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Reliability of an offshore wind turbine with an uncertain S-N curve.

S. Drexler, 2021-01-14

NTNU, Department of Civil and Environmental Engineering

Overview

- Introduction to structural reliability
- Uncertainties within the FLS
- Reliability analysis of an OWT MP structure
- Results and Discussion

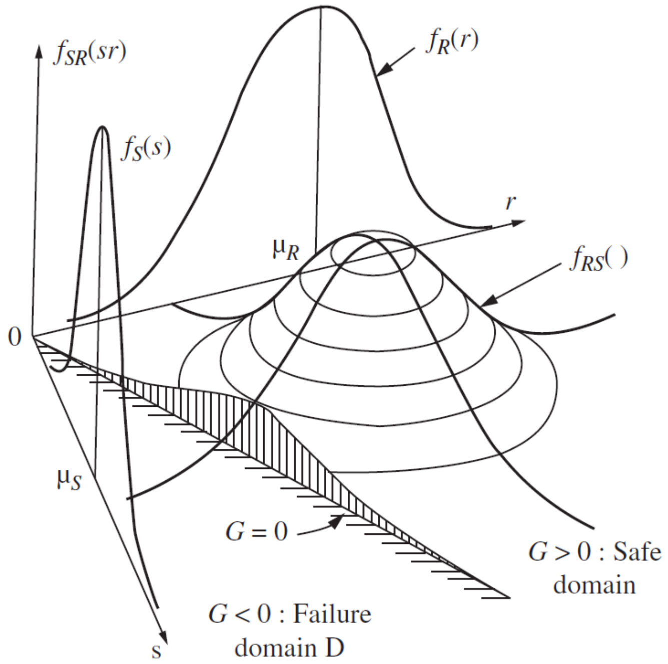
Introduction to structural reliability

Reliability Analysis

- Limit state violation $G(\mathbf{X}) \leq 0$
- Reliability $\mathfrak{R}(\boldsymbol{X}) = 1 - p_f$
- Failure probability p_f

$$p_f = P\left[G(\mathbf{X}) \leq 0\right] = \int \cdots \int_{G(\mathbf{X}) \leq 0} f_X(\mathbf{x}) d\mathbf{x}$$

- Determination of p_f
  - First-Order-Reliability Methods (FORM)
  - Monte Carlo Simulation (MCS)



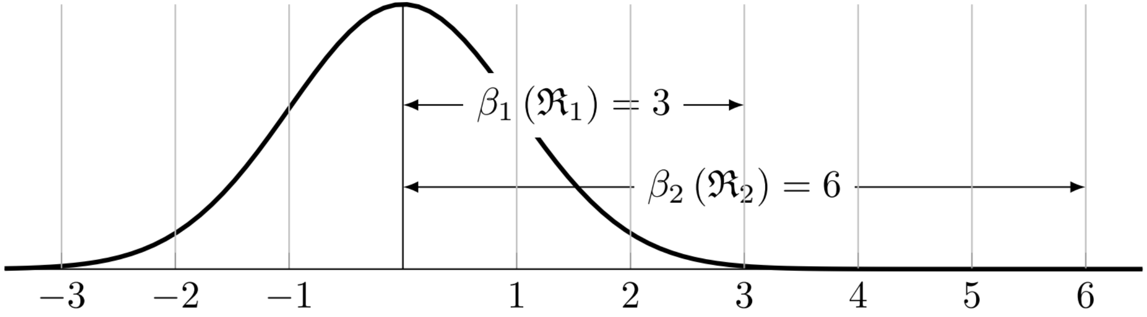
$G = R - S \qquad G(R, S) \leq 0$

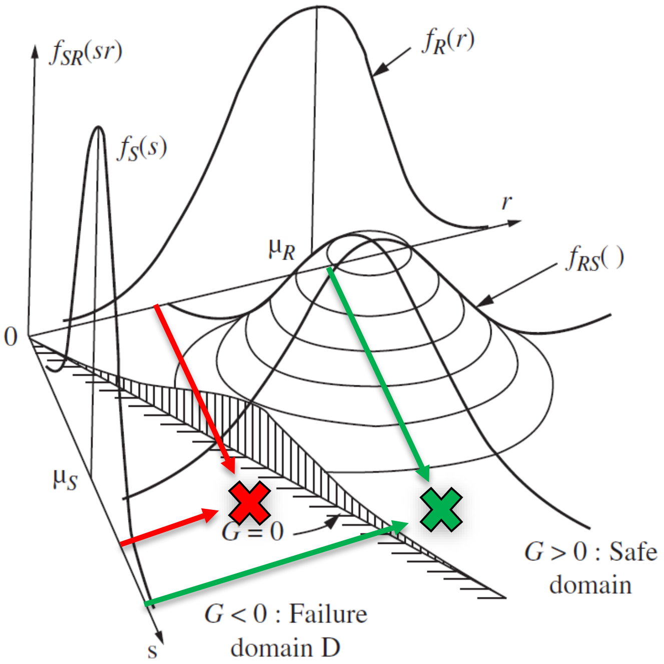
Reliability Analysis

- Principle of MCS
  - estimation by sampling $p_f \approx \frac{n_f}{N}$
- Reliability index β

$$\beta = \Phi^{-1}(\mathfrak{R}) = \Phi^{-1}(1 - p_f)$$

$$\mathfrak{R}_1 = 99.865\% \quad \mathfrak{R}_2 = 99.999\%$$





$$G = R - S \qquad G(R, S) \leq 0$$

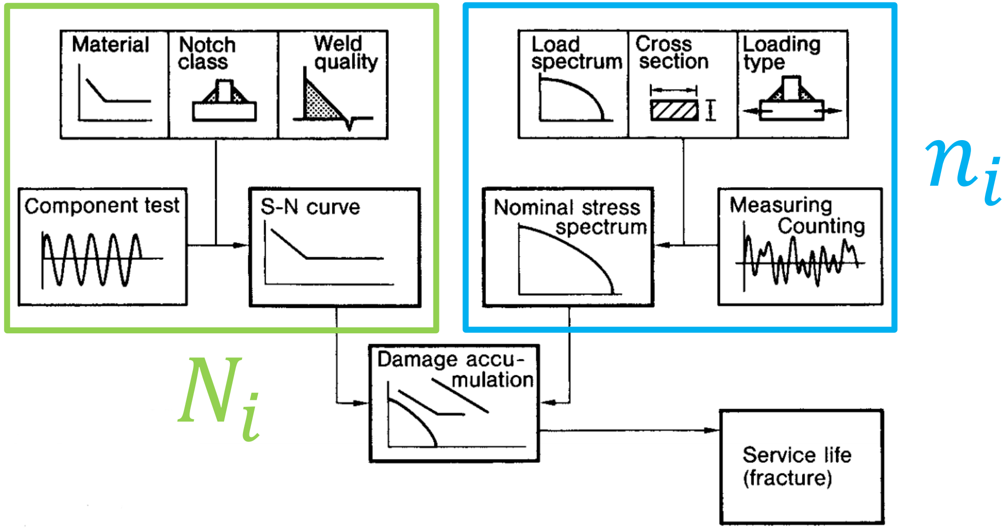
Uncertainties within the FLS

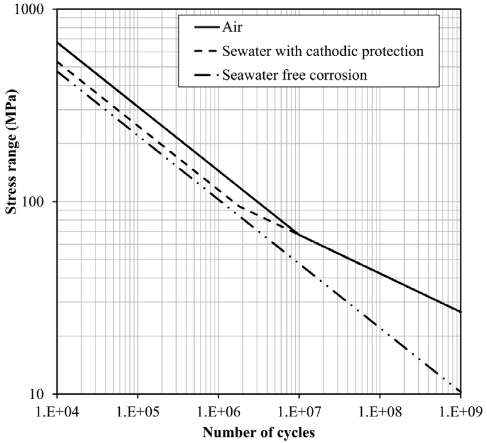
Fatigue evaluation

- Palmgren-Miner damage hypothesis

D = accumulated fatigue damage
k = number of different stress ranges
n_i = number of stress cycles experiences at $\Delta\sigma_i$
N_i = number of stress cycles to failure at $\Delta\sigma_i$

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

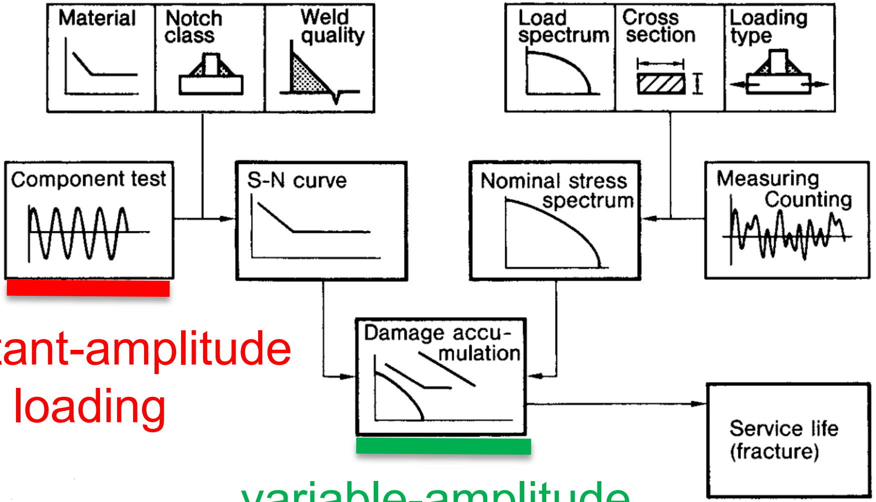




Uncertainties within the FLS

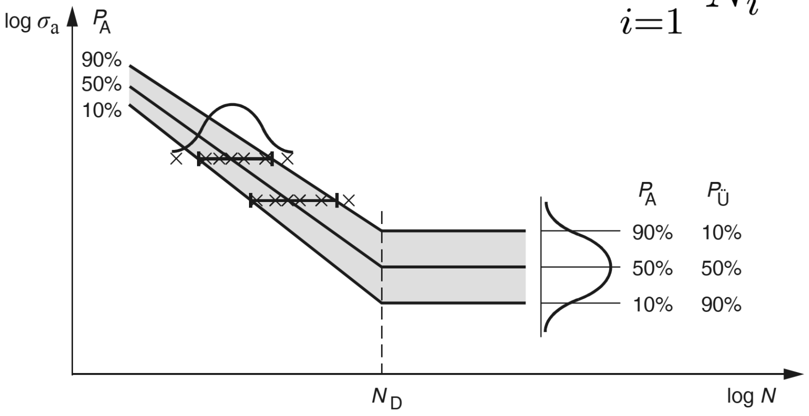
- Limit state function for fatigue

$$G\left(R-S\right) \leq D_{cr} - \sum_{i=1}^{k} \frac{n_i}{N_i}$$



constant-amplitude loading

variable-amplitude loading



© M. Sander, "Sicherheit und Betriebsfestigkeit von Maschinen und Anlagen Konzepte und Methoden zur Lebensdauervorhersage," 2018.

JCSS recommends 2 r.v.

- S/N curve
- Palmgren-Miner

D_{cr}

Reliability analysis of an OWT MP structure

Objective

- Comparison of
  - Two r.v. approach
    - S/N curve
    - Palmgren-Miner
  - Single r.v. approach
    - Palmgren-Miner

	Parameter	Distribution	Mean μ	CoV
K	Stiffness	lognormal	1.0	0.005
G	Geometry	lognormal	1.0	0.010
D_{cr}	Miner sum	lognormal	1.0	0.300
S	S-N data	normal	–	$\sigma = 0.2$

NREL 5-MW Baseline Wind Turbine	
Rating	5 MW
Rotor orientation, configuration	Upwind, 3 blades
Drivetrain	High speed, multiple-stage gearbox
Rotor, hub diameter	126 m, 3m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
OC3 Monopile	
Monopile diameter	6 m
Wall thickness	60 mm
Considered length	30 m
Upwind shallow water site	
Water depth	21.4 m MSL
Current normal, extreme	0.6 m/s, 1.2m /s
Weibull parameters wind	A=10.61 m/s, k=2.08 m/s
Design assumptions	
Design lifetime	20 years

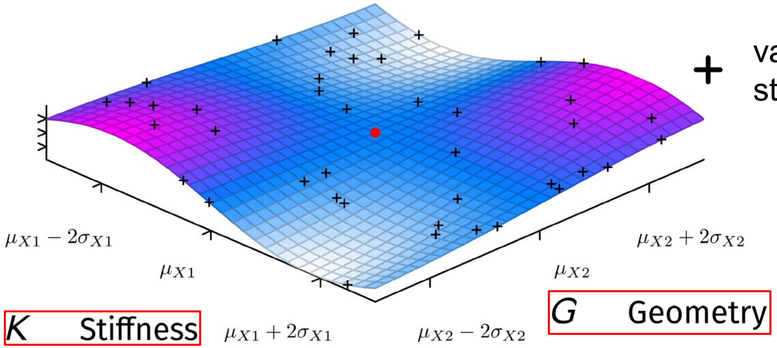
Methodology

$$G\left(R-S\right) \leq D_{cr} - \sum_{i=1}^{k} \frac{n_i}{N_i}$$

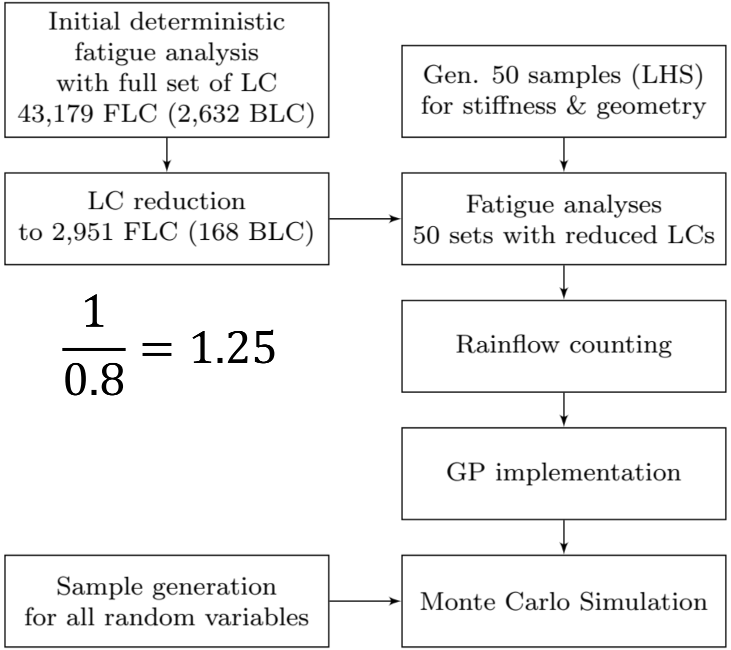
MCS: 1,064,000

K	Stiffness
G	Geometry
D_{cr}	Miner sum
S	S-N data

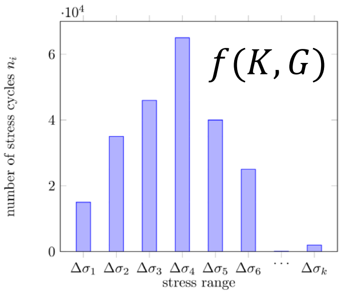
- Surrogate Model
  - Gaussian Process Regression (GPR)
  - Latin Hypercube Sampling (LHS)



+ values obtained by structural analysis



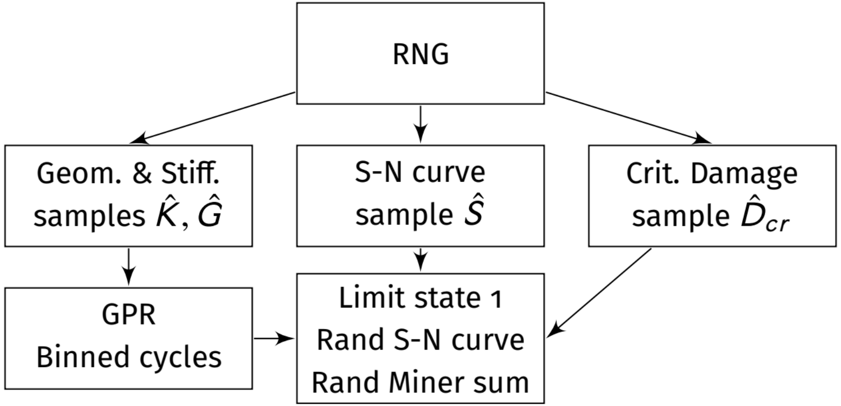
$$\frac{1}{0.8} = 1.25$$



MCS implementation

$$G_1(K, G, D_{cr}, S) = \hat{D}_{cr} - \sum_{i=1}^{k} \frac{\hat{n}_i}{\hat{N}_i}$$

- S-N curve is constant



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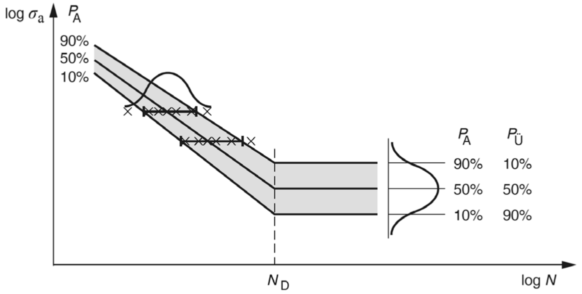
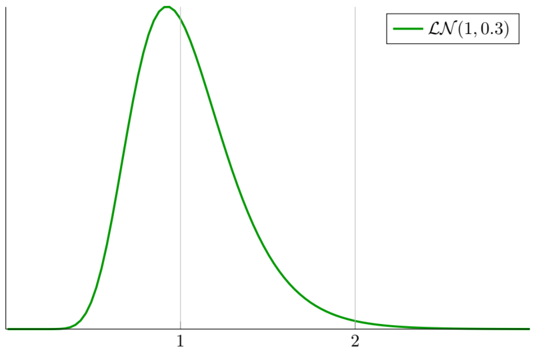
Item	Amount
Evaluated nodes along the MP height	13
Circumferential evaluation points	60
Stress bins per evaluation point	270
Number of GPR models	210, 600

Results and Discussion

Results and Discussion

		LSF 1: G_1	LSF 2: G_2	LSF 3: G_3	LSF 4: G_4
	Random variables	S/N PM	S/N PM	S/N PM	S/N PM
N_{total}	MC trials total	$1,064{,}000$	$1,064{,}000$	$1,064{,}000$	$1,064{,}000$
n_{failed}	MC trials failed	221	1,696	792	96
p_f	Failure probability	$2.077 \cdot 10^{-4}$	$15.940 \cdot 10^{-4}$	$7.444 \cdot 10^{-4}$	$0.649 \cdot 10^{-4}$
β	Reliability index	3.53	2.95	3.18	3.83





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Thank you for your attention

Contact: sebastian.drexler@ntnu.no