Probabilistic design of wind turbine blades

John Dalsgaard Sørensen  
Aalborg University & Risø-DTU  
Denmark  
jds@civil.aau.dk

Henrik Stensgaard Toft  
Aalborg University  
Denmark  
hst@civil.aau.dk

• Introduction
• Reliability-based design of wind turbines
• Reliability of blade with defects  
  – Example - ULS
• Calibration of safety factors  
  – Example – Fatigue
• Summary / conclusions
Introduction

Goal: minimize the total expected life-cycle costs
   → minimize COE

Initial costs: dependent on reliability level
O&M costs: dependent on O&M strategy, availability and reliability
Failure costs: dependent on reliability
Introduction

Research projects:

• **UpWind (EC)** – Integrated wind turbine design
  – Uncertainty modeling and reliability / standards

• **Probabilistic Design of Wind Turbines (DSF)**

• **Reliability-based analysis applied for reduction of cost of energy for offshore wind turbines (DSF)**
  – Reliability-based analysis and design of wind turbine blades
  – Risk-based operation and maintenance of offshore wind turbines
  – Reliability-based design of wind turbine foundations

• **Norwegian Centre for Offshore Wind Energy (NORCOWE)**
  – Reliability analysis of wind turbines - basis for O&M planning
  – Risk-based operation and maintenance of offshore wind farms
Reliability modeling of wind turbines

Analysis of failure probabilities based on different types of information:

- Observed failure rates
  Classical reliability theory

- Probabilistic models → failure probabilities

Structural Reliability Theory:
  - Limit state equations
  - Stochastic models for uncertain parameters
  - Failure probabilities by FORM / SORM / simulation
Reliability-based design

**Challenges** by Probabilistic / reliability-based design:
- Limit state equations – related to design equations
- Stochastic models for uncertain parameters
- System modelling
- Target / minimum reliability level

**Benefits** by Probabilistic / reliability-based design:
- Optimal design for each component → uniform reliability
- Uncertainties related to the specific site, component and manufacturing process can be used
- Information from tests / monitoring can be taken into account in a rational way – by a Bayesian statistical approach
Reliability-based design

System aspects
• Series / parallel system?
• Damage tolerance
• Robustness

Robustness (system reliability) can be increased by
• Increased redundancy
  – mechanical load sharing
  – statistical parallel system effects
• Increased ductility
• Protecting the wind turbine to (unforeseen) incidents and defects
• Good quality control in all phases
Reliability-based design

Target / minimum reliability level:
• Building codes: e.g. Eurocode EN1990:2002:
  – annual $P_F = 10^{-6}$
• IEC 61400-1 & -3: wind turbines
  – annual $P_F \sim 10^{-4} - 10^{-3}$
• Observation of failure rates for wind turbines
  – Failure of blades: approx. $10^{-4} - 10^{-3}$ per year
  – Wind turbine collapse: approx. $10^{-5} - 10^{-4}$ per year

Design wind turbine (component) such that
• Probability of failure $P_F \leq \max P_F$
Reliability-based design of blades

- Combination of
  - Theoretical & computational models
  - Tests of coupons / materials
  - Tests of subcomponents
  - Few full-scale tests
  - Information from prototype wind turbines
  - Quality control / NDI
  - Measurements of climatic conditions

- 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.
Reliability of blades – with defects

Local production defects:
- Delaminations
- Wrinkles
- Matrix cracks
- Voids
- Defects in glued joints
- ...

Model parameters:
- Type of defect
- Size of defect
- Position of defect

Delaminations:
Reliability of blades – with defects

Uncertainties in calculation of the load carrying capacity for wind turbine blades

1. Material properties
   – Physical uncertainty (Aleatory)
   – Statistical uncertainty (Epistemic)

2. Finite Element calculation
   – Model uncertainty (Epistemic)

3. Failure criteria
   – Model Uncertainty (Epistemic)
Reliability of blades – with defects
- Stochastic model for Defects

Model 1
Completely Random Distribution

Model 2
Random Cluster Distribution
Reliability of blades – with defects
- System reliability

System model of wind turbine blade:

Probability of failure for the system:

\[ P_F = P\left(\bigcup_{i=1}^{n} \bigcap_{j=1}^{m} (g_{ij} \leq 0)\right) \]
Reliability of blades – with defects
- Load Carrying Capacity of Main Spar

Failure of components by:
• Maximum Strain
• First Ply Failure

Limit state function for component including the influence of a defect:
\[ g(\alpha) = z X_R \alpha R(\varepsilon_{\text{max}}, \mathbf{E}) - X_L L \]

\( \alpha \)  strength reduction due to defect

Probability of failure for a component including defects:
\[ P_{F,\text{component}} = \sum_{\alpha} P(g(\alpha) \leq 0) P(\alpha) \]
Reliability of blades – with defects
- Non Destructive Inspection (NDI)

Updated probability of failure for a component:

\[ P_{F_{\delta,\text{component}}} = \sum_{\alpha} \left[ P\left(g\left(\alpha = 1\right) \leq 0\right) \cdot PoD\left(\alpha\right) + P\left(g\left(\alpha \leq 0\right) \leq 1 - PoD\left(\alpha\right)\right)\right] \cdot P\left(\alpha\right) \]

- Defects are assumed perfect repaired if detected by NDI

POD-curve:
Probability of Detection

Distribution function of defect size without / with NDI

![POD-curve](image1.png)

![Distribution function of defect size](image2.png)
Reliability of blades – with defects

Example

- Average 1 defect per blade
- Average delamination size: 20 cm
- Average size minimum detectable delamination: 10 cm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>5</td>
<td>Number of parallel systems</td>
</tr>
<tr>
<td>$m$</td>
<td>5</td>
<td>Number of components in each parallel system</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>1.0</td>
<td>Model 1: Average number of defects</td>
</tr>
<tr>
<td>$\chi_S$</td>
<td>$5.0,m^{-1}$</td>
<td>Average delamination size $\mu_s = 1/\chi_S$</td>
</tr>
<tr>
<td>$\chi_\delta$</td>
<td>$10.0,m^{-1}$</td>
<td>Average NDI size $\mu_\delta = 1/\chi_\delta$</td>
</tr>
</tbody>
</table>
## Reliability of blades – with defects

### Example

<table>
<thead>
<tr>
<th>Description</th>
<th>Defects</th>
<th>$P_F$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>No defects</td>
<td>$3.1 \cdot 10^{-3}$</td>
<td>2.74</td>
</tr>
<tr>
<td>Reference</td>
<td>Model 1</td>
<td>$11.7 \cdot 10^{-3}$</td>
<td>2.27</td>
</tr>
<tr>
<td>Reference, NDI</td>
<td>Model 1</td>
<td>$4.6 \cdot 10^{-3}$</td>
<td>2.61</td>
</tr>
<tr>
<td>Larger system: $n = 5, m = 8$</td>
<td>Model 1</td>
<td>$6.7 \cdot 10^{-3}$</td>
<td>2.48</td>
</tr>
<tr>
<td>Less reliable NDI: $\chi_\delta = 5m^{-1}, , NDI$</td>
<td>Model 1</td>
<td>$6.0 \cdot 10^{-3}$</td>
<td>2.51</td>
</tr>
<tr>
<td>More defects: $\lambda = 2$</td>
<td>Model 1</td>
<td>$21.8 \cdot 10^{-3}$</td>
<td>2.02</td>
</tr>
</tbody>
</table>
Calibration of partial safety factors

Partial safety factors (psf) for loads and strength parameters can be calibrated to a given reliability level taking into account:

- Uncertainty on loads
- Uncertainty on strength parameters
- Model uncertainty for computational model & failure criteria
- Statistical uncertainty (number of tests)

such that less uncertainty $\rightarrow$ less partial safety factors $\rightarrow$ cost reduction

Uniform reliability $\rightarrow$ cost reduction
Example - calibration of psf - fatigue

Uncertainties:
• Physical uncertainty - SN-curves
• Statistical uncertainty - limited number of tests
  o Bayesian modelling
• Model uncertainty - Miners rule

Linear SN-curve:

\[ N = K \Delta \sigma^{-m} \]  \[ \log N = \log K - m \log \Delta \sigma \]

Physical + Statistical uncertainty:
\log K \quad \text{Bayesian statistics}
Example - calibration of psf - fatigue

OPTIDAT database: geometry R04 MD

<table>
<thead>
<tr>
<th>$R$-ratio</th>
<th>Number of tests</th>
<th>Number of run-outs</th>
<th>$m$</th>
<th>log $K$</th>
<th>$\sigma_{\log K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>15</td>
<td>0</td>
<td>10.5</td>
<td>27.8</td>
<td>0.36</td>
</tr>
<tr>
<td>0.1</td>
<td>45</td>
<td>2</td>
<td>9.5</td>
<td>27.2</td>
<td>0.26</td>
</tr>
<tr>
<td>-0.4</td>
<td>28</td>
<td>0</td>
<td>7.6</td>
<td>23.4</td>
<td>0.44</td>
</tr>
<tr>
<td>-1.0</td>
<td>84</td>
<td>3</td>
<td>6.7</td>
<td>21.4</td>
<td>0.88</td>
</tr>
<tr>
<td>-2.5</td>
<td>10</td>
<td>2</td>
<td>12.0</td>
<td>35.2</td>
<td>0.63</td>
</tr>
<tr>
<td>10.0</td>
<td>34</td>
<td>0</td>
<td>22.2</td>
<td>58.7</td>
<td>0.64</td>
</tr>
<tr>
<td>2.0</td>
<td>6</td>
<td>3</td>
<td>29.7</td>
<td>73.8</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Example - calibration of psf - fatigue

- $R = -2.5$
- $R = -1.0$
- $R = -0.4$
- $R = 0.1$
Example - calibration of psf - fatigue

Constant life diagram for geometry R04 MD
Example - calibration of psf - fatigue

Variable amplitude fatigue tests

Load spectrum: Wisper and Wisperx

Miners rule for linear damage accumulation:

\[ D = \sum_{i=1}^{n} \frac{1}{N(\Delta \sigma_i)} \]

Limit state equation:

\[ g = \Delta - \sum_{i=1}^{n} \frac{1}{N(\Delta \sigma_i)} \]

\[ \Delta \quad \text{model uncertainty: LN}(\mu_\Delta, \sigma_\Delta) \]
# Example - calibration of psf - fatigue

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Dist.</th>
<th>Mean</th>
<th>Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$</td>
<td>Uncertainty Miners Rule</td>
<td>LN</td>
<td>0.55</td>
<td>0.49</td>
</tr>
<tr>
<td>$X_{exp}$</td>
<td>Model Uncertainty – Exposure</td>
<td>LN</td>
<td>1.00</td>
<td>0.05</td>
</tr>
<tr>
<td>$X_{aero}$</td>
<td>Model Uncertainty – Aerodynamics</td>
<td>LN</td>
<td>1.00</td>
<td>0.10</td>
</tr>
<tr>
<td>$X_{dyn}$</td>
<td>Model Uncertainty - Dynamic Response</td>
<td>LN</td>
<td>1.00</td>
<td>0.05</td>
</tr>
<tr>
<td>$X_{stress}$</td>
<td>Model Uncertainty - Stress Calculation</td>
<td>LN</td>
<td>1.00</td>
<td>0.03</td>
</tr>
<tr>
<td>$X_{stat}$</td>
<td>Statistical Uncertainty - Load Assessment</td>
<td>LN</td>
<td>1.00</td>
<td>0.024</td>
</tr>
<tr>
<td>log $K$</td>
<td>Physical Uncertainty SN-curve</td>
<td>N</td>
<td>27.768</td>
<td>0.358</td>
</tr>
<tr>
<td>$m$</td>
<td>Parameter SN-curve</td>
<td>D</td>
<td>10.541</td>
<td>-</td>
</tr>
<tr>
<td>$\nu_{th}$</td>
<td>Load cycles per year</td>
<td>D</td>
<td>2.88 \cdot 10^6</td>
<td>-</td>
</tr>
<tr>
<td>$T$</td>
<td>Life time in years</td>
<td>D</td>
<td>20</td>
<td>-</td>
</tr>
</tbody>
</table>
Example - calibration of psf - fatigue

Partial safety factors calibrated to a reliability index $\beta = 3.1$:

<table>
<thead>
<tr>
<th>Reference</th>
<th>$\gamma_n \gamma_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference</strong></td>
<td><strong>1.37</strong></td>
</tr>
<tr>
<td>Uncertainty Miners rule</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sim LN(1.00;0.30)$</td>
<td>1.23</td>
</tr>
<tr>
<td>$\Delta \sim LN(0.90;0.55)$</td>
<td>1.27</td>
</tr>
<tr>
<td>$\Delta \sim LN(0.45;0.40)$</td>
<td>1.39</td>
</tr>
<tr>
<td><strong>Model uncertainty aerodynamic</strong></td>
<td></td>
</tr>
<tr>
<td>$X_{aero} \sim LN(1.00;0.05)$</td>
<td>1.32</td>
</tr>
<tr>
<td>$X_{aero} \sim LN(0.95;0.10)$</td>
<td>1.31</td>
</tr>
<tr>
<td><strong>Model uncertainty SN-curve</strong></td>
<td></td>
</tr>
<tr>
<td>$\log K \sim N(27.768;0.200)$</td>
<td>1.34</td>
</tr>
</tbody>
</table>

IEC 61400-1:

$\gamma_m \gamma_m = 1.38$
Summary / Conclusions

• Basis for reliability-based / probabilistic design
• Reliability analysis of blades with defects
  – Updating by NDI and Bayesian methods
  – Illustrated by example – extreme load
• Calibration of partial safety factors
  – Illustrated by example – fatigue

Future work
• Stochastic models for probabilistic design to be ‘standardized’
• Stochastic modelling of defects – for ‘real’ blades
• Reliability-based calibration of partial safety factors using test results at different levels by Bayesian methods
• Reliability-based test planning
Thank You For Your Attention

John D Sørensen, Aalborg University & Risø-DTU
Henrik S Toft, Aalborg University