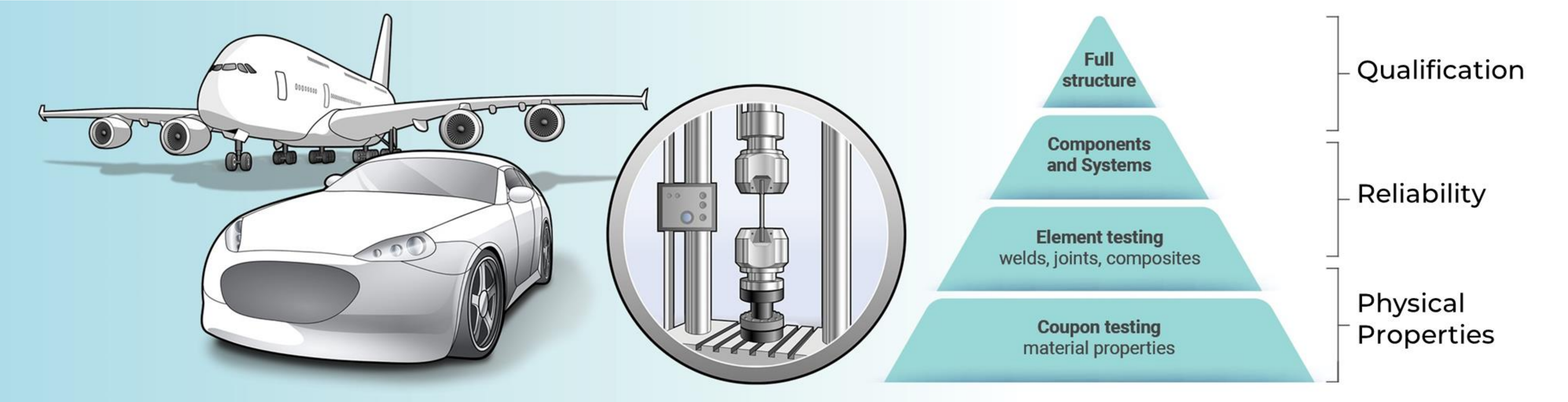
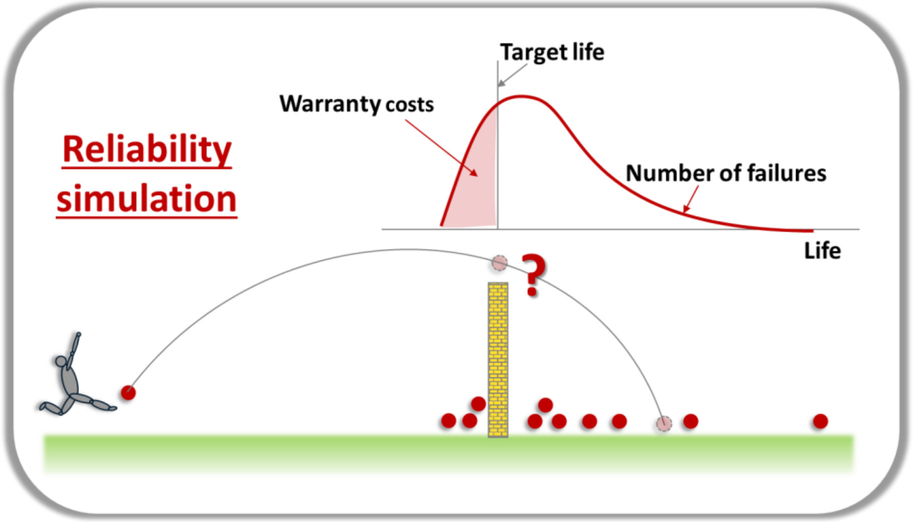



# 2023 HBK Technology Days

14 November 2023




- **Complementary simulation and qualification testing for high confidence in fatigue reliability**

Dr. Andrew Halfpenny,
Director of Technology – nCode Products, HBK

# Complementary simulation and qualification testing for high confidence in fatigue reliability

## Abstract


- In the aerospace, automotive, and power generation industries, it is becoming increasingly necessary to qualify components based on their reliability or risk of failure. Fatigue design of mechanical systems has historically followed a deterministic process. That means, for a given set of input loads and component strength parameters, it will return a consistent fatigue life estimate with no variation. In reality, the input loads and component strengths are statistically variable and uncertain. They have a mean expected value, a statistical variability, and uncertainty associated with them.
- This presentation considers how digital simulation, physical component testing, uncertainty analysis, and statistical reliability analysis, are used to support the fatigue design requirement, and thereby reduce a company's exposure to unacceptable safety and warranty risks. It concludes with two cost-effective and fairly easy to implement enhancements to offer significant improvements in predicted confidence of an existing design, simulation, verification, and validation process:
  1. Additional test instrumentation applied in the qualification test to verify the simulation results.
  2. Qualification tests that must be continued to failure to verify the fatigue simulation.


## About the presenter, Dr. Andrew Halfpenny, Director of Technology – nCode Products, HBK

- Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Master's 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.

# Complementary simulation and qualification testing for high confidence in fatigue reliability

## SV&V (Simulation, Verification & Validation)

Dr Andrew Halfpenny

Director of Technology – nCode Products

# Motivation – The OEM's Pain

| | |
|---|---|
| Engineering Software: | "A Solution Delivery Platform to Target Customer Pain" |
| Purpose: | to 'democratize' advanced technologies |
| That is: | to provide the latest analytical and design tools,<br>to engineers who are experts in engineering,<br>and not necessarily experts in mathematical methods. |

e.g. Automotive OEM:

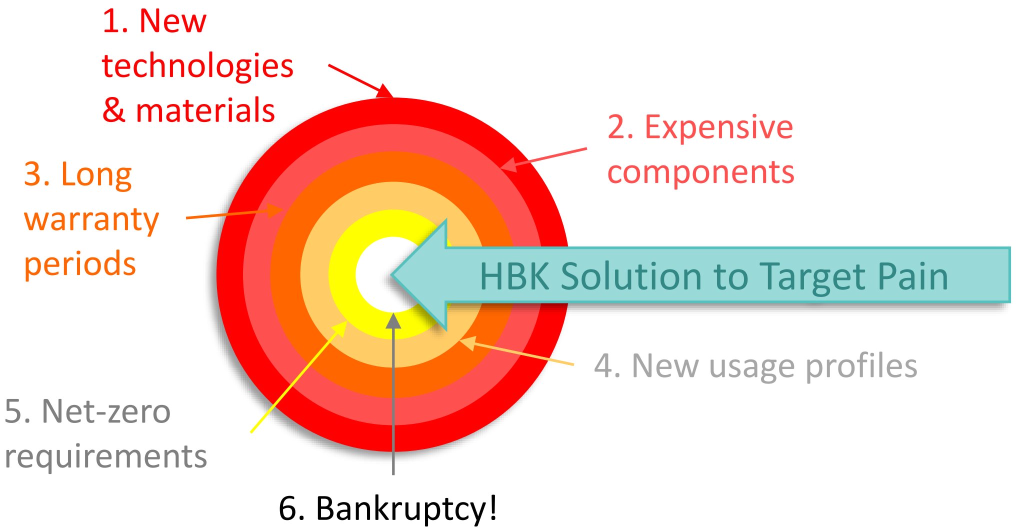
*"In the past,*
*if we had reliability issues,*
*we'd swap components early under warranty.*

*But EV batteries contain thousands of unserviceable components.*

*There's a mandatory 10 year / 150,000 mile warranty.*
***A reliability issue here could sink the company!**"*

And

*"In the past, **we** would select a warranty period based on **market forces** and **over 50 years** of historical maintenance data.*
*Today, warranties are dictated by **politicians** for **brand new concepts** with **no historical data** whatsoever!"*







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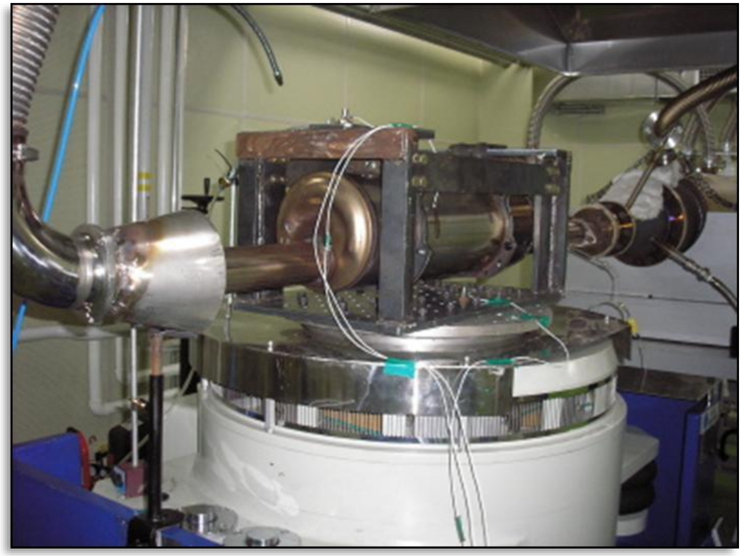
# Motivation – The Engineer's Pain

## The past

- Pass this test and you're good to go 😃
- Test based on 50+ years of market experience!
- Confidence is high 😁



## The present

- What's the correct test to use? 😟
- I have limited market experience.
- My new requirement is expressed as:

"For a **duty cycle** of 10 years / 150,000 miles,

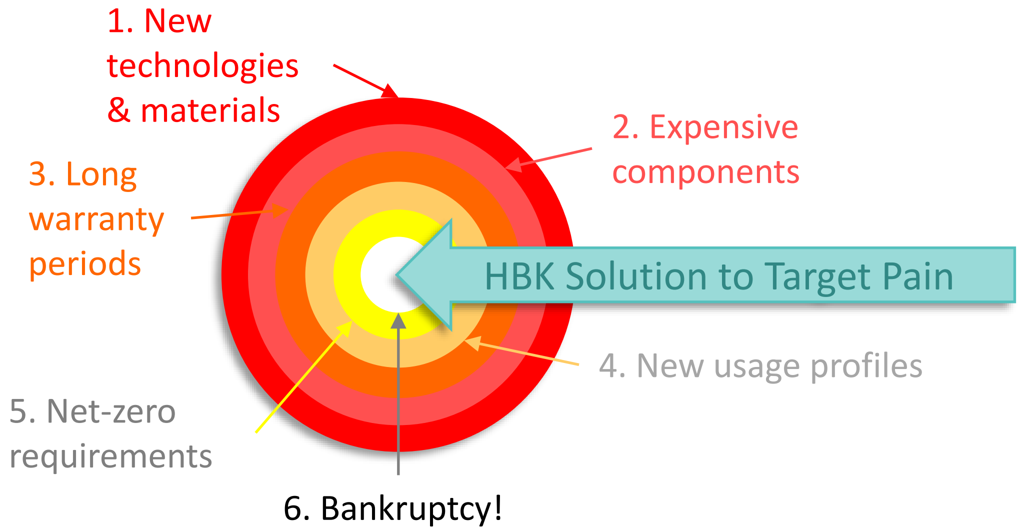
I require **reliability** exceeding 95%
(i.e. fewer than 5% failures),

with a **confidence level** of at least 90%"

- But, how do I estimate my confidence level?

# Contents









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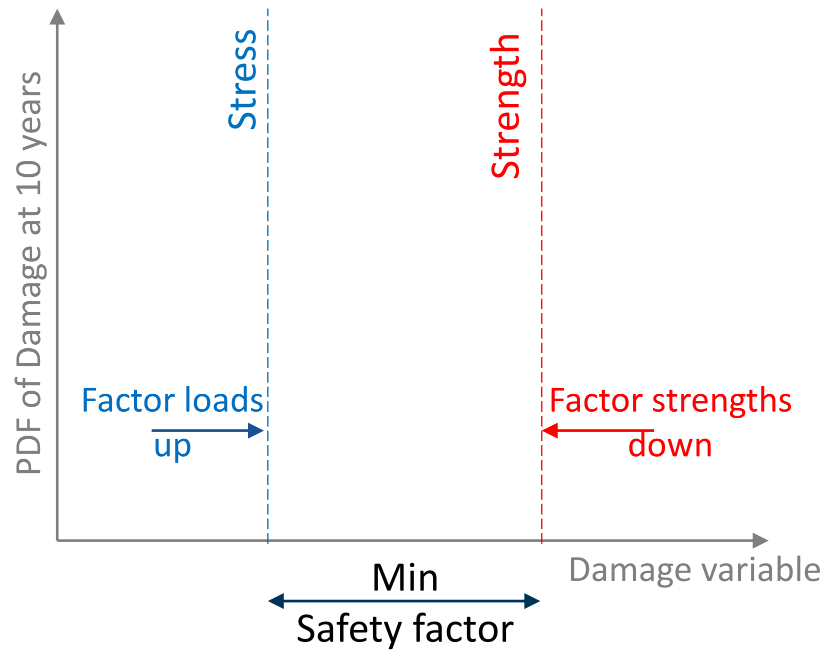
# Changing role of simulation

## Traditional “Deterministic design”

1. Build a CAE simulation model
2. Apply safety factors
   >1 to input loads
   <1 to strengths
   + additional factor for “modelling errors”
3. Design to ‘worst case’
4. Qualification test – sign-off




Modelling Variability & Uncertainty

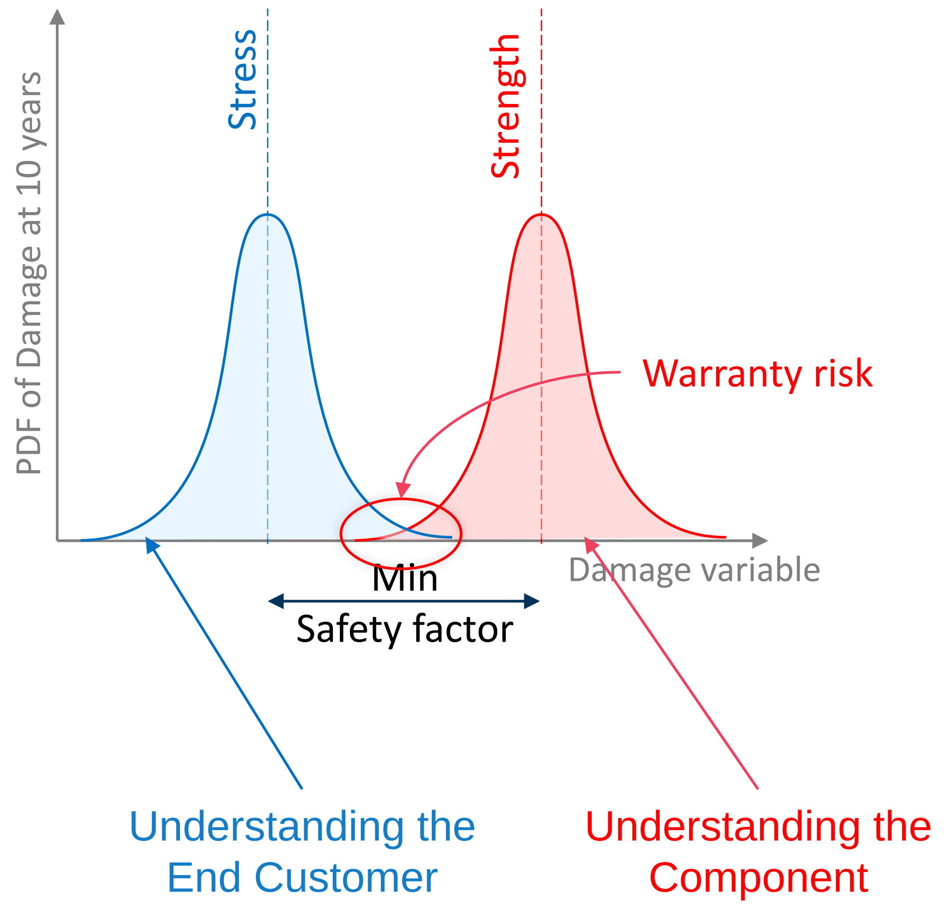
# Changing role of simulation

## Traditional “Deterministic design”

1. Build a CAE simulation model
2. Apply safety factors
   >1 to input loads
   <1 to strengths
   + additional factor for “modelling errors”
3. Design to ‘worst case’
4. Qualification test – sign-off

## New “Stochastic design”

1. Build a CAE simulation model
2. Propagate variabilities & uncertainties through the model
   – load and strength parameters expressed statistically
3. Design to optimise warranty risk
4. **Verify simulation model** against qualification test
5. **Validate design requirements** thro’ combination of test & simulation




Modelling Variability & Uncertainty

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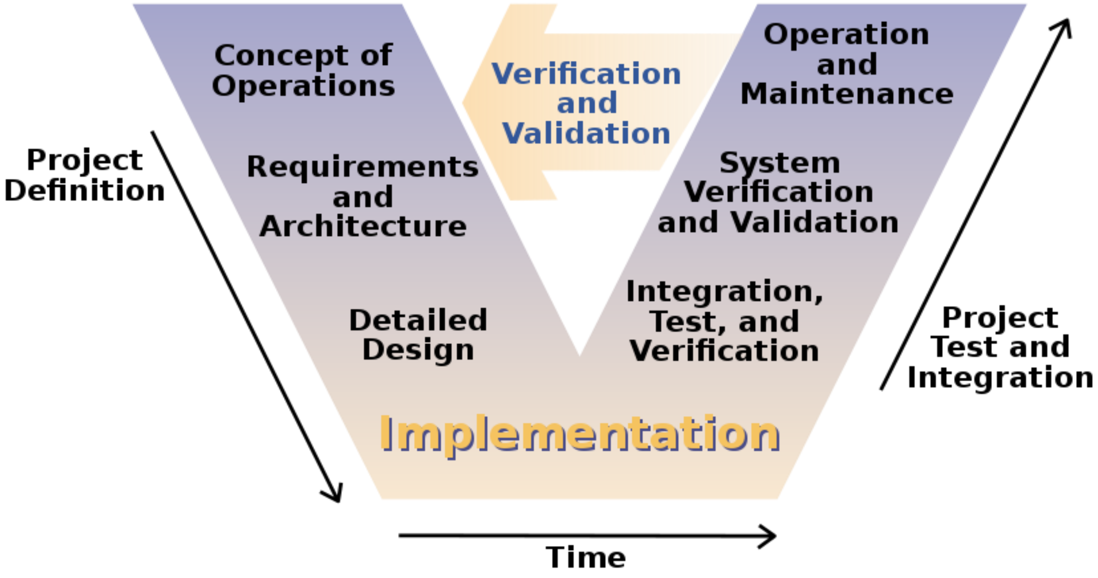
# Changing role of physical testing

## Challenge:

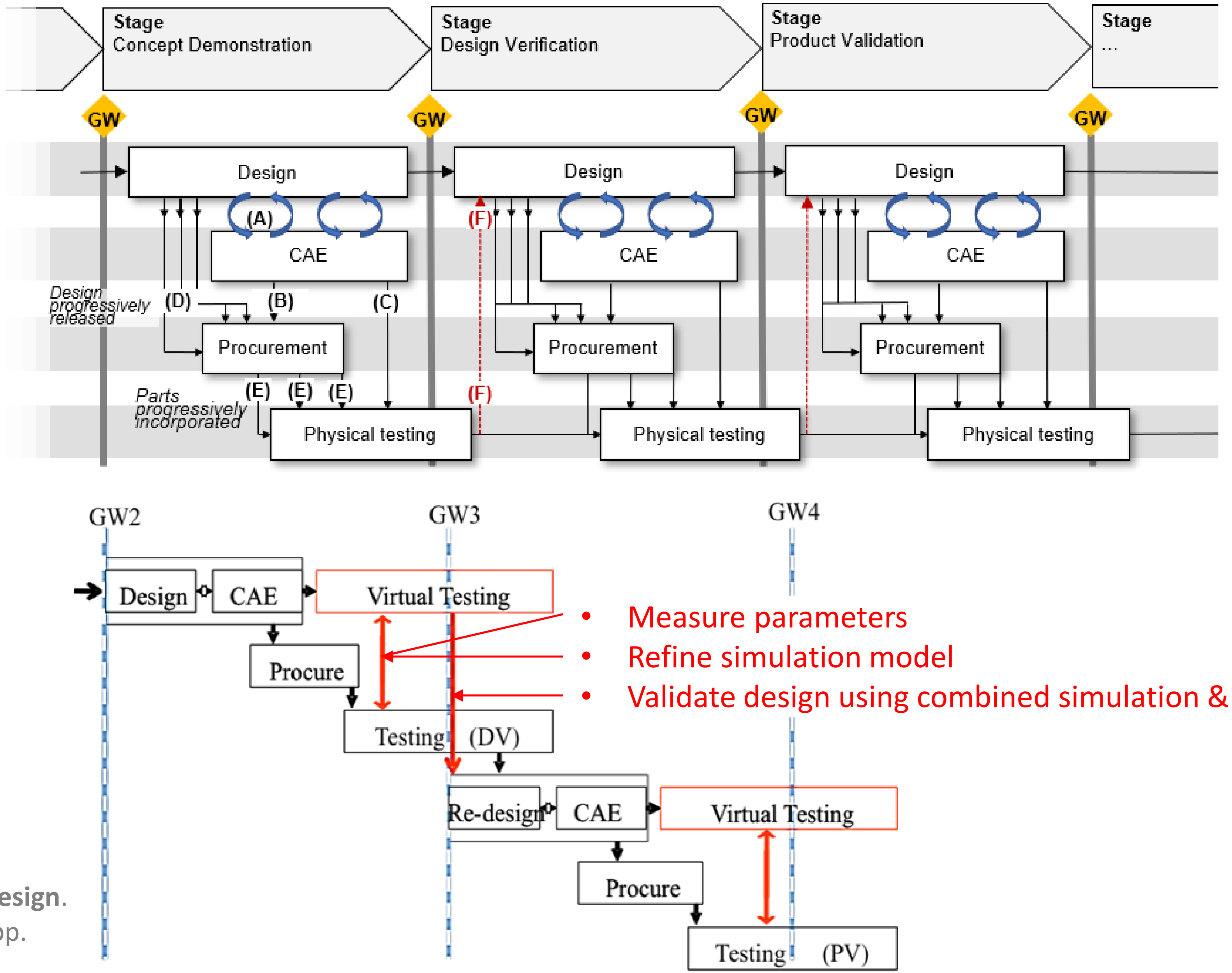
- ‘V’ Model – “Systems development model”
- Factor of 10 rule – cost of change increases with factor of 10 with each design stage
- ∴ need to move Verification & Validation left

## Solution:

- Closer integration of virtual & physical testing → quantifiable confidence in design
- Validate at component level much earlier → reduce cost and risk
- Improved overlapping of testing and design



# Improved overlapping of testing and design




1. Simulate the test – Virtual Testing
2. Use additional measurement instrumentation:
   a) to obtain improved analysis parameters
   b) to verify stress/strain simulation results
3. Run qualification tests to failure to verify fatigue simulation

- Measure parameters
- Refine simulation model
- Validate design using combined simulation & test

Tahera, Khadija; Earl, Chris and Eckert, Claudia (2017). **A Method for Improving Overlapping of Testing and Design**. IEEE Transactions on Engineering Management, 64(2) pp. 179–192.

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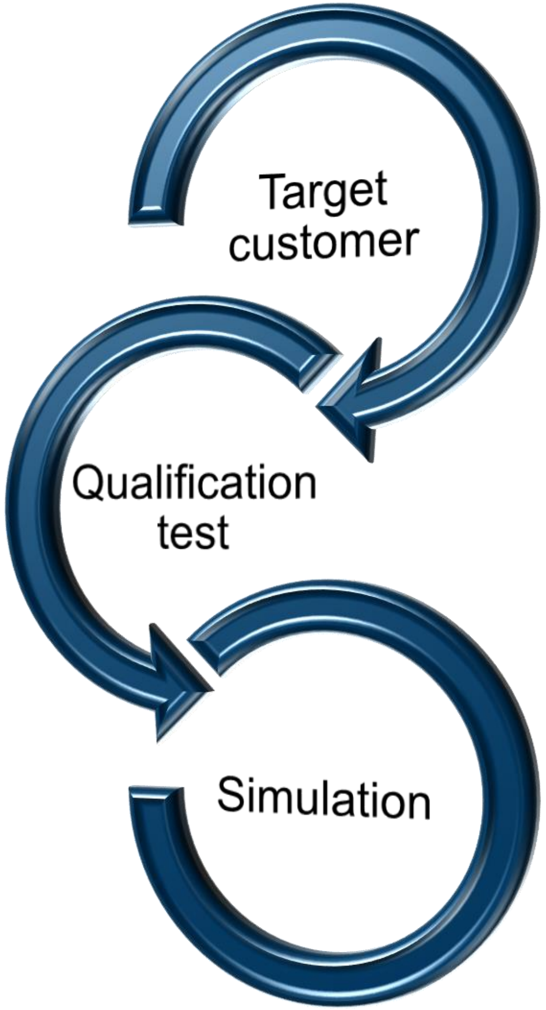
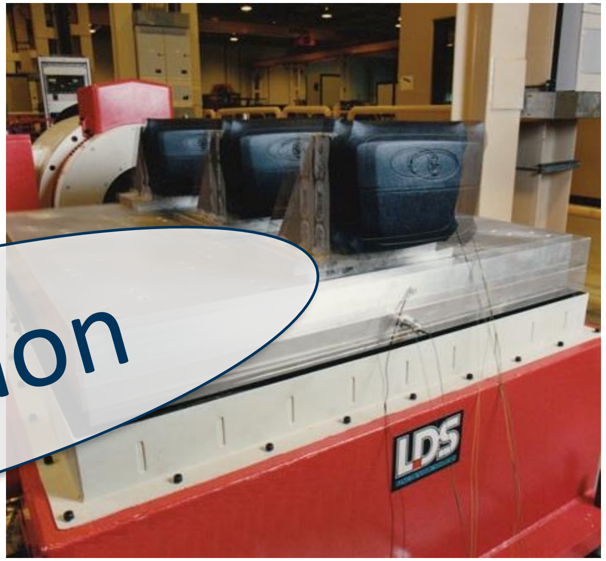
# Simulation, Verification & Validation (SV&V)





1. Statistical target customer analysis

2. Make it scientifically reproducible



3. Accelerated qualification testing


4. Simulate the qualification test

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# Contents



# Virtual Physical Test

- ✓ **Simulation before the test –**

- ✓ **Simulation during the test –**

- ✓ **Simulation after the test –**

# Virtual Physical Test

- ✓ **Simulation before the test –**
  - ✓ <u>Is it likely to pass the test?</u>
    - ✓ What's the expected safety margin?
    - ✓ Can I optimise the design further?
    - ✓ Am I sufficiently confident to commit to expensive prototyping right now?
  - ✓ <u>Where will it fail?</u>
    - ✓ Where should I look?
    - ✓ Is failure subtle or obvious?
    - ✓ Do these failure modes correlate with previous experience?
  - ✓ <u>Is it ok to simplify the test?</u>
    - ✓ Do I still get the correct failure modes?
    - ✓ How does it affect life?
    - ✓ Do I need supplemental tests or run tests longer?




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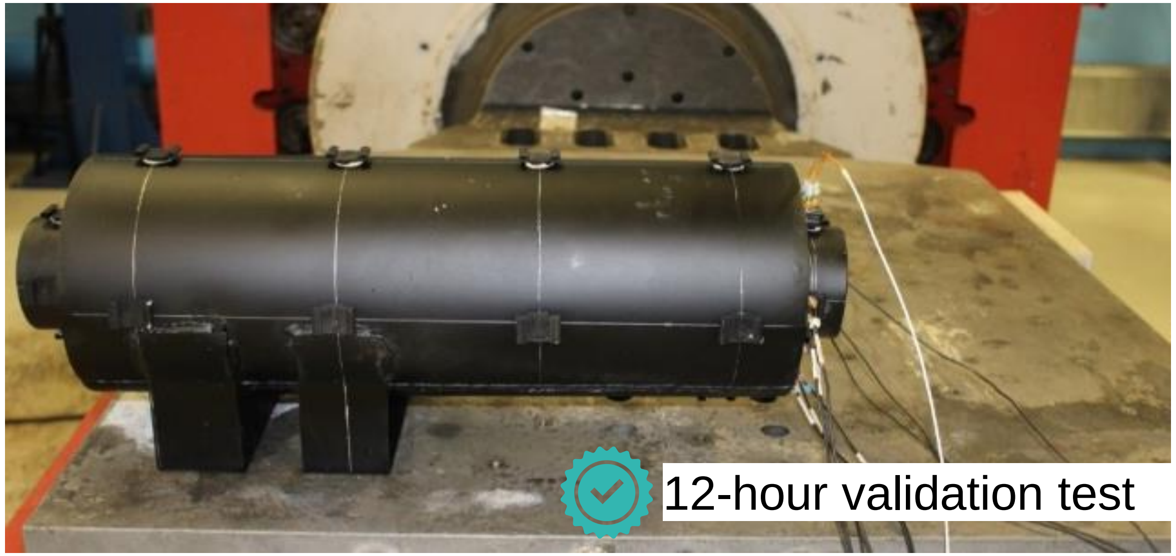
# Virtual 🤝 Physical Test

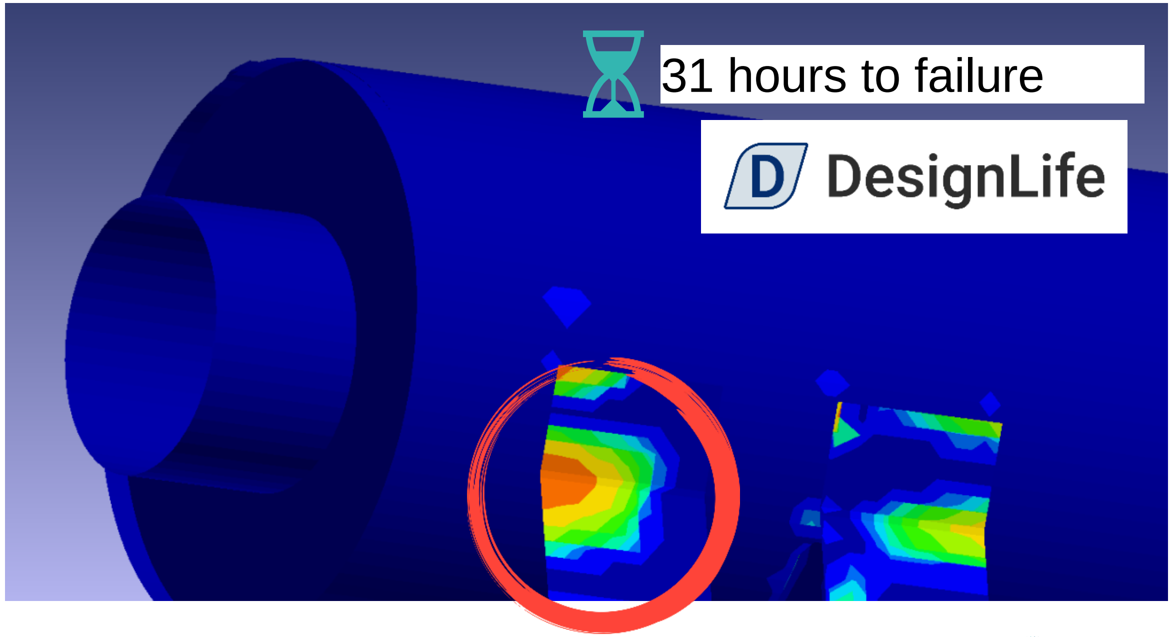
✓ **Simulation during the test –**

- ✓ Where is the best place to mount sensors?
  - ✓ Measurement optimization analysis (strain gauges, accelerometers, displacement transducers, thermocouples, etc.)
- ✓ How do test measurements compare with simulation?
  - ✓ Virtual strain gauges, accelerometers, displacement transducers, etc.
- ✓ Can I improve my model?
  - ✓ Modal analysis to calculate actual damping
  - ✓ Load reconstruction based on measured response

# Virtual 🤝 Physical Test

- ✓ **Simulation after the test –**
  - ✓ What should I do if it fails the test?
    - ✓ Simulate the failure mode
    - ✓ Check the fixtures/boundary constraints/damping
    - ✓ Play what-if games to fix it
  - ✓ How confident am I?
    - ✓ What’s my warranty exposure?
    - ✓ Should I test to failure?
    - ✓ How many tests should I do?



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# Virtual Physical Test

- ✓ **Simulation after**
  - ✓ What shoul
    - ✓ Simulat
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    - ✓ Play wh
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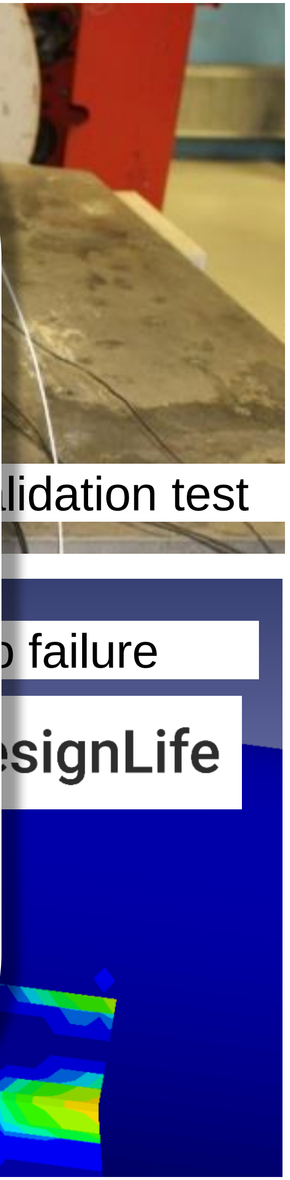
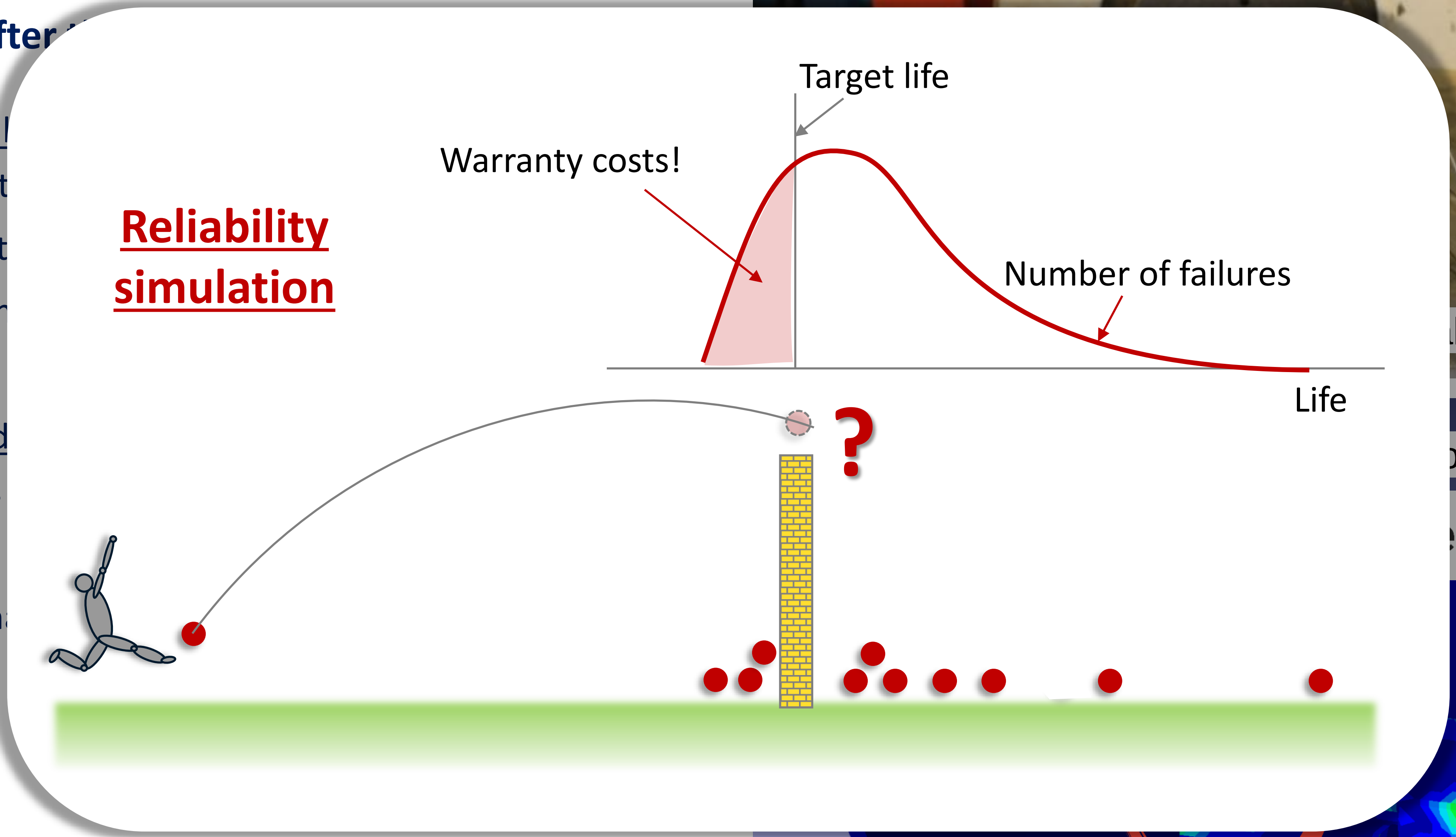
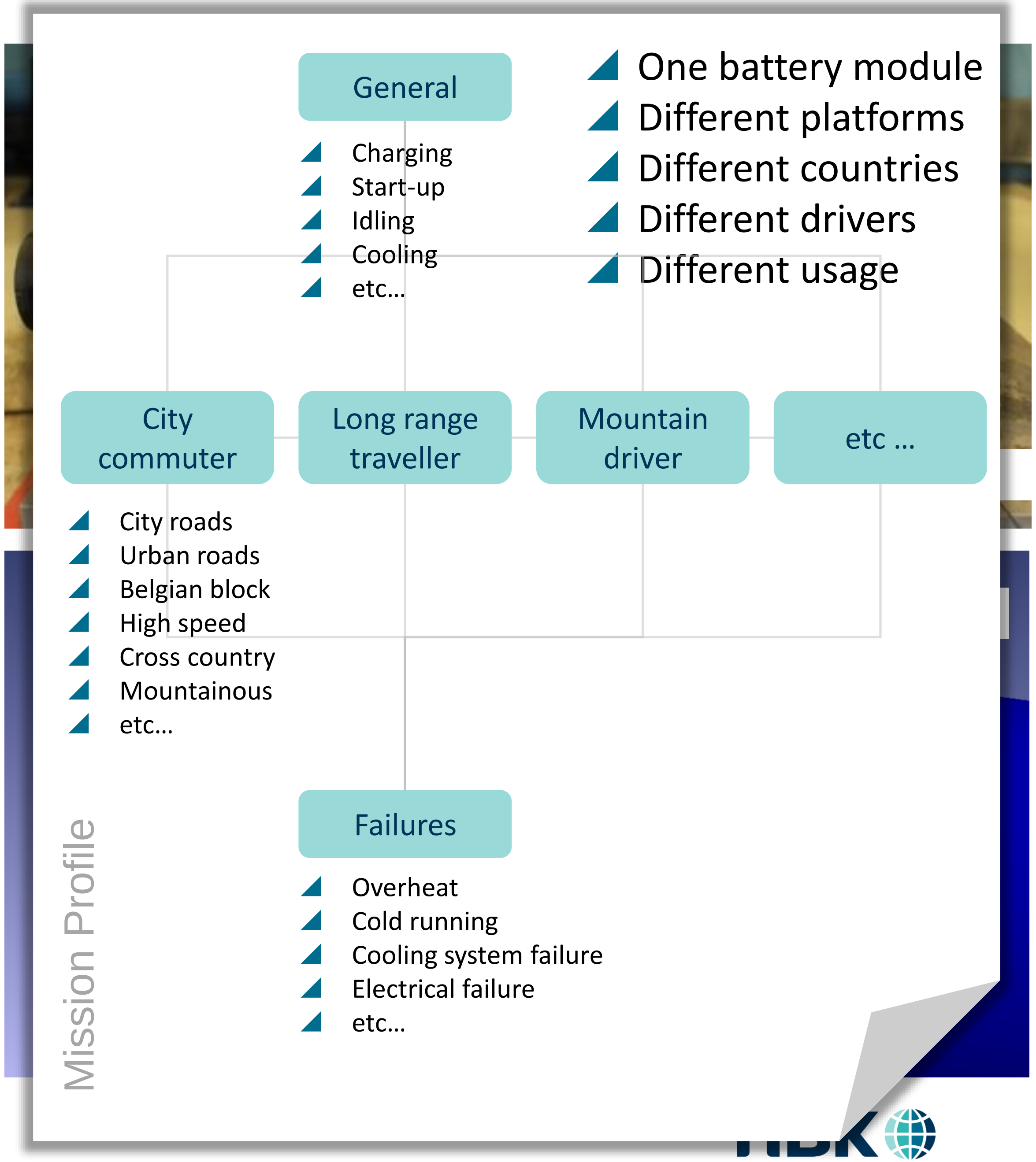


# Virtual Physical Test

✓ **Simulation after the test –**

- ✓ <u>What should I do if it fails the test?</u>
  - ✓ Simulate the failure mode
  - ✓ Check the fixtures/boundary constraints/damping
  - ✓ Play what-if games to fix it
- ✓ <u>How confident am I?</u>
  - ✓ What's my warranty exposure?
  - ✓ Should I test to failure?
  - ✓ How many tests should I do?
- ✓ <u>How is my reliability affected by different platforms, usage mix, country, etc.</u>
  - ✓ Do I expect more warranty issues from India than Europe?



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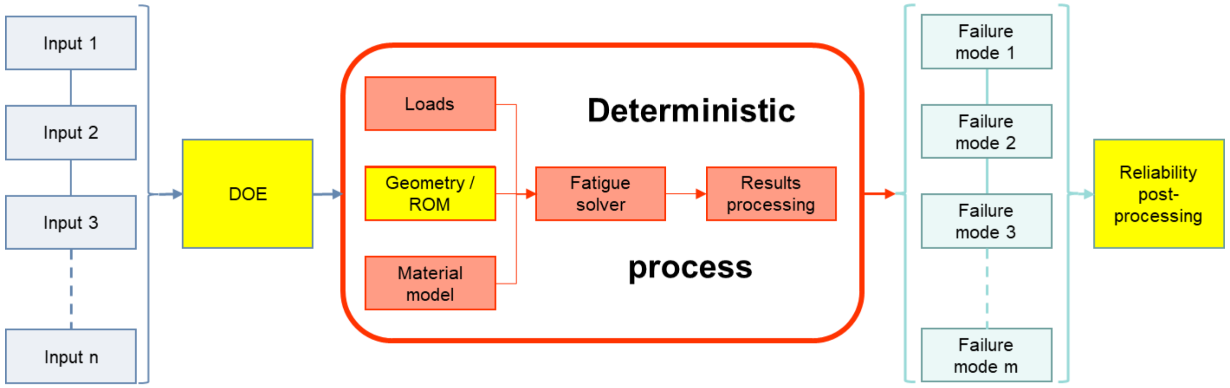





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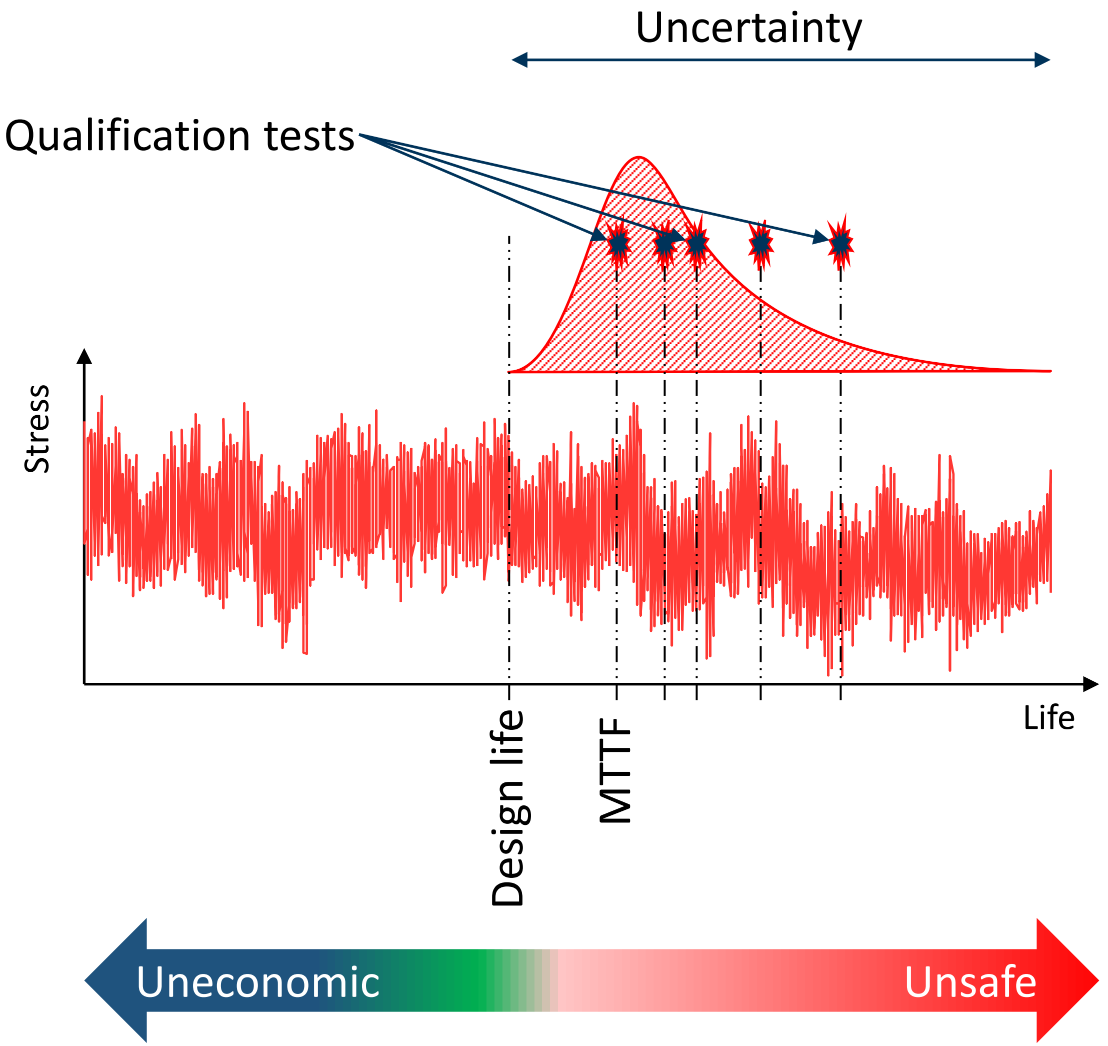
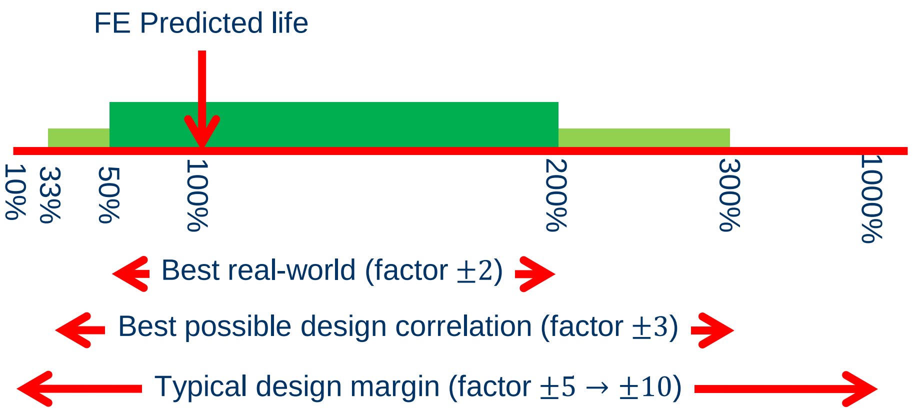
# Simulation Verification – The Uncertainty Challenge







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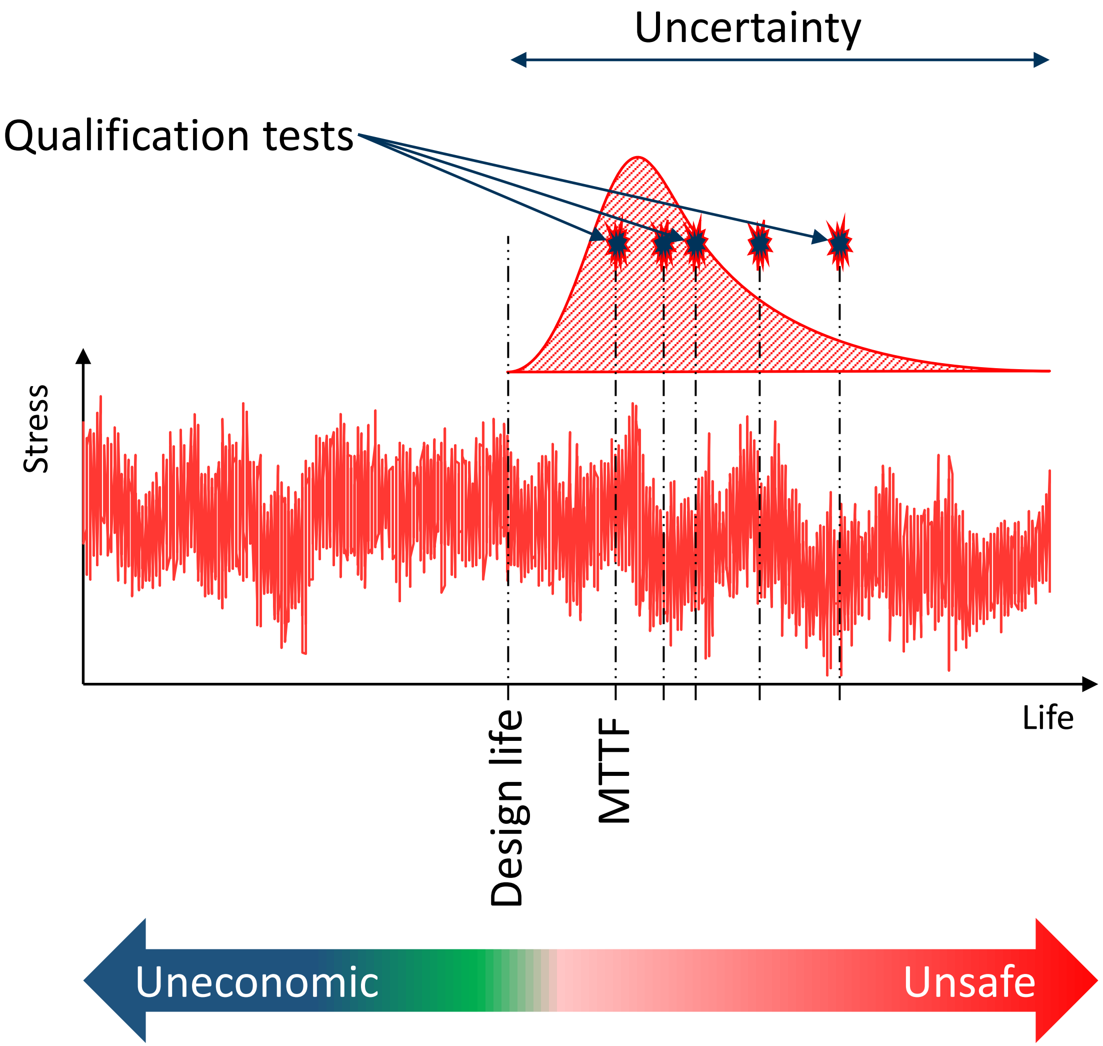
# Simulation Verification – The Uncertainty Challenge





## Uncertainty classification

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

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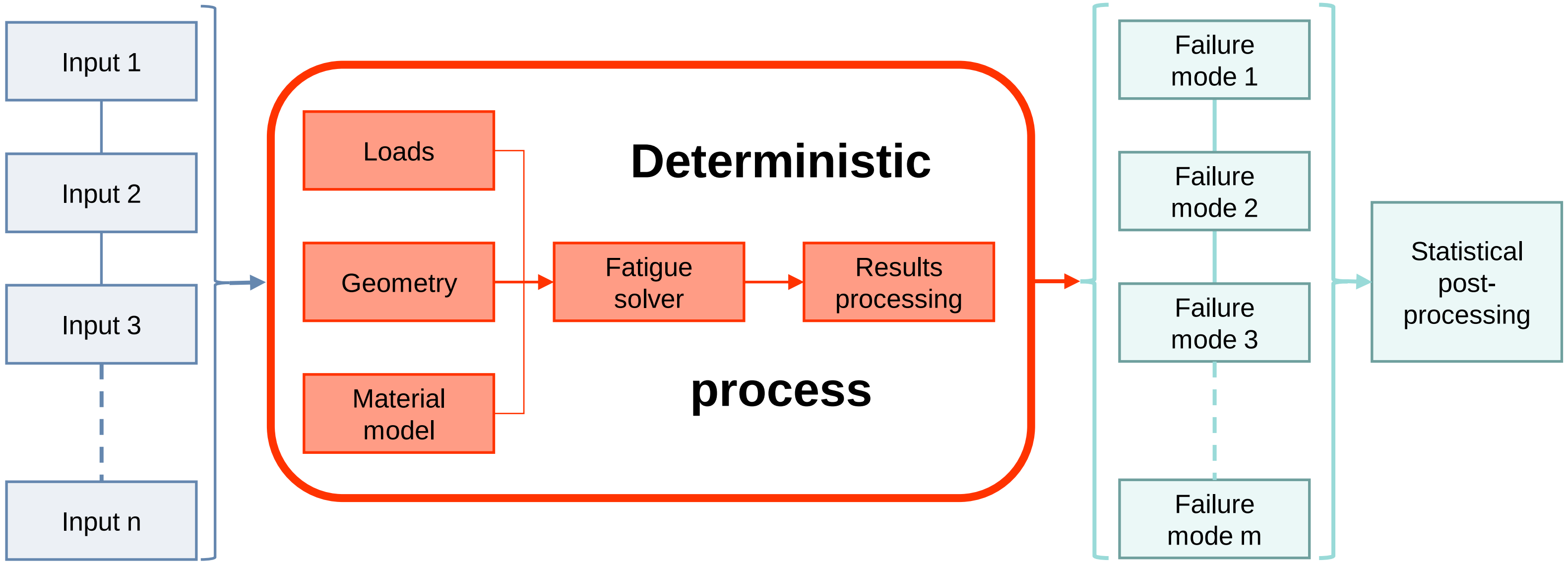
# Probabilistic Design Simulation Method




### Input parameter uncertainties

- Loading and material strength parameters.
- Mean values and probability distributions.

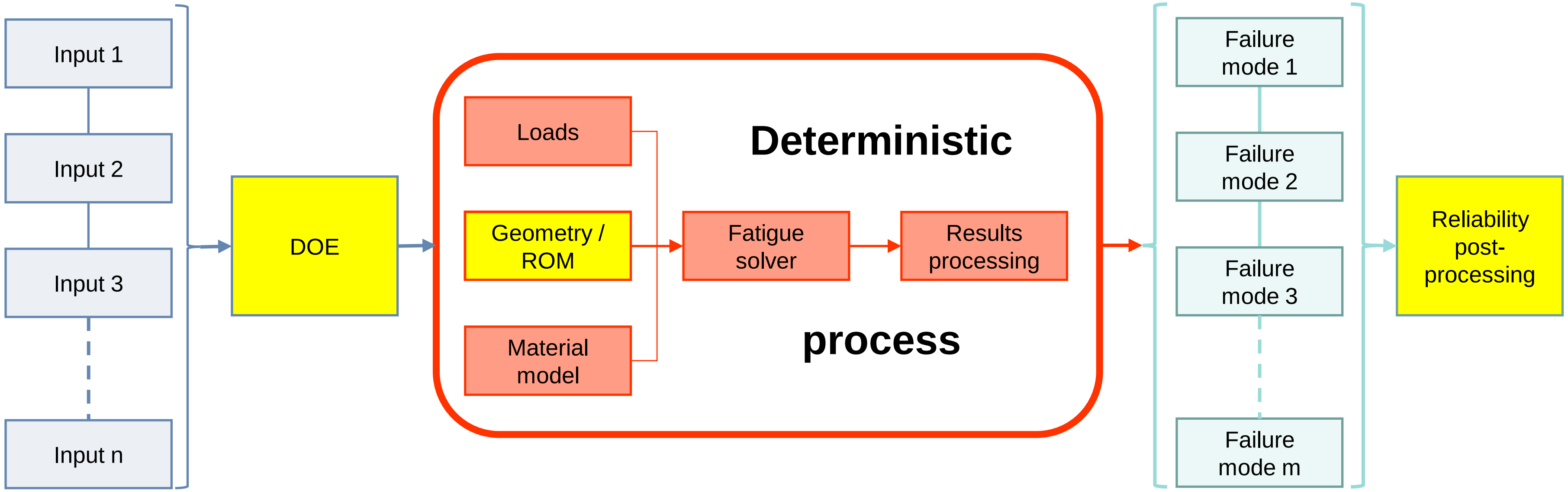
### Monte Carlo simulation

- Wrapper around an existing deterministic fatigue analysis process.
- Multiple runs substituting different input values for each run based on their statistical distributions.

### Statistical Analysis

- Collate life based on failure mode.

# Probabilistic Design Simulation Method




## DOE – Design of Experiments

Design space optimization to reduce number of simulated runs and improve statistical sampling.

- Design for Reliability (50%-99%).
    - Latin Hypercube Method.
- Design for Robustness (>99% extremities)
    - Factorial Methods.
    - Response Surface Methods.

## ROM (Reduced Order Model)

or 'Surrogate' model

FE model replaced with a simplified model to reduce iteration time.

- Linear static superposition.
- Steady-state linear dynamic modal superposition.
- PSD vibration analysis.
- Linearisation, non-linear regression modelling, or full FE simulation.

## Statistical Reliability Analysis

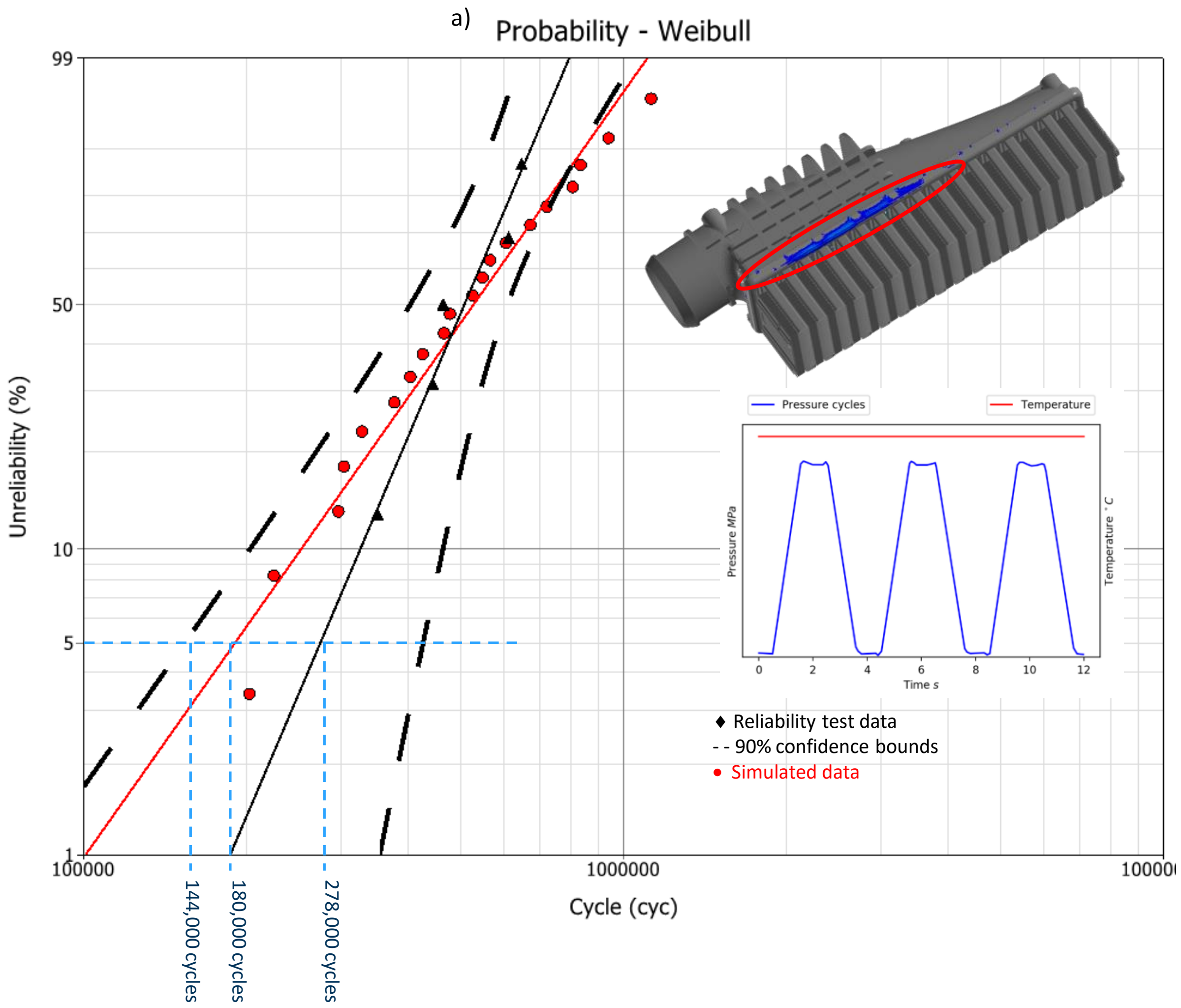
- Statistical uncertainty analysis based on a priori assumptions of statistical distributions:
    - Log-normal
    - Weibull

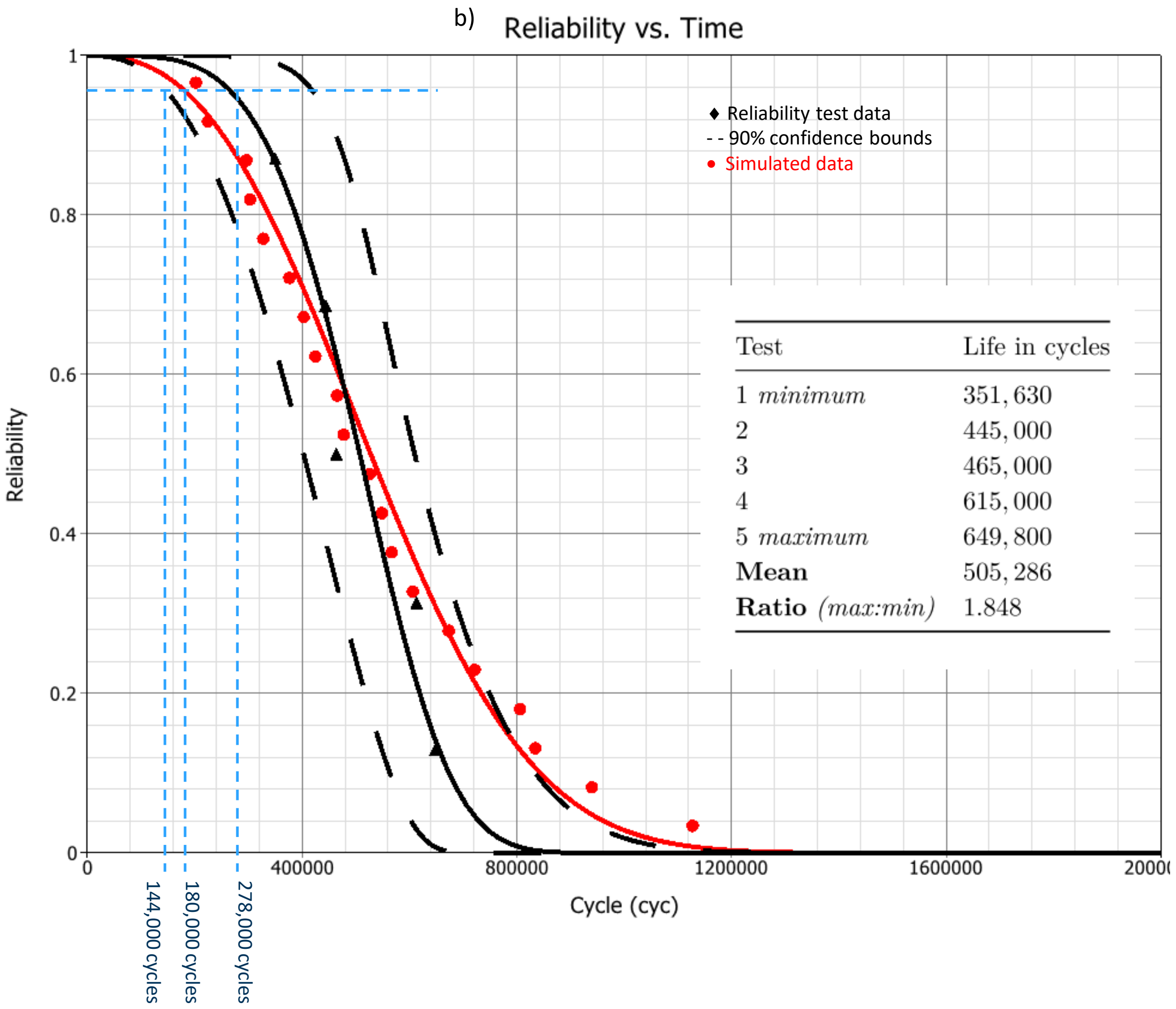
## Comparing simulated results with test

- Comparison of both mean expected life values and their statistical variabilities and uncertainties.

# Case Study – Parameter Estimation







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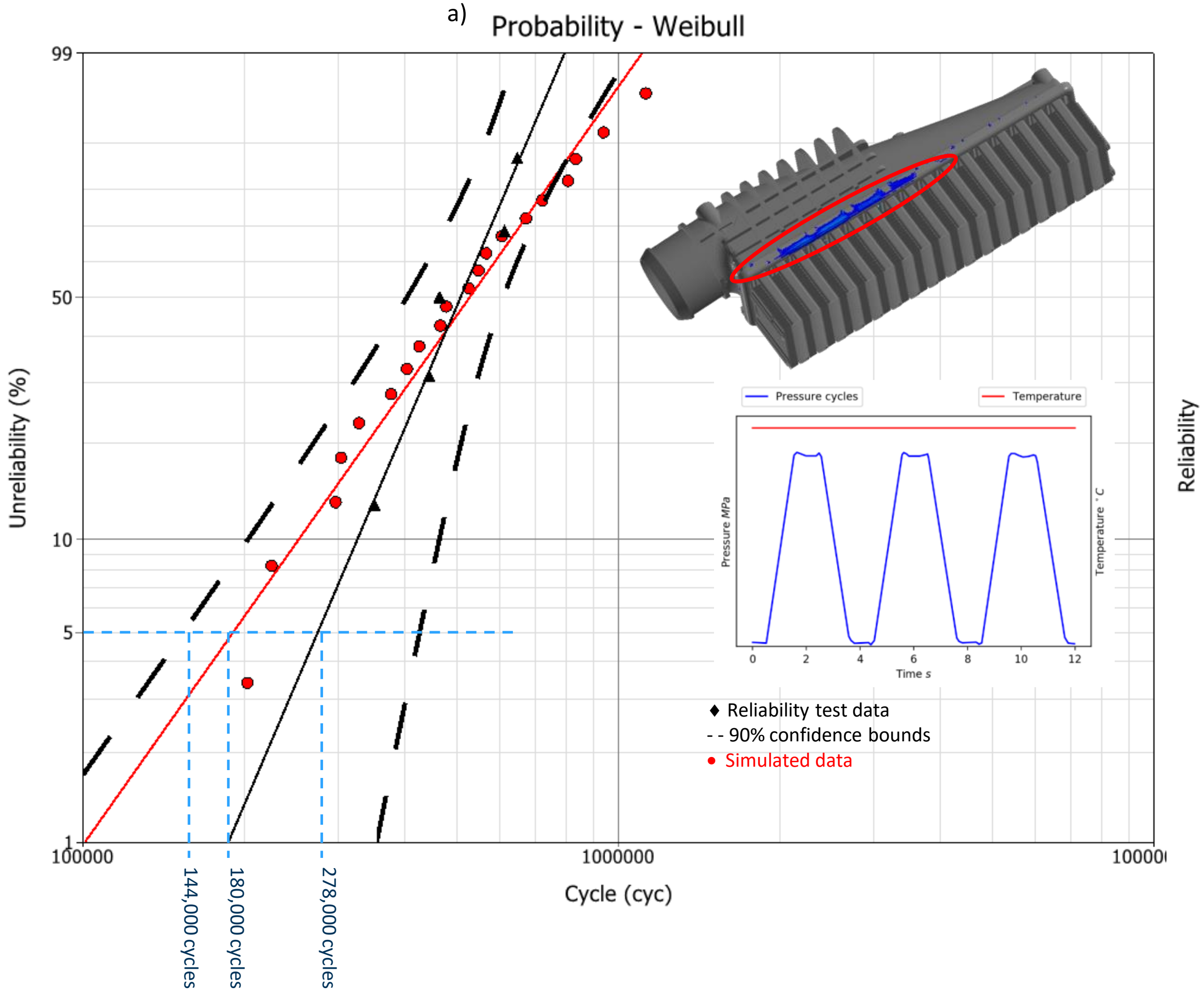
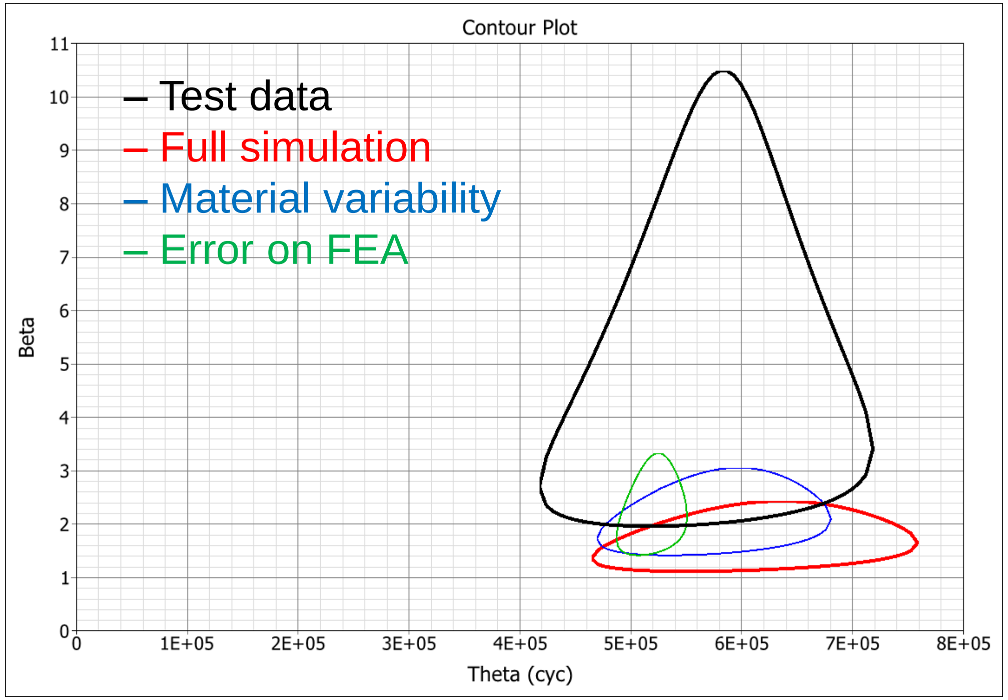
# Case Study – Parameter Estimation

a)




Material variability (Aleatoric) exceeds FEA modelling errors (Epistemic) ∴ no benefit from improving FEA without improving the material first.

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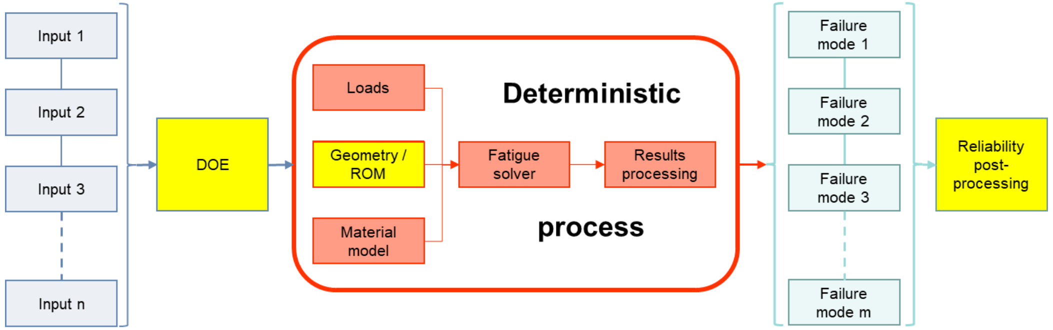
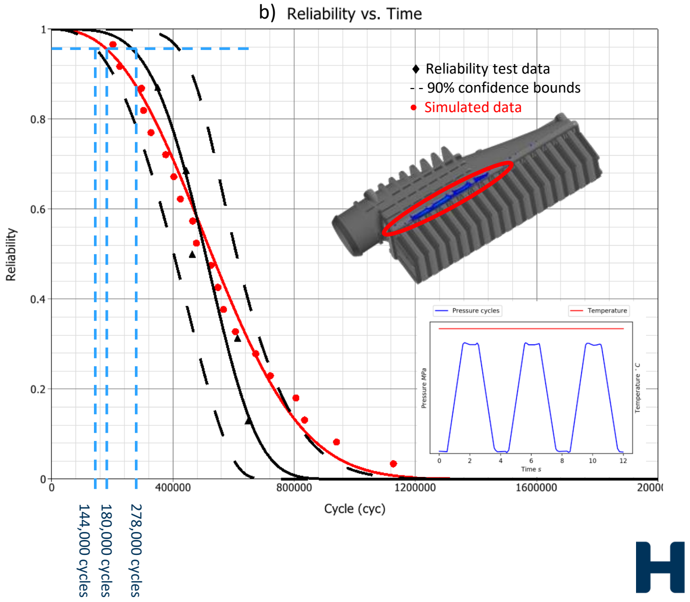
# Conclusions

- Increasingly necessary to qualify components based on their reliability and risk of failure.
- Easily accomplished using simple and cost-effective additions to the qualification test:
  1. Simulate the test.
  2. Use additional measurement instrumentation to verify simulation results.
  3. Run qualification tests to failure to verify fatigue life simulation.




- Fatigue lives vary exponentially so important to model variability & uncertainty.
- Probabilistic fatigue analysis used to verify simulation model with test.
- Reliability target validated using a combination of simulation and physical testing.



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# Q & A


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Fatigue Design 2023 (FatDes 2023)

Achieving high confidence in fatigue reliability by quantifying the effects of uncertainty

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[b]Hottinger Bruel & Kjaer France, 2-4 rue Benjamin Franklin, 94370 Sucy-en-brie, France
[c]Hottinger Bruel & Kjaer USA

Abstract

Across all industries, it is becoming increasingly necessary to qualify components based on their reliability and risk of failure. This paper considers how the existing design, simulation, verification, and validation process, may be enhanced to offer significant improvements in predicted confidence. Particular attention is paid to simulating the variability and uncertainty of fatigue life predictions. This allows simulation to be better verified using evidence from fewer qualification tests. The paper highlights the need for additional low-cost measurements during qualification testing, and a need to test to failure. It considers how Reduced Order Modelling, Design of Experiments, and statistical reliability analysis, are used in simulating the variability and uncertainty of fatigue failure. It demonstrates how simulation and physical tests mutually benefit one another, and concludes with a case study comparing simulated variability and uncertainty with the values measured in a typical qualification test.

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Peer-review under responsibility of the scientific committee of the Fatigue Design 2023 organizers.

Keywords: Fatigue; Reliability; Monte Carlo; Design Of Experiments (DOE); Reduced Order Modelling (ROM); Weibull

1. Introduction

In the aerospace, automotive, and power generation industries, it is becoming increasingly necessary to qualify components based on their reliability or risk of failure. For example, all new EVs (Electric Vehicles) sold in the US require an 8-year or 100,000 mile (160,000 km) battery warranty. EV batteries are complex mechanical structures that support dynamic masses, and transmit loads and vibration through thousands of joints and components. Fatigue failure therefore presents a significant risk to the overall reliability of the battery system. The design requirement over a population of EVs is expressed in terms of a statistical reliability target, for example:

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Peer-review under responsibility of the scientific committee of the Fatigue Design 2023 organizers.

Halfpenny. A, et al. ***"Achieving high confidence in fatigue reliability by quantifying the effects of uncertainty."*** Structural Integrity Procedia, Elsevier, 2023



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# Thank You

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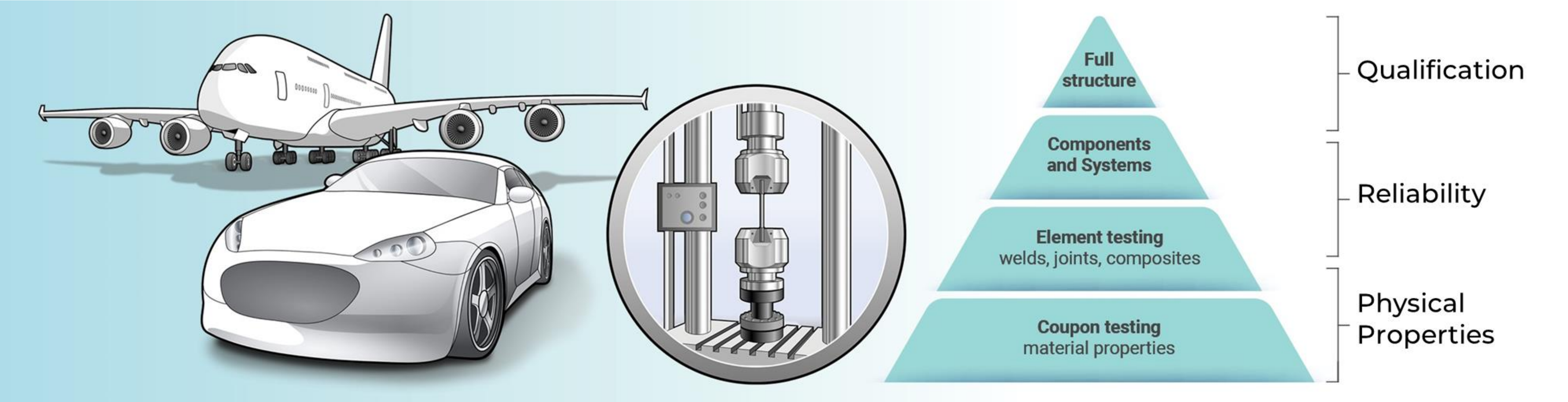
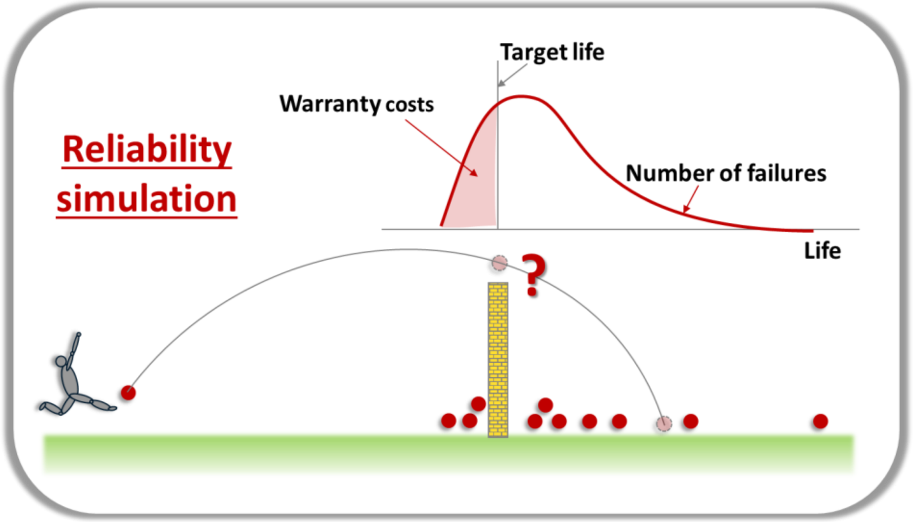



# 2023 HBK Technology Days

## 14 November 2023




- **Complementary simulation and qualification testing for high confidence in fatigue reliability**

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