RELIABILITY OF WAVE ENERGY CONVERTERS – CALIBRATION OF FATIGUE DESIGN FACTORS

3RD SDWED SYMPOSIUM

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Loads on the Structure

Fatigue loads are of importance for wave energy convertors.
What is ‘Fatigue Design Factor’ (FDF)?

- For fatigue processes, **time** is of importance and drives the process.
- FDF defines the **safety factor**, which is related to life-time.

**Definition of FDF:**

\[
FDF = \frac{T_{FAT}}{T_{Life}}
\]

- Using a linear SN-curve:

\[
FDF = (\gamma_m \gamma_f)^m
\]

- Safety factors are dependent on:
  - **Uncertainty** in fatigue **loads**
  - **Uncertainty** in fatigue **strength**
  - **Consequences** in case of failure
  - **Inspections** performed: Yes/No
  - The **complexity** how loads are estimated (e.g. static/dynamic load estimation).

\(T_{Life}\) Real life-time of device (e.g. 20 years)

\(T_{FAT}\) Life-time used for the structural design (e.g. 60 years)

\(\gamma_m\) Partial safety factor for fatigue strength

\(\gamma_f\) Partial safety factor for fatigue load

\(m\) SN-curve parameter (between 3 and 5)
How to measure/model Fatigue? (I)

- Weakening of material caused by repeatedly applied loads.
- Physical explanation: evolution of cracks which weaken the structure (time-dependent process).

- Miner’s Rule:

\[
D = \sum n_i / N_i
\]

\[
N_i = K (\Delta s)^{-m}
\]

\[
\Delta s_i = \frac{\Delta F_i}{A}
\]

\[
\text{example}\]

Failure: \( D \geq 1 \)

No Failure: \( D < 1 \)

\( n_i \) Number of cycles given certain load range during life-time

\( N_i \) Number of cycles to failure given certain load range

\( K, m \) SN-curve parameters

\( \Delta s_i \) Stress range

\( \Delta F_i \) Load range

\( A \) Cross-section area
How to measure/model Fatigue? (II)

- **SN-curve:**
  - consider number $N$ of cycles for a certain stress amplitude $\Delta s$ leading to failure ($D=1$).
  - SN-curve often shown in Loglog scale plots.
  - Example with one linear and two bilinear SN-curves:

![SN Curves for different Environments (SN Curve F; t=50mm)](image)
How to measure/model Fatigue? (III)

- Fracture Mechanics (1-dimensional):

\[ \frac{da}{dN} = C \left( \Delta K(a) \right)^m \]

\[ \Delta K(a) = Y \Delta \sigma_e \sqrt{\pi a} \]

\[ \frac{a}{2c} = f \left( \frac{a}{T} \right) \]

Failure: \( a(t) = T \)

Assumption: Repair of crack when crack is found at an inspection.

- Alternatively: 2-dimensional crack growth model
Probability of Detection (PoD)

• When performing an inspection, the smallest detectable crack is dependant on the inspection method.

• During inspections not all cracks might be detected:

\[ \text{PoD} = P(c, \text{inspection method}) \]

• Inspection methods:
  • Magnetic particle inspection (MPI)
  • Eddy current
  • Visual inspection
Summary of Fatigue Modelling used for FDF Calibration

Consideration of inspections

- NO: SN-curves and Miner’s rule
- YES: Fracture mechanics model
Probabilistic Reliability Assessment (I)

• Probability of failure can be obtained by using e.g. First Order Reliability Methods (FORM):

\[ P_F = P(g \leq 0) \]

• Reliability index defined as:

\[ \beta = -\Phi^{-1}(P_F) \]

\( \Phi(\cdot) \) is the standardized normal distribution

• Relation between probability of failure and reliability index:

<table>
<thead>
<tr>
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<th>10^{-4}</th>
<th>10^{-3}</th>
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<td>( P_F )</td>
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<td>2.3</td>
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<td>10^{-4}</td>
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<td>10^{-2}</td>
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Probabilistic Reliability Assessment (II)

- Probabilistic reliability assessments consider uncertainties as **stochastic variables**.

- Stochastic modelling of uncertainties:
  - Physical uncertainties
  - Modelling uncertainties
  - Statistical uncertainties
  - Measurement uncertainties
Calibration Principle

- A combination of deterministic and probabilistic calculations can be used in order to assess the reliability of a design and calibrate FDF values (or equivalent partial safety factors) fulfilling a certain reliability index.
Example: Wavestar Device

- Wavestar is chosen because
  - Hydrodynamic in-house code available (Load time-series provided by WP4).
  - Estimation of model uncertainty based on wave tank tests.
- Focus on welded detail between PTO and Floater:
## Required FDF values

<table>
<thead>
<tr>
<th>Inspection strategy</th>
<th>Annual rel. index $\Delta \beta$</th>
<th>Time interval (years)</th>
<th>Number of inspections</th>
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<tr>
<td></td>
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<td>20</td>
<td>10</td>
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<tr>
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<td></td>
<td></td>
<td>6.5</td>
<td>6.4</td>
</tr>
<tr>
<td>visual (50 mm)</td>
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<td>3.3</td>
<td>2.6</td>
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<tr>
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<td></td>
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<td>6.5</td>
<td>6.1</td>
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</table>

Resulting required FDF values are decreased when implementing inspections.

Resulting required FDF values are in the range between 1 and 6.5.
Comparison with nearby industries

- Comparison of required FDF values used in offshore wind turbine standards as well as for steel structures used in oil and gas industry.

<table>
<thead>
<tr>
<th>Failure critical detail</th>
<th>Inspections</th>
<th>Offshore wind turbines</th>
<th>Oil and Gas[^3]</th>
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<tbody>
<tr>
<td>Yes</td>
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<td>2</td>
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</table>

[^1]: DNV-OS-J101: Design of offshore wind turbines
[^2]: DNV-OS-J103: Design of floating wind turbine structures
[^3]: ISO 19902 Petroleum and Natural Gas Industries – Fixed steel offshore structures
Conclusions

• Fatigue is modelled using a SN-curve and Miner’s rule (no inspections) as well as Facture mechanics (inspections implemented).

• The Wavestar example showed that FDF values can be reduced from 6.5 (no inspections) to 1 (annual inspection actions).

• Resulting required FDF values are in the range as proposed for floating wind turbines (DNV-OS-J103).

• Focus only on one working principle/device. In order to give recommendations for standards, more examples need to be considered.
Thank you very much for your attention!
The International Research Alliance

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Structural Design of Wave Energy Devices

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