SUMMARY OF STRENGTH DISTRIBUTIONS AND PROBABILISTIC DAMAGE CALCULATIONS

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Summary of the presentation

- Aims & background
- Reliability assessment under HCF
  - ✧ simple method;
  - ✧ SNCF method;
  - ✧ probabilistic damage;
- Input data for probabilistic analysis
  - ✧ damage index;
  - ✧ S-N diagrams for full-scale axles;
  - ✧ target failure probability;
- Application
  - ✧ procedure
  - ✧ example
  - ✧ formulation of simple safety factor

Aims

The general aims of of this part of WP2 within EURAXLES is:

- how to correctly obtain a safe-life design so that a local fatigue HCF assessment will give a failure probability of the order of 10^{-5} for a railway axle?
- to provide data for reliability calculations in real applications;
- revise current approaches and define a new reliability format for fatigue assessment of railway axles under HCF.

↓

Probabilistic analysis

Background – static analysis

- Eurocodes and other standards (BS7910) prescribe that the maximum failure probability during life is $P_f = 7 \cdot 10^{-5}$;
- let us examine the simple format prescribed by the Eurocode for static strength:

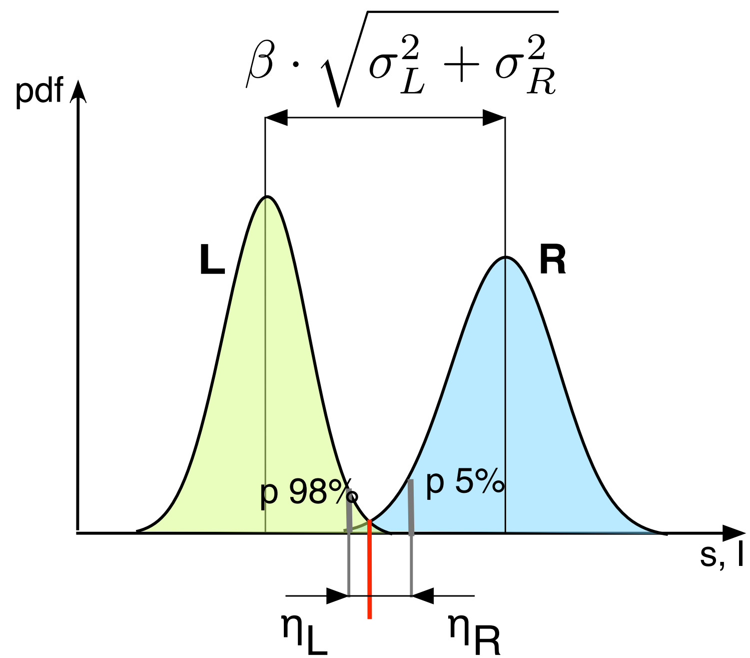
If we consider a gaussian distribution for load **L** and one for resistance **R**:

$$P_f = \Pr[\mathbf{L} > \mathbf{R}] = \int_0^\infty f_L(l) \cdot F_R$$

$$P_f = \Pr[(R - L) < 0] = \Phi(-\beta)$$

where the *safety margin* is:

$$\beta = \frac{\mu_R - \mu_L}{\sqrt{\sigma_L^2 + \sigma_R^2}}$$

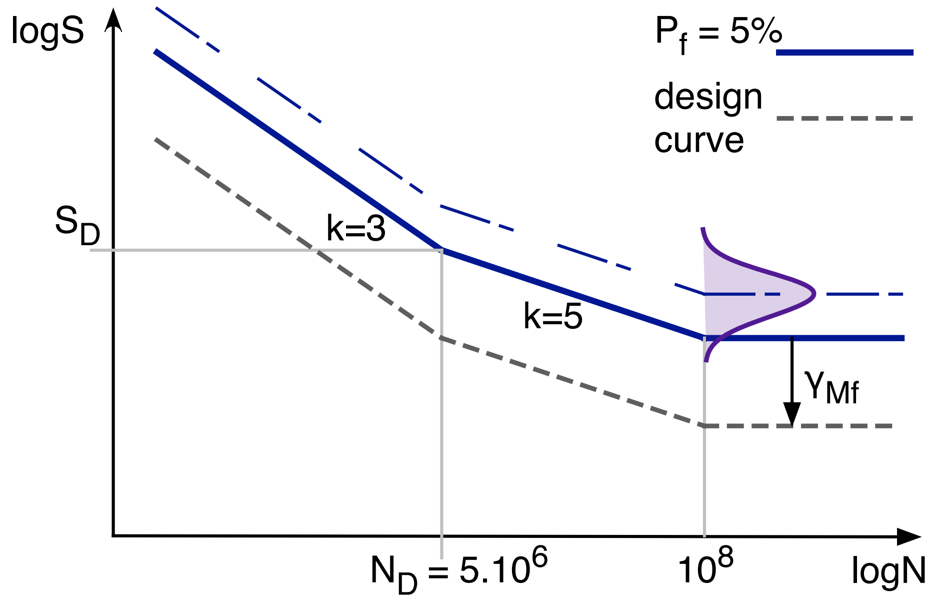


- Failure probability depends on both standard deviations;
- it is possible to calculate partial safety factors η

Background fatigue analysis - 1

According to *EUROCODE*:

- fatigue assessment should be based onto a S-N diagram with 5% failure probability;
- a suitable safety factor (γ_{Mf}) should be applied for obtaining a design fatigue curve;
- damage calculation → $D_{crit} = 1$.



Minimum γ_{Mf} factor

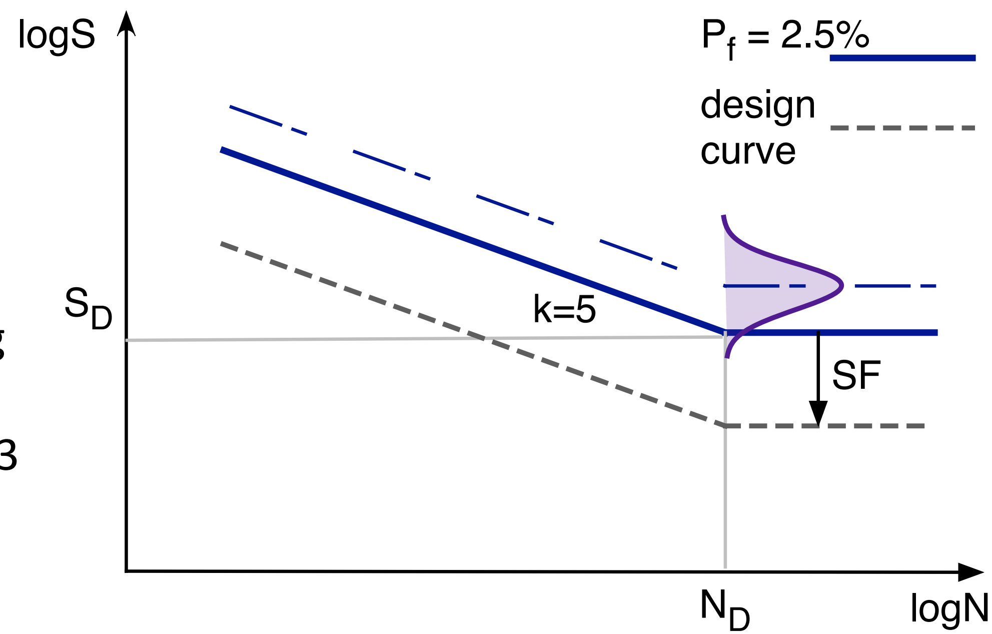
	Consequences of failure	
Assessment method	Low consequences	High consequences
Damage tolerant	1.00	1.15
Safe life	1.15	1.35

- inspections ?
- no relation with the scatter !

Background fatigue analysis - 2

According to *FKM Guidelines*:

- fatigue assessment should be based onto a S-N diagram with 2.5% failure probability;
- a suitable safety factor (SF) should be applied for obtaining a design fatigue curve;
- damage calculation → D_{crit} = 0.3



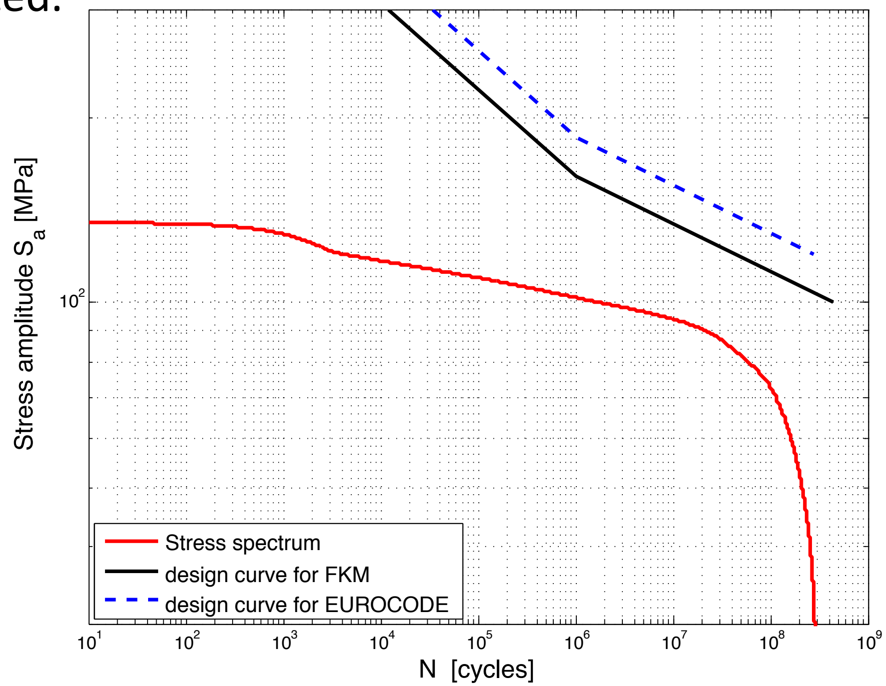
Minimum SF factor

	Consequences of failure	
	Low consequences	High consequences
No regular inspection	1.20	1.30
Regular inspection	1.35	1.5

- inspections ?
- no relation with the scatter !

Example

- Application to an HS trailer axle, whose stress spectrum was measured within **WIDEM** Project.
- The axle, originally made in 30NiCrMoV12 steel, has been redesigned so that it is compliant with EN13104 and local stress spectra have been recalculated.



- design safe for both guidelines

- reliability ?

	EUROCODE		*FKM Guideline*	
	Miner Index	Life prediction [Km]	Miner Index	Life prediction [Km]
no inspections	0.00616	$162 \cdot 10^6$	0.0264	$11.32 \cdot 10^6$
regular inspections	$7.667 \cdot 10^{-4}$	$1304 \cdot 10^6$	0.0064	$46.35 \cdot 10^6$

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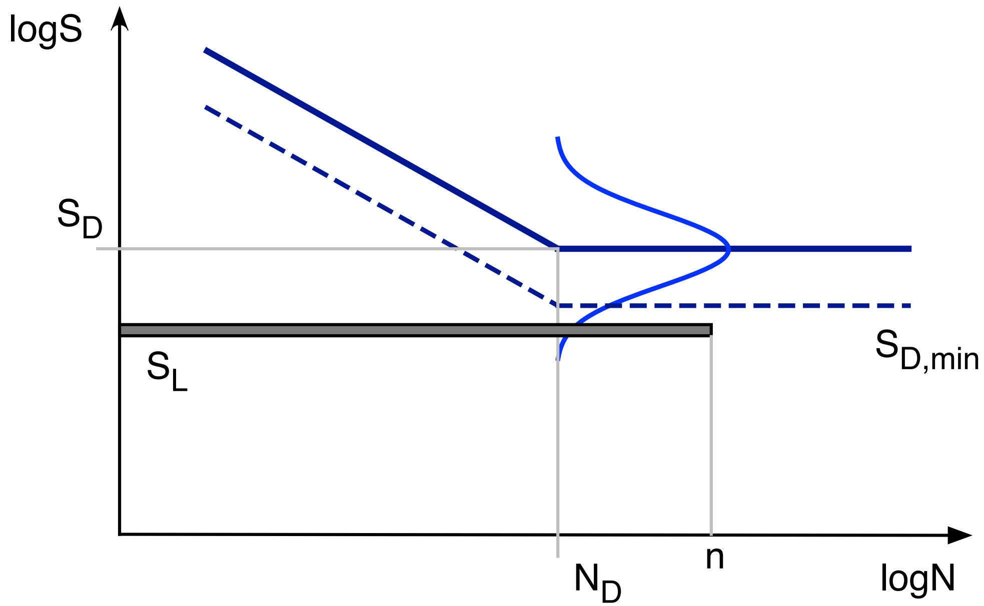
Simple method

Most simple fatigue assessment is consider a single stress level $\mathbf{S_L}$



we have: $$P_f = \Phi(-\beta)$$

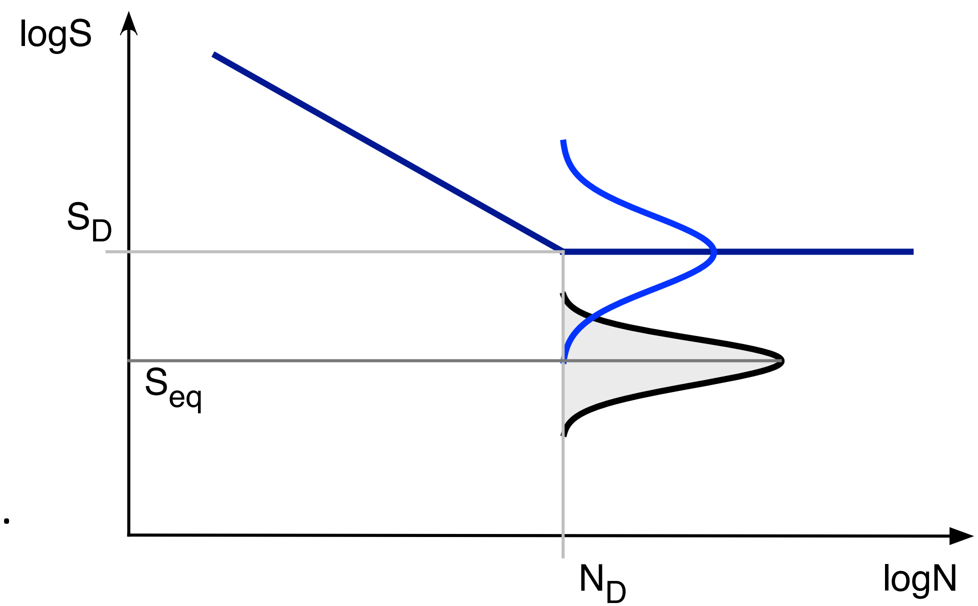
where: $$\beta = \frac{\mu_{logS_D} - logS_L}{\sigma_{logS_D}}$$

SNCF method

The **first step** of the method by SNCF consists in calculating an equivalent constant amplitude stress consists in calculating an equivalent constant amplitude stress ($N_{\{eq\}}$, $S_{\{eq\}}$) which has the same damage as the analysed spectrum.

$$S_{eq} = \left(\frac{D}{D_{crit}}\right)^{(1/k)} \cdot S_D$$

The **second step** of the SNCF method consists in generating various load spectra to take into account the various axle usages. Equivalent loads for these different spectra are calculated and finally the distribution of equivalent load is then obtained.



Probabilistic damage assessment

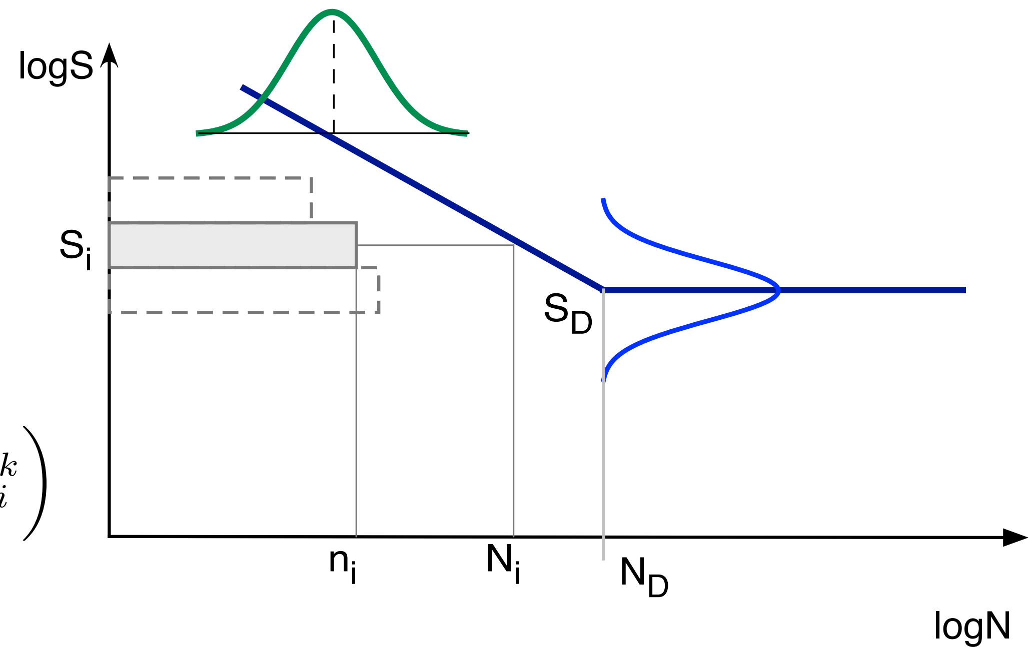
Under the assumption:

$$N = \frac{C}{S^k} \qquad \begin{cases} \mu_{logC} = log(N_D \cdot S_D^k) \\ \sigma_{logC} = \sigma_{logN} \end{cases}$$

The fatigue damage is

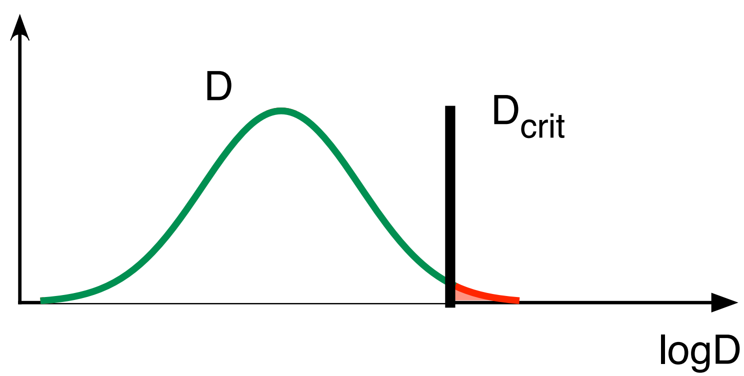
$$D = \frac{1}{C} \cdot \sum_{i=1}^{l} n_i \cdot S_i^k$$

$$\log D = -\log C + \log \left(\sum_{i=1}^{l} n_i \cdot S_i^k \right)$$



The failure probability is:

$$P_f = \Pr[D_S > D_{crit}]$$



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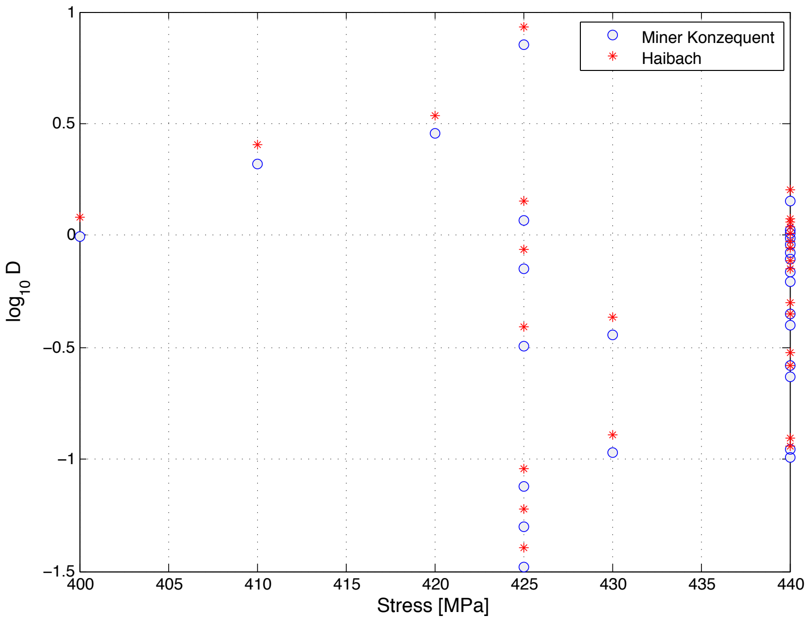
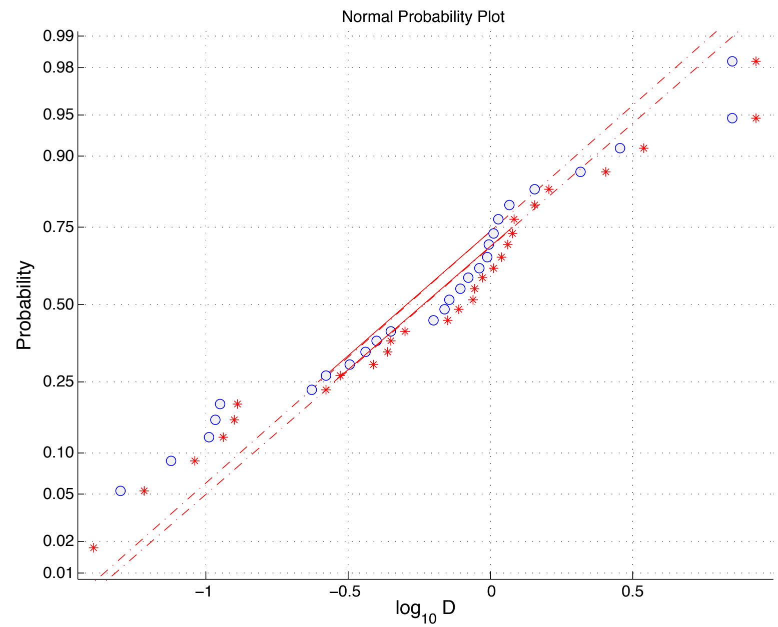
Miner Index

Data by Polimi & IWM



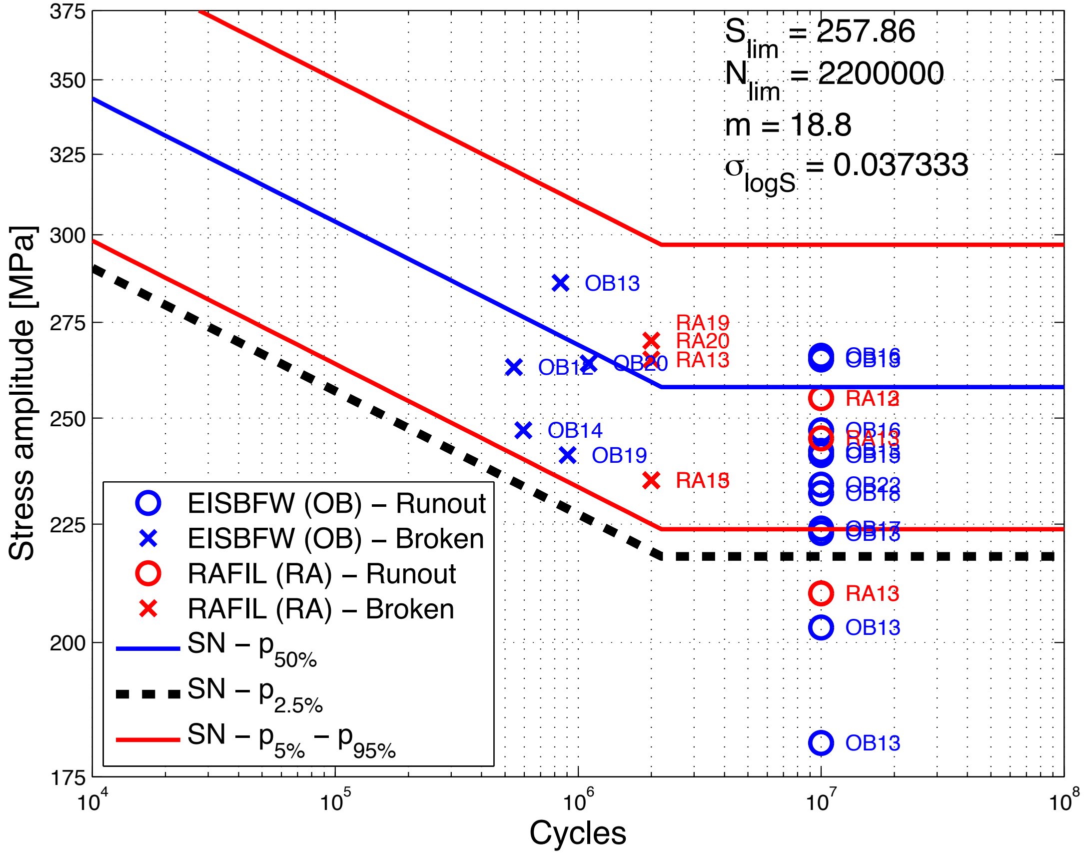


- KM is almost equivalent to Haibach
- Mean values : μ_D = 0.52 – KM μ_D = 0.62 - Haibach
- Std deviation of Miner index: σ_{log10D} = 0.583 KM σ_{log10D} = 0.585 Haibach

we can take D_{crit} = 0.5

S-N diagram for EA1N

Fatigue limit of full-scale axles is very close to the one of small scale specimens

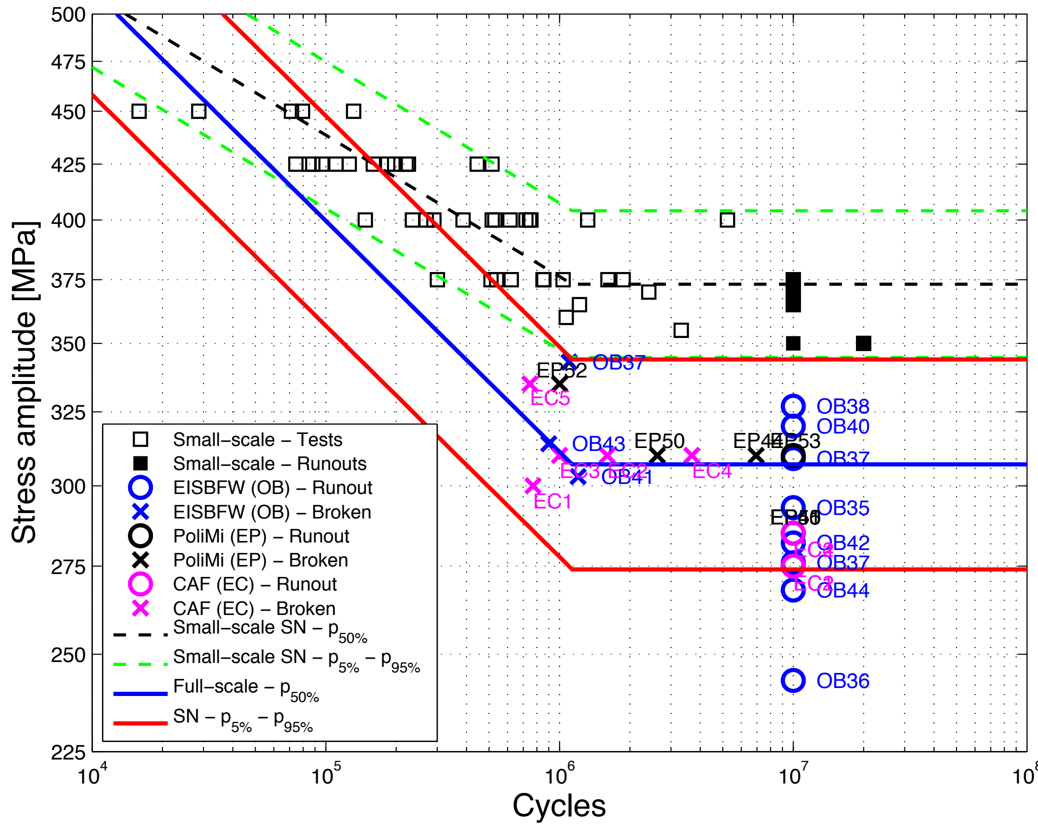


- fatigue limit from full-scale dataset;
- same slope as small scale.

The original S-N diagram compares very well with the experimental data

S-N diagram for EA4T

In the case of A4T there is a significant decrease of full-scale properties respect to the small scale specimens .

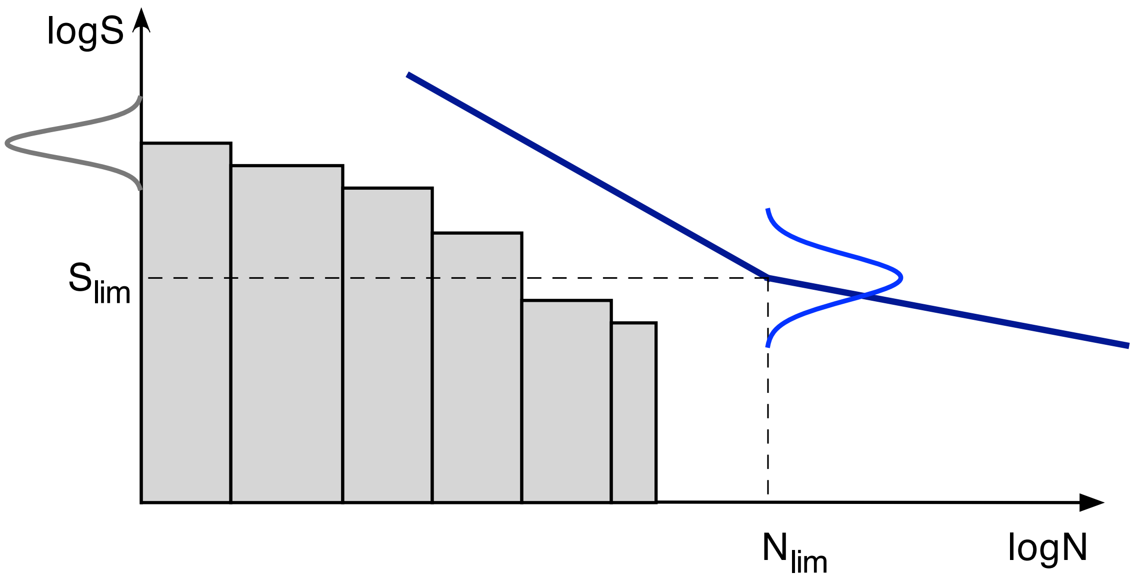


- fatigue limit from full-scale dataset;
- correction for the slope.

This ‘corrected’ S-N diagram compares very well with the experimental data

Target failure probability

It is really needed to design for a given reliability ?



stress

$\pm 2\sigma$ range for stress	CV_S
± 0.02	0.01
± 0.10	0.05
± 0.20	0.10
± 0.30	0.15

fatigue strength

	CV_{S_D}
$\sigma_{logS_D} = 0.021$	0.048
$\sigma_{logS_D} = 0.033$	0.075
$\sigma_{logS_D} = 0.045$	0.103
$\sigma_{logS_D} = 0.057$	0.131

The idea behind the standards is that designing for a given reliability implies **robustness of the design**

Target failure probability

According to Eurocode, the maximum failure probability for the the entire life of a structure is:

$$P_{f,EN1990} = 7 \cdot 10^{-5}$$

which corresponds to a failure rate (30 years of service) :

$$\lambda_{med,EN1990} = 2 \cdot 10^{-6} \quad [\text{failure/year}]$$

This figure is very close to present failure rate of Europe's axle fleet, but if we want to improve the target should be (according to a study by RSSB):

$$\lambda_{med,target} = 2 \cdot 10^{-7} \quad [\text{failure/year}]$$

$$P_{f,target} = 7 \cdot 10^{-6}$$

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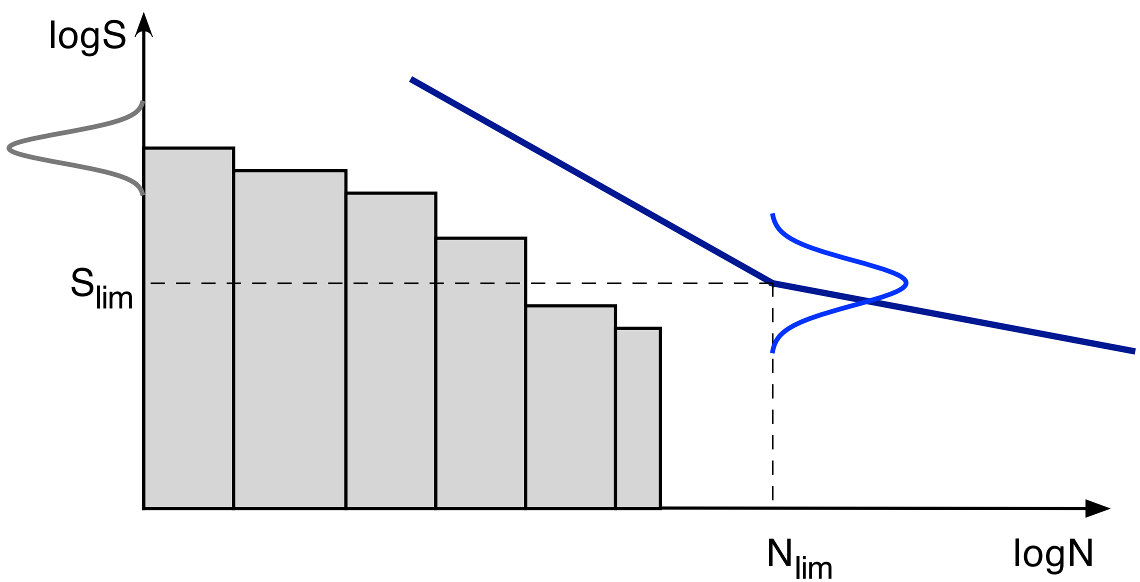
Procedure for probabilistic design

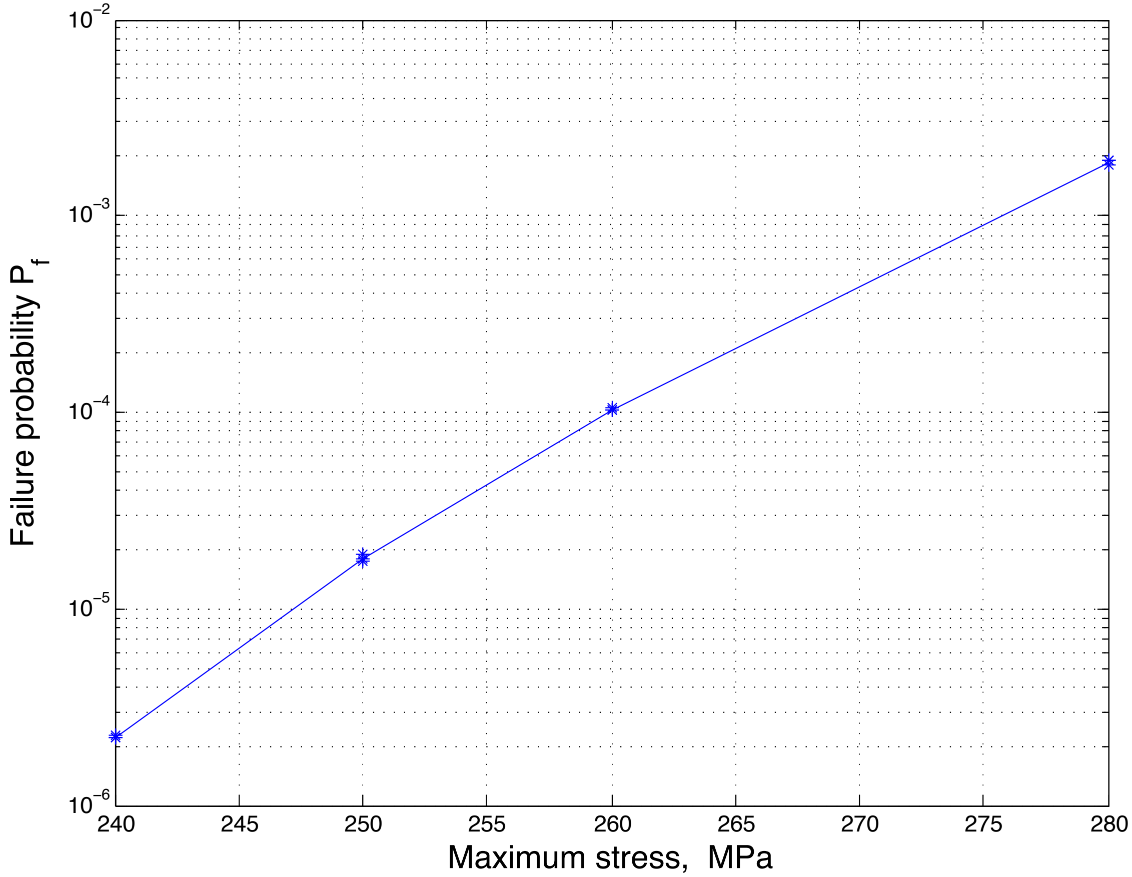
For a given set of input parameters (spectrum, S_{max}, CV):

- random extraction of a spectrum;
- random extraction of an S-N diagram;
- calculation of the distribution of the Miner index due to service D_s;
- calculation of the failure probability: $P_f = \Pr[D_S > D_{crit}]$



Example of application

Application to an HS axle with a prospectile life of 10^7 km (CV_S =0.05) under WIDEM spectrum

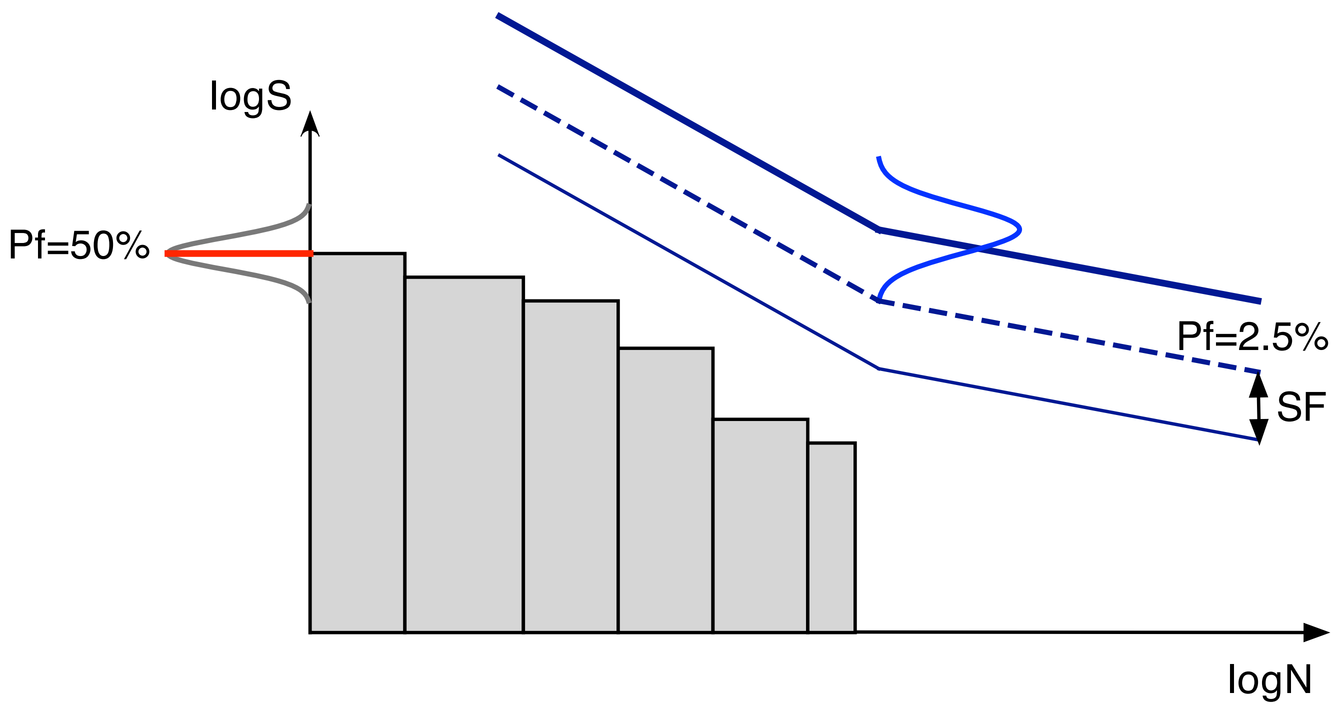


$$S_{max,perm} : P_f \leq \begin{Bmatrix} P_{f,EN1990} \\ P_{f,target} \end{Bmatrix}$$

The dependence of P_f on the maximum stress can be readily obtained

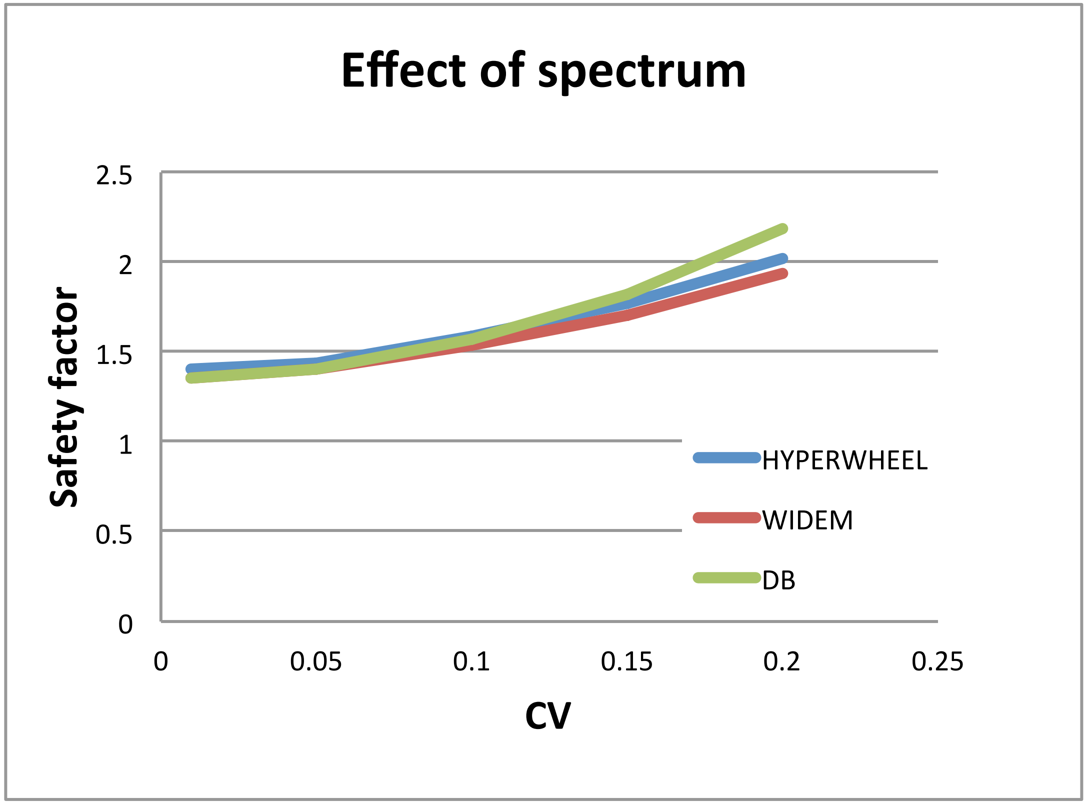
Safety factor to be adopted - 1

- Determination of S_{max} for obtaining Pf = 7.10^{-6}
- determination of the safety factor SF needed for calculating the S_{max} with a simple deterministic calculation according to FKM method (50% percentile for stresses, 2.5% percentile for life, Miner Index =0.3)



Safety factor to be adopted - 2

- 3 different load spectra have been considered
  - HYPERWHEEL
  - WIDEM
  - DB



Effect of spectrum shape is negligible

Conclusions

We have addressed the problem, within the EURAXLES project, to propose a simple method for a safe fatigue design:

- inputs from fatigue experiments (small scale and full-scale);
- proposal a probabilistic format ;
- elaboration of a simple semi-probabilistic approach based onto a safety factor.

Is it enough ?

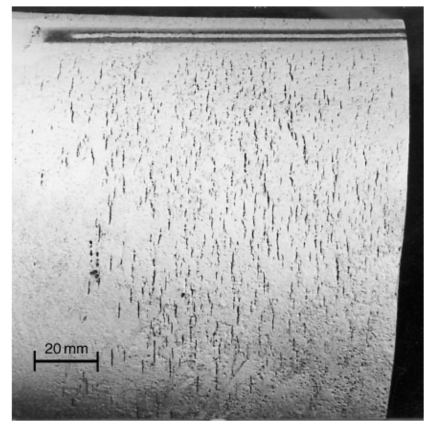
'protection and maintenance policy applied to the axle ensures the efficiency of the protection against impacts and corrosion throughout the life of the axle and ensures that the original surface condition of the axle material is maintained' (quote from EN13103)

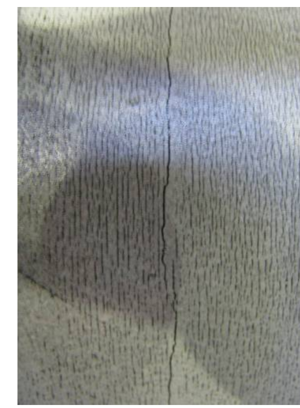
The role of maintenance - 1

The axles during their long service are exposed to different damages able to lead to premature failures, even if the axles have been designed with a target low failure probability → **new failure modes**

Impacts

Corrosion





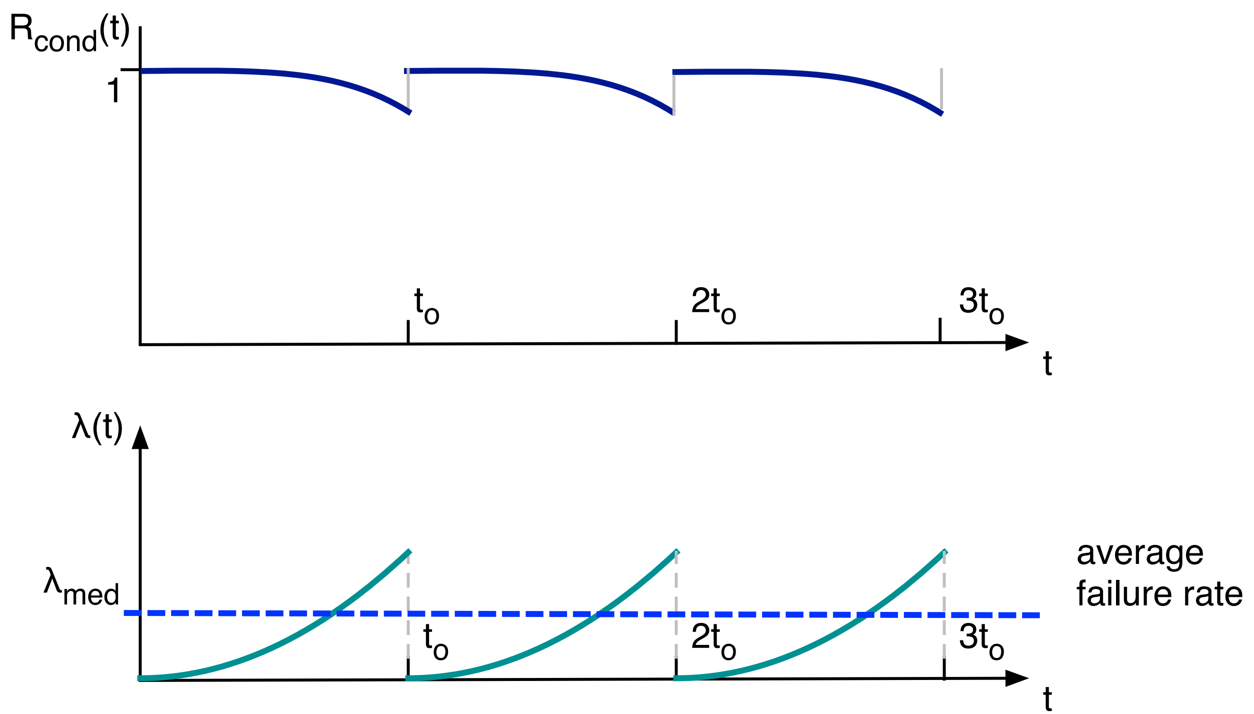
Maintenance actions are aimed at 'restoring' the axles to their initial state by removing the axles with high damages or restoring the disrupted paint protection

The role of maintenance - 2

The concepts applied to fatigue design → **minimum inspection periodicity**

In reality if we look at the maintenance as able to 'restore as new'

the conditional reliability (the probability of a successfull mission t, after a maintenance at it_o)



$$\lambda_{med,target} = 2 \cdot 10^{-7} \quad [\text{failure/year}]$$