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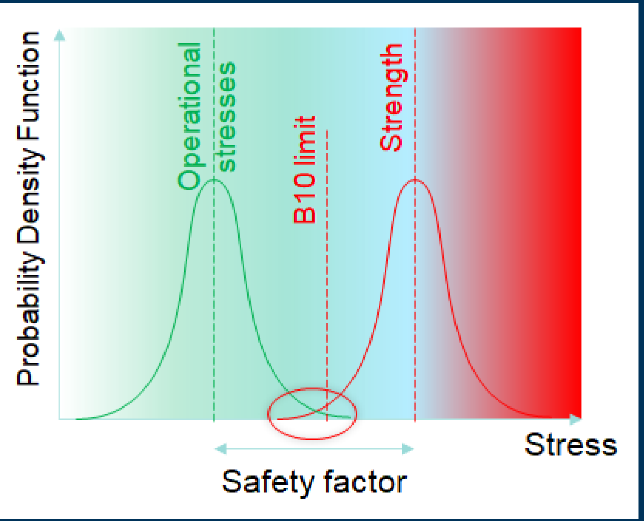

Uncertainty Quantification and Propagation through Measurement and Analysis

Presented by Dr. Andrew Halfpenny
Chief Technologist, HBM Prenscia
HBK

Session #5: Mathematical Modelling for Data Analytics, Durability, and Reliability #1

Uncertainty Quantification and Propagation through Measurement and Analysis

Abstract

The fatigue design of mechanical systems has historically followed a 'deterministic' process. That means, for a given set of inputs they will return a consistent set of fatigue life results with no scatter. In reality the inputs are statistically uncertain -- they have an expected value and a variability. Deterministic design methods take no implicit account of uncertainty. In practice, the designer applies a safety factor to each input parameter along with an additional safety factor to the final result to allow for 'modelling errors'. In most cases, the engineer is fairly certain that the simulation results are conservative, but cannot state with any confidence what the final safety margin, reliability or failure rate will be. Furthermore, it is almost impossible to qualify the simulation by experimental testing because the test lives are significantly higher than the conservative simulations would suggest.

In comparison, a 'Probabilistic Fatigue Simulation' method is 'stochastic' in nature. In this presentation we review the concepts of 'Stochastic Design' under the following headings:

1. Uncertainty sources: including Epistemic (or reducible) uncertainties, and Aleatoric (or irreducible) uncertainties
2. Uncertainty propagation: including 'Analytical methods' and 'Numerical simulation methods' covering:
   - Monte Carlo Simulation, Design of Experiments (DOE), Response Surface Analysis, Reduced Order Modelling (ROM)
3. Uncertainty quantification: including Design for 'Reliability', and Design for 'Robustness'

Probabilistic Fatigue Simulation offers many significant advantages over the traditional deterministic design approach:

1. Calculate life & variability in life
2. Identify the most critical input uncertainties
   - Optimize for design uncertainty, Avoid large safety factors, Minimize risk exposure
3. Design for Reliability
   - Understanding the shape of the statistical life curve, Design for an acceptable reliability target, Quantify warranty exposure, Manage maintenance schedules, Cost vs. risk vs. benefit analysis, Maintain good brand reputation
4. Design for Robustness
   - Understanding the edge cases, Design for the worst-case scenarios
5. Validate simulation against physical test data
   - Validation includes mean time to failure and the statistical distribution

About the presenter, Dr. Andrew Halfpenny

Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Masters in Civil and Structural Engineering. With over 25 years of experience in structural dynamics, vibration, fatigue and fracture, he has introduced many new technologies to the industry including: FE-based vibration fatigue analysis, crack growth simulation and accelerated vibration testing. He holds a European patent for the ‘Damage monitoring tag’ and developed the new vibration standard used for qualifying UK military helicopters.

He has worked in consultancy with customers across the UK, Europe, Americas and the Far East, and has written publications on Fatigue, Digital Signal Processing and Structural Health Monitoring. He sits on the NAFEMS committee for Dynamic Testing and is a guest lecturer on structural dynamics with The University of Sheffield..

Uncertainty Quantification and Propagation through Measurement and Analysis

THE FUTURE OF FATIGUE SIMULATION

Dr Andrew Halfpenny
Director of Technology – nCode Products

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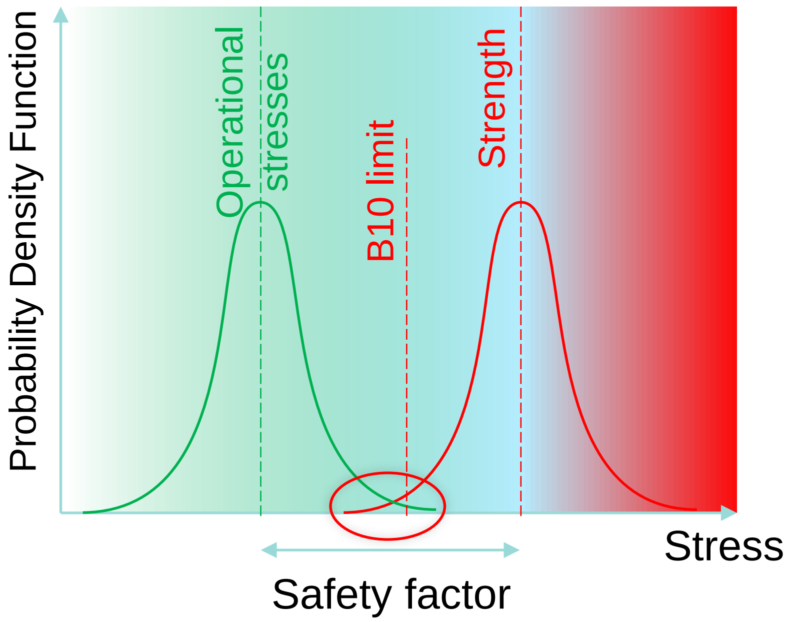
   - Why do we need fatigue simulation?

2. The role of simulation & qualification in design

3. Quantifying design uncertainty

4. Case study



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The De Havilland Comet

Why do we need fatigue simulation?

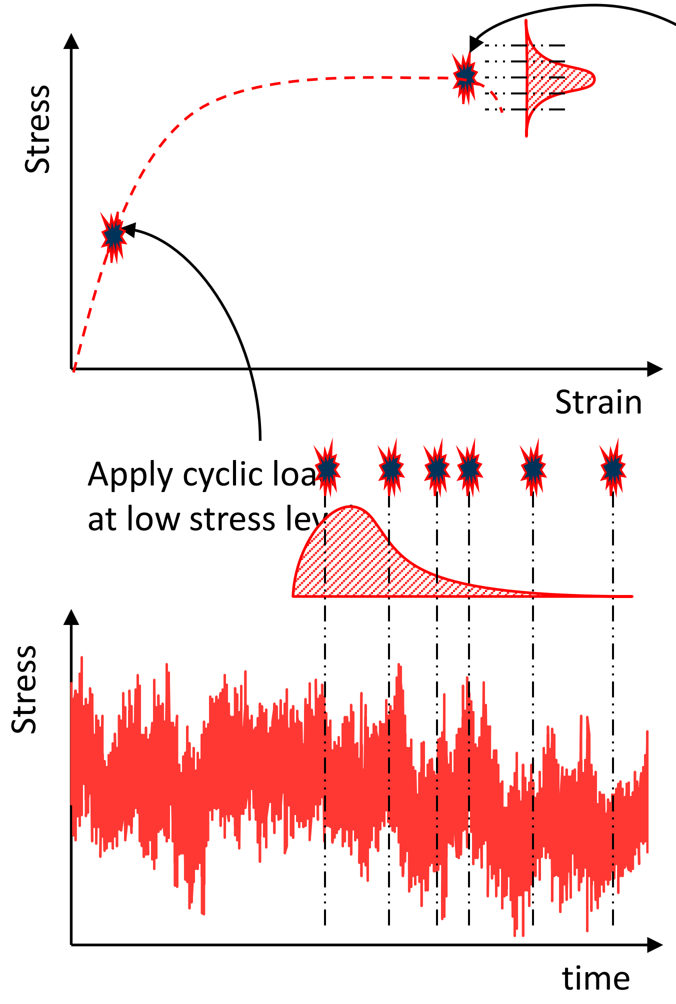
Southwest, Boeing 737, 2009

Southwest Boeing 737-700, April 2018

Southwest Boeing 737, 2011

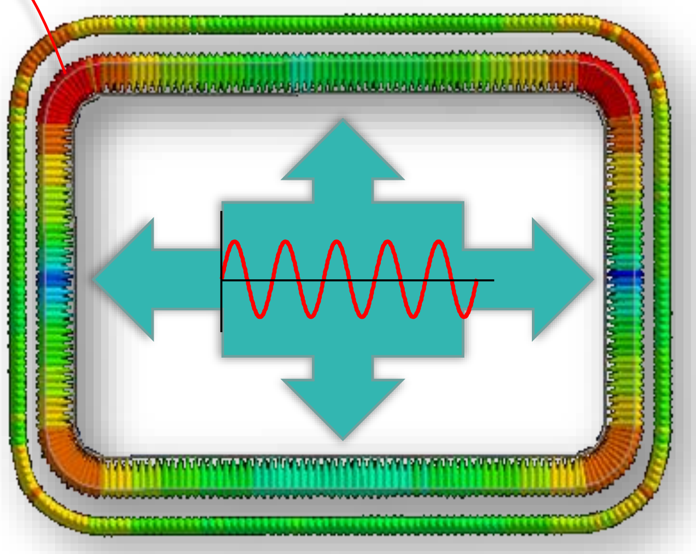
What is fatigue?

Stress V’s Strain Plot



STATIC failure:

Failure when stress exceeds UTS in a single pass



FATIGUE failure:

Fatigue is the progressive weakening of a material caused by varying loads, even though the resulting stresses are well within the static strength limits.

The component seems to get ‘Tired’, hence the name FATIGUE

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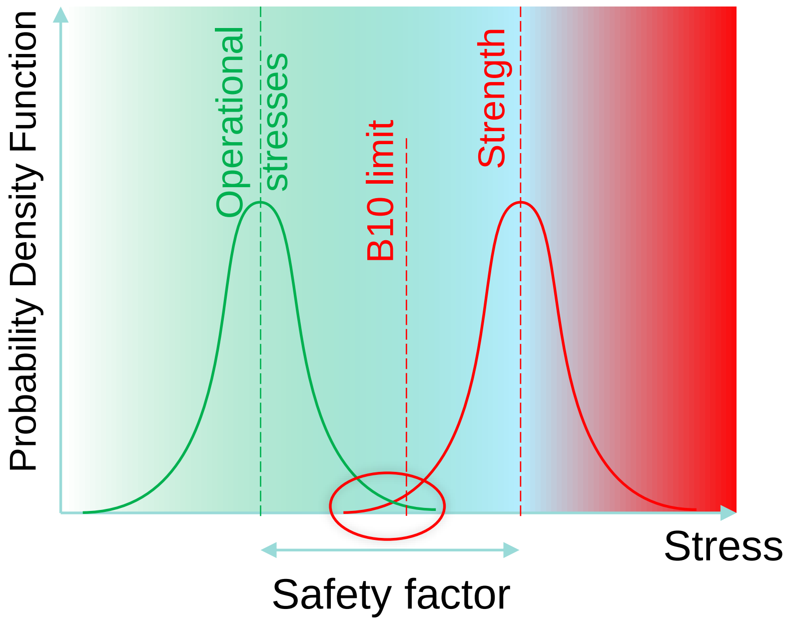
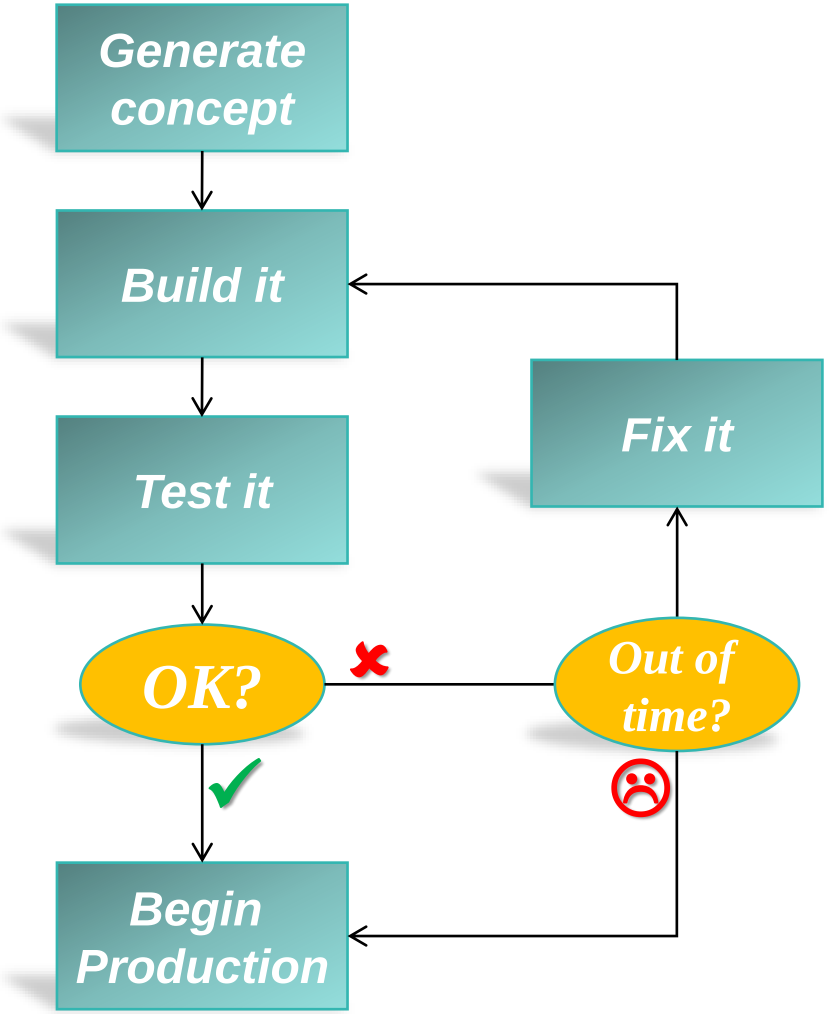
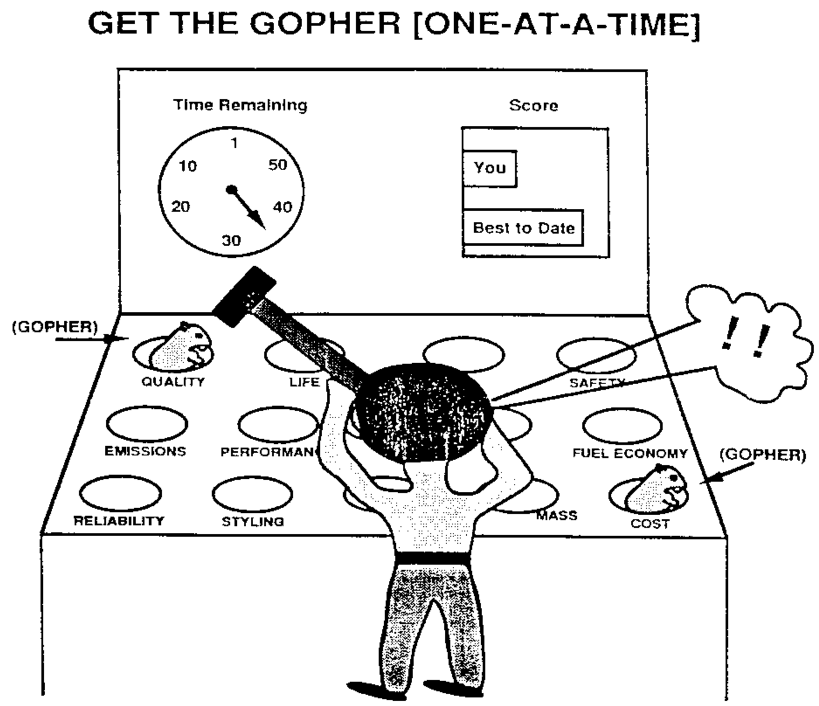


Fatigue design before simulation





- Fixing one problem often leads to another
- Can you test every conceivable failure mode?
- Do you know every conceivable failure mode?

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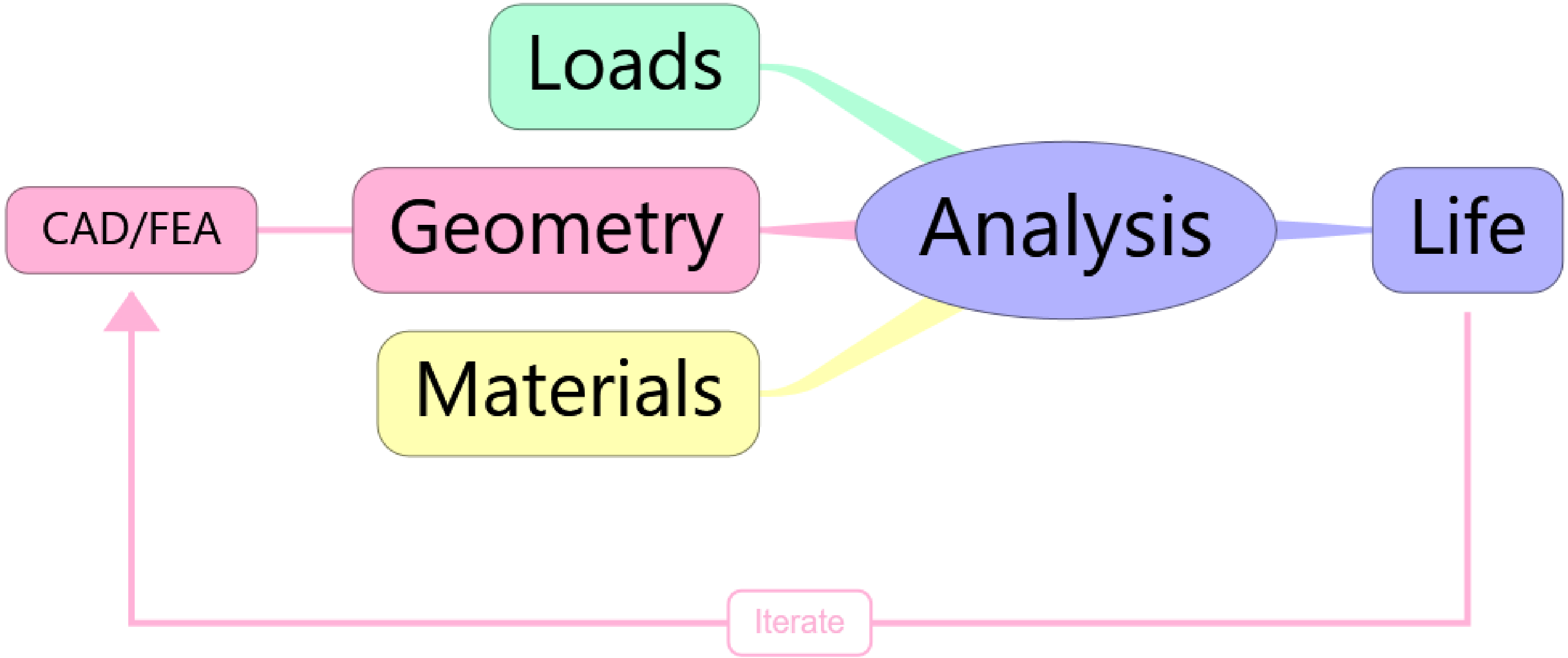
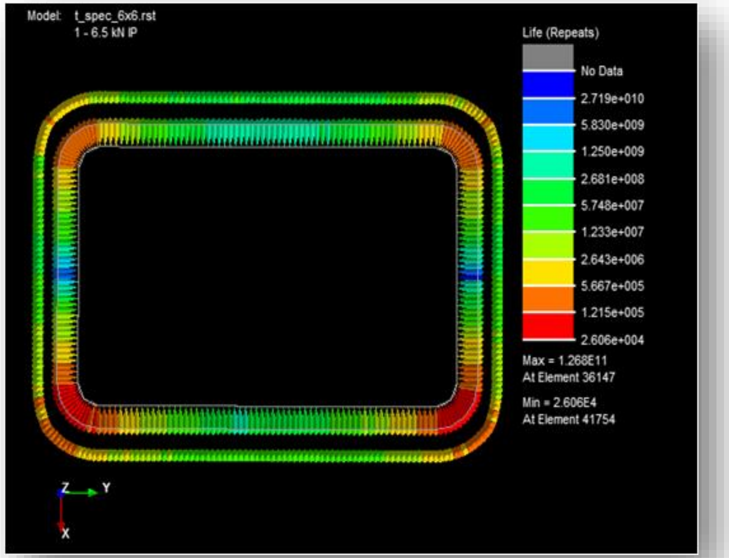
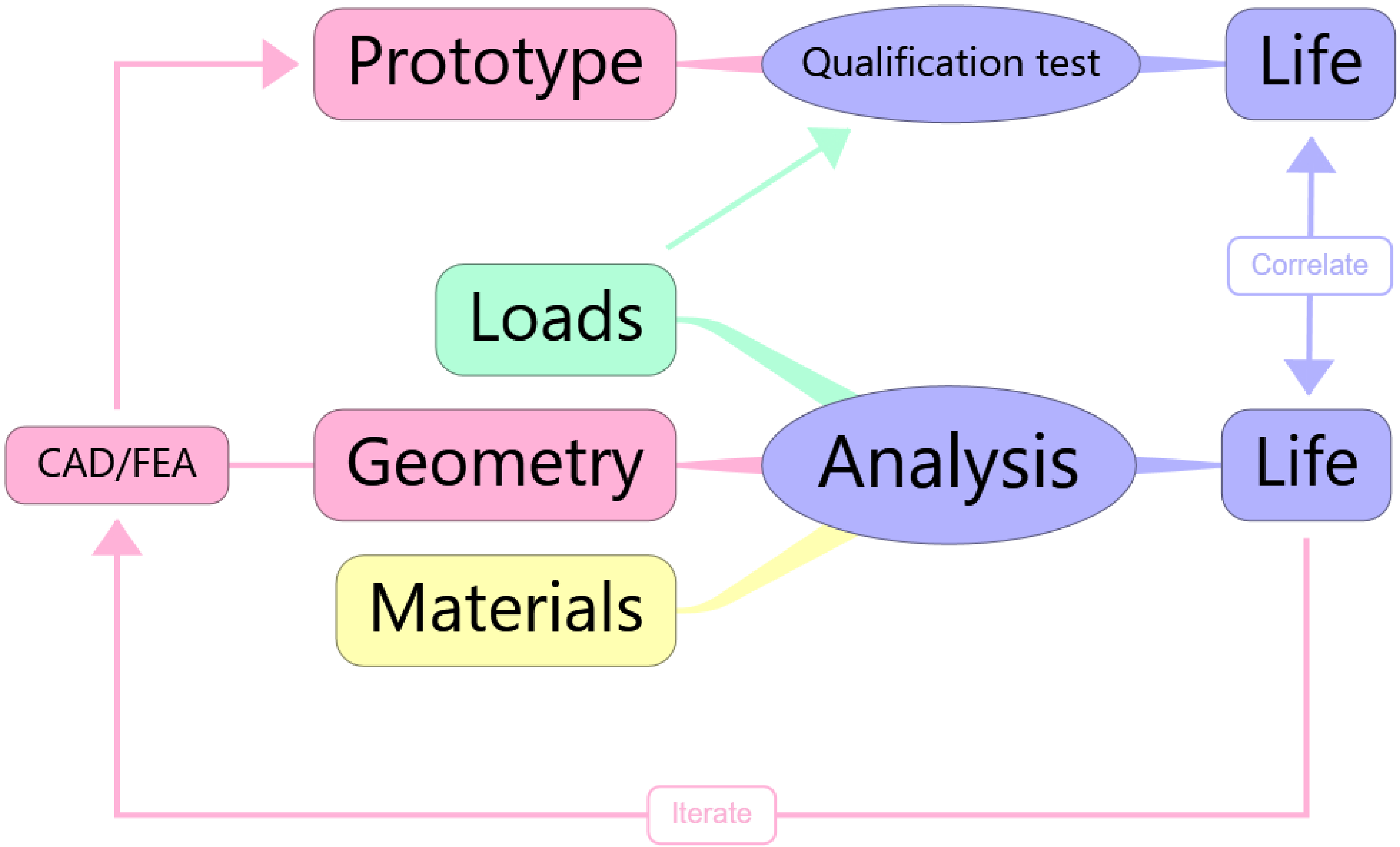
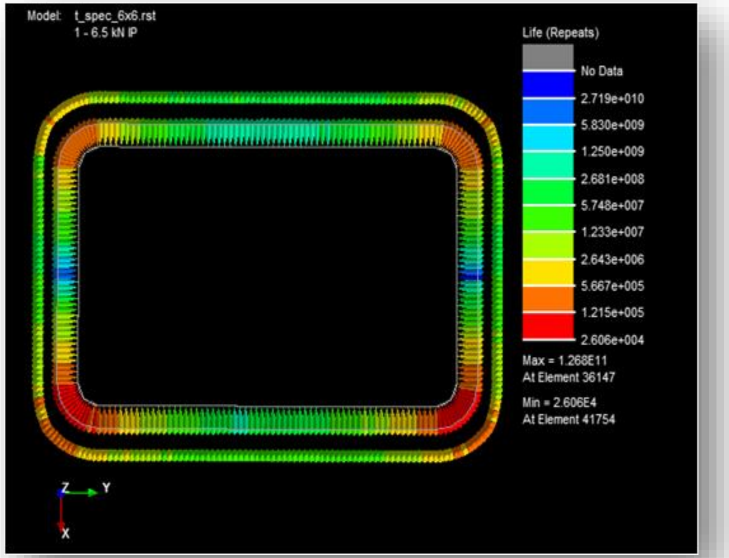
Fatigue simulation



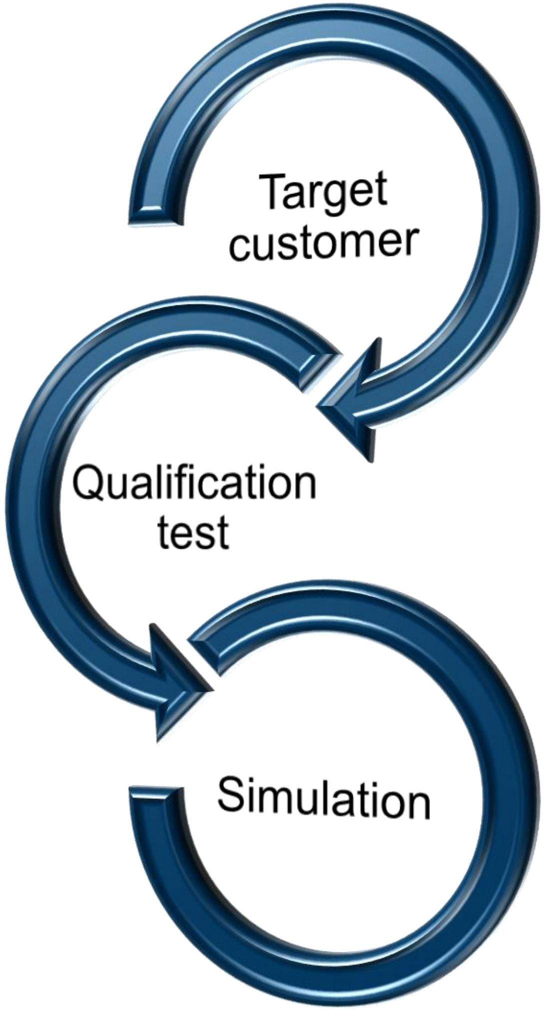


Fatigue simulation and qualification testing





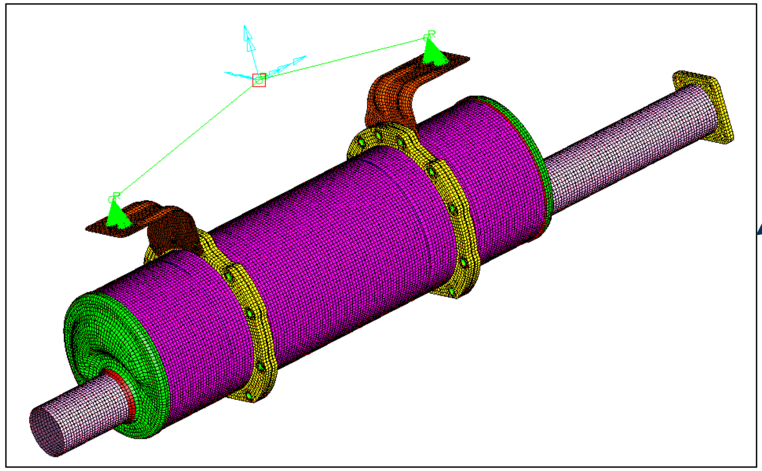
Improved target user analysis



1. Statistical target customer analysis

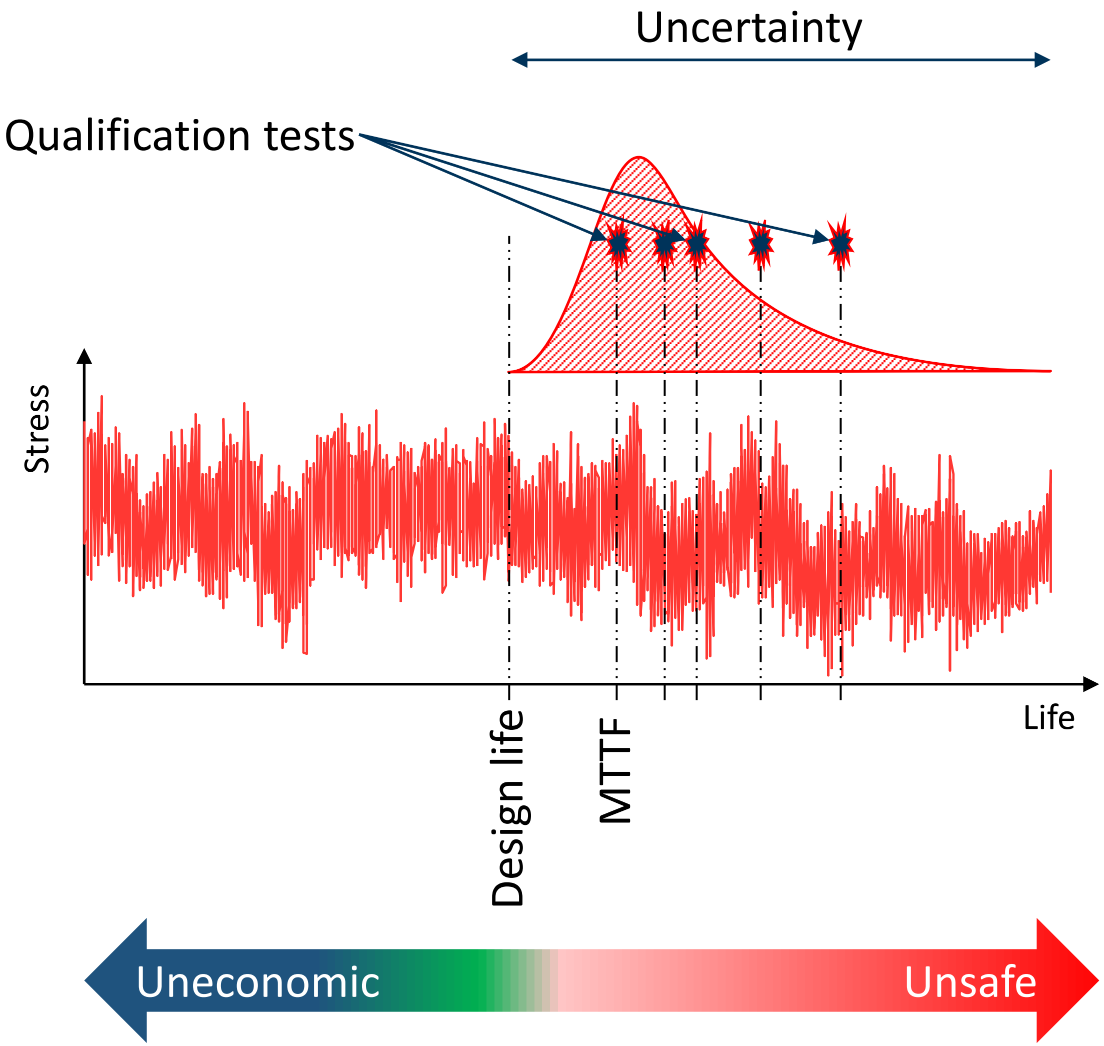
2. Make it scientifically reproducible

3. Accelerated qualification testing



4. Simulate the qualification test

Uncertainty in simulation and test



Uncertainty classification

- ***Epistemic uncertainties***
  - can be reduced by better knowledge
  - due to errors in measurement or modelling assumptions
- ***Aleatoric uncertainties***
  - cannot be reduced by better knowledge
  - due to naturally occurring phenomena

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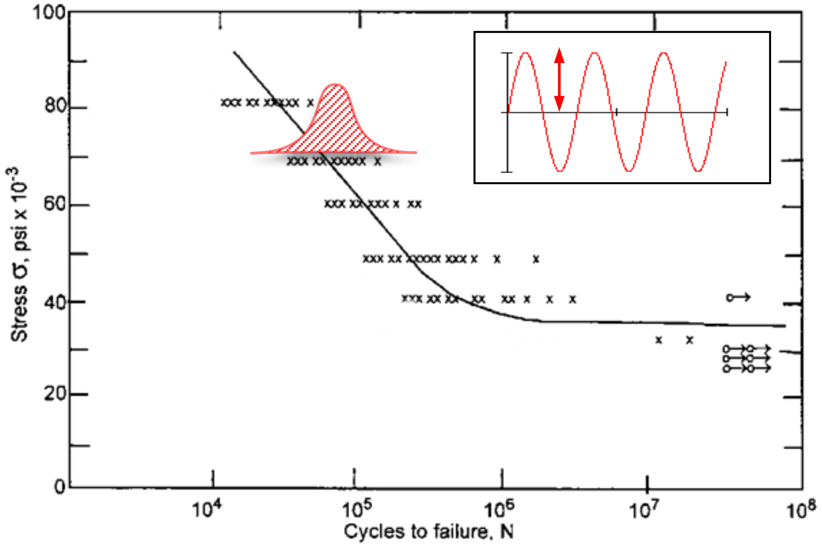
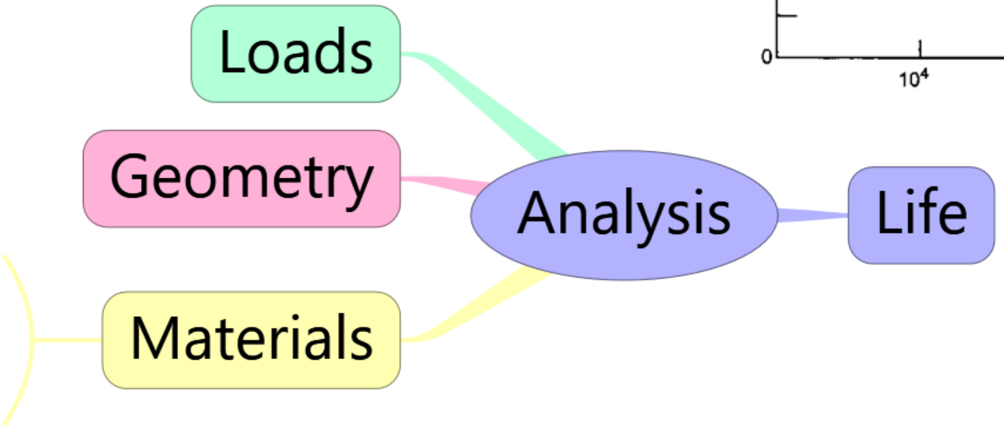
Where's the uncertainty come from?

- **Aleatoric uncertainty**
- Epistemic uncertainty

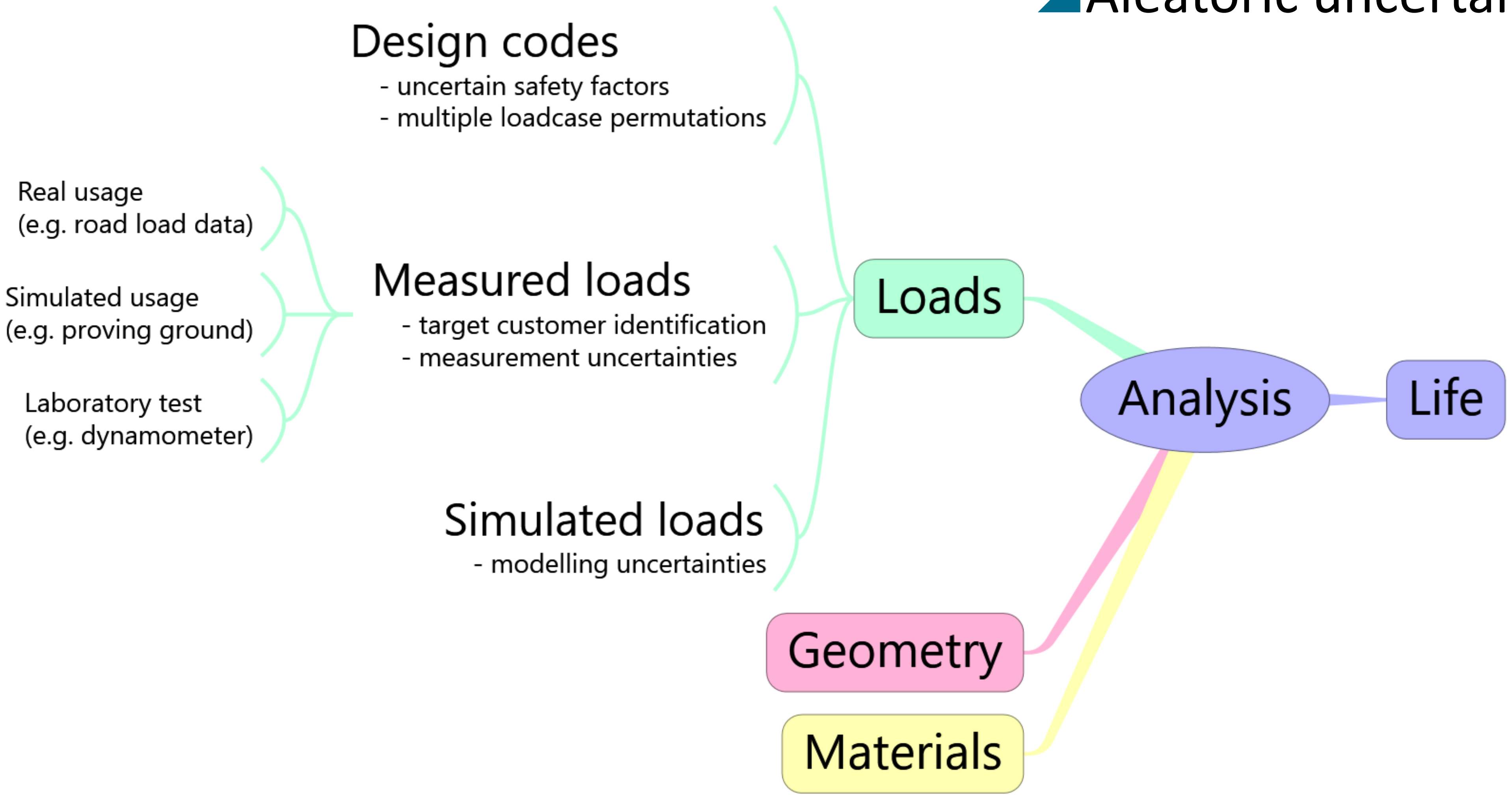




Parametric tests
- inherent material uncertainties
- measurement uncertainties

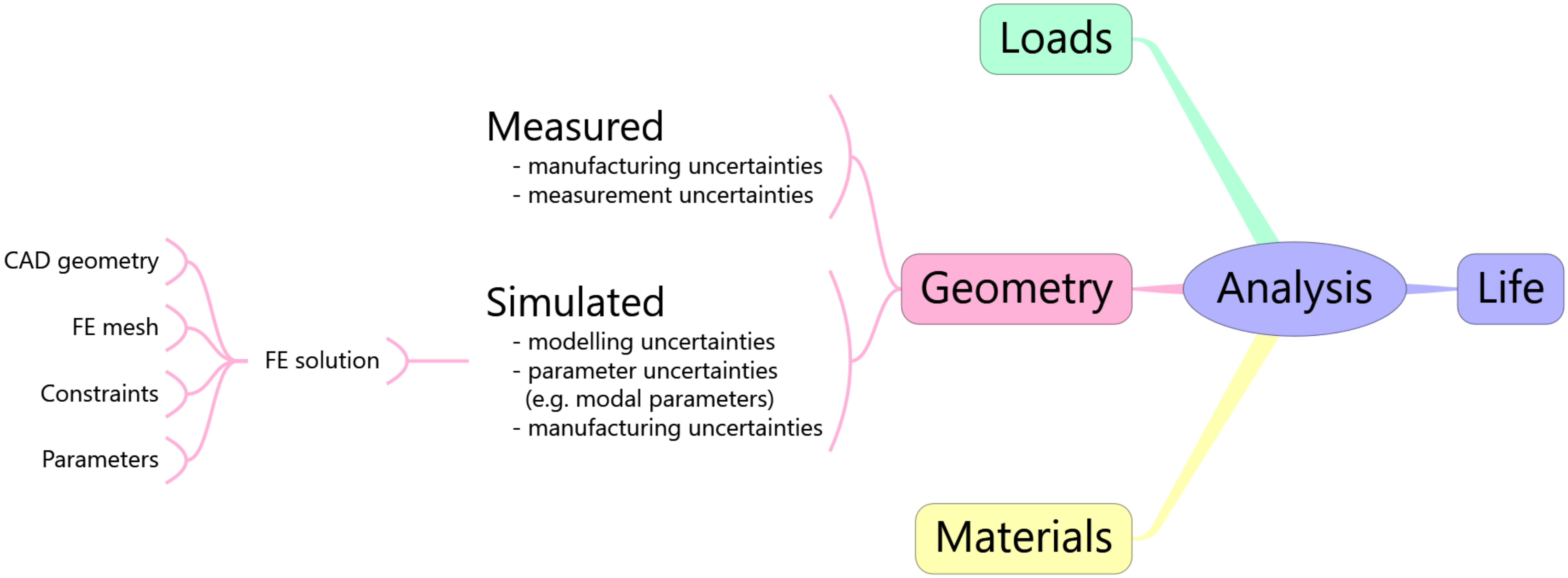
Where's the uncertainty come from?

- Epistemic uncertainty
- Aleatoric uncertainty



Where's the uncertainty come from?

- **Epistemic uncertainty**
- Aleatoric uncertainty



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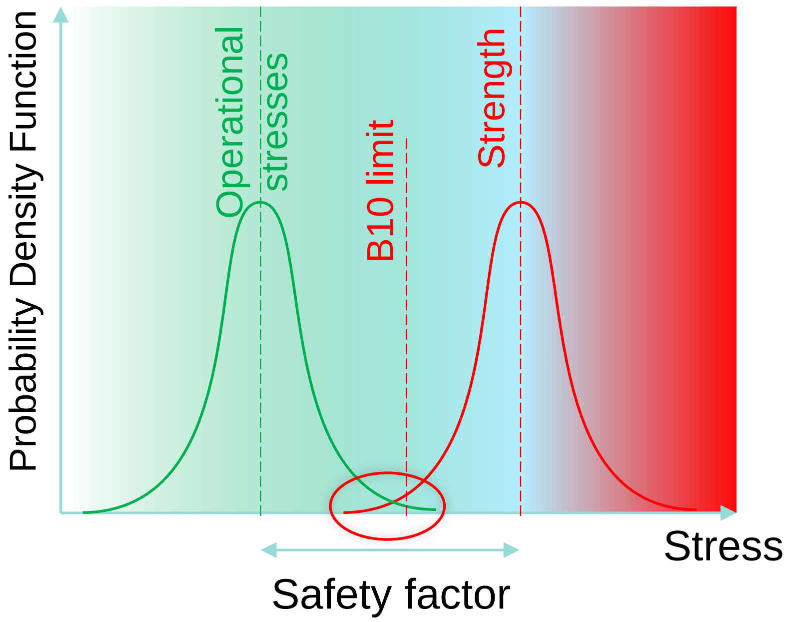
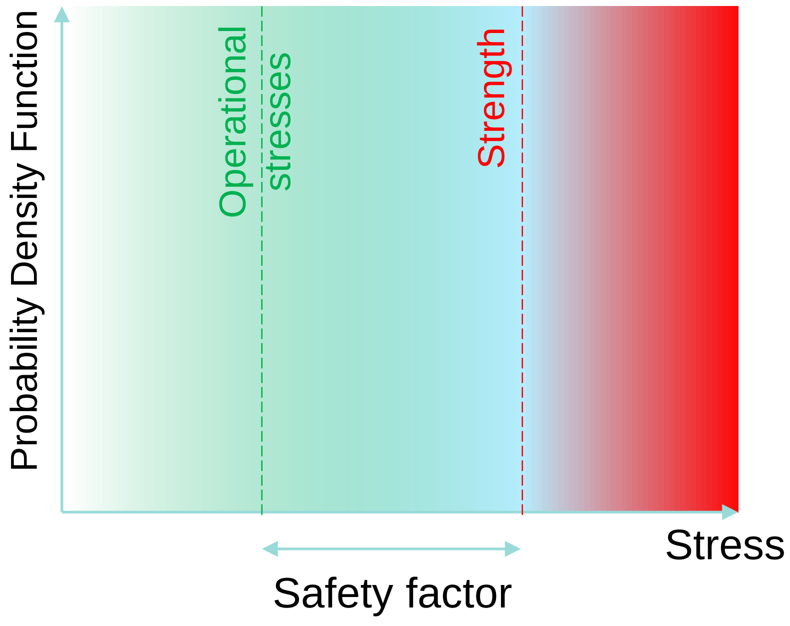


Deterministic vs. Stochastic Design Methodology

Deterministic Design



- Deterministic (one-shot) analysis
- Assume all worst-case conditions act simultaneously
- Add final safety factor for uncertainties & ‘modelling errors’
- Variability of input and output values unknown
- Risk of failure is unknown

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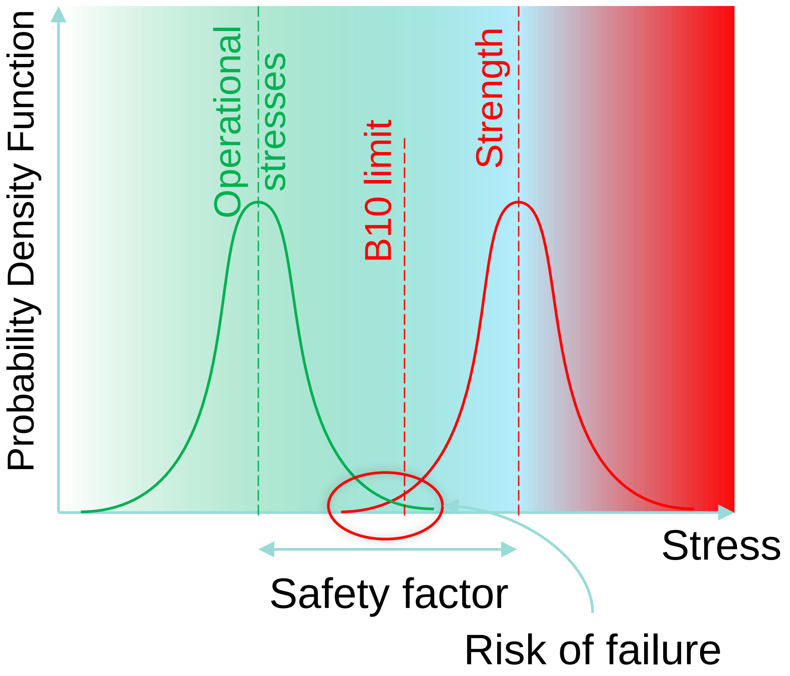
Deterministic vs. Stochastic Design Methodology

- De
- As
  sin
- Ad
  ‘m
- Va
- Risk of failure is unknown

stochastic

~~**Probabilistic Design**~~



- Stochastic analysis
- Variability of input and output values known
- Clear and quantifiable risk of failure

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Uncertainty Quantification (UQ) design process

Uncertainties
- measurement
- manufacturing
- parameter
- modelling
- etc...

Uncertainty Propagation
Propagating the uncertainties through the mathematical model

Uncertainty propagation methods

Analytical methods
- Linear static/dynamic
- Non-linear

Numerical Simulation methods
- Monte Carlo simulation
- Design of Experiments (DOE)
- Response Surface analysis
- Reduced Order Modelling (ROM)

Uncertainty Quantification
Uncertainty in the fatigue life results
1. Calculate life and variability of life
2. Identify most significant sources of uncertainty
   - '*Epistemic*' or '*Aleatoric*'?
3. Qualify the simulation with physical testing

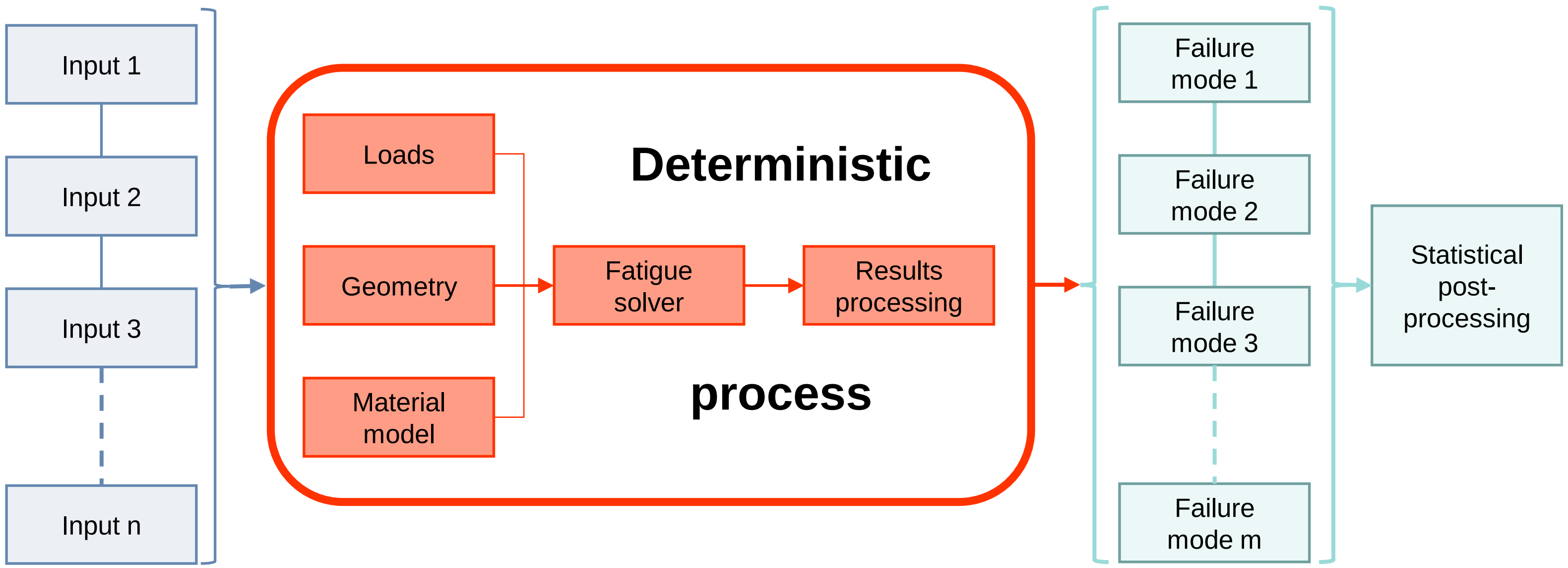
Uncertainty design methods

Design for *Reliability*
- understand the shape of the life curve
- design for an acceptable reliability target
  - quantify warrantee exposure
  - manage maintenance schedules
  - cost vs. risk vs. benefit analysis

Design for *Robustness*
- understand the edge cases
- design for worst case scenario

Design / Uncertainty optimisation

Probabilistic Design Simulation Method



Uncertainties

- mean values
- probability distributions

Monte Carlo

- wrapper around an existing deterministic fatigue analysis
- multiple runs using different input values following the specified probability distributions

Statistical Analysis

- collate results
- statistical analysis of uncertainty in fatigue results

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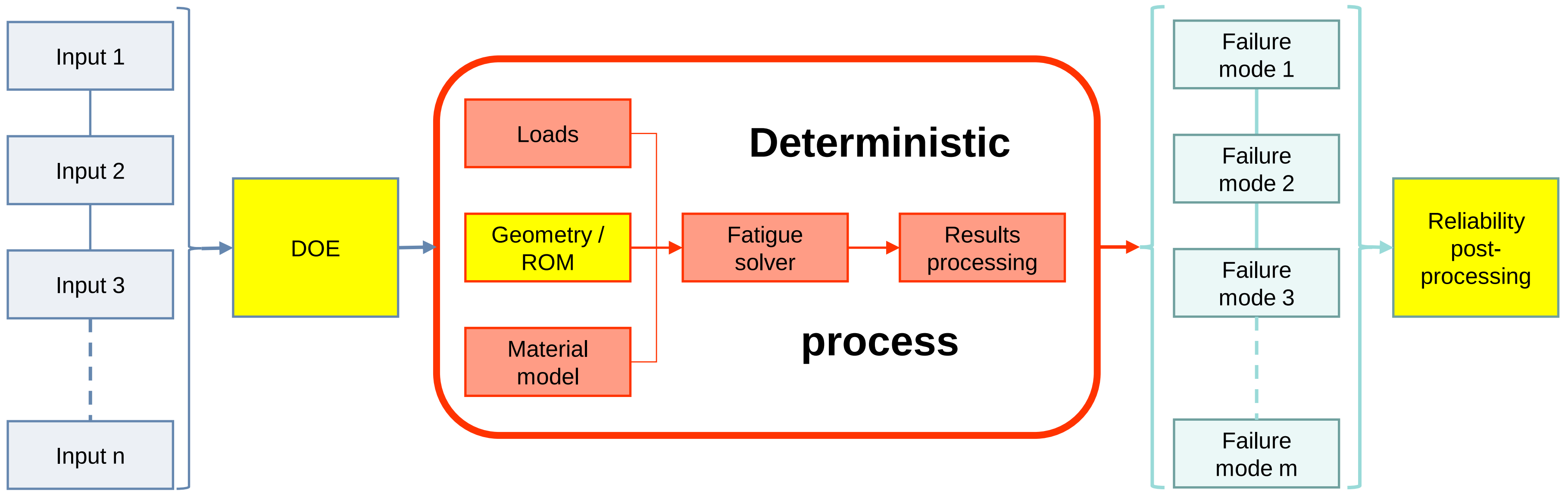
Probabilistic Design Simulation Method



DOE – *Design of Experiments*
Design space optimization to reduce number of simulated runs and improve statistical sampling

- Design for Reliability
  - Latin Hypercube Method
- Design for Robustness
  - Factorial Methods
  - Response Surface Methods

ROM (Reduced Order Model)
FE model order reduction to reduce complexity of the iterative FEA simulations

- Linear static
- Steady-state linear dynamic
- Non-linear

Statistical Reliability Analysis
A priori assumption for fatigue life distribution can reduce Design for Reliability simulation runs significantly

- log-normal
- Weibull

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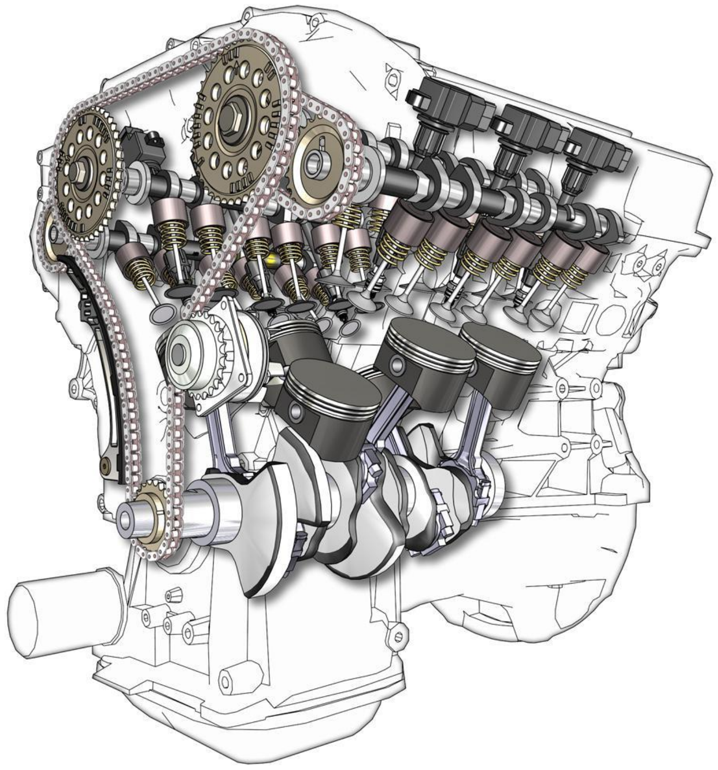
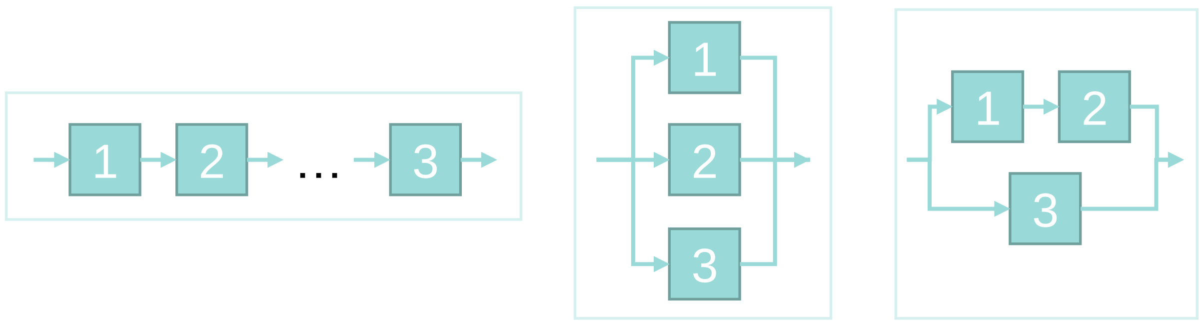
Combining life uncertainties for assemblies of systems

- 'Block Diagram' of the system
- Each block uses fatigue life curve for a particular failure mode
- Combine failure curves for systems in parallel, series or combination
- Merge physical reliability tests with simulation and maintenance records





a) Series systems b) Parallel systems c) Combined systems

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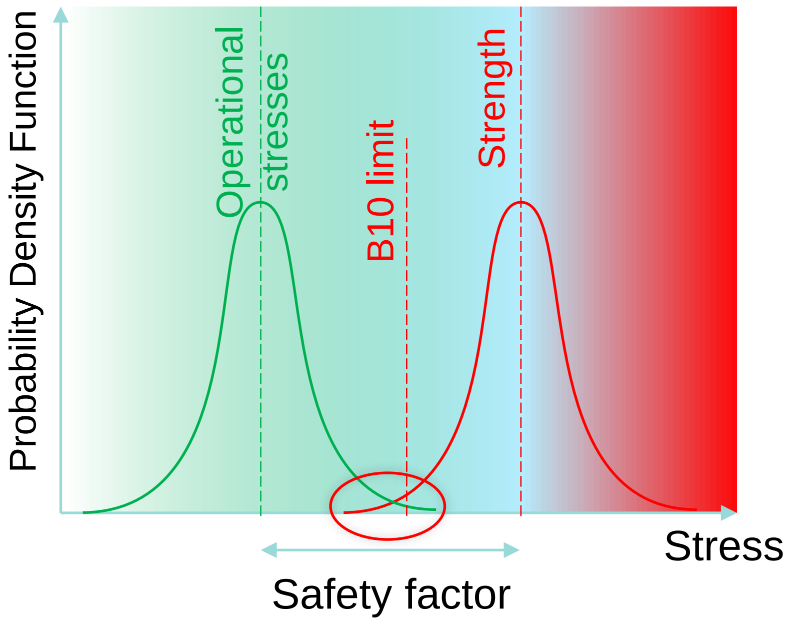
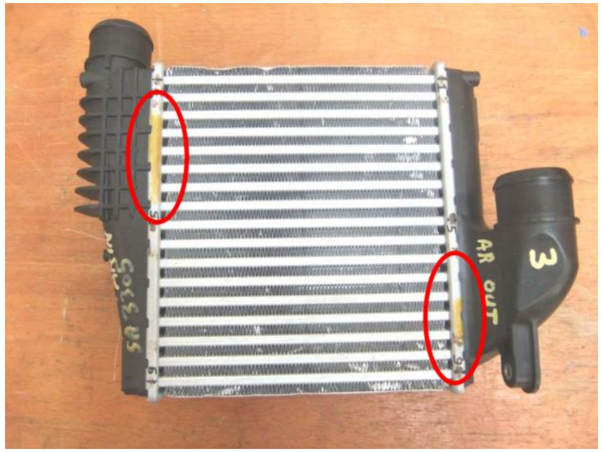
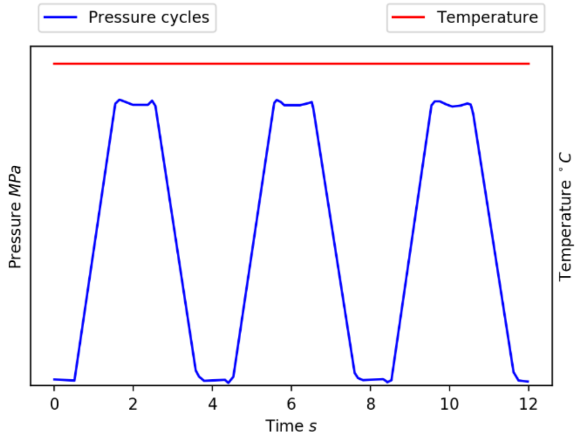
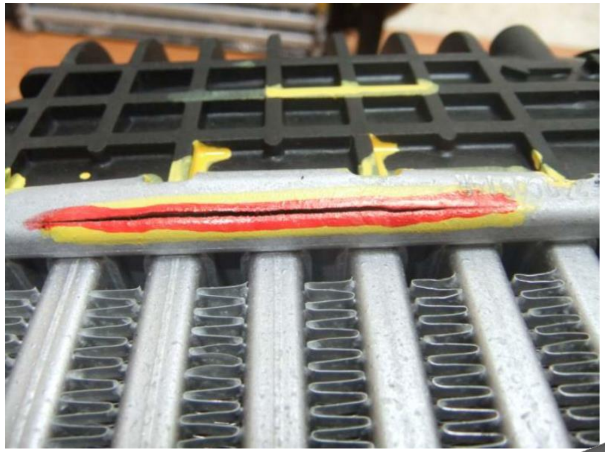


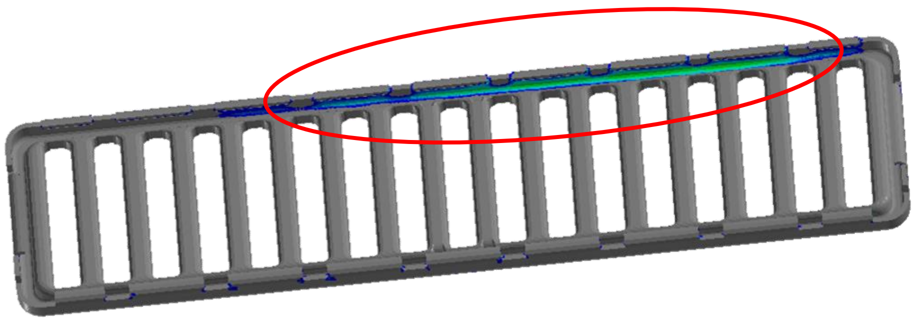
Case Study – Air-cooled Intercooler

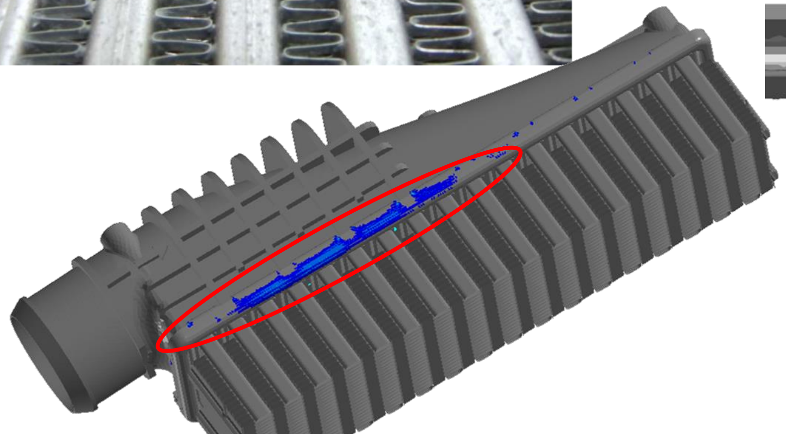


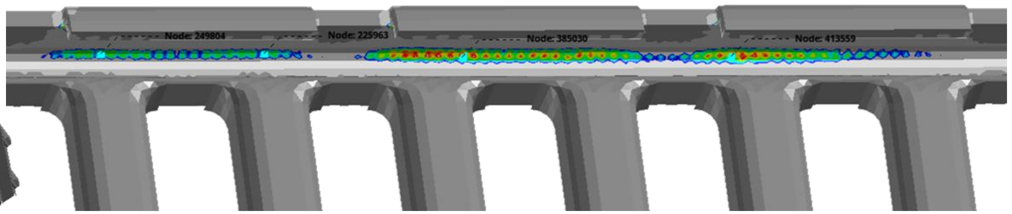


Test	Life in cycles
1 *minimum*	351, 630
2	445, 000
3	465, 000
4	615, 000
5 *maximum*	649, 800
Mean	505, 286
Ratio *(max:min)*	1.848









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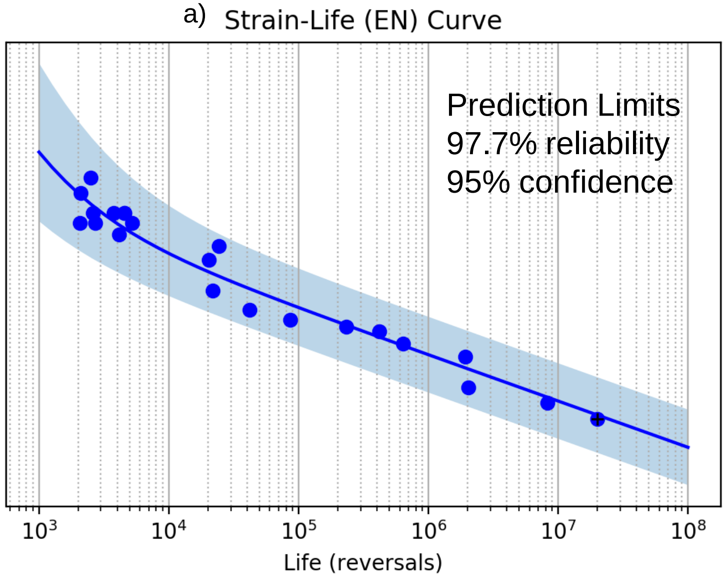
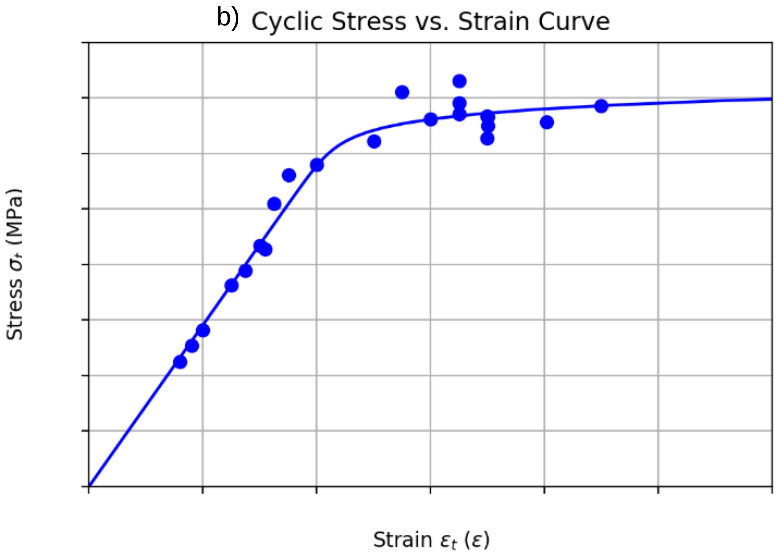
Case Study – Uncertainty Quantification





Consider two principal sources of uncertainty

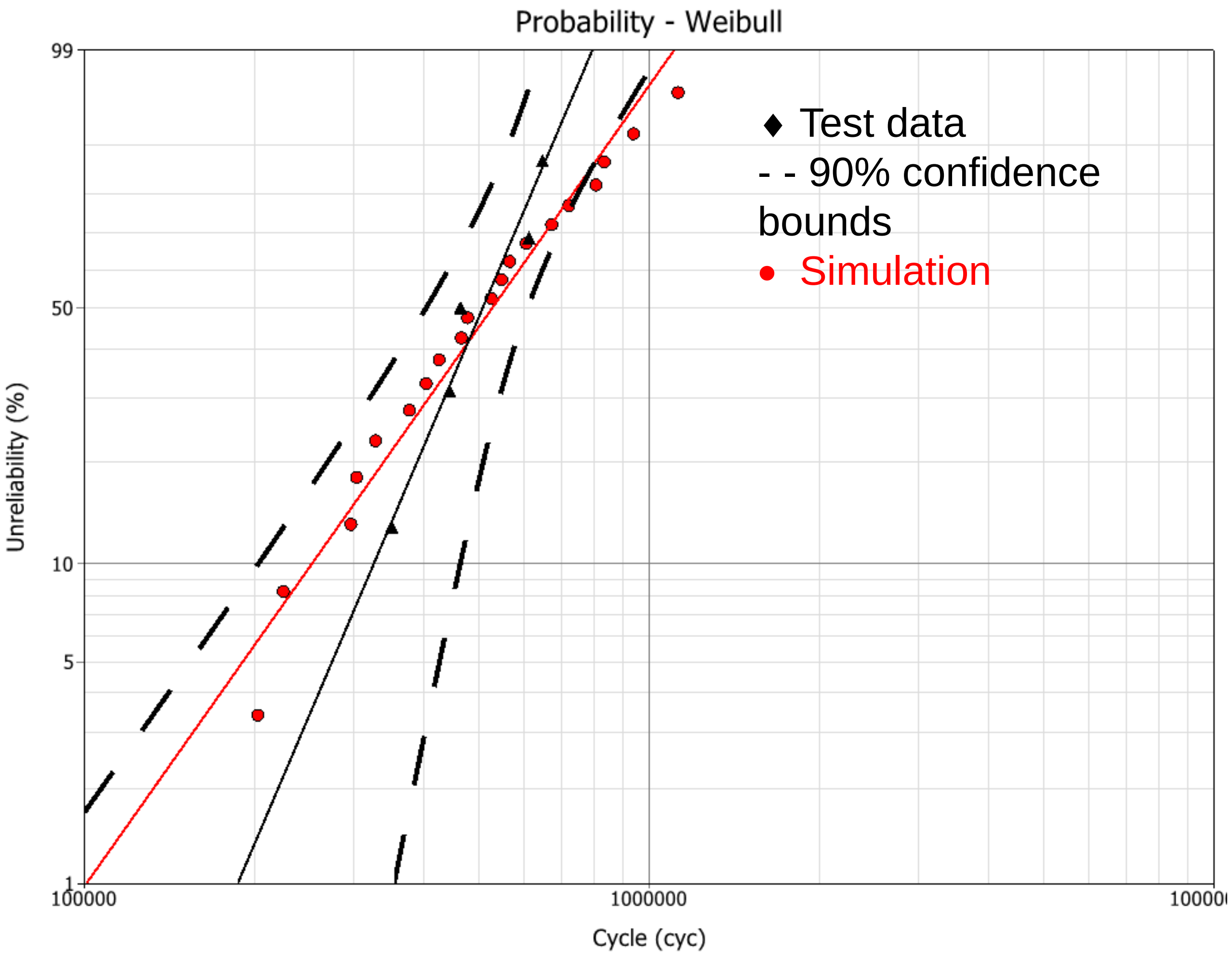
1. Material scatter
2. FEA modelling error $\pm 10\%$

Material scatter – *aleatoric* uncertainty
(irreducible uncertainty due to material scatter which is a naturally occurring physical phenomenon)

FEA modelling error – *epistemic* uncertainty
(as uncertainty that can be reduced with further work and sophistication)

Parameter	Distribution	Location	Scale
Error on FEA stress	uniform	1.0	$\pm 10\%$ of max stress
Material variability	normal	50%	16.6%

Case Study – Parameter Estimation



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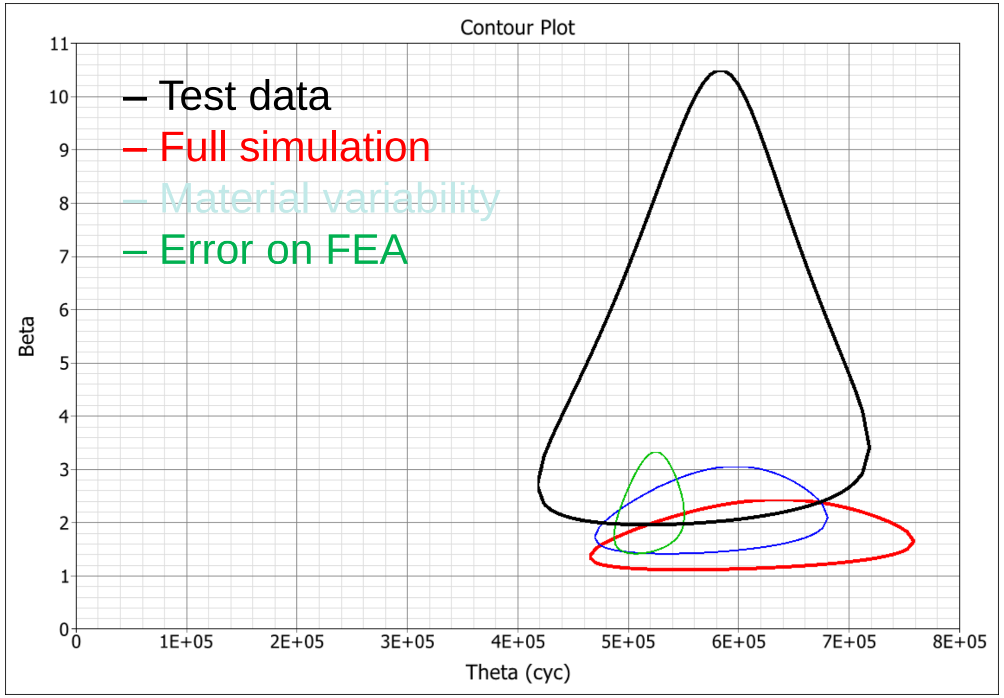
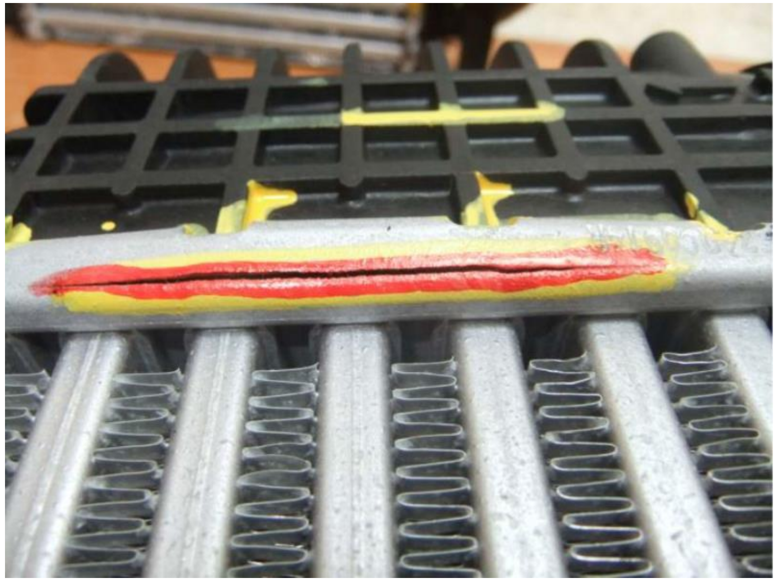
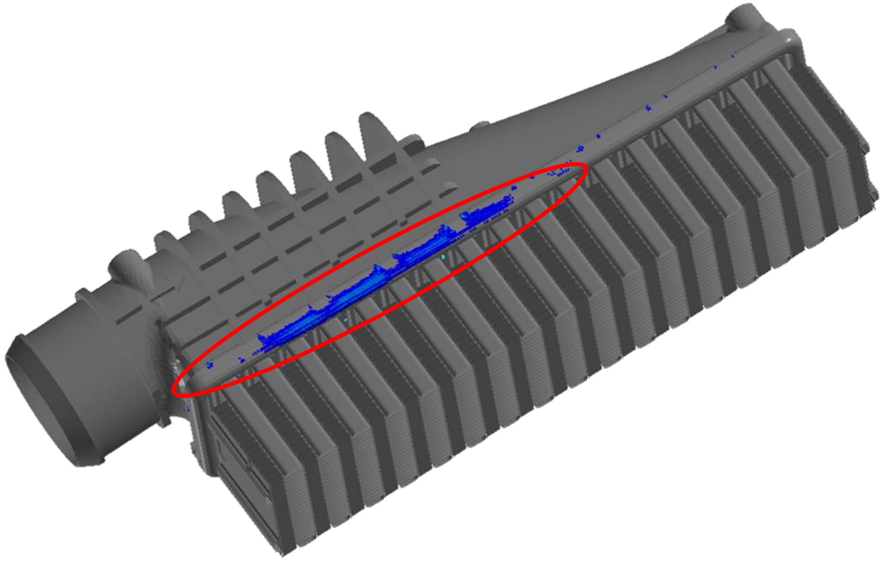


Case Study Conclusion

- Simulation is found to give excellent correlation with the experimental results
- Simulation should offer a reliable platform on which to perform additional design simulations and extrapolation of the reliability statistics
- No advantage in trying to obtain better FEA simulation. Precision limited by material behaviour





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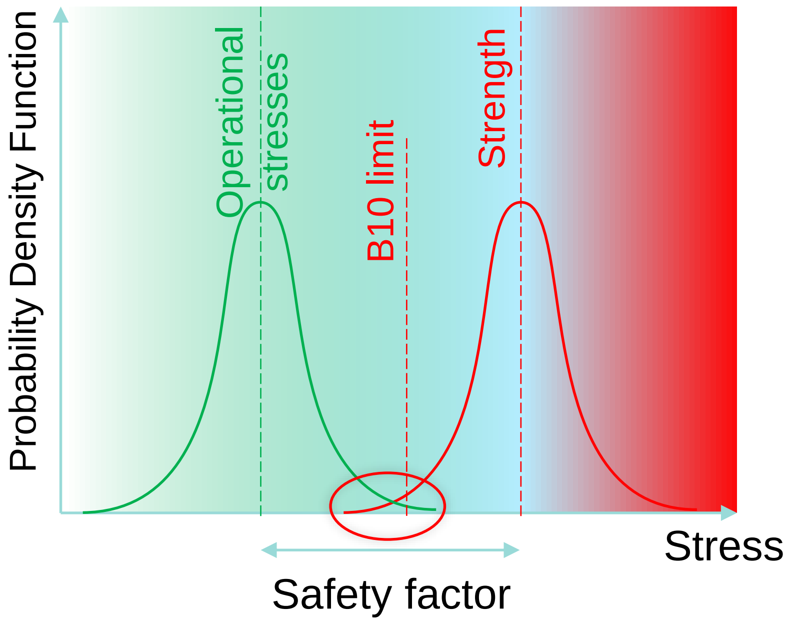

Conclusion

Demonstrated advantages of Stochastic (or Probabilistic) fatigue design over Deterministic

1. Calculate life & variability in life
2. Identify the most critical input uncertainties
   - Optimize for design uncertainty
   - Avoid large safety factors
   - Minimize risk exposure
3. Design for Reliability
   - Understanding the shape of the statistical life curve
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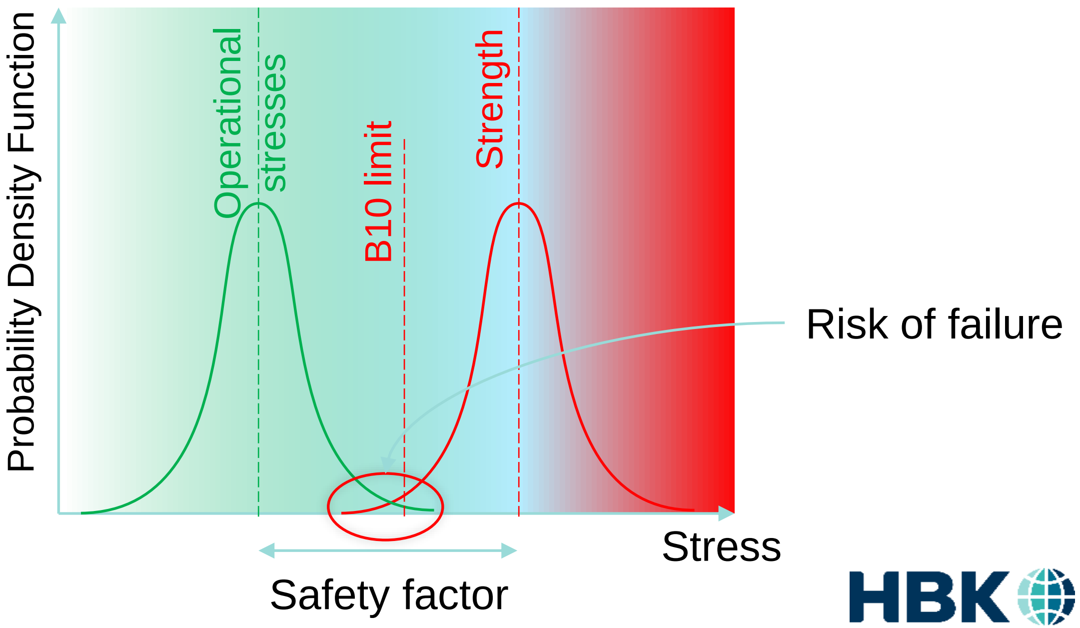

Thank You

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Q&A

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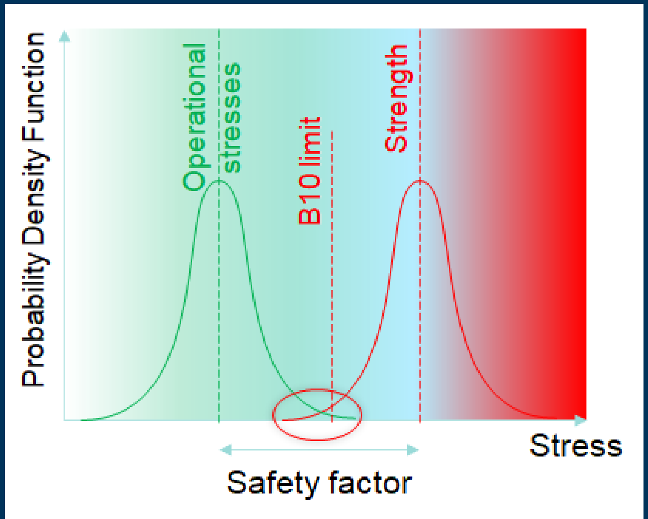

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