RAMBØLL

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AWESOME
PhD'S IN WIND POWER O&M

Fatigue crack growth for monopiles

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Does load sequence and weather seasonality influence fatigue crack growth?

Why should we model fatigue crack propagation?

Trend: Aging offshore wind farms

Needs:

- Optimize maintenance and inspection scheduling
- Reassess fatigue lifetime
- Decide about lifetime extension

Challenges:

- Uncertainties in loading, material resistance, design models
- Design lifetime differs from reality
- Update lifetime prediction through monitoring and inspections

→ Fatigue crack propagation

Fatigue design in offshore wind today

- SN-curve approach
- Linear damage accumulation
- Does not describe crack propagation
- Neglects sequence effects

$$D = \sum_i \frac{n_i}{N_i}$$

D: damage [-]
n_i: number of occurred stress cycles [-]
N_i: number of stress cycles until failure [-]

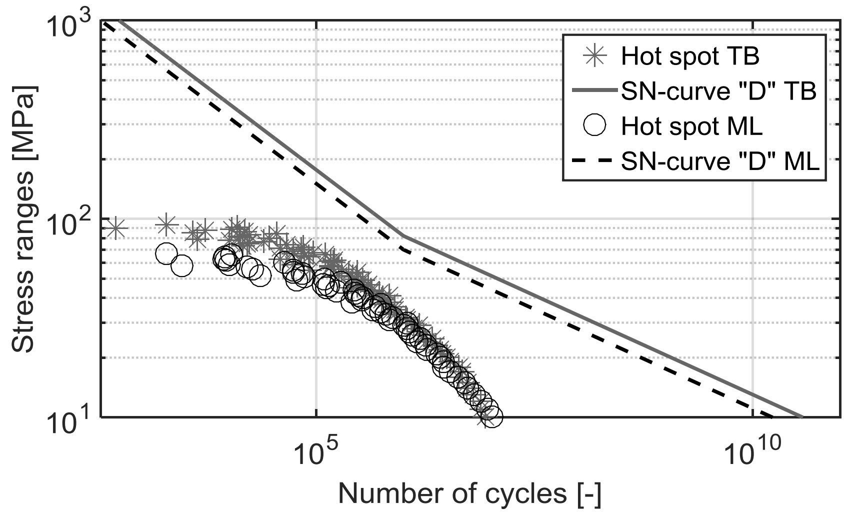

Fig 1. SN-curves and number of stress cycles during 20 years.

Agenda

- Methods
  - Fatigue crack propagation
  - Markov weather model
- Results
  - Load sequence
  - Weather seasonality
- Conclusion

Fatigue crack propagation

- Paris law

$$\frac{da}{dN} = C(\Delta K_I)^m$$

$$\Delta K_I = \Delta S \cdot Y\sqrt{\pi \cdot a}$$

a : crack depth [mm]
N : number of cycles [-]
ΔK_I : stress intensity factor […]
ΔS : stress range [MPa]
Y : geometry factor [-]
C, m : material constants [-]

- Physical and mathematical sequence effect
- Calibration of C with SN-curve results

Tab 1. Damage, extrapolated lifetime and calibrated C.

Location	20 year damage [-]	$T_{failure}$ [years]	ln(C) [-]
TB	1.21	16.48	-28.52
ML	0.61	32.89	-28.36

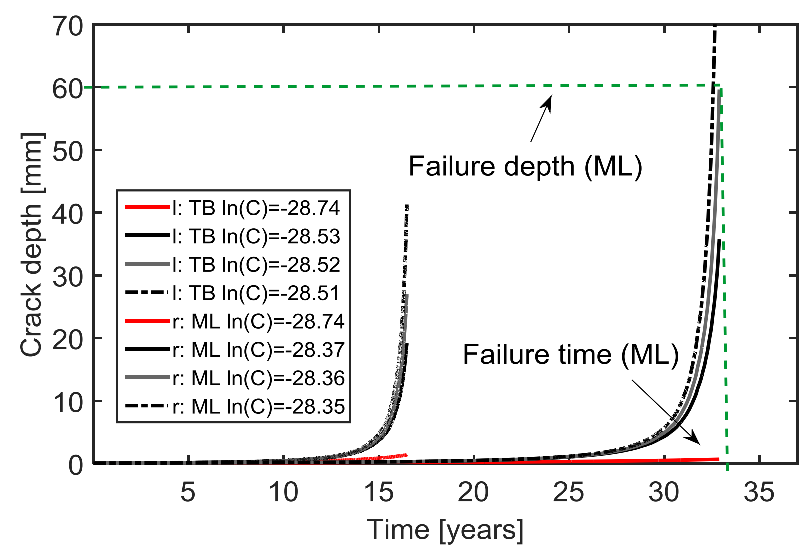

Fig 2. Crack growth at tower bottom (TB) and mudline (ML) for various C parameter.

Markov weather model

- Requirements:
  - Wind distribution
  - Seasonal trend
  - Weather persistence
- Stochastic process with finite memory
- Transition matrix T_M from historical data (22-years of wind speed in 6h resolution)

$$T_M = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1s} \\ p_{21} & p_{22} & \cdots & p_{2s} \\ \cdots & \cdots & \cdots & \cdots \\ p_{s1} & p_{s2} & \cdots & p_{ss} \end{bmatrix}$$

with
T_M: transition matrix [-]
p: transition probability [-]

- Discrete time series for wind speed: 2 – 30 m/s with 6h time steps

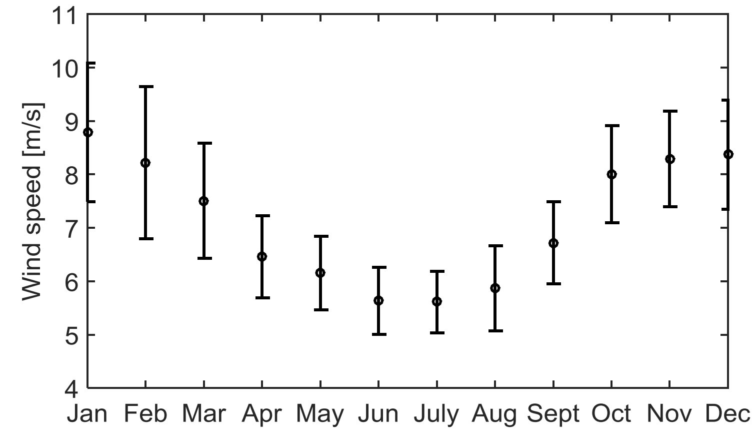

Fig 3. Monthly wind speed variation.

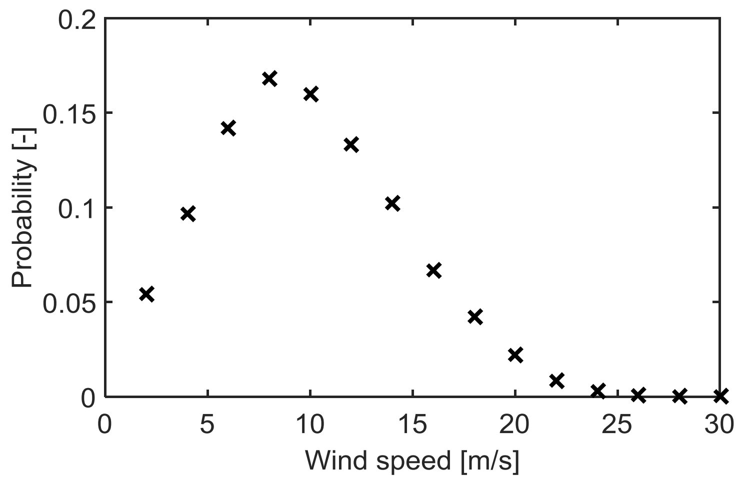

Fig 4. Wind speed distribution.

Does load sequence and weather seasonality influence fatigue crack growth?

Case study

- NREL 5MW and monopile from OC3 project (Nichols et al. 2009)
- Met-ocean data from Upwind project (Fischer et al. 2010)
- 15 fatigue load cases: power production, idling
- Structural response (1h time series) to aerodynamic and hydrodynamic loading with impulse-based substructuring

⟹ Analysis of *mathematical effect* of load sequence only

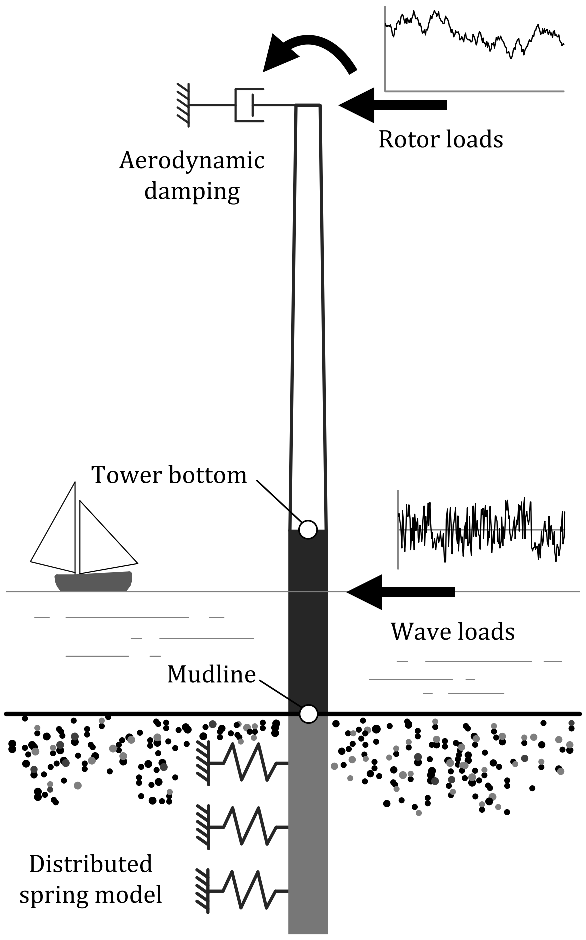

Fig 5. Model of offshore wind monopile.

Results: load sequence

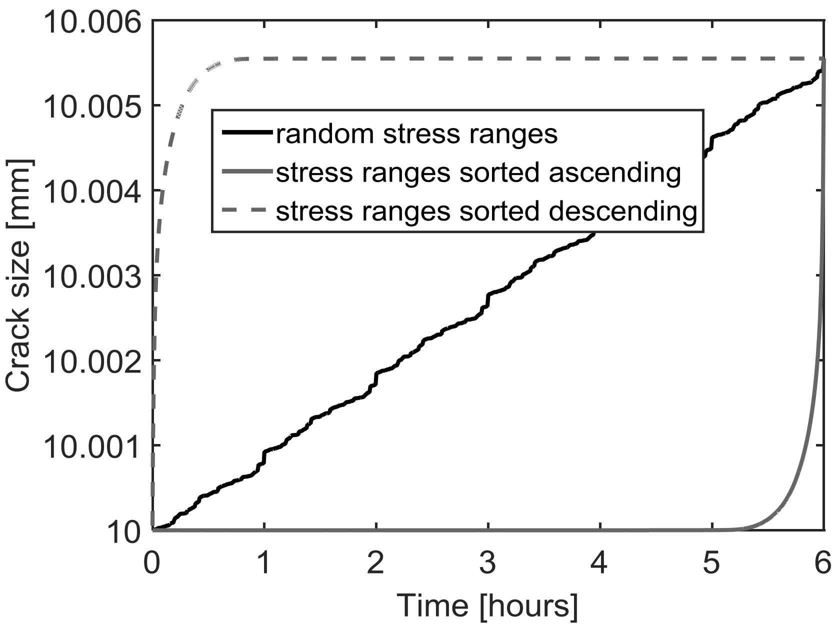

Fig 6. Crack growth for 6h time interval assuming 10mm initial crack size.

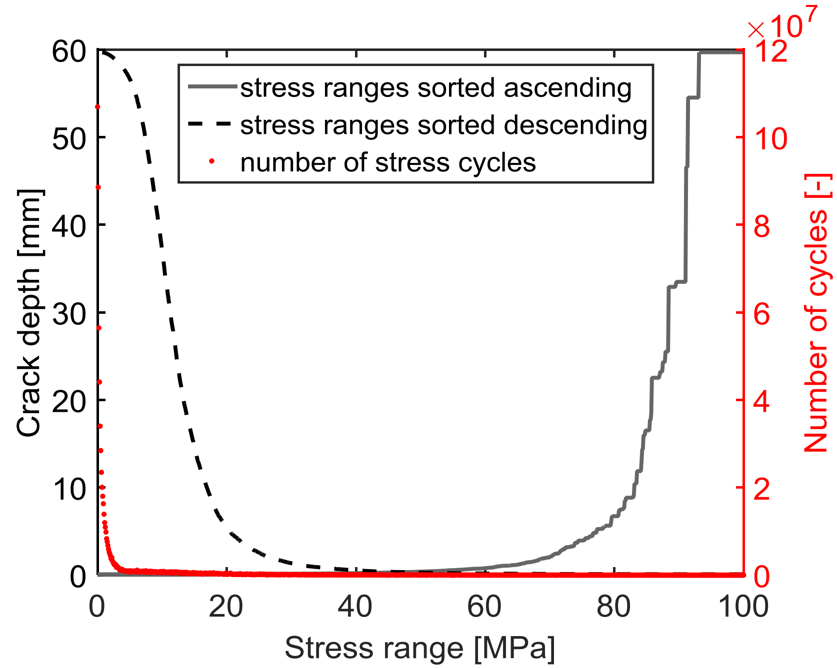

Fig 7. Crack growth during structural lifetime as a function of stress ranges. Red line gives number of stress cycles.

Results: weather seasonality

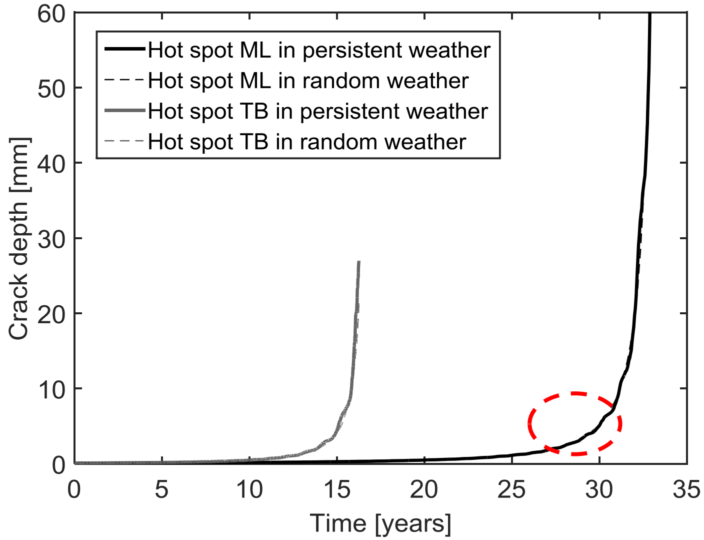

Fig 8. Comparison of crack growths in persistent weather and random weather.

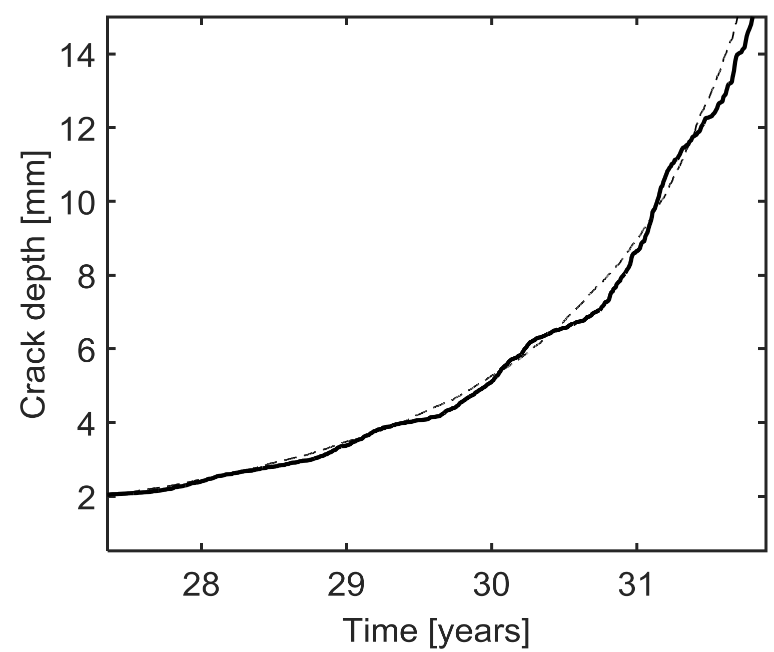

Fig 9. Zoom into Figure 8.

Conclusion

Under the assumptions made in this study…

1. Not necessary to reassess lifetimes regarding history of load sequence
2. Inspection and repair planning of aging wind turbines should account for weather seasonality
3. Interesting for future:
   What is the impact of ultimate loads on fatigue lifetime?

Thanks for your attention

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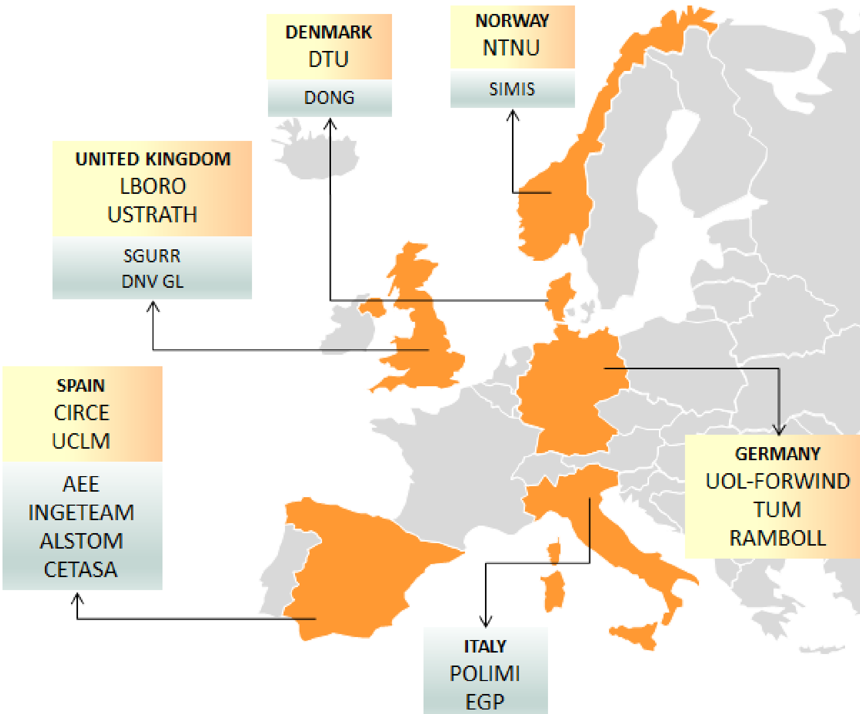
Appx. 1: Parameters of crack growth model

Tab 2. Parameters applied in crack growth model.

Parameter	Unit	Value	Source
a_0	mm	0.1	DNV 2014
a_C	mm	60/27	Li et al 2011, Dong et al 2012
m	-	3.1	DNV 2014
ln(C)	[...]	-28.36/-28.52	calibrated
Y	-	1	Kirkemo 1998

Appx. 2: AWESOME

- 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

Appx. 3: References

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