material properties are determined (usually as 5% quantile values or “cautious estimates”)
• The soil is assumed to consist of a number of well defined layers
• Within each detected layer the soil is regarded as a homogeneous material
• The application of partial safety factors then provides the design values, and a deterministic design of each foundation is performed
Probabilistic Design of Wind Turbines (Foundations)

- Three possible structural design regimes – offshore wind turbines
  - Soft–soft \( (f_1 < 1P) \)
  - Soft–stiff \( (1P < f_1 < 3P) \)
  - Stiff–stiff \( (3P < f_1) \)
- Note
  - \( f_1 \): First natural frequency
  - \( 1P \): Rotor rate
  - \( 3P \): Blade passage rate
- Main design problem
  - Obtain enough stiffness
  - Estimate stiffness correctly
Probabilistic Design of Wind Turbines (Foundations)
Probabilistic Design of Wind Turbines (Foundations)

- Example: Stochastic model for monopile foundation
Probabilistic Design of Wind Turbines (Foundations)

• Sample random field simulation results

Mapping of the three-dimensional random field in the finite-element model

Plastic strains at fully developed failure mechanism
Probabilistic Design of Wind Turbines (Foundations)

- Cumulative distribution of bearing capacity is found by crude Monte Carlo simulation with 1000 realizations
Operation & Maintenance (OM)

Risk-based methods be used to optimal planning of:

- Quality control / NDI
- Future inspections / monitoring (time / type)
- Decisions on maintenance / repair on basis of (unknown) observations from future inspections / monitoring

taking into account uncertainty and costs
Operation & Maintenance (OM)

Maintenance strategies:
• Corrective (unplanned):
  exchange / repair of failed components
• Preventive (planned):
  Timetabled: Inspections / service after predefined scheme
  Conditioned: Monitor condition of system and decide next inspection based on degree of deterioration
  Based on Pre-posterior Bayesian decision model
Risk Analysis - example

How close to roads can wind turbines be placed?
Load cases for Wave Energy Devices (WEDs)

The following load cases are generally of importance:

- Extreme wave and wind loads during **normal operation**.
- Extreme wave and wind loads during operation simultaneous with a **fault** of
  - **electrical component**.
  - **mechanical component**.
  - **control system**.
- Extreme wave and wind loads when the WED is in ‘**parked**’ **position**.
- Extreme loads during Transport & Installation
- Fatigue failure due to wave and wind loads.
Reliability modeling of WT 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)
# Load cases – offshore wind turbines

## Table 1 - Design load cases

<table>
<thead>
<tr>
<th>Design situation</th>
<th>DLC</th>
<th>Wind condition</th>
<th>Waves</th>
<th>Wind and wave directionality</th>
<th>Sea currents</th>
<th>Water level</th>
<th>Other conditions</th>
<th>Type of analysis</th>
<th>Partial safety factor</th>
</tr>
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<tbody>
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<td>1.1a 1.1a</td>
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<td>V&lt;sub&gt;s&lt;/sub&gt; &lt; V&lt;sub&gt;cr&lt;/sub&gt;</td>
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<td>MSL</td>
<td>For extrapolation of extreme loads on the RNA</td>
<td>U</td>
<td>N</td>
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<td>1.1a 1.1a</td>
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### Support structure

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### RNA

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<td>NCM</td>
<td>MSL</td>
<td>U</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.68 1.68</td>
<td>NDD</td>
<td>V&lt;sub&gt;s&lt;/sub&gt; &lt; V&lt;sub&gt;cr&lt;/sub&gt;</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>U</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.68 1.68</td>
<td>NDD</td>
<td>V&lt;sub&gt;s&lt;/sub&gt; &lt; V&lt;sub&gt;cr&lt;/sub&gt;</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>U</td>
<td>N</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Design situation

- **1.1a**: NTM, V<sub>s</sub> < V<sub>cr</sub>
- **1.2**: NTM, V<sub>s</sub> < V<sub>cr</sub>
- **1.3**: NTM, V<sub>s</sub> < V<sub>cr</sub>
- **1.4**: NTM, V<sub>s</sub> < V<sub>cr</sub>
- **1.5**: NTM, V<sub>s</sub> < V<sub>cr</sub>
- **1.68**: NTM, V<sub>s</sub> < V<sub>cr</sub>

### Wind condition

- **NDD**: No conditions
- **COD**: Code
- **UNI**: Uniform
- **NWWLR**: Non-WWLR

### Waves

- **MDD**: Medium
- **LDD**: Large
- **HDD**: High

### Wind and wave directionality

- **V<sub>s</sub>**: Wind speed
- **V<sub>cr</sub>**: Critical wind speed
- **V<sub>cr</sub>**: Critical wave height

### Other conditions

- **Sea**: Sea state
- **Wind**: Wind speed
- **Wave**: Wave height
- **Direction**: Direction of wind or wave

### Type of analysis

- **P**: Probability
- **U**: Uniform
- **N**: Normal

### Partial safety factor

- **(1.25)**: Factor of safety
Reliability modeling - Wind turbine components …

Power curve:
- Generator Torque Ctrl for variable speed operation to maximize power capture at below-rated wind
- Blade Pitch Ctrl to limit power & structural loads at above rated wind

Rated speed

Wind Speed (m/s)

Power output (KW)
Reliability assessment in normal operation (DLC 1)

Loads on wind turbines depends on:

- Structural dynamics
- Aerodynamics
- Control system
- Wind climate
Reliability assessment in normal operation (DLC 1)
Reliability assessment in normal operation (DLC 1)
Reliability assessment in normal operation (DLC 1)

Stochastic model for annual maximum load:

\[ P = X_{\text{dyn}} X_{\exp} X_{\text{aero}} X_{\text{str}} L \]

\( L \) 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':

\[ P = X_{\text{dyn}} X_{\text{exp}} X_{\text{aero}} X_{\text{str}} L \]

- **\(X_{\text{dyn}}\)** uncertainty related to modeling of the dynamic response, including uncertainty in damping ratios and eigenfrequencies
- **\(X_{\text{exp}}\)** uncertainty related to the modeling of the exposure (site assessment) - such as the terrain roughness and the landscape topography
- **\(X_{\text{aero}}\)** uncertainty in assessment of lift and drag coefficients and additionally utilization of BEM, dynamic stall models, etc
- **\(X_{\text{str}}\)** uncertainty related to the computation of the load-effects given external load

Limit state equation for structural component:

\[ g = z \delta R - X_{\text{dyn}} X_{\text{exp}} X_{\text{aero}} X_{\text{str}} L \]
Reliability assessment in parked position (DLC 6)

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

\[ P = X_{dy} X_{exp} X_{aero} X_{str} L \]

\( L \) extreme load effect from wind pressure: Gumbel distributed

Limit state equation for structural component:

\[ g = z \delta R - X_{dy} X_{exp} X_{aero} X_{str} L \]
Reliability assessment with faults (DLC 2)

Probability of failure of structural component $i$ when fault (e.g. electrical component):

$$P_{f,i} = P(F_i | \text{fault}) P_{\text{annual}}(\text{fault})$$

- probability of failure of structural component $i$ given fault
- annual probability of fault
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:

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

$P\left(F_i|V \in I_1 \cap \text{grid loss} \cap \text{EOG}\right)$ 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

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

Extreme Operating Gust:
Reliability level

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

• Fixed steel offshore structures: e.g. ISO 19902:2004
  manned: annual $P_F \sim 3 \times 10^{-5}$ or $\beta = 4.0$
  unmanned: annual $P_F \sim 5 \times 10^{-4}$ or $\beta = 3.3$

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

\[ 5 \times 10^{-4} \]  

(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-based calibration of safety factors

- Example 1: calibration of material partial safety factors for revision of IEC 61400-1

- Example 2: calibration of safety factors for fatigue of welded details in substructures for offshore wind turbines
Example: Reliability-based calibration of material partial safety factors

Load bearing capacity:

\[ Y = b \delta R(X, a) \]

Conversion factor, accounting for bias in \( R(\cdot) \), scale effects, time duration effects, failure type, etc.

Design values:

Model 1: \( R_d = \frac{R(X_d, a_d)}{\gamma_\Delta} \) and \( X_d = \eta \frac{X_k}{\gamma_m} \)

Model 2: \( R_d = \frac{R(\eta X_k, a_k)}{\gamma_M} \)

Model 3: \( R_d = \frac{R_k}{\gamma_M} \)
Example: Reliability-based calibration of material partial safety factors

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. $\eta = 1$ and $b = 1$

Limit state equation: 
$$g = z \delta R - X_{dyn} X_{exp} X_{aero} X_{str} L$$

Design equation: 
$$\frac{z R_k}{\gamma_R} - \gamma_f L_k \geq 0$$
Example: Reliability-based calibration of material partial safety factors

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution</th>
<th>Mean</th>
<th>COV</th>
<th>Quantile</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Lognormal</td>
<td>-</td>
<td>$V_R$</td>
<td>5%</td>
<td>Strength</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Lognormal</td>
<td>-</td>
<td>$V_\delta$</td>
<td>Mean</td>
<td>Model uncertainty</td>
</tr>
<tr>
<td>$L - DLC 1.1$</td>
<td>Weibull</td>
<td>-</td>
<td>0.15</td>
<td>0.98</td>
<td>Annual maximum load effect obtained by load extrapolation</td>
</tr>
<tr>
<td>$L - DLC 6.1$</td>
<td>Gumbel</td>
<td>-</td>
<td>0.2</td>
<td>0.98</td>
<td>Annual maximum wind pressure - European wind conditions</td>
</tr>
<tr>
<td>$X_{dyn}$</td>
<td>Lognormal</td>
<td>1.00</td>
<td>0.05</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>$X_{exp}$</td>
<td>Lognormal</td>
<td>1.00</td>
<td>0.15</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>$X_{aero}$</td>
<td>Gumbel</td>
<td>1.00</td>
<td>0.10</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>$X_{str}$</td>
<td>Lognormal</td>
<td>1.00</td>
<td>0.03</td>
<td>Mean</td>
<td></td>
</tr>
</tbody>
</table>

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

$\gamma_f = 1.35$
Example: Reliability-based calibration of material partial safety factors

Partial safety factor for load bearing capacity, $\gamma_R \cdot \gamma_f = 1.35$.
DLC 1.1 with Weibull distribution COV=0.15. Target (annual) reliability index = 3.3.

<table>
<thead>
<tr>
<th>$V_{\delta} = 0.00$</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_R = 0.05$</td>
<td>1.16</td>
<td>1.18</td>
<td>1.24</td>
<td>1.35</td>
</tr>
<tr>
<td>0.10</td>
<td>1.12</td>
<td>1.14</td>
<td>1.20</td>
<td>1.29</td>
</tr>
<tr>
<td>0.15</td>
<td>1.11</td>
<td>1.13</td>
<td>1.19</td>
<td>1.28</td>
</tr>
<tr>
<td>0.20</td>
<td>1.13</td>
<td>1.15</td>
<td>1.20</td>
<td>1.28</td>
</tr>
<tr>
<td>0.25</td>
<td>1.17</td>
<td>1.18</td>
<td>1.23</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Partial safety factor for load bearing capacity, $\gamma_R \cdot \gamma_f = 1.35$.
DLC 6.1 with Gumbel distribution COV=0.20. Target (annual) reliability index = 3.3.

<table>
<thead>
<tr>
<th>$V_{\delta} = 0.00$</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_R = 0.05$</td>
<td>1.14</td>
<td>1.16</td>
<td>1.20</td>
<td>1.28</td>
</tr>
<tr>
<td>0.10</td>
<td>1.09</td>
<td>1.11</td>
<td>1.15</td>
<td>1.22</td>
</tr>
<tr>
<td>0.15</td>
<td>1.07</td>
<td>1.08</td>
<td>1.12</td>
<td>1.19</td>
</tr>
<tr>
<td>0.20</td>
<td>1.06</td>
<td>1.08</td>
<td>1.11</td>
<td>1.18</td>
</tr>
<tr>
<td>0.25</td>
<td>1.07</td>
<td>1.09</td>
<td>1.12</td>
<td>1.19</td>
</tr>
</tbody>
</table>
Example: Reliability-based calibration of material partial safety factors

Model 1: $\gamma_m$ and $\gamma_\Delta = \frac{\gamma_\delta}{b}$  
Approximately:  
$\gamma_M = \frac{\gamma_\delta \gamma_R}{b}$

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

Model 3:  
$\gamma_M = \gamma_R$

$b$  
Bias

Partial safety factor for material parameters:  
$\gamma_m = 1.0, \; \gamma_R = 1.0$

<table>
<thead>
<tr>
<th>Coefficient of variation for model uncertainty for resistance model in model 1, $V_\delta$</th>
<th>$\leq 5%$</th>
<th>$10%$</th>
<th>$15%$</th>
<th>$20%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_\delta$</td>
<td>1.20</td>
<td>1.25</td>
<td>1.35</td>
<td>1.45</td>
</tr>
</tbody>
</table>
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: $f_{yk} = 235\text{MPa} \ (\text{COV}=5\%)$
- $E$-module: $210,000\text{MPa}$

- Test results only based on axial loading. EN 1993 calculation model: $\text{COV}=13\%$, $b = 1 / 0,85$
- The bias is normally slightly less for bending. The COV for bending is unknown.
  - $\gamma_R = 1,31$
  - $\gamma_M = 1,31 \times 0,85 \approx 1,1$
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

Cases considered for offshore wind turbine substructure:

- Wave load dominated detail
- Wind load dominated detail
  - Single wind turbine
  - Wind farm
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

- Linear SN-curve: \( N = K \Delta \sigma^m \)
- Single wind turbine - Free wind flow

Design equation:

\[
G(z) = 1 - \int_{U_{in}}^{U_{out}} \frac{\nu \cdot FDF \cdot T_L}{K_C} D_L(m; \sigma_{\Delta \sigma}(U)) f_U(U) dU = 0
\]

Standard deviation of stress ranges:

\[
\sigma_{\Delta \sigma}(U) = \alpha_{\Delta \sigma}(U) \frac{\hat{\sigma}_u(U)}{z}
\]

\[
D_L(m; \sigma_{\Delta \sigma}) = \int_{0}^{\infty} s^m f_{\Delta \sigma}(s|\sigma_{\Delta \sigma}(U)) ds
\]
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

Limit state equation:

\[
g(t) = \Delta - \int_{U_{in}}^{U_{out}} \int_0^\infty \frac{V \cdot t}{K} (X_W X_{SCF})^m D_L (m; \alpha_{\Delta\sigma}(U) \sigma_u(U)/z) \ f_{\sigma_u}(\sigma_u|U) f_U(U) d\sigma_u dU
\]
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

- Wind turbines in wind farm – with wake effects
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

- Linear SN-curve
- Wind turbines in wind farm – with wake effects

Design equation:

\[ G(z) = 1 - \int_{U_{in}}^{U_{out}} \frac{v \cdot FDF \cdot T_L}{K_C} D_L(m; \alpha_{\Delta\sigma}(U)\hat{\sigma}_{u,\text{eff}}(U)/z)f_U(U) dU = 0 \]

\[ \hat{\sigma}_{u,\text{eff}}(U) \approx \left[ (1 - N_w \cdot p_w)\hat{\sigma}_u^m + \sum_{j=1}^{N_w} p_w \hat{\sigma}_{u,j}^m \right]^{1/m} \]

\[ \hat{\sigma}_{u,j}(U) = \sqrt{\frac{0.9 \cdot U^2}{(1.5 + 0.3d_j \sqrt{U/c})^2 + \hat{\sigma}_u^2}} \]
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

- Linear SN-curve
- Wind turbines in wind farm – with wake effects

Limit state equation:

\[
g(t) = \Delta - \int_{U_{in}}^{U_{out}} \int_{0}^{\infty} \frac{V \cdot t}{K} \left( X_W X_{SCF} \right)^m \times \\
\left\{ (1 - N_W \cdot p_W) D_L(m; \alpha_{\Delta\sigma}(U)\sigma_u(U)/z) + p_W \sum_{j=1}^{N_W} D_L(m; \alpha_{\Delta\sigma}(U)\sigma_{u,j}(U)/z) \right\} \times \\
f_{\sigma_u}(\sigma_u|U)f_U(U)d\sigma_u dU
\]

\[
\sigma_{u,j}(U) = \sqrt{X_{\text{wake}} \frac{U^2}{(1.5 + 0.3 d_j \sqrt{U/c})^2} + \sigma_u^2}
\]
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

**Wave load dominating**

- Design lifetime = 20 year
- Number of stress ranges per year is $= 5 \times 10^6$
- Acceptable annual probability of failure: $10^{-4} - 10^{-3}$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution</th>
<th>Expected value</th>
<th>Standard deviation / Coefficient Of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$</td>
<td>N</td>
<td>1</td>
<td>$COV_\Delta = 0.30$</td>
</tr>
<tr>
<td>$X_{wave}$</td>
<td>LN</td>
<td>1</td>
<td>$COV_{wave} = 0.10$</td>
</tr>
<tr>
<td>$X_{wind}$</td>
<td>LN</td>
<td>1</td>
<td>$COV_{wind} = 0.10$</td>
</tr>
<tr>
<td>$X_{SCF}$</td>
<td>LN</td>
<td>1</td>
<td>$COV_{SCF} = 0.10$</td>
</tr>
<tr>
<td>$\log K_1$</td>
<td>N</td>
<td>from $\Delta \sigma_D$</td>
<td>$\sigma_{\log K_1} = 0.20$</td>
</tr>
<tr>
<td>$\log K_2$</td>
<td>N</td>
<td>from $\Delta \sigma_D$</td>
<td>$\sigma_{\log K_2} = 0.25$</td>
</tr>
</tbody>
</table>

$log K_1$ and $log K_2$ are fully correlated
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

- Linear SN-curve with $m = 3$
- Required $FDF$ and corresponding partial safety factors $\gamma_m \gamma_f$ in ( ) for given $\Delta \beta_{\text{min,FAT}}$ ($\Delta P_{F,\text{max,FAT}}$)

| $P(\text{COL}|\text{FAT})$ | 3.1 ($10^{-3}$) | 3.5 ($2 \times 10^{-4}$) | 3.8 ($10^{-4}$) |
|-----------------------------|-----------------|-------------------------|-----------------|
| 1.0                         | 2.40 (1.34)     | 3.38 (1.50)             | 4.32 (1.63)     |
| 0.5                         | 1.98 (1.26)     | 2.88 (1.42)             | 3.73 (1.55)     |
| 0.1                         | 1.11 (1.03)     | 1.87 (1.23)             | 2.60 (1.37)     |
| 0.01                        | (-)             | (-)                     | 1.26 (1.08)     |

- $\Delta \beta_{\text{min,FAT}} = 3.5$:

<table>
<thead>
<tr>
<th>$COV_{SCF}$</th>
<th>0.00</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FDF (\gamma_f \gamma_m)$</td>
<td>2.83 (1.42)</td>
<td>2.97 (1.44)</td>
<td>3.38 (1.50)</td>
<td>4.10 (1.60)</td>
</tr>
</tbody>
</table>
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

Wind load dominating – single WT
- Linear SN-curve with $m = 3$
- Number of stress ranges per year is $= 5 \times 10^7$
- Required $FDF$ and corresponding partial safety factors $\gamma_m \gamma_f$ in ( ) for given $\Delta \beta_{\min, FAT}$ ($\Delta P_{F, \max, FAT}$)

| $P_{\text{COL} | \text{FAT}}$ | 3.1 ($10^{-3}$) | 3.5 ($2 \times 10^{-4}$) | 3.8 ($10^{-4}$) |
|-----------------|-----------------|-----------------|-----------------|
| 1.0             | 1.61 (1.17)     | 2.27 (1.31)     | 2.90 (1.43)     |
| 0.5             | 1.33 (1.10)     | 1.93 (1.25)     | 2.51 (1.36)     |
| 0.1             | 1.0 (1.0)       | 1.25 (1.08)     | 1.74 (1.20)     |
| 0.01            | 1.0 (1.0)       | 1.0 (1.0)       | 1.0 (1.0)       |
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

Wind load dominating – wind farm

- Linear SN-curve with $m = 3$
- Required $FDF$ and corresponding partial safety factors $\gamma_m \gamma_f$ in ( ) for given $\Delta \beta_{\text{min,FAT}}$ ( $\Delta P_{F,\text{max,FAT}}$ )

| $P(\text{COL|FAT})$ | $3.1 \times 10^{-3}$ | $3.5 \times 10^{-4}$ | $3.8 \times 10^{-4}$ |
|---------------------|----------------------|----------------------|----------------------|
| 1.0                 | 1.80 (1.22)          | 2.54 (1.37)          | 3.26 (1.48)          |
| 0.5                 | 1.49 (1.14)          | 2.17 (1.29)          | 2.81 (1.41)          |
| 0.1                 | 1.0 (1.0)            | 1.40 (1.12)          | 1.95 (1.25)          |
| 0.01                | 1.0 (1.0)            | 1.0 (1.0)            | 1.0 (1.0)            |
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

Calibration with inspections

- Risk Based Inspection planning has been developed during the last 10-15 years
  - used for inspection planning for fatigue cracks in e.g. oil & gas jacket structures

- Fracture mechanics model calibrated to SN model such that same reliability level is obtained

- POD-curve: \( POD(x) = 1 - \exp\left(-\frac{x}{\lambda}\right) \)

- Equidistant inspection times
Example: Reliability-based calibration of safety factors for fatigue of welded details in offshore wind turbines

- Linear SN-curve with $m = 3$, $\Delta \beta_{\text{min,FAT}} = 3.5$

- Wind load dominating - Single wind turbine:

<table>
<thead>
<tr>
<th>POD: $\lambda$</th>
<th>2 mm</th>
<th>5 mm</th>
<th>10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inspections</td>
<td></td>
<td></td>
<td>2.27 (1.31)</td>
</tr>
<tr>
<td>1 inspection</td>
<td>1.92 (1.24)</td>
<td>2.15 (1.29)</td>
<td>2.20 (1.30)</td>
</tr>
<tr>
<td>2 inspections</td>
<td>1.65 (1.18)</td>
<td>1.94 (1.25)</td>
<td>2.11 (1.28)</td>
</tr>
<tr>
<td>3 inspections</td>
<td>1.46 (1.13)</td>
<td>1.82 (1.22)</td>
<td>2.05 (1.27)</td>
</tr>
</tbody>
</table>

- Wind load dominating – wind farm:

<table>
<thead>
<tr>
<th>POD: $\lambda$</th>
<th>2 mm</th>
<th>5 mm</th>
<th>10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inspections</td>
<td></td>
<td></td>
<td>2.54 (1.37)</td>
</tr>
<tr>
<td>1 inspection</td>
<td>2.15 (1.29)</td>
<td>2.40 (1.34)</td>
<td>2.49 (1.36)</td>
</tr>
<tr>
<td>2 inspections</td>
<td>1.83 (1.22)</td>
<td>2.17 (1.29)</td>
<td>2.35 (1.33)</td>
</tr>
<tr>
<td>3 inspections</td>
<td>1.64 (1.18)</td>
<td>2.05 (1.27)</td>
<td>2.28 (1.32)</td>
</tr>
</tbody>
</table>

- Wave load dominating:

<table>
<thead>
<tr>
<th>POD: $\lambda$</th>
<th>2 mm</th>
<th>5 mm</th>
<th>10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inspections</td>
<td></td>
<td></td>
<td>3.38 (1.50)</td>
</tr>
<tr>
<td>1 inspection</td>
<td>2.85 (1.42)</td>
<td>3.18 (1.47)</td>
<td>3.27 (1.48)</td>
</tr>
<tr>
<td>2 inspections</td>
<td>2.44 (1.35)</td>
<td>2.90 (1.43)</td>
<td>3.15 (1.46)</td>
</tr>
<tr>
<td>3 inspections</td>
<td>2.18 (1.30)</td>
<td>2.66 (1.39)</td>
<td>3.05 (1.45)</td>
</tr>
</tbody>
</table>
Example: Grouted connections

- Monopiles including grouted connection between Monopiles (MP) and Transition pieces (TP) have been widely used for wind turbine structures since 2002
- In Europe: 600+ OWT’s using grouted connections
- Unexpected behavior of grouted connections between MP and TP

From the Journal "Ingeniøren" in Denmark, Spring 2010
Example: Grouted connections

Repair / Mitigation options

- Elastomer spring bearings
- ...
- Perform inspections and 'wait-and-see' based on Risk-based Inspection Planning
Summary

• Reliability of wind turbine (WT) and wave energy device (WED) components are very important for decreasing Levelised Cost Of Energy (LCOE)
• Structural reliability methods (time in-variant)
• General model presented for modeling reliability of structural, mechanical or electrical component.
• Reliability models presented for different components
• Example: reliability based calibration of material partial safety factors for IEC 61400-1
• Example: reliability-based calibration of partial safety factors for fatigue critical details in offshore wind turbine substructures
Literature - More information

Literature - More information

• Sørensen, J.D.: Notes in Structural Reliability Theory. Department of Civil Engineering, Aalborg University, 2011.
• JCSS: www.jcss.byg.dtu.dk

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Thank you for your attention!

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