Updating Fatigue Failure Probability

Considering Monitoring and Inspection Data

Quang Mai

December 7, 2018

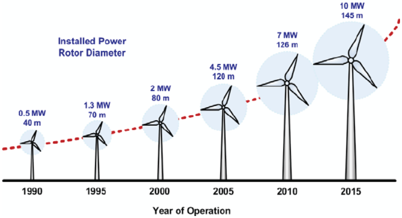
Faculty of Applied Sciences


Strain
Measurement Data
Crack Inspection
& Repair
Data
Wind
Measurement Data
Wave
Measurement Data

Introduction

Wind Energy – the fastest growing energy source

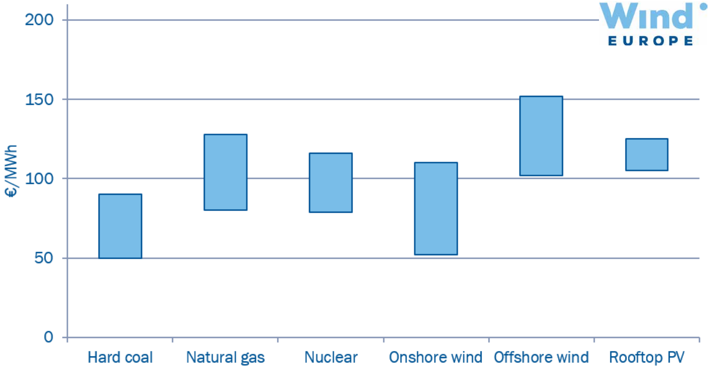
- Less environmental impact
- Fast installation
- Fast development!



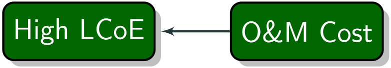
Levelized Cost of Electricity

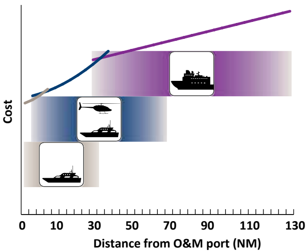
High LCoE

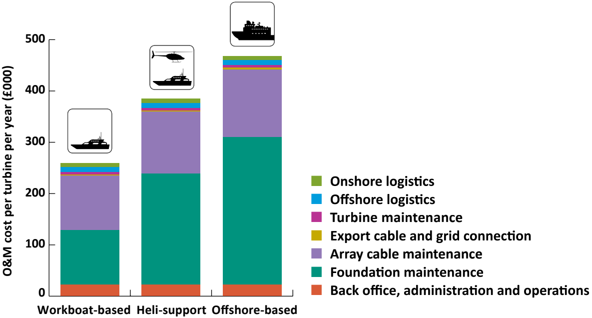
(lifetime costs per unit of electricity – MWh)



Levelized Cost of Electricity

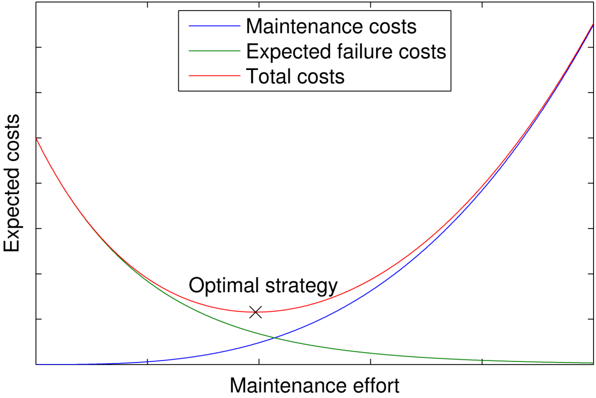






Levelized Cost of Electricity

High LCoE ← O&M Cost → Risk-based Inspection



Levelized Cost of Electricity

High LCoE ← O&M Cost → Risk-based Inspection

High Decommissioning Cost

Levelized Cost of Electricity

High LCoE ← O&M Cost → Risk-based Inspection

High Decommissioning Cost → Life Extension

Levelized Cost of Electricity

High LCoE ← O&M Cost → Risk-based Inspection

High Decommissioning Cost → Life Extension

Majority of reported offshore failures are fatigue failures!

$\Rightarrow$ Update Failure Probability in Fatigue Failure Mode!

Message Objective

Using **Failure Assessment Diagram** and **Occurence of Weather Conditions** in the Limit State Function improves the accuracy of the **Updated Failure Probability**.

Road Map

Introduction

Background

FAD in Updating Considering Inspection

Occurence of Weather Conditions in Updating Considering Monitoring

Conclusion

Background

Road Map

Introduction

Background

- Fatigue Assessment
- Failure Probability
- Updating Principle

FAD in Updating Considering Inspection

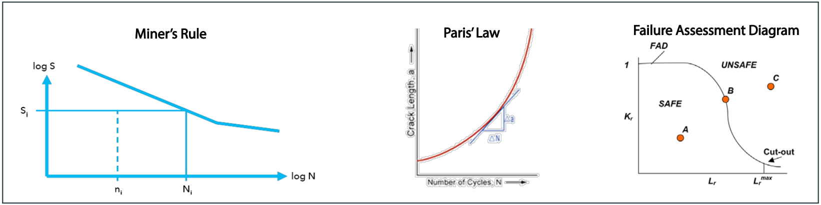
Occurence of Weather Conditions in Updating Considering Monitoring

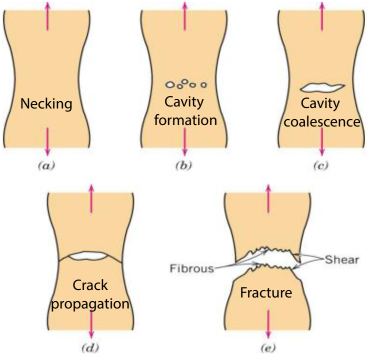
Conclusion

Background

Fatigue Assessment

Fatigue Assessment





Fatigue Assessment: Miner's Rule

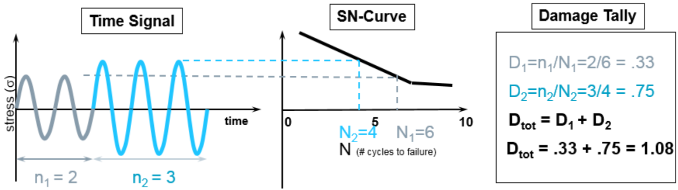
Fatigue Damage:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

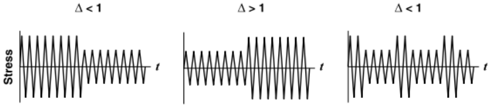
Safety condition: $D \leq \Delta$, or

Limit State Function:

$$g = \Delta - D \geq 0$$



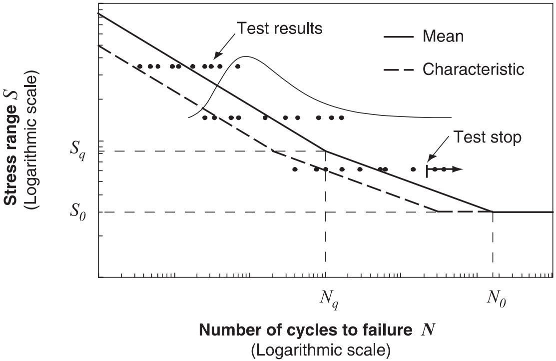
Fatigue Assessment: Miner's Rule



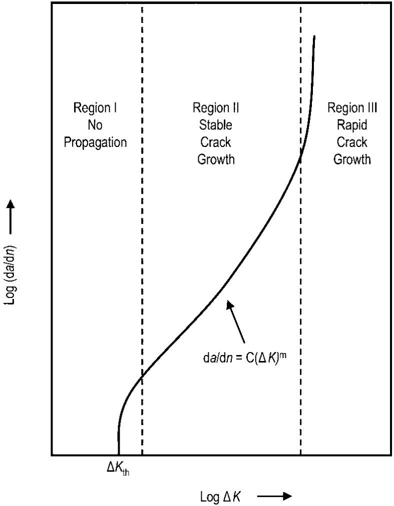
Sequence effects, Dowling (1971)

Limit State Function:

$$g = \Delta - D$$

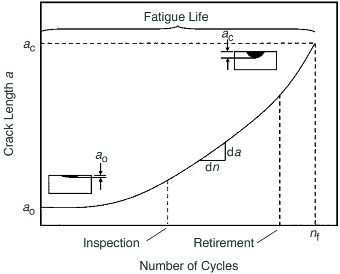


Fatigue Assessment: Paris' Law



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

$$\Delta K = Y \Delta\sigma\sqrt{\pi a}$$



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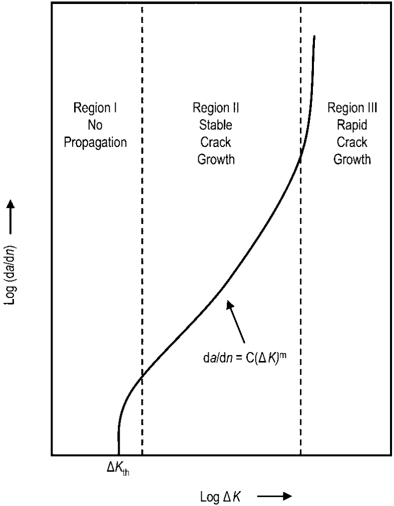
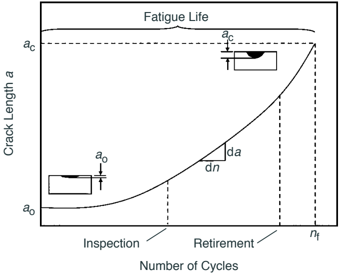


Limit State Functions:

$$g_1 = a_c - a$$

$$g_2 = K_{mat} - K$$



Fatigue Assessment: Failure Assessment Diagram

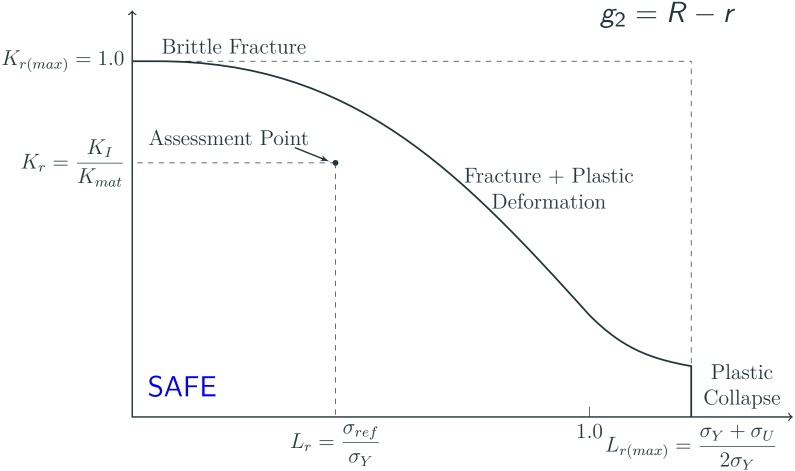
Assessing acceptability of cracks

Limit State Function:

$g_1 = K_{rFAD} - K_r$

or:

$g_2 = R - r$



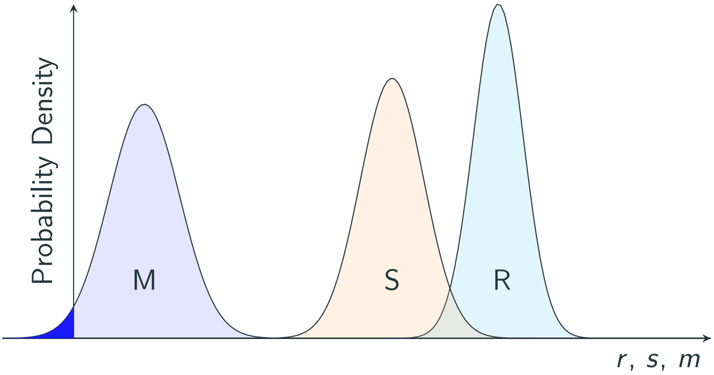
Background

Failure Probability

Failure Probability

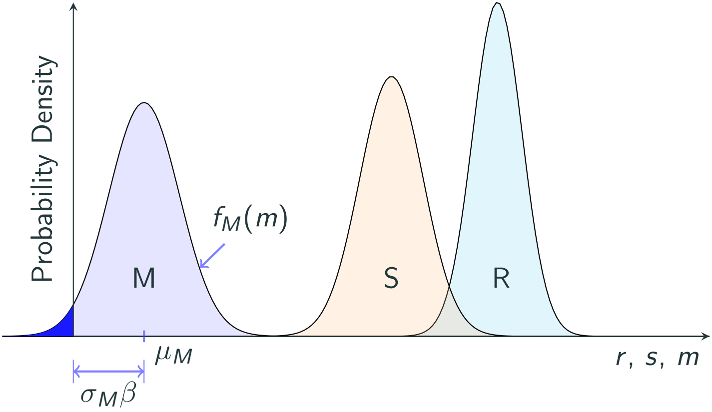
Safety margin (Limit State Function):

$$M = R - S$$



Failure Probability

$$P_F = \int_{-\infty}^{0} f_M(m)\, dm = \Phi\left(\frac{0-\mu_M}{\sigma_M}\right) = \Phi\left(-\ \beta\ \right)$$



Background

Updating Principle

Updating Principle

$$\text{Bayes Theorem: } \mathrm{P}\left(A|B\right) = \frac{\mathrm{P}\left(A, B\right)}{\mathrm{P}\left(B\right)}$$

Updating Principle

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Event updating

Variable updating

Updating Principle

$$\boxed{M} = R - \boxed{S}$$

Event updating

Variable updating

Updating Principle

$$\boxed{M} = R - \boxed{S}$$

Crack inspection:

$$\mathrm{P}\left(\boxed{M} < 0|I\right) = \frac{\mathrm{P}\left(M < 0 \cap I\right)}{\mathrm{P}\left(I\right)}$$

Load Monitoring data:

$$\boxed{f_{S|I}\left(s|I\right)} = C \cdot \mathrm{P}\left(I|s\right) f_S\left(s\right)$$

Updating Principle

$$\boxed{M} = R - \boxed{S}$$

Crack inspection:

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FAD in Updating Considering Inspection

Road Map

FAD in Updating Considering Inspection

Motivation & Literature Review

Motivation

LSF 1: $g = a_c - a$

a_c: critical crack size

a: crack size

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a_c: critical crack size $\Rightarrow$ ambiguous, for ships & pipelines!

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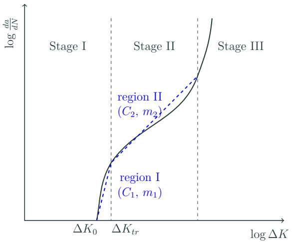
a: crack size

LSF 2: $\begin{cases} g_1 = a_c - a \\ g_2 = K_{mat} - K_{max} \end{cases}$

K_{mat}: fracture toughness

K_{max}: maximum stress intensity factor



Motivation

LSF 1: $g = a_c - a$

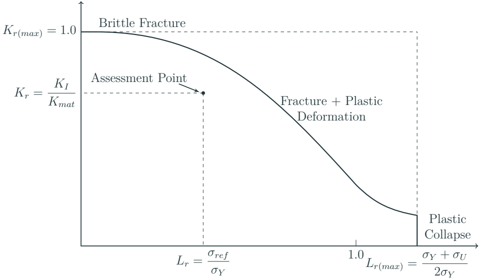
a_c: critical crack size $\Rightarrow$ ambiguous, for ships & pipelines!

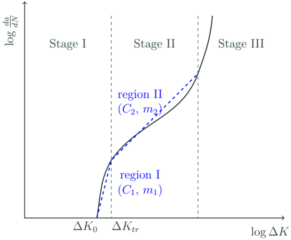
a: crack size

LSF 2: $\begin{cases} g_1 = a_c - a \\ g_2 = K_{mat} - K_{max} \end{cases}$ $\Rightarrow$ fracture+plastic deformation?

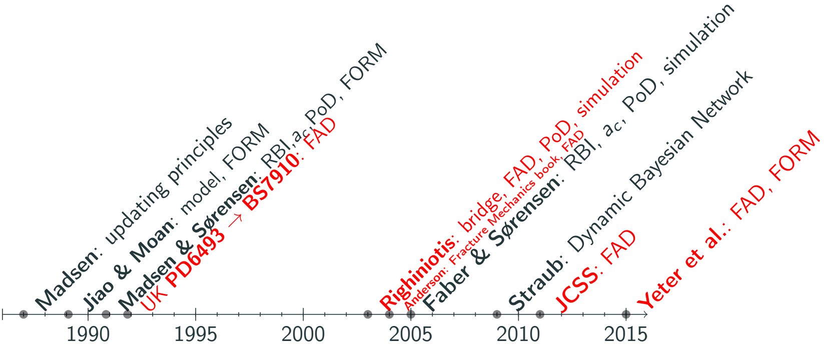
K_{mat}: fracture toughness

K_{max}: maximum stress intensity factor





Evolution of updating considering crack inspection data:



Gap:

Advantages and disadvantages of using Failure Assessment Diagram in updating failure probability considering crack inspection data for existing OWT support structures?

FAD in Updating Considering Inspection

FAD Gives Higher Failure Probability Values

Road Map

Limit State Functions to Compare

LSF 1:

$$g = a_c - a$$

LSF 2:

$$\begin{cases} g_1 = a_c - a \\ g_2 = K_{mat} - K_{max} \end{cases}$$

LSF 3:

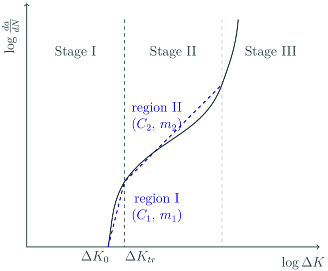
$$g = K_{rFAD} - K_r$$

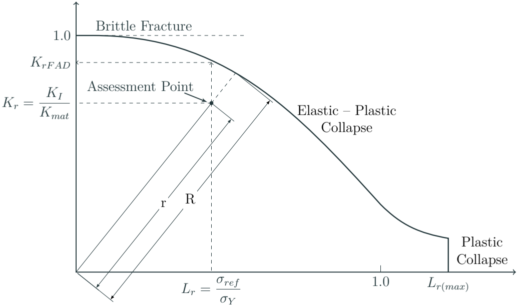
or:

$$g = R - r$$

Considered Uncertainties: C, a_0, a_0/c_0, and FAD

FAD uncertainty: from Offshore Technology Report (HSE, 2000)





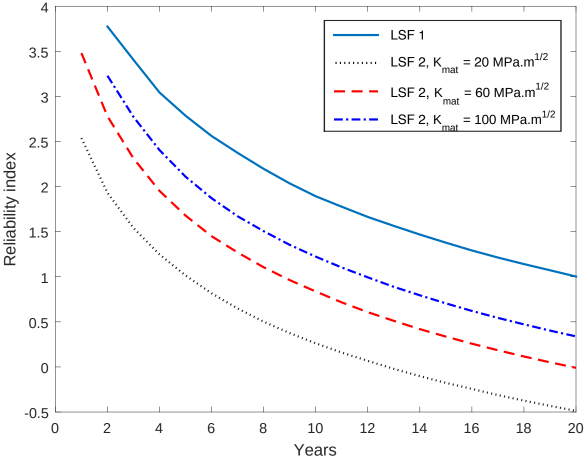
Method to Calculate Failure Probabilities

- Monte Carlo Simulation: 10^5 samples of crack propagations
- Crack depth and crack length are coupled
- Constant amplitude stress history
- Failure Probability:

$$P_f = \frac{1}{N} \sum_{j=1}^{N} I\left[g\right]$$

$$I\left[g\right] = \begin{cases} 0 & \text{if } g > 0 \\ 1 & \text{if } g \leq 0 \end{cases}$$

Results & Discussions: LSF-2 vs. LSF-1



LSF 1:

$$g = a_c - a$$

LSF 2:

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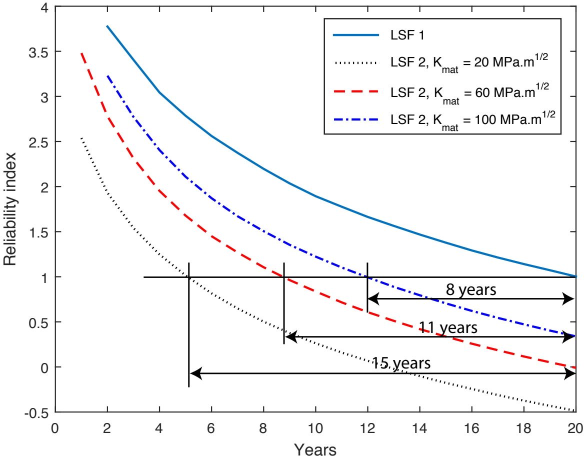
Results & Discussions: LSF-2 vs. LSF-1



LSF-1:

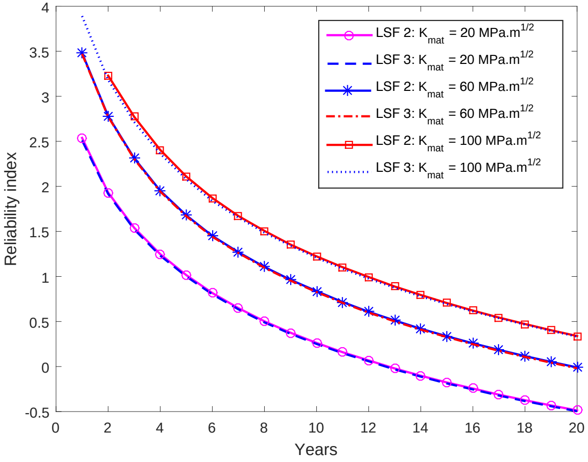
$g = a_c - a$

$\Rightarrow$ Under-estimate P_f

LSF-2:

$$\begin{cases} g_1 = a_c - a \\ g_2 = K_{mat} - K_{max} \end{cases}$$

Results & Discussions: LSF-3 vs. LSF-2



Use of S_{max}:

$$K_{max} = S_{max} Y \sqrt{\pi a}$$

$$\sigma_{ref} = \frac{S^*_{max}}{S_Y}$$

$$K_r = \frac{K_{max}}{K_{mat}}$$

$$\frac{S_{max}}{S_Y} = 0.32$$

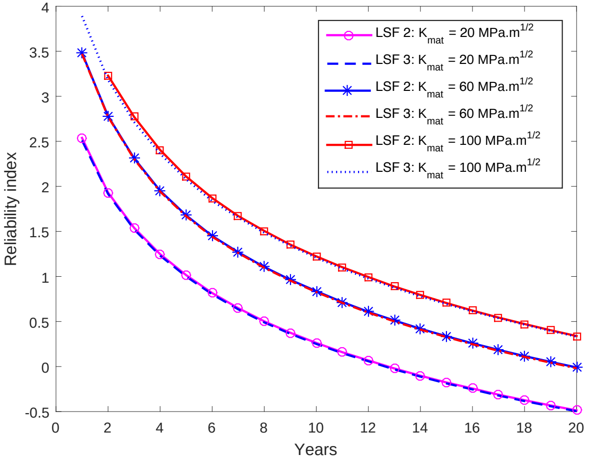
LSF-3:

$$g = K_{rFAD} - K_r$$

LSF-2:

$$\begin{cases} g_1 = a_c - a \\ g_2 = K_{mat} - K_{max} \end{cases}$$

Results & Discussions: LSF-3 vs. LSF-2



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LSF-3:

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$$\boxed{S_{max} \ll S_Y \quad \equiv}$$

LSF-2:

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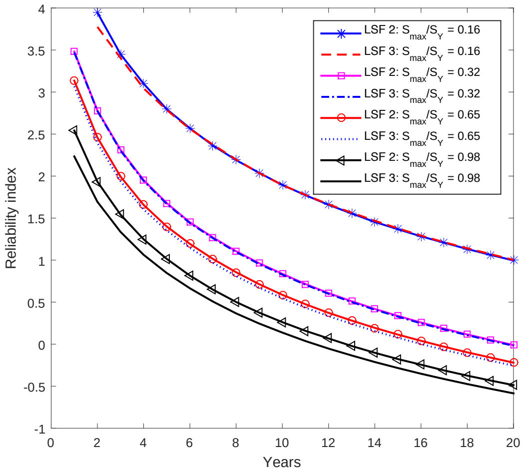
Results & Discussions: LSF-3 vs. LSF-2



Use of S_{max}:

$$K_{max} = S_{max} Y \sqrt{\pi a}$$

$$\sigma_{ref} = \frac{S^*_{max}}{\sigma_Y}$$

$$K_r = \frac{K_{max}}{K_{mat}}$$

$$K_{mat} = 60 \text{ MPa m}^{1/2}$$

$$S_Y = 368.75 \text{ MPa}$$

$$S_U = 750.00 \text{ MPa}$$

LSF-3:

$$g = K_{rFAD} - K_r$$

LSF-2:

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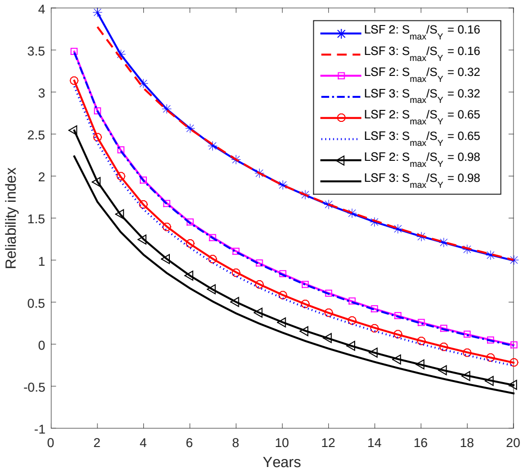
Results & Discussions: LSF-3 vs. LSF-2



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$$S_Y = 368.75 \text{ MPa}$$

$$S_U = 750.00 \text{ MPa}$$

LSF-3:

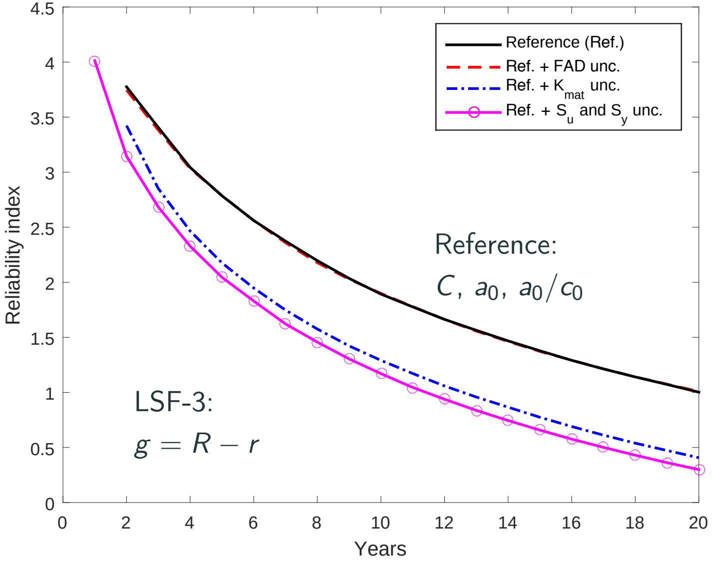
$$g = K_{rFAD} - K_r$$

$$\boxed{S_{max} > 65\% S_Y \quad \neq}$$

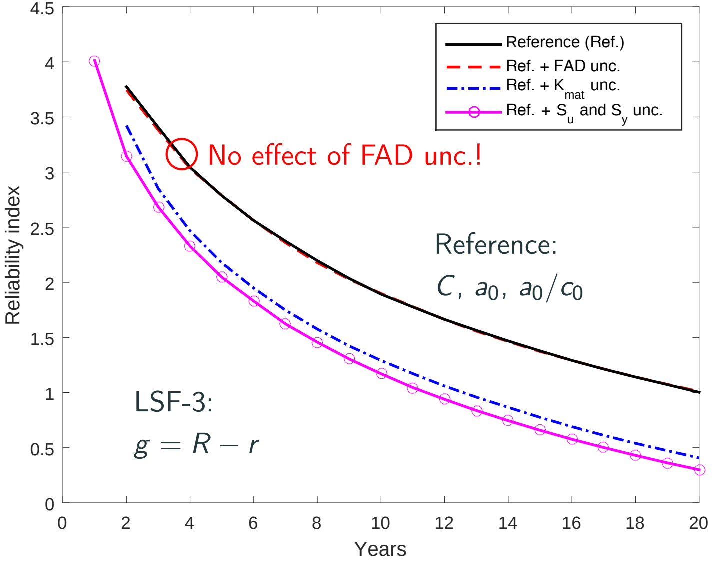
LSF-2:

$$\begin{cases} g_1 = a_c - a \\ g_2 = K_{mat} - K_{max} \end{cases}$$

Results & Discussions: FAD Uncertainty



Results & Discussions: FAD Uncertainty



FAD in Updating Considering Inspection

FAD in Updating

Road Map

The Updating Problems

Safety Margin using FAD: $g = K_{rFAD} - K_r$

The Updating Problems

Safety Margin using FAD: $g = K_{rFAD} - K_r$

Crack Detection Event: $I_d = c - c_d$

c: crack length,

c_d: detectable length

The Updating Problems

Safety Margin using FAD: $g = K_{rFAD} - K_r$

Crack Detection Event: $I_d = c - c_d$

Probability of Detection: $P\left(c_d\right) = 1 - \dfrac{1}{1 + \left(\dfrac{c_d}{x_0}\right)^b}$

The Updating Problems

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Crack Detection Event: $I_d = c - c_d$

Probability of Detection: $P\left(c_d\right) = 1 - \dfrac{1}{1 + \left(\dfrac{c_d}{x_0}\right)^b}$

Update P_F when No crack is detected:

$$P\left[g \leq 0 | I_d < 0\right] = ?$$

The Updating Problems

Safety Margin using FAD: $g = K_{rFAD} - K_r$

Crack Detection Event: $I_d = c - c_d$

Probability of Detection: $P\left(c_d\right) = 1 - \dfrac{1}{1 + \left(\dfrac{c_d}{x_0}\right)^b}$

Update P_F when No crack is detected:

$$P\left[g \leq 0 | I_d < 0\right] =?$$

Update P_F when Crack is detected and repaired imperfectly:

$$P\left[g \leq 0 | I_d \geq 0 \bigcap R_{im}\right] =?$$

The Updating Problems

Safety Margin using FAD: $g = K_{rFAD} - K_r$

Crack Detection Event: $I_d = c - c_d$

Probability of Detection: $P(c_d) = 1 - \dfrac{1}{1 + \left(\dfrac{c_d}{x_0}\right)^b}$

Update P_F when No crack is detected:

$$P[g \leq 0 | I_d < 0] = ?$$

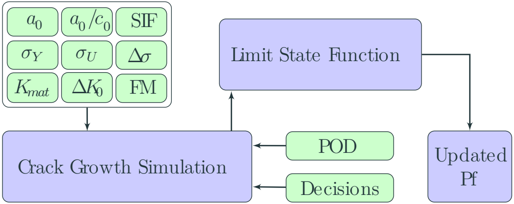
Update P_F when Crack is detected and repaired imperfectly:

$$P\left[g \leq 0 | I_d \geq 0 \bigcap R_{im}\right] = ?$$

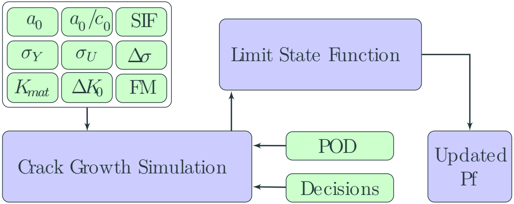
Update P_F when Crack is detected and repaired perfectly:

$$P\left[g \leq 0 | I_d \geq 0 \bigcap R_p\right] = ?$$

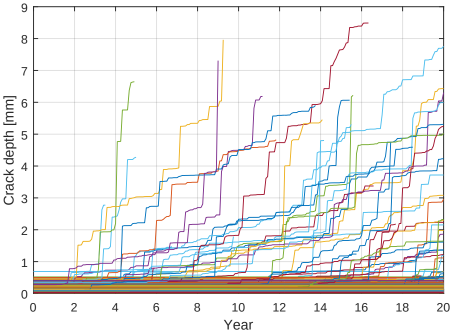
Method to Solve: Procedure



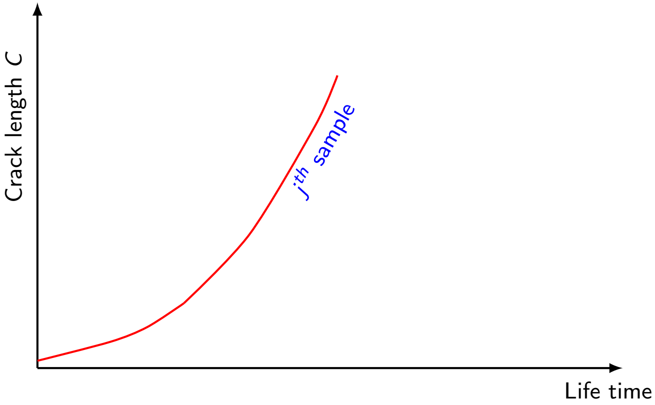
Method to Solve: Procedure



constant amplitude during 1 month!



Method to Solve: Updating



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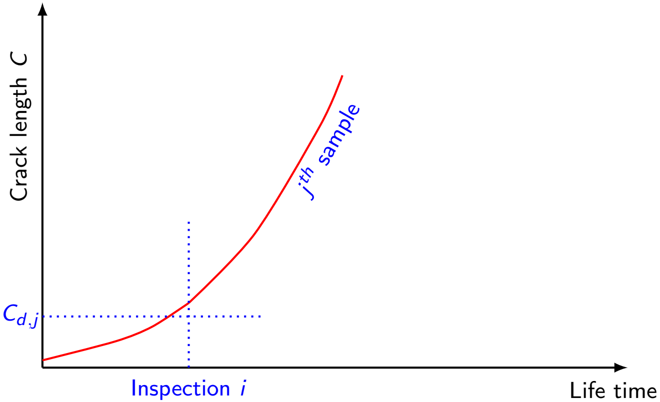

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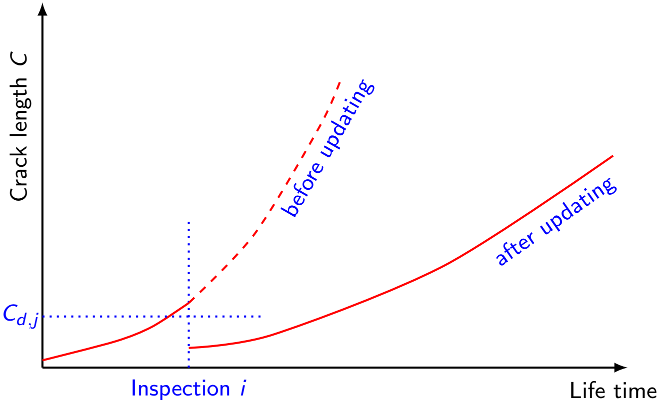
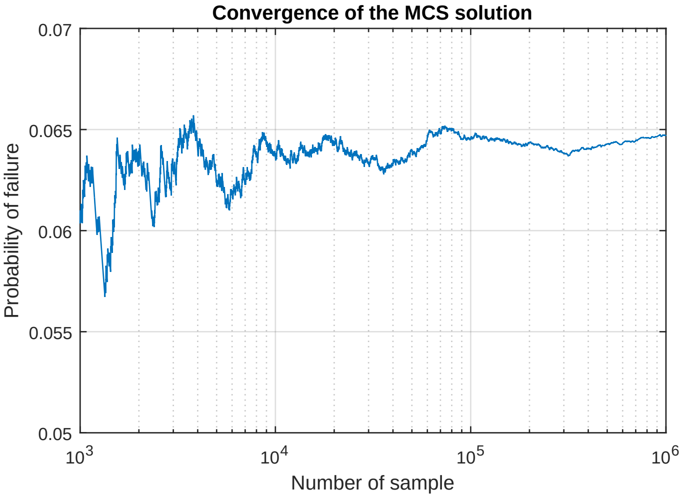


Results & Discussions



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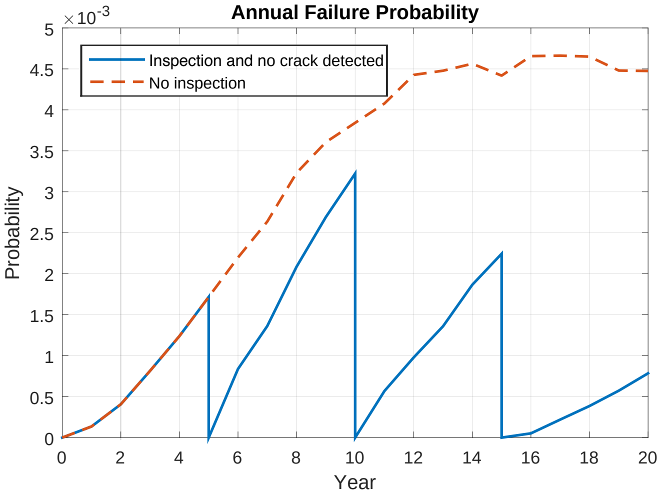

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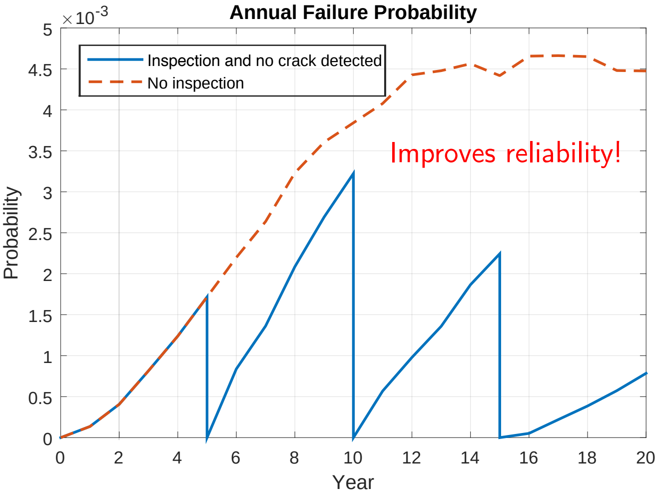
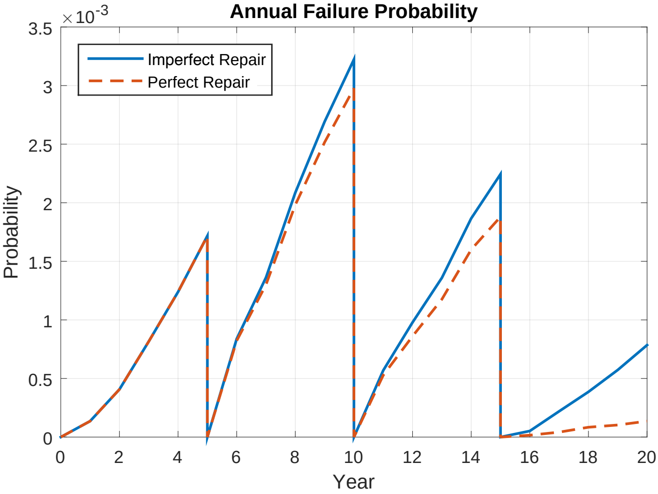
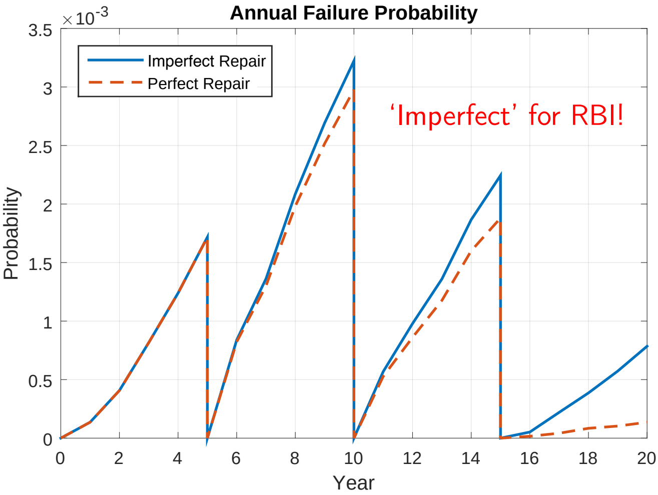
Results & Discussions



Results & Discussions



Results & Discussions



Road Map

Conclusion on FAD

Gap:

Advantages and disadvantages of using Failure Assessment Diagram in updating failure probability considering crack inspection data for existing OWT support structures?

Conclusion on FAD

Disadvantages

- Time consuming.
- Fails to find very small failure probability such as 'detected & not repaired'

Advantages

- Releases the assumption about a_c
- more conservative P_F results $\Rightarrow$ better for inspection planning!

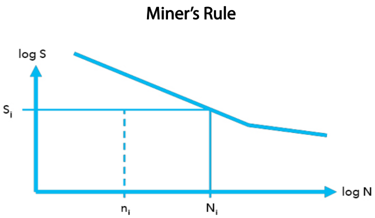
Occurence of Weather Conditions in Updating Considering Monitoring

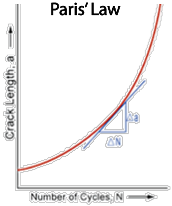
Road Map

Occurence of Weather Conditions in Updating Considering Monitoring

Motivation & Literature Review

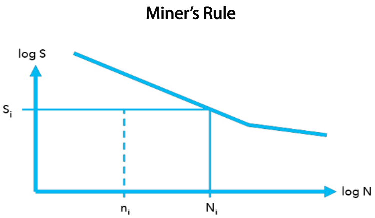
Motivation

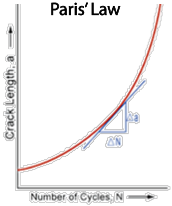


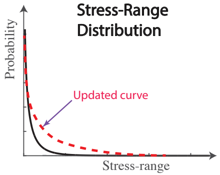


What to do with
Load monitoring data?

Motivation



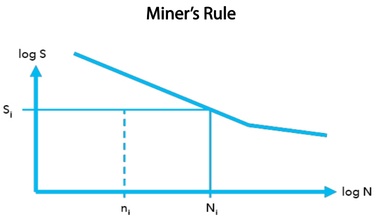


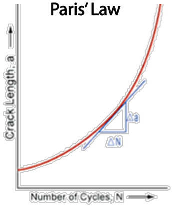


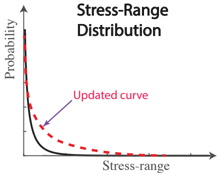
Measure strain

Calculate stress

Motivation







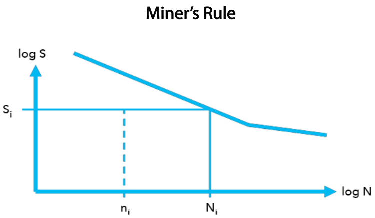
Measure strain:

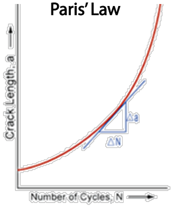
not everywhere!

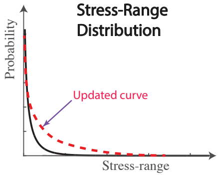
long-term!

Calculate stress

Motivation







Measure strain:

not everywhere!

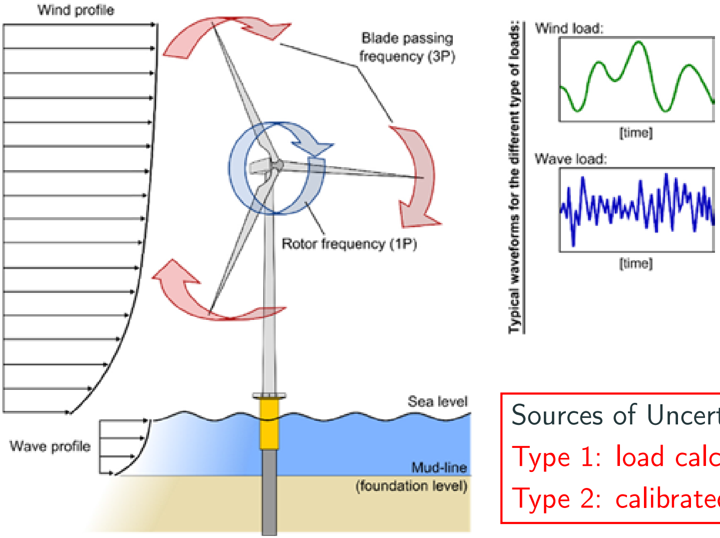
long-term!

Calculate stress:

time consuming!

too much uncertainties!

Motivation: Uncertainties in FEM



Sources of Uncertainties:
Type 1: load calculation
Type 2: calibrated FEM

Motivation: The Idea

Use measured data: $\Rightarrow$ No load calculation

Use FEM to extrapolate stress: $\Rightarrow$ No need to measure everywhere

Use Occurence of Weather Conditions in LSF:

$\Rightarrow$ Wind & Wave instead of strain

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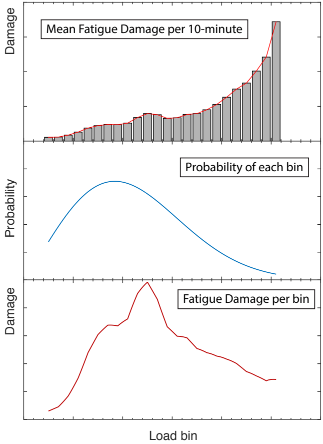

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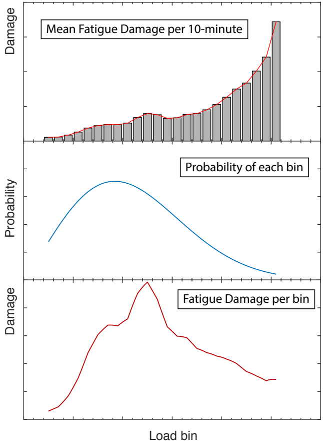
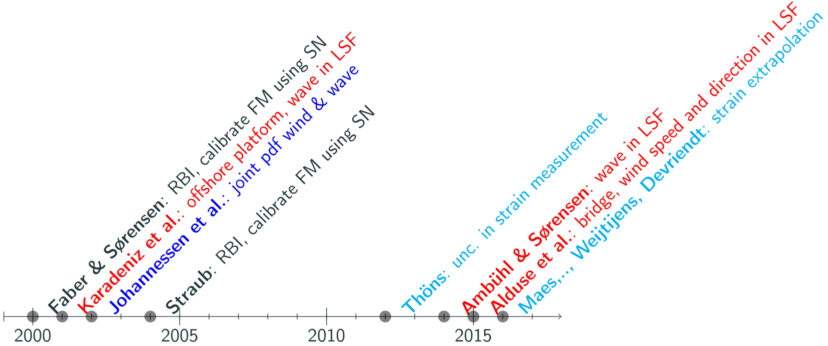


$$
\begin{aligned}
g &= \Delta - D_{total} \\
&= \Delta - \textstyle\sum_{e=1}^{n} D_{bin_e} \\
&= \Delta - \textstyle\sum_{i=e}^{n} P_{bin_e} \cdot D_{10m,bin_e} \cdot n_{10m,yr}
\end{aligned}
$$

Literature Review



Gap:

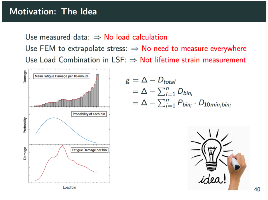
How to perform reliability assessment of existing offshore wind turbine support structures using directly the Occurence of Weather Conditions (wind and wave)?

Occurence of Weather Conditions in Updating Considering Monitoring

Methodology

Methodology

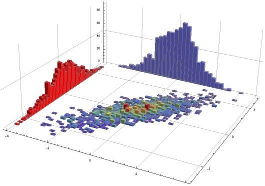
$$g = \Delta - \sum_{e=1}^{n} P_{bin_e} \cdot D_{mod,bin_e}$$



Methodology

$$g = \Delta - \sum_{e=1}^{n} \underbrace{P_{bin_e}} \cdot D_{mod,bin_e}$$

$$P\left(U_{10}, H_s, T_p\right) = \int \int \int f\left(U_{10}, H_s, T_p\right) du\ dh\ dt$$



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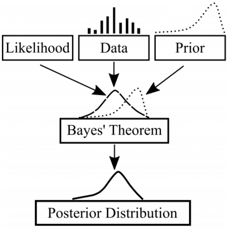
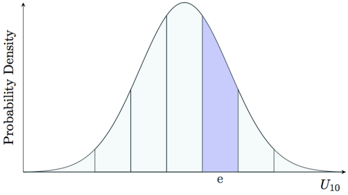


$$f_{K_w}(k_w \mid \hat{\mathbf{k}}_w)$$

Methodology

$$g = \Delta - \sum_{e=1}^{n} \underbrace{P_{bin_e}} \cdot \overbrace{D_{mod,bin_e}}^{\frac{D_{1cyc,bin_e} \cdot n_{cyc,bin_e}}{n_{10min,bin_e}} \cdot n_{10min,total}}$$

$$P\left(U_{10}, H_s, T_p\right) = \int\int\int f\left(\underbrace{U_{10}}, H_s, T_p\right) du\ dh\ dt$$



$$f_{K_w}(k_w \mid \hat{\mathbf{k}}_w)$$

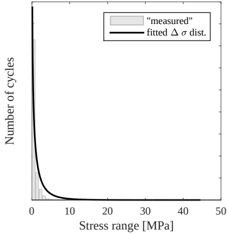
Methodology

$$\frac{(\alpha \cdot X_m \cdot X_{SCF})^m}{K} k_{s,bin_e}^m \Gamma\left(\frac{m}{\lambda_{s,bin_e}}+1\right)$$

$$\frac{\overbrace{D_{1cyc,bin_e}} \cdot n_{cyc,bin_e}}{n_{10min,bin_e}} \cdot n_{10min,total}$$

$$g = \Delta - \sum_{e=1}^{n} \underbrace{P_{bin_e}} \cdot \overbrace{D_{mod,bin_e}}$$

$$P\left(U_{10}, H_s, T_p\right) = \int \int \int f\left(\underbrace{U_{10}}, H_s, T_p\right) du\ dh\ dt$$



$$f_{K_w}(k_w \mid \hat{\mathbf{k}}_w)$$

Methodology: Limit State Function

$$g = \Delta - \sum_{i=1}^{T} \sum_{j=1}^{n_{U_{10}}} \sum_{k=1}^{n_{H_s}} \sum_{l=1}^{n_{T_p}} \frac{\left(\alpha_f X_m X_{SCF}\right)^m}{K} k_{s,jkl}^m \Gamma\left(\frac{m}{\lambda_{s,jkl}} + 1\right) \times \cdots$$

$$\mathrm{P}\left(U_{10,j}, H_{s,k}, T_{p,l} | k_{w,i}\right) \frac{n_{c,jkl}}{n_{m,jkl}} n_m^*$$

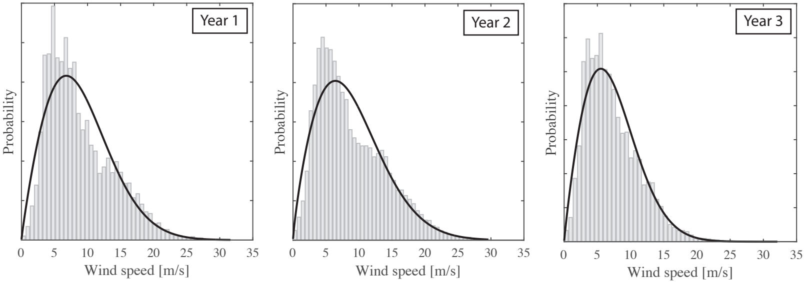
Update Wind Speed Distribution

Given three years (or more) of measured wind speed, how to update the design wind speed distribution?

$$
\begin{aligned}
f_{K_w}(k_w|\mu,\sigma) &= f_N(k_w|\mu,\sigma) \\
&= \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{k_w-\mu}{\sigma}\right)^2\right)
\end{aligned}
$$

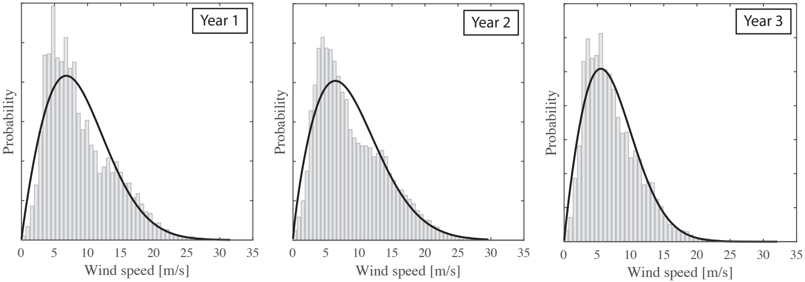
The predictive density function of k_w given measured data becomes a Student's t-distribution.

Keep the 'design' shape parameter:



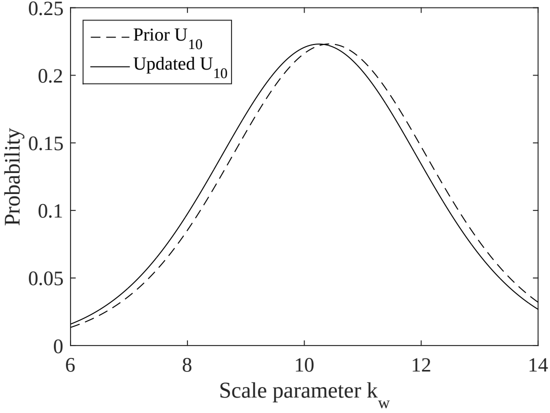
Methodology: Update Wind Speed Distribution

Keep the 'design' shape parameter:



$$\hat{\mathbf{k}}_w = [10.005 \quad 9.993 \quad 8.176] \text{ m/s}$$

Methodology: Update Wind Speed Distribution

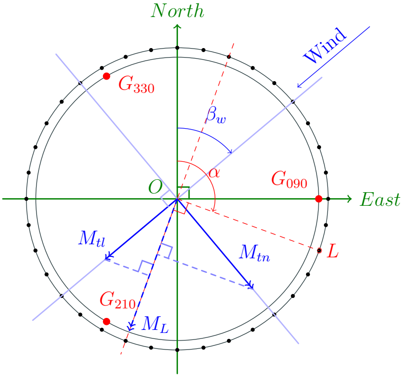


Occurence of Weather Conditions in Updating Considering Monitoring

Application

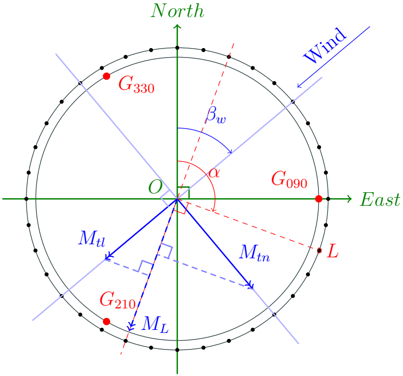
Application

- 3 MW offshore wind turbine



Application

- 3 MW offshore wind turbine
- Monopile, diameter of 5.2 m



Application

- 3 MW offshore wind turbine
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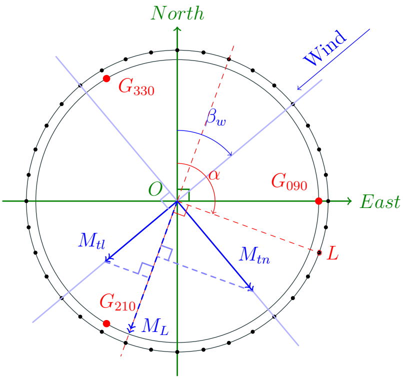
- Optical strain sensors



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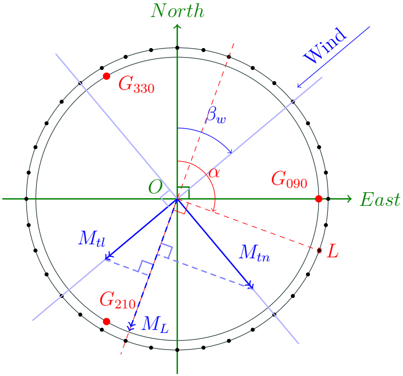
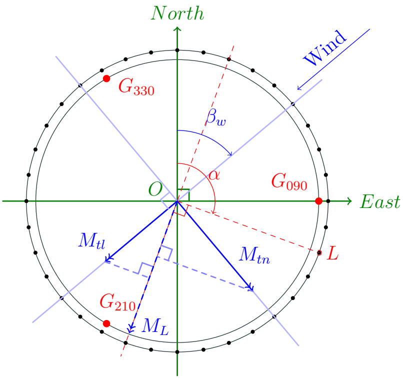
- Optical strain sensors
- Before construction: 15 years of wind data



Application

- 3 MW offshore wind turbine
- Monopile, diameter of 5.2 m
- Optical strain sensors
- Before construction: 15 years of wind data
- After construction: 3 years of wind and wave data + 1 year strain data (concurrently measured with the wind)



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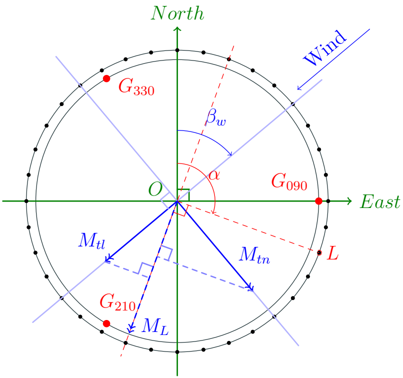

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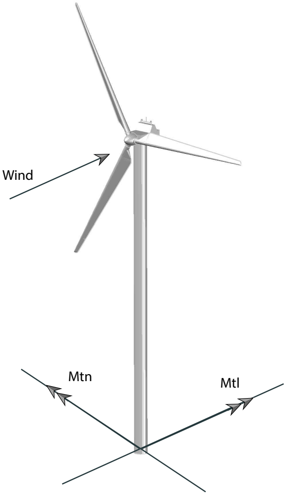

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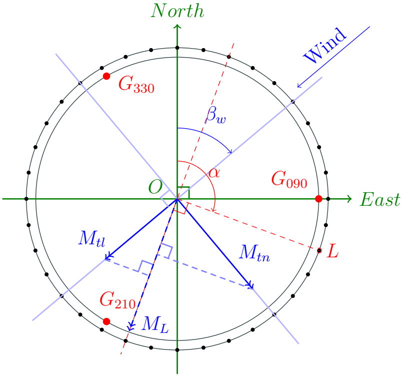
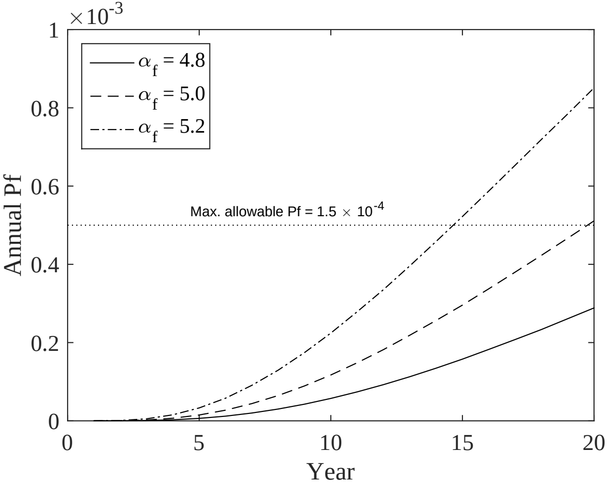
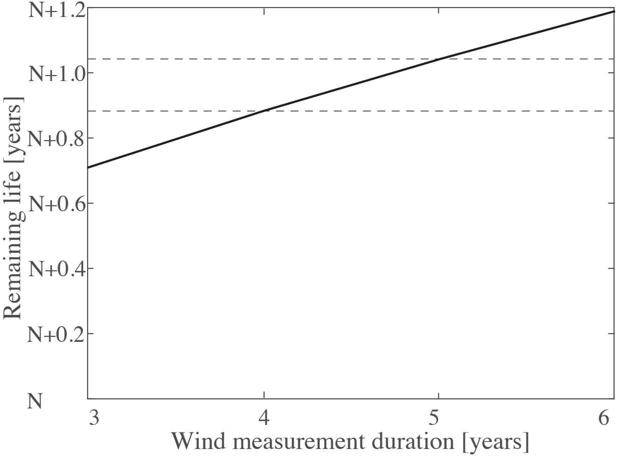


Application: Estimating Remaining Fatigue Life



Application: Results & Discussion



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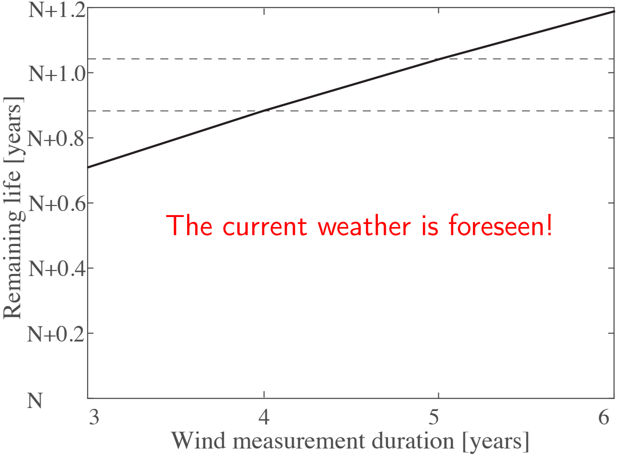

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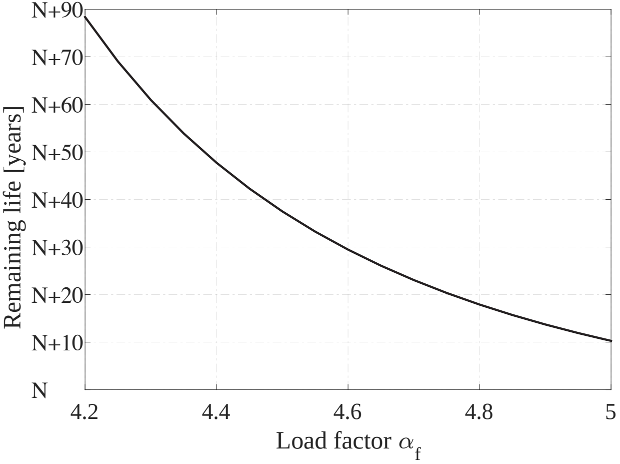

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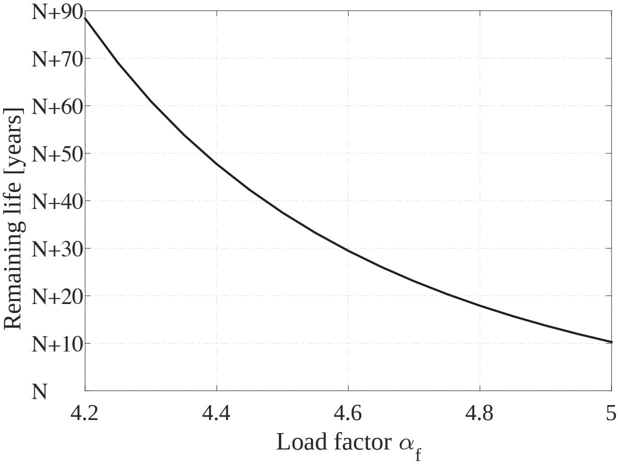
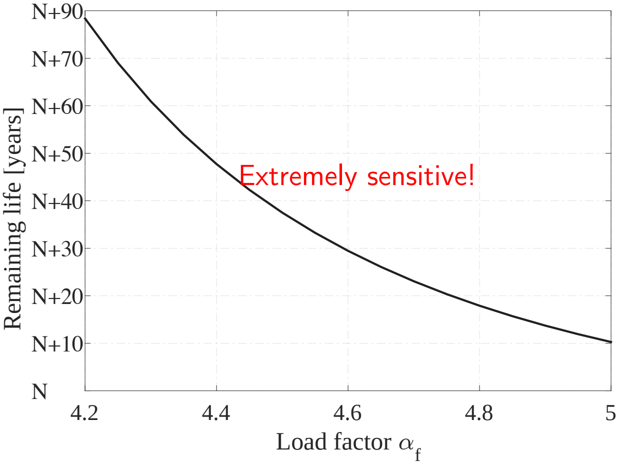


α_f is deterministic!

represents: Stress Concentration Factor (SCF) at hot-spots, or
Stress Extrapolating Factor for unmeasured locations

Application: Results & Discussion



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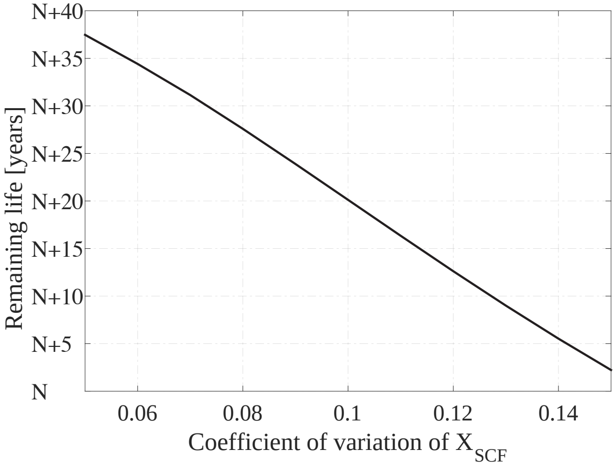
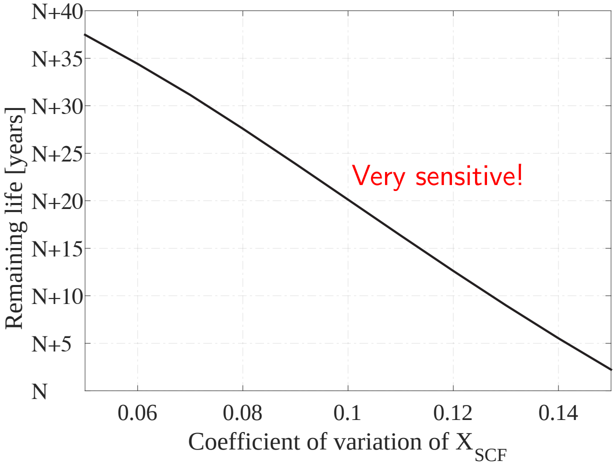


X_{SCF} is stochastic part of SCF!

Coefficient of variation = std./mean

Application: Results & Discussion



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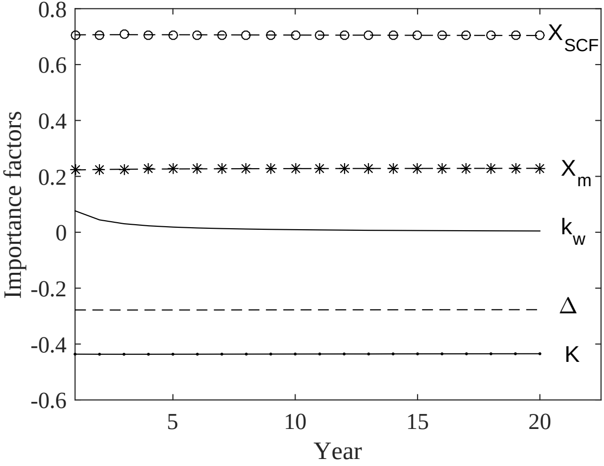
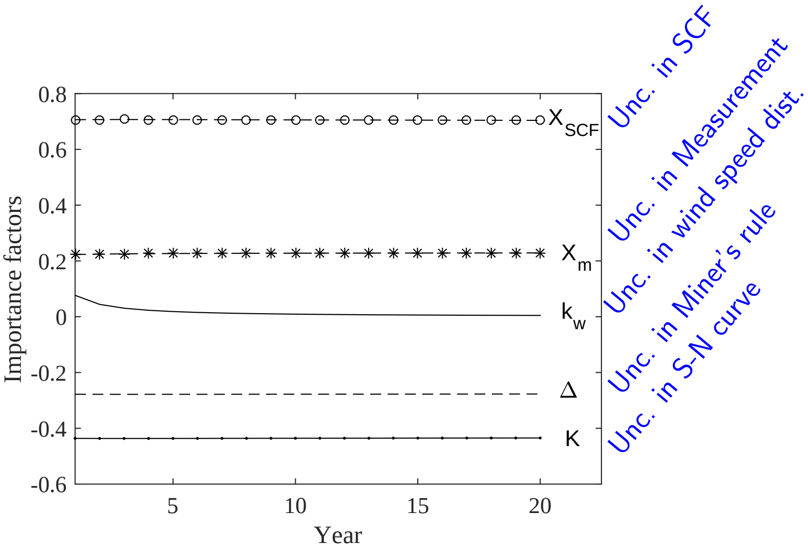

0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Importance factors
5
10
15
20
Year
X_{SCF}
X_m
k_w
Δ
K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Year
X_{SCF}
X_m
k_w
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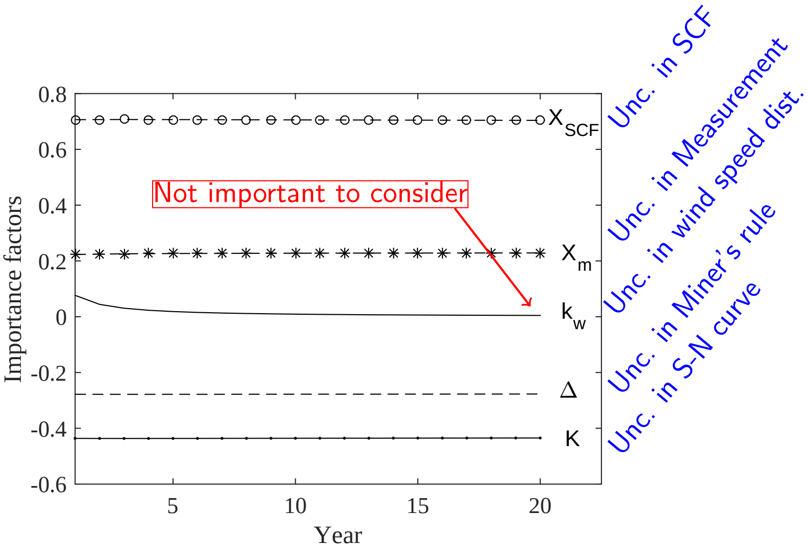
K
Unc. in SCF
Unc. in Measurement
Unc. in wind speed dist.
Unc. in Miner's rule
Unc. in S-N curve

Application: Results & Discussion



Road Map

Occurence of Weather Conditions in Updating Considering Monitoring

- Motivation & Literature Review
- Methodology
- Application

Conclusion on Using Occurence of Weather Conditions in LSF

Gap:

How to perform reliability assessment of existing offshore wind turbine support structures using directly the Occurence of Weather Conditions (wind and wave)?

Conclusion on Using Occurence of Weather Conditions in LSF

Disadvantages

- Assumed that fatigue damage caused by each Weather Condition is constant.
- Depends on the stress extrapolation method to derive stress for locations that is not measured.

Advantages

- Fast
- Less uncertainty than a time domain analysis.

Conclusion

Road Map

- FAD in Updating Considering Inspection
  - Motivation & Literature Review
  - FAD Gives Higher Failure Probability Values
  - FAD in Updating
- Occurence of Weather Conditions in Updating Considering Monitoring
  - Motivation & Literature Review
  - Methodology
  - Application

Conclusion: Future Works

- Combining two types of new information in RBI,

Conclusion: Future Works

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Conclusion: Future Works

- Combining two types of new information in RBI,
- Corrosion and crack inspection in updating failure probability,
- Load extrapolation for other types of OWT support structures,
- Quantifying uncertainty of load extrapolation methods,
- Considering the random process of the peak tensile stress in calculating failure probability

Message Objective

Using **Failure Assessment Diagram** and **Occurence of Weather Conditions** in the Limit State Function improves the accuracy of the **Updated Failure Probability**.

Practical Implications

P_f results are higher when K_{mat} is included in the LSF of a_c $\Rightarrow$ it needs to consider to be conservative.

Practical Implications

The peak tensile stress affects the safety state of any crack size $\Rightarrow$ the time when a high peak tensile stress occurs is important. This is a **first passage time** problem where the random process of the peak tensile stress first encounters a threshold.

This is a challenge of considering the fracture toughness criterion.

Practical Implications

FAD approach predicts higher P_f values when the applied peak tensile stress is larger than 65% the yield strength, in comparison to the LSF using (a_c, K_{mat}) $\Rightarrow$ the use of FAD should be recommmended for reliability assessment of existing offshore structures with high stress (designed to the limit, corroded, damage tolerant design)

Practical Implications

When FAD approach is utilized, the uncertainties in yield and ultimate strengths are important because they define the region of plastic collapse $\Rightarrow$ they should be investigated to improve the reliability of the structure.

Practical Implications

The information about cracks and intervention actions helps to improve our belief in the structural safety (reducing the probabilty of failure). It is the basic to optimizing inspection plans to reduce the O&M costs of offshore wind turbines.

Practical Implications

An imperfect repair leads to a higher failure probability than a perfect repair. $\Rightarrow$ an imperfect repair should be considered in the decision tree for a conservative inspection plan.

Practical Implications

Updating using Monitoring data: the impact of the year-to-year variation of the annual mean wind speed becomes negligible after 4 years. $\Rightarrow$ it can be ignored in the LSF to reduce significantly calculation time and give a chance to consider a finer descretized Occurence of Weather Conditions.

Practical Implications

The value of the predicted remaining fatigue life obtained from the present methodology can be useful for decision making to down-rate, curtail, or extend the lifetime of the wind turbine support structures.

Practical Implications

To apply the proposed method for locations where strain gauges cannot be installed, a load extrapolation method is needed, which inturn requires a good calibrated finite element model. A model uncertainty is also needed in the LSF.

Practical Implications

vbox Histogram of measured strain is distorted by high frequencies of small strain cycles, by considering the corresponding accumulated fatigue damage during fitting process, the weighting factor of each bin can be modified to preserve total fatigue damage.

The use of Miner's Rule

Fatigue damage accumulated by one load cycle is calculated as:

$$D_i = \frac{1}{N_i} = \frac{1}{K_c} S_i^m$$

For a large number of stress cycle, the expected fatigue damage can be estimated as:

$$\begin{aligned} \mathrm{E}\left[D_i\right] &= \frac{1}{K_c} \sum_0^\infty S_i^m \mathrm{P}\left(S_i\right) \\ &= \frac{1}{K_c} \int_0^\infty S^m f\left(s\right) ds \end{aligned}$$

If the stress-range is Weibull distributed (k, λ), the expected fatigue damage per cycle becomes:

$$\mathrm{E}\left[D_i\right] = \frac{1}{K_c} k^m \Gamma\left(\frac{m}{\lambda} + 1\right)$$

Why Link Strain with Wind and Wave?

People may ask:

- Why not to use measured strain directly?

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- Why not to use wind and wave to get strain from a Finite Element Model and then quantify the model uncertainty using the measured strain?

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Why not to use measured strain directly?

- You may need to measure strain for the whole lifetime.

Why Link Strain with Wind and Wave?

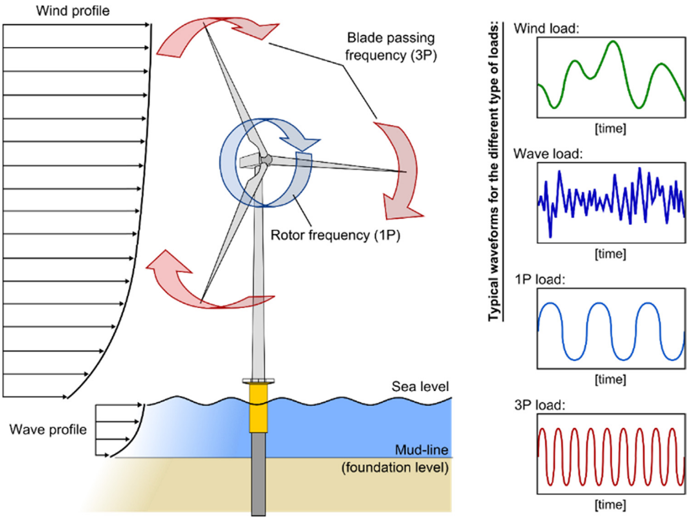
Why not to use measured strain directly?

- You may need to measure strain for the whole lifetime.
- In offshore structures, there are locations where you cannot install strain gauges.

Why Link Strain with Wind and Wave?

Why not to use wind and wave to get strain from a Finite Element Model and then quantify the model uncertainty using the measured strain?

Why Link Strain with Wind and Wave?



Why Link Strain with Wind and Wave?

Why not to use wind and wave to get strain from a Finite Element Model and then quantify the model uncertainty using the measured strain?

- You consider one irrelevant uncertainty more than the method proposed in this thesis.
- You take a lot of time to perform time domain analyses.

Joint Distribution of Wind and Wave

The probability of occurence of jkl^{th} bin which is used to link to fatigue damage is:

$$\mathrm{P}\left(U_{10,j}, H_{s,k}, T_{z,l}\right) = \int\int\int f\left(U_{10}, H_s, T_z\right) dw\ dh\ dt$$

this integration need to be calculated numerically.

If only U_{10} is considered in the bin, the probability of j^{th} bin becomes:

$$\begin{aligned} \mathrm{P}\left(U_{10,j}\right) &= F_W\left(a_j \leq U_{10} < b_j; k_w, \lambda_w\right) \\ &= \exp\left(-\left(\frac{a_j}{k_w}\right)^{\lambda_w}\right) - \exp\left(-\left(\frac{b_j}{k_w}\right)^{\lambda_w}\right) \end{aligned}$$

Joint Distribution of Wind and Wave

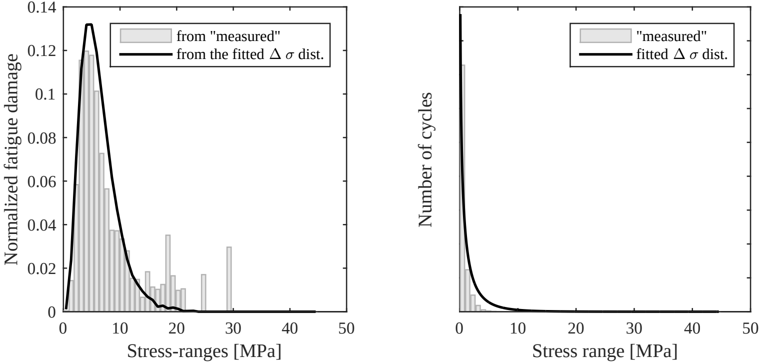
$$f\left(U_{10}, H_s, T_z\right) = f\left(U_{10}\right) \times f\left(H|U_{10}\right) \times f\left(T_z|H_s\ U_{10}\right)$$

where:

- $f\left(U_{10}\right)$ marginal distribution of the 10-minute mean wind speed, Weibull $(k_w,\, \lambda_w)$,
- $f\left(H_s|U_{10}\right)$ conditional distribution of significant wave height given U_{10}, Weibull (scale $= \mathit{func}\left(U_{10}\right)$, shape $= \mathit{func}\left(U_{10}\right)$),
- $f\left(T_z|H_s\ U_{10}\right)$ conditional distribution of mean wave period given H_s and U_{10}, Lognormal (mean $= \mathit{func}\left(H_s, U_{10}\right)$, std $= \mathit{func}\left(H_s, U_{10}\right)$).

The use of Miner's Rule

The assumption that stress-ranges follow a Weibull distribution is not perfect!



(a) Distribution of fatigue damage **(b)** Distribution of stress-range

Figure 1: Fitting stress-range in wind class [0 to 5 m/s]

Total Fatigue Damage

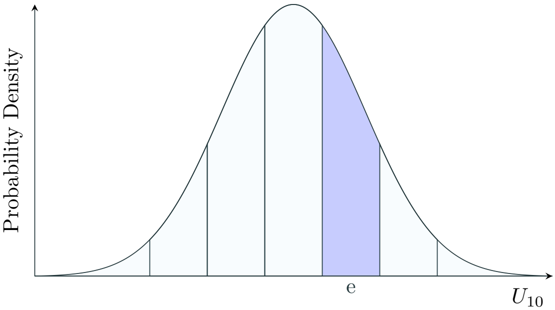
$$D = \sum_{i=1}^{T} \sum_{j=1}^{n_{U_{10}}} \sum_{k=1}^{n_{H_s}} \sum_{l=1}^{n_{T_p}} \frac{\alpha_f^m}{K_c} k_{s,jkl}^m \Gamma\left(\frac{m}{\lambda_{s,jkl}} + 1\right) \times \cdots$$

$$\mathrm{P}\left(U_{10,j}, H_{s,k}, T_{p,l} | k_{w,i}\right) \frac{n_{c,jkl}}{n_{m,jkl}} n_m^*$$

- $n_{cj} = n_{U_{10}} \times n_{H_s} \times n_{T_z}$ is total number of bins;
- $n_{c,jkl}$ is number of stress cycles in the bin number jkl;
- $n_{m,jkl}$ is number of oceanographic records in the bin number jkl;
- $n_m^* = \sum_{j=1}^{n_{cl}} n_{m,j}$ is total of observed oceanographic data per year;
- $\mathrm{P}\left(U_{10,j}, H_{s,k}, T_{p,l} | k_{w,i}\right)$ is the probability of the bin jkl given the scale parameter of the wind speed distribution $k_{w,i}$ in the i^{th} year.

Total Fatigue Damage

$$D = T \sum_{e=1}^{n_b} \frac{\alpha_f^m}{K_c} k_{s,e}^m \Gamma\left(\frac{m}{\lambda_{s,e}} + 1\right) n_{c,e}$$



Equality vs. Inequality Events

Equality: when crack is measured a certain value. Not considered here because it is a very small failure probability problem, MCS is not suitable.

Importance Factors

The 'importance factor' of a random variable is a measure of the sensitivity of the reliability index to randomness of that random variable at the design point.

The 'importance factors' offer a way to rank the importance of the input variables with respect to the failure event of the welded joint.

The vector of 'importance factors' is denoted as $\boldsymbol{\alpha}$,

$$\boldsymbol{\alpha} = -\frac{\nabla g(\boldsymbol{x})}{|\nabla g(\boldsymbol{x})|} \tag{1}$$

where $\nabla g(\boldsymbol{x})$ is the gradient vector of the limit state function at the design point $\boldsymbol{x}$, which is assumed to exist, as shown in Eq.(2):

$$\nabla g(\boldsymbol{x}) = \left(\frac{\partial g}{\partial x_1}(\boldsymbol{x}), \quad \cdots, \quad \frac{\partial g}{\partial x_n}(\boldsymbol{x}) \right) \tag{2}$$

Minimum Number of Stress Cycles

- Weibull (scale = k, shape = λ) of stress-range distributions in:
  - Case 1: wind speeds in bin 1 (5-10 m/s): $k = 1.922$, $\lambda = 0.6172$
  - Case 2: wind speeds in bin 2 (10-15 m/s): $k = 4.2385$, $\lambda = 0.7793$
  - Case 3: wind speeds in bin 3 (20-30 m/s): $k = 9.408$, $\lambda = 1.0774$
- SN curve: $\log a_2 = 15.606$; $\log a_1 = 11.764$; $m_1 = 3$; $m_2 = 5$

No. of cycles (n)	Case 1	Case 2	Case 3
10^7	5.5%	3.4%	1.4%
5×10^6	7.3%	4.5%	1.7%
10^6	19.5%	9.3%	4.3%

Table 1: Error in fatigue damage

Minimum wind measurement for design

15 years is not a long data set for design because, to estimate the 50-year return period wind speed, a minimum 20 years of data is required (Coles et al. 2001)