Design of wind turbine systems
SS 2016

Tutorial 5
Loads and components

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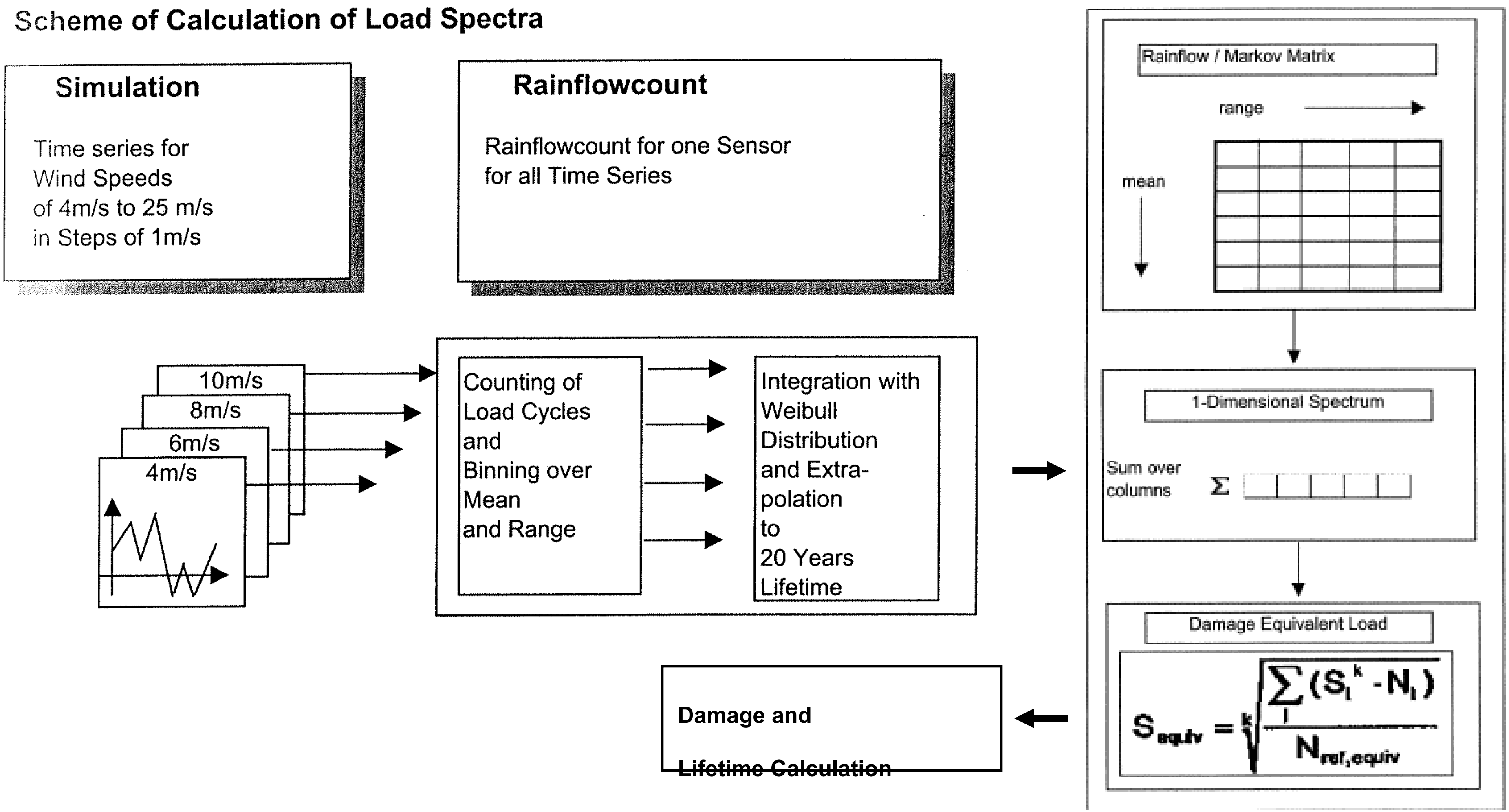
ForWind – Wind Energy Systems

Fatigue Analysis - Damage Calculation



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Wöhler curve (I)

- Also knows as S-N curve
- Each material has a proper set of curves
- Defines the number of cycles
  leading to failure for a cyclic loading characterized by
  - a given mean stress σ_{mi}
  - a given range σ_{rj}
- Curves derived from experimental
  fatigue test on materials and sections

Material	Wöhler Slope (m)
Steel	4
Cast Iron	5-7
Composites	9-12

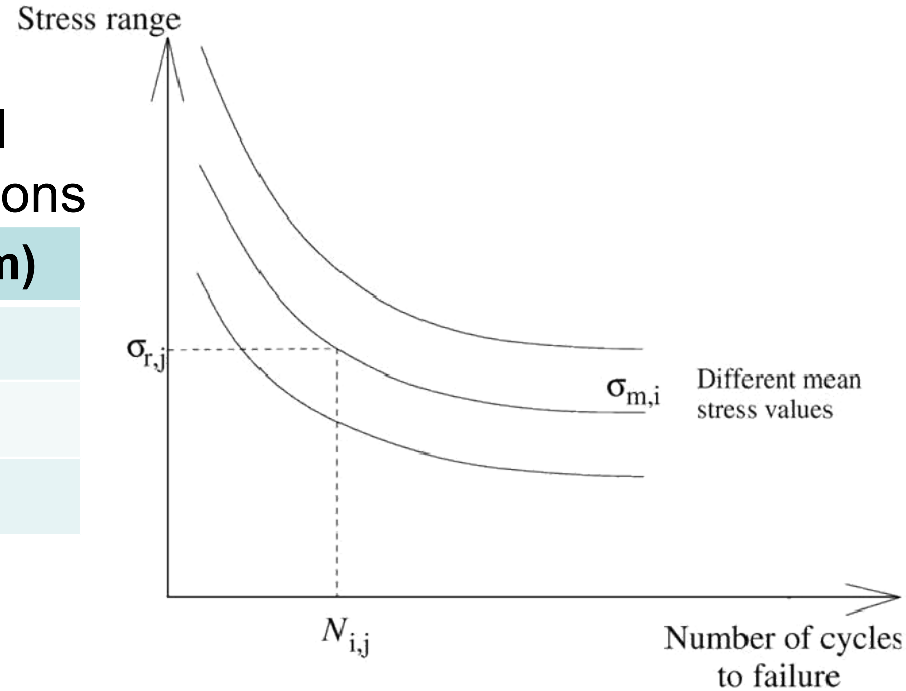


Fig. Hansen 2008

Wöhler curve (II)

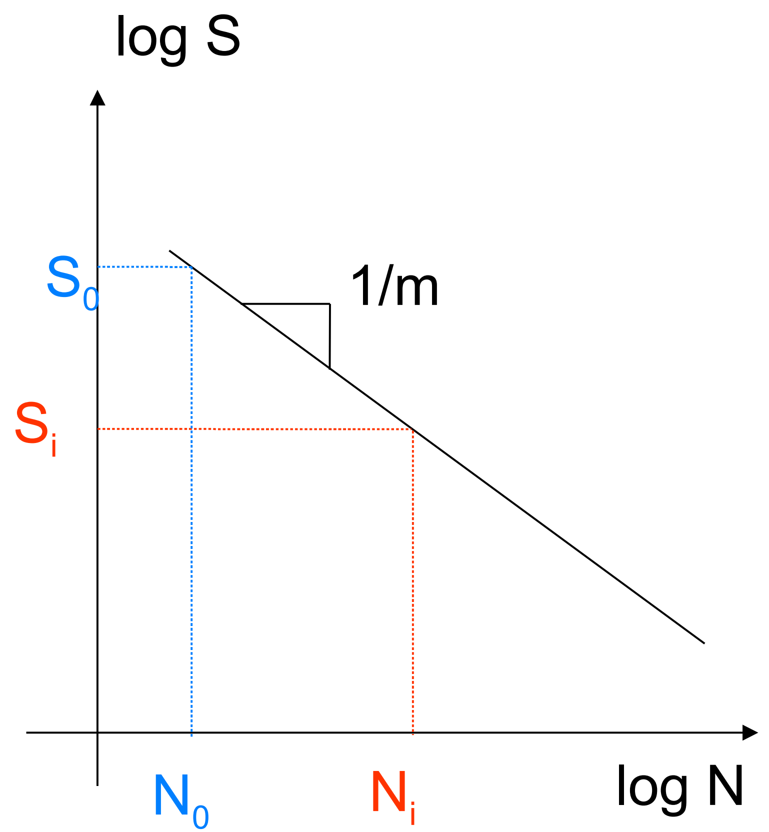
SN-curve:

- **Generally plotted in log(S)-log(N) diagrams**
- **Assumed Neq (2E+07,1E+08 for WTs)**
- **S = stress amplitude [MPa]**
- **N = number of cycles**
- **m = Wöhler slope ㅂ typical of the material**

$$\log S_0 - \frac{1}{m}\log N_i = \log S_i$$

Equivalent to

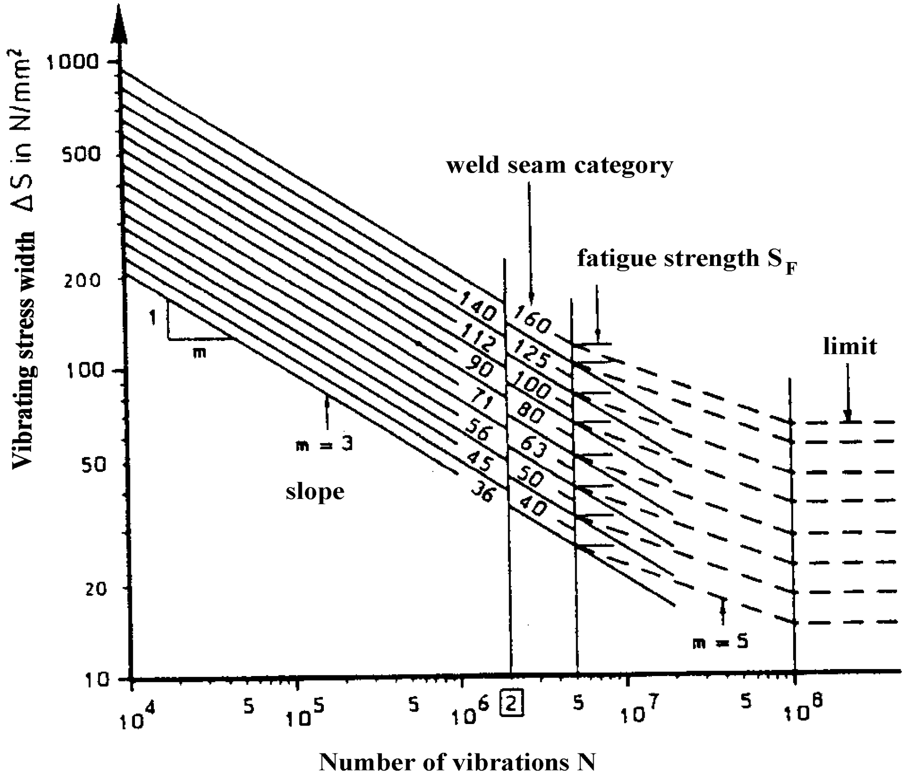
$$N_i = \left(\frac{S_0}{S_i}\right)^m$$

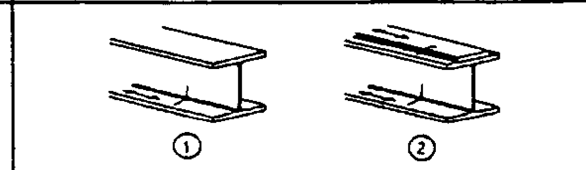
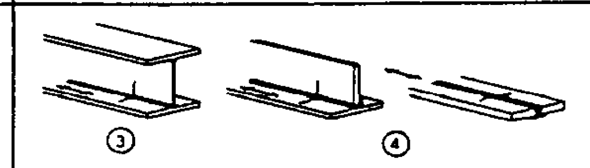
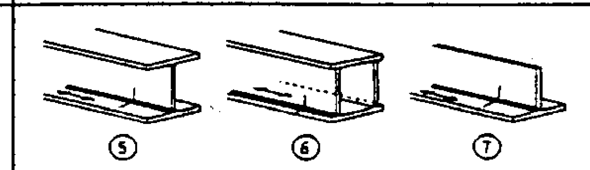
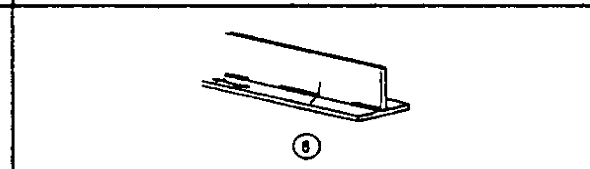
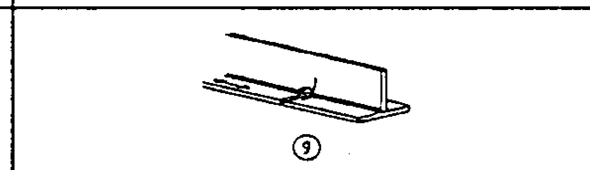


Wöhler curve (III)

S-N curves, depending on:

- geometry => notch class, detail category
- size => thickness correction
- environment => inverse slope, knee points



cate-gory	weld seam detail
125	
112	
100	
80	
71	

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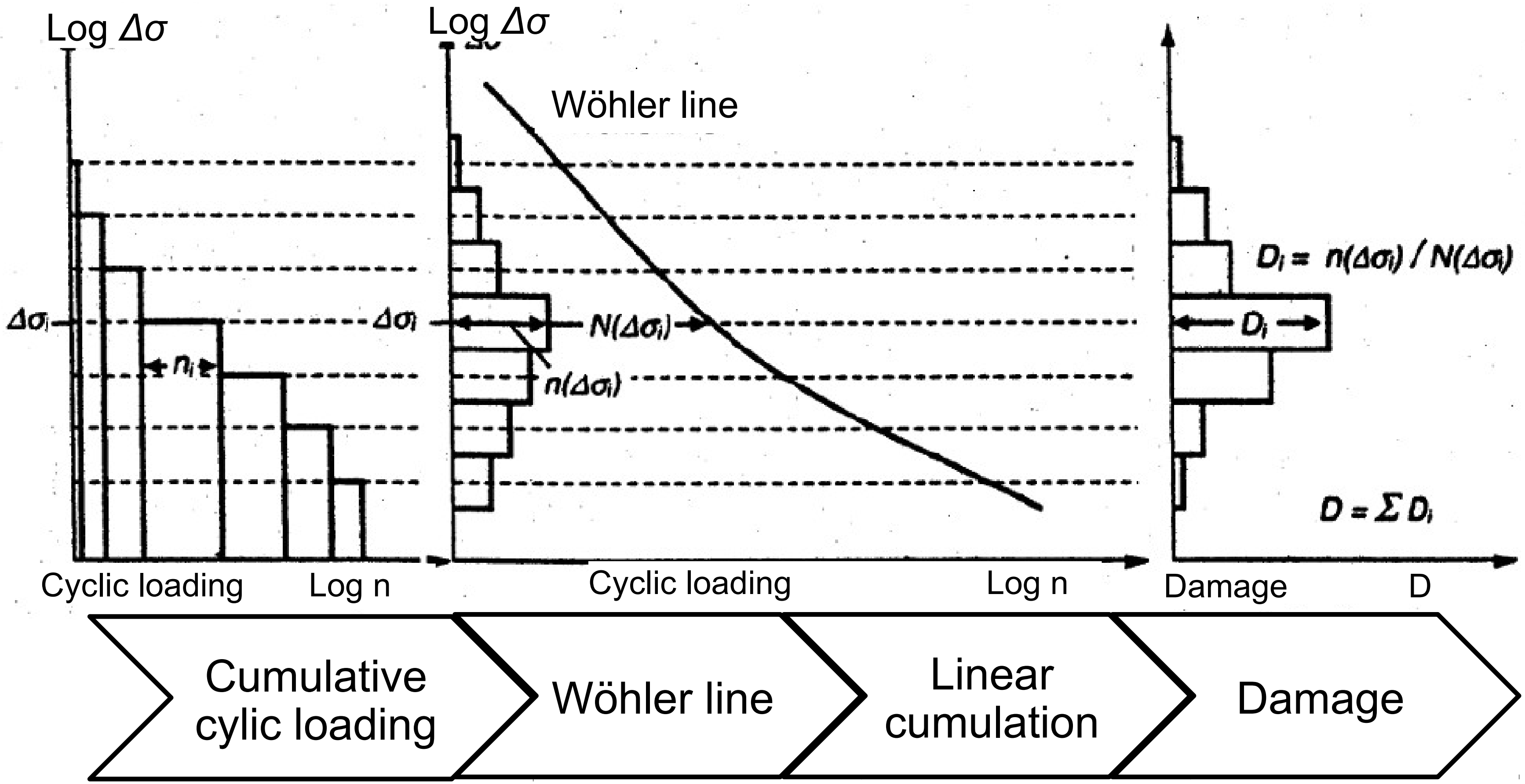
Linear damage accumulation hypothesis according to Palmgren-Miner (I)

Hypothesis: partial damages $D_i = n_i / N_i$ can be added linearly



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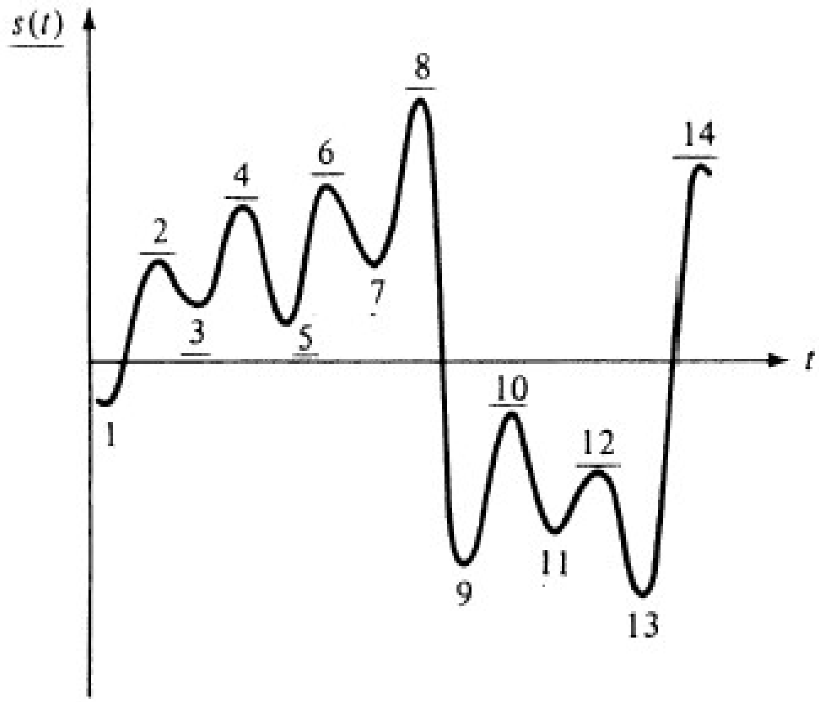
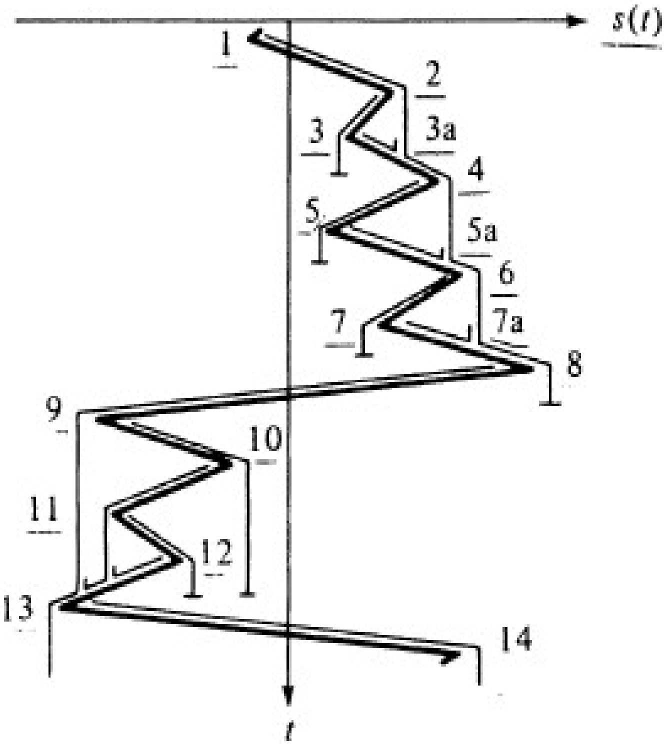
Rainflow Counting



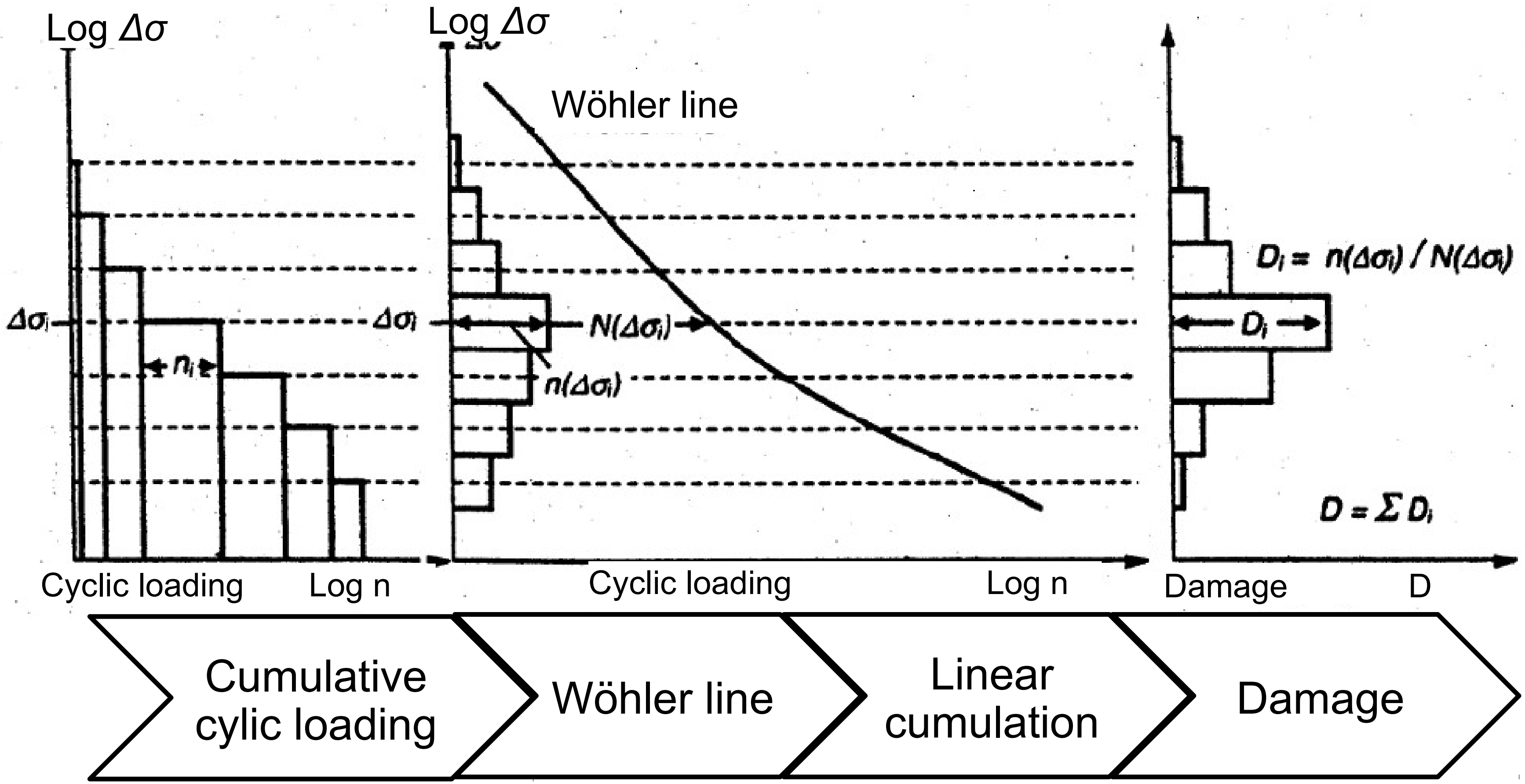
(a)



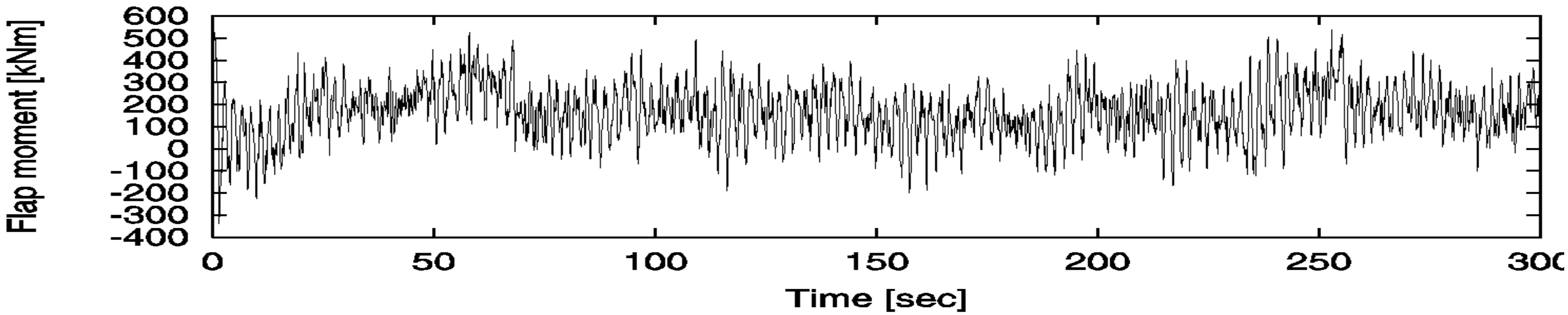
(b)

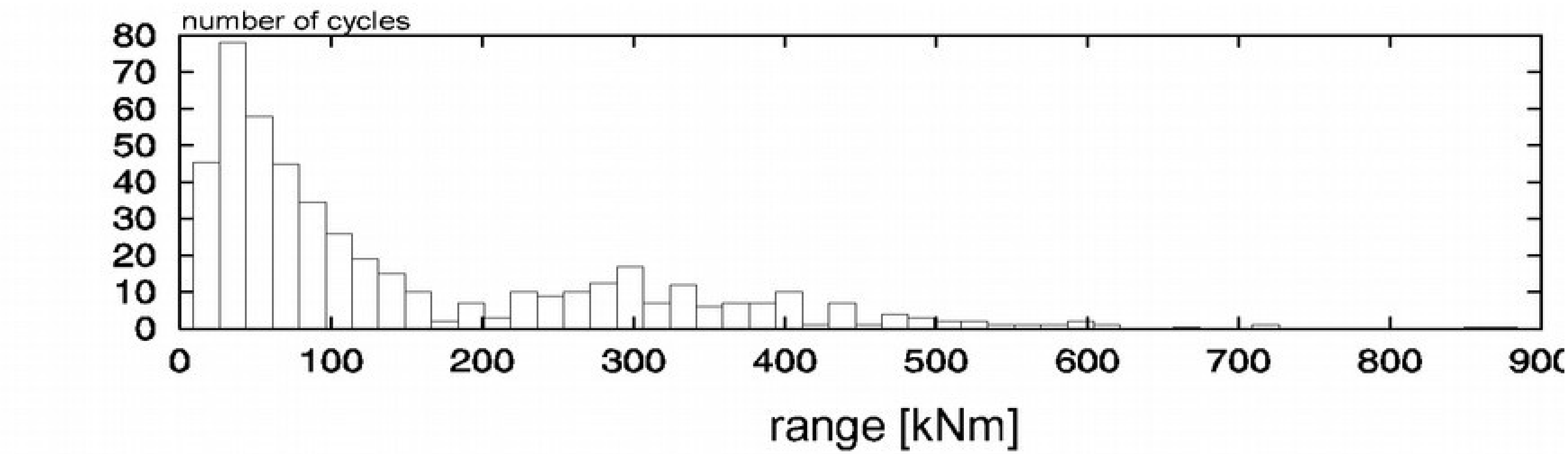
Linear damage accumulation hypothesis according to Palmgren-Miner (I)

Hypothesis: partial damages $D_i = n_i / N_i$ can be added linearly



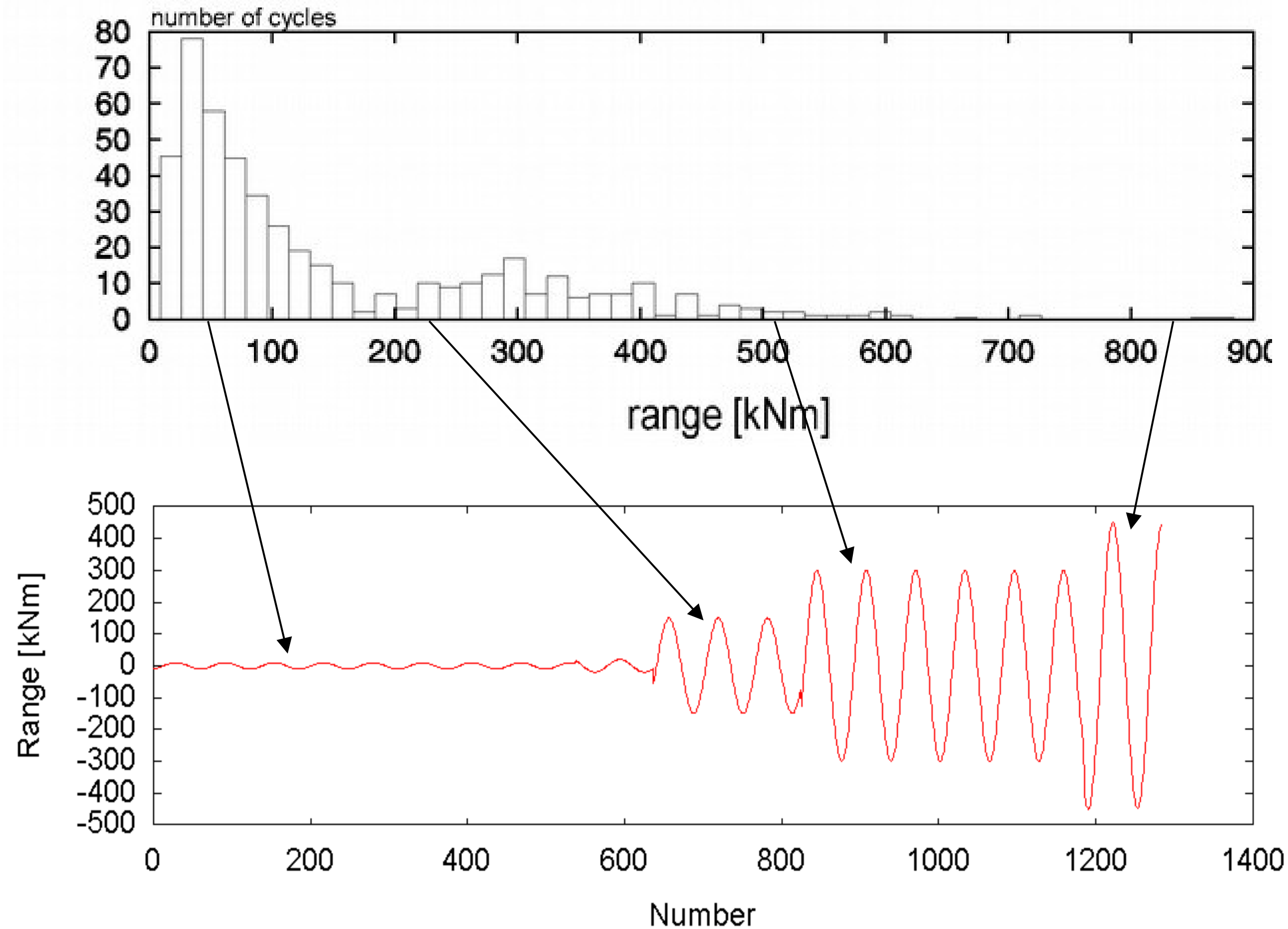
Rainflow Counting





Fatigue load spectrum for ONE load case

Rainflow Counting = time series rearrangement



Linear damage accumulation hypothesis according to Palmgren-Miner (II)

$$D = \sum_i \frac{n_i(\Delta\sigma_i)}{N_i(\Delta\sigma_i)}$$

D	damage	$\Delta\sigma_i$	i^{th} stress range with n_i cycles
n_i	number of endured stress cycles	N_i	number of endurable stress cycles

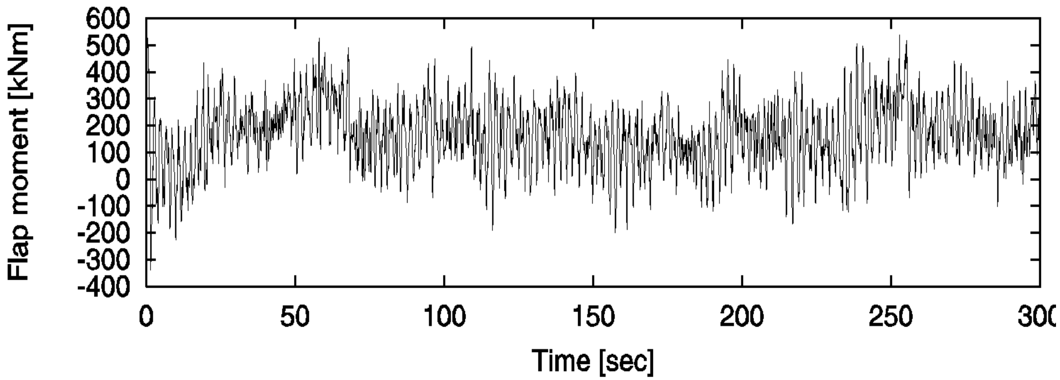
- Partial damage contributions $D_i = n_i / N_i$ are summarized *linearly*
- No influence of load history
- Design criterion $D \leq D_{design} \leq 1$
  - Wind energy:
    $D_{design} = 1$ (safety margin included in design resistance)
  - Offshore technology:
    $D_{design} = 0{,}1$ to $0{,}3$ (safety margin considered in design damage)
- Calculated lifetime = design lifetime / damage

Comparison of fatigue load spectra by means of damage equivalent loads

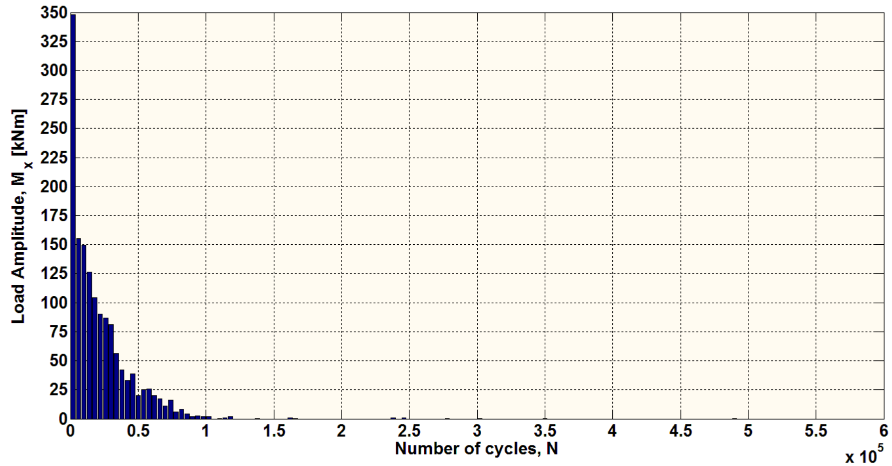
$$\boxed{\Delta\sigma_{eq} = \left(\frac{\sum n_j \Delta\sigma_j^m}{N_R}\right)^{1/m}}$$

$\Delta\sigma_{eq}$	equivalent stress range	m	inverse slope of S-N curve
N_R	reference number, e.g. $2 \cdot 10^6$	$\Delta\sigma_j$	j-th stress range with n_j cycles

From time series to Equivalent load

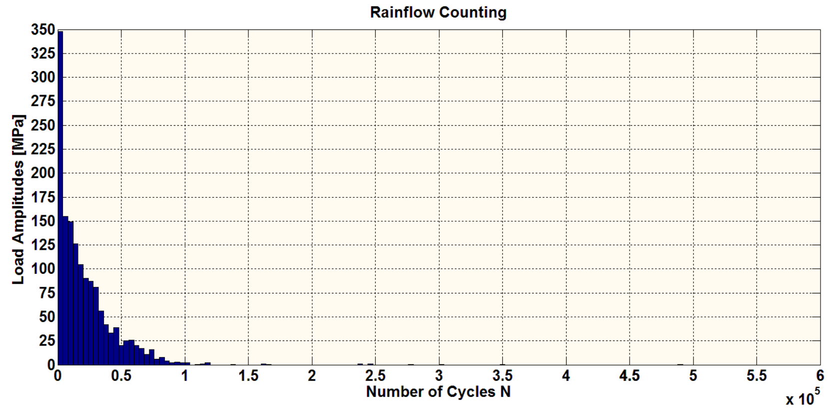


Starting Load time series

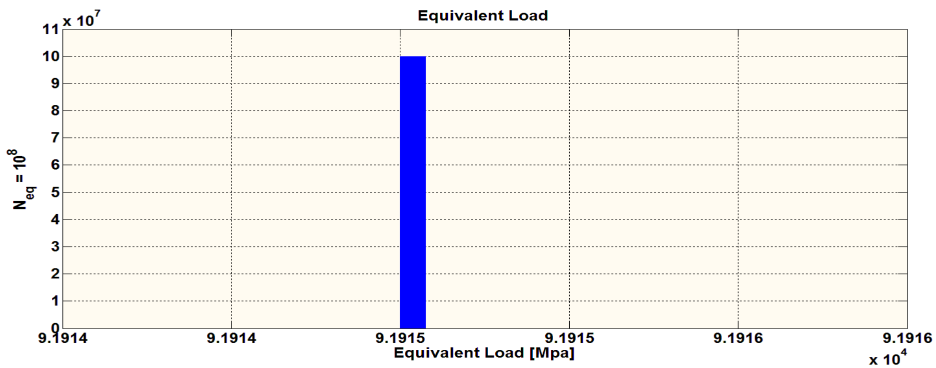


Apply RFC to the time series

From time series to Equivalent load

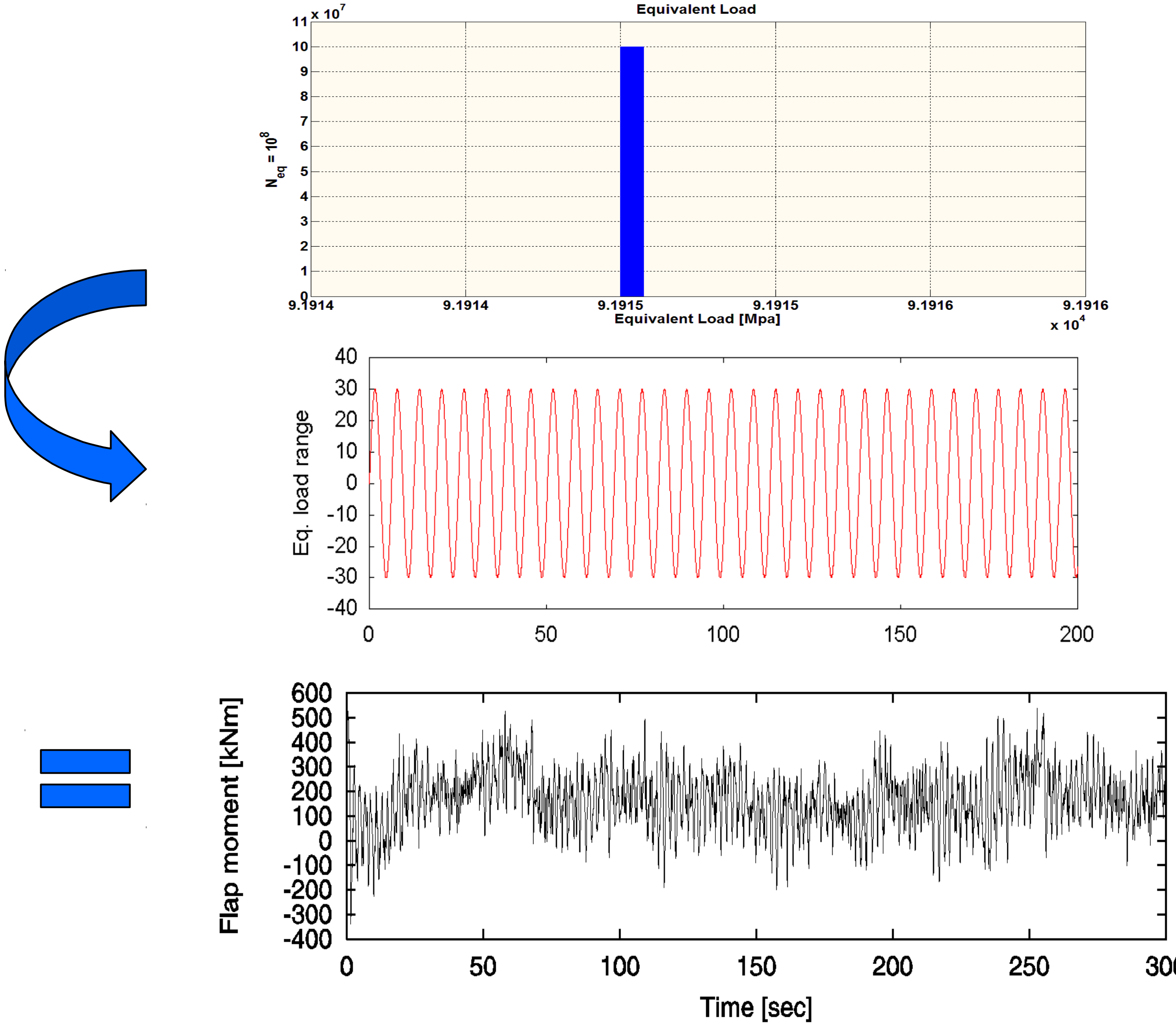


$$\Delta\sigma_{eq} = \left(\frac{\sum n_j \Delta\sigma_j^m}{N_R}\right)^{1/m}$$



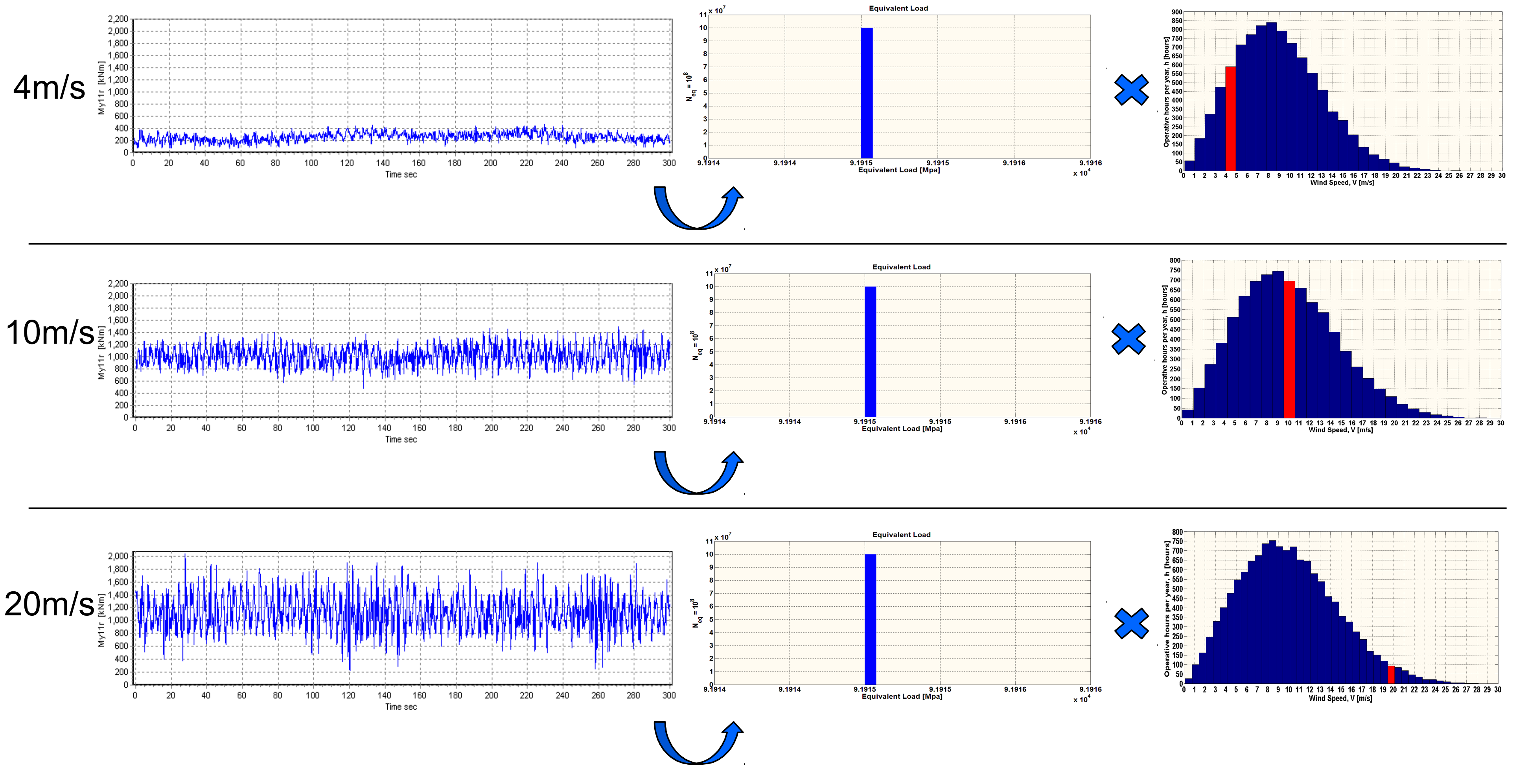
Calculate the equivelent load for a given reference cycle number

From time series to Equivalent load



The two time series are equivalent: they produce the same effect on the turbine

How to use damage equivalent loads



Σ all LC's

Pros and cons of damage-equivalent loads (DELs)

Pros

- \+ DELs are proportional to load magnitude of sectional forces
- \+ while damage is proportional to the 3rd to 12th power of loading (inverse slope of S-N curve)
- \+ strength reserve of DELs is nearly proportional to wall thickness reserve of component => simple design optimisation
- \+ easy comparison of fatigue load spectra with different shape
- \+ easy dimensioning, when reference number of cycles equals $2 \cdot 10^6$

Cons

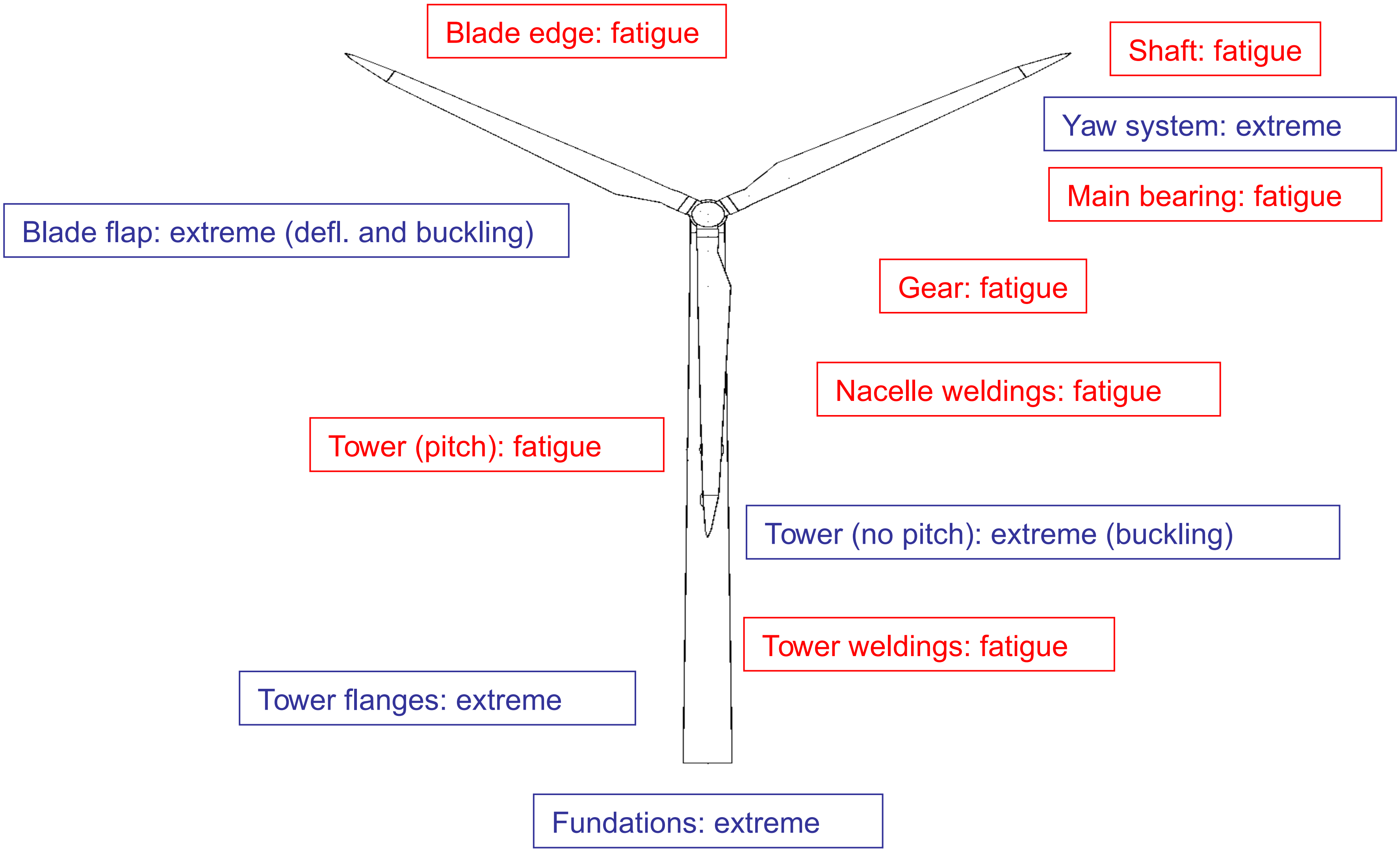
- \- valid only for S-N curves with constant slope
- \- conservative with respect to load spectra and time series approach

Conclusions – Fatigue

Fatigue analysis of wind turbine response

- Simulation of production at various wind speed bins, start, stops, fault load cases, etc.
- Rainflow-counting of time series and factoring with frequency of occurrence of load cases
  - stress time series at hot spot or
  - sectional forces at cross section or
  - sectional forces at component interface
- S-N curve and Palmgren-Miner hypothesis
- Concept of damage equivalent loads (DEL)
  frequently used for comparison of sectional forces and stresses

Dominant Loads: Fatigue or Extreme?



Literature

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