Fatigue crack detection for lifetime extension of monopile-based offshore wind turbines

Jutta Stutzmann\textsuperscript{1,2}, \textbf{Lisa Ziegler}\textsuperscript{3,4}, Michael Muskulus\textsuperscript{4}

\textsuperscript{1} University of Stuttgart, Germany
\textsuperscript{2} Chalmers University of Technology, Sweden
\textsuperscript{3} Rambøll, Germany
\textsuperscript{4} Norwegian University of Science and Technology

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 642108.
Why lifetime extension?

- Design lifetime at least 20 years
- Lifetime extension possible if structural reserves are left
- Increases profit and reduces environmental impact
What do we need for lifetime extension?

We need to...
- keep the target safety level
- know structural reserves and remaining useful lifetime

This can be done by...
- analytical assessments
- practical assessments

Problems of inspections are...
- access
- safety risks
- costs
- detection uncertainty

Is it worth to do inspections?
Agenda

1. Inspection of fatigue cracks
2. Simulation of fatigue cracks
3. How to link inspections and simulations: Bayes Theorem
4. Results: Reduction of uncertainty
Inspection for fatigue cracks

- Probability of detection
  - Inspection method (eddy current, visual inspection, ...)
  - Ease of access
  - Crack size

\[
PoD(a_n) = 1 - \frac{1}{1 + \left(\frac{a_n}{X_0}\right)^b}
\]

PoD parameters given in DNVGL RP-C210
Simulation of fatigue cracks

- DeepWind 2016: Load sequence is negligible using Paris law
- Integration of Paris law now possible 😊

\[
\frac{da}{dN} = C(\Delta K_I)^m \quad \text{with} \quad \Delta K_I = \Delta SY\sqrt{\pi a}
\]

\[
CS^m\Delta N = \int_{a_0}^{a} \frac{da}{Y^m(a\pi)^m}
\]

\[a: \text{crack depth [mm]} \quad \Delta S: \text{stress range [MPa]}\]
\[N: \text{number of cycles [-]} \quad Y: \text{geometry factor [-]}\]
\[\Delta K_I: \text{stress intensity factor} \quad C, m: \text{material constants}\]

- Variable amplitude loading
  ⮕ bins of 1MPa
Simulation of fatigue cracks

- Why integration of Paris Law?
  - Because it is fast
- Why do we need it fast?
  - Monte Carlo Simulation

**Monte Carlo Simulations**

- Uncertainties: $C$, $Y$, $a_0$
- Deterministic loads from case study
- Distribution of crack size in year 20
Simulation of fatigue cracks

- Why integration of Paris Law?
  - Because it is fast
- Why do we need it fast?
  - Monte Carlo Simulation

Monte Carlo Simulations
- Uncertainties: \( C, Y, a_0 \)
- Deterministic loads from case study
- Distribution of crack size in year 20

Remaining useful lifetime
- Time until \( a_n \) reaches \( a_{\text{fail}} \)
How to link inspections and simulations: Bayes Theorem

Fatigue

- crack

simulation

Inspection
How to link inspections and simulations: Bayes Theorem

\[
P(a_n \mid z) = \frac{P(a_n)P(z \mid a_n)}{P(z)}
\]

- \(P(a_n)\): Probability of crack size \(a_n\)
- \(P(z \mid a_n)\): Probability of detection (POD)
- \(P(z)\): Probability of inspection outcome

\[P(z) = \sum_{a_{\text{min}}}^{a_{\text{max}}} POD(a_n)P(a_n)\]
**Inspection outcomes and Bayesian updating**

\[ P(\bar{a}_n \cap z) \]

\[ P(a_n \cap \bar{z}) \]

\[ P(a_n | \bar{z}) \]

\[ P(\bar{z} | a_n) = 1 - \text{PoD} (a_n) \]

\[ P(z | a_n) = \text{PoD}(a_n) \]

\[ P(z | a_n) = 1 - P(\bar{z} | a_n) \]

\[ P(z | a_n) = \text{PoD}(a_n) \]

\[ P(a_n | z) \]

- **P(a_n):** Probability of crack size \( a_n \)
- **P(z):** Probability of detection
- **\( \bar{x} \):** complement of \( x \)
- **P(z | a_n):** Probability of detection (POD)
- **P(a_n | z):** Updated probability of crack size
Results: Reduction of uncertainty

<table>
<thead>
<tr>
<th></th>
<th>Median crack size $a_n$ [mm]</th>
<th>Median RUL [years]</th>
<th>Standard deviation RUL [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inspection</td>
<td>0.04</td>
<td>78</td>
<td>446</td>
</tr>
<tr>
<td>With detection</td>
<td>0.20</td>
<td>33</td>
<td>47</td>
</tr>
<tr>
<td>Without detection</td>
<td>0.04</td>
<td>83</td>
<td>103</td>
</tr>
</tbody>
</table>
Results: Reduction of uncertainty

- Results influenced by tails of distribution
- Case with detection: 10% of RUL is below 10 years
- Case without detection: 10% of RUL is below 30 years
- Larger reduction of uncertainty in case of detection
- Individual results for every structural detail – Where is the hot spot?
Conclusion

Inspections are costly and risky. Is it worth to do it?

We showed the value of inspections is:
- Reduction of uncertainty
- Eliminate risks of large cracks

Conclusion:
- A trade-off between costs and benefits necessary!
- Is the safety level without inspections acceptable? ➞ Design fatigue factor of 3 = inspection free
- Alternative: Structural health monitoring
Thanks for your attention

Lisa Ziegler
PhD researcher
lisa.ziegler@ramboll.com
+49 (0) 151 44 006 445

Rambøll Wind
Hamburg, Germany
www.ramboll.com/wind

Jutta Stutzmann
Student MSc Sustainable Energy
jutta@stutzmann.de
+49 (0) 160 81 34 855

University of Stuttgart
Chalmers University of Technology
• AWESOME = Advanced wind energy systems operation and maintenance expertise
• Marie Skłodowska-Curie Innovative Training Networks
• 11 PhD’s
• O&M
  - Failure diagnostic and prognostic
  - Maintenance scheduling
  - Strategy optimization

www.awesome-h2020.eu
Lifetime extension – a future problem?

Lifetime extension assessment

Analytical assessment

• Renewed simulations with focus on fatigue
• Calculate remaining useful lifetime

Practical assessment

• Inspections, maintenance history
• Foundations are one component
• Cracks as fatigue damage
• Other failure modes: corrosion, scour,...
Case study

- NREL 5MW and monopile from OC3 project (Nichols et al. 2009)
- Met-ocean data from Upwind project (Fischer et al. 2010)
- Fatigue load cases: power production, idling
- Structural response to aerodynamic and hydrodynamic loading (impulse-based substructuring)

Simulation of fatigue crack growth with Paris law

Model of offshore wind monopile.