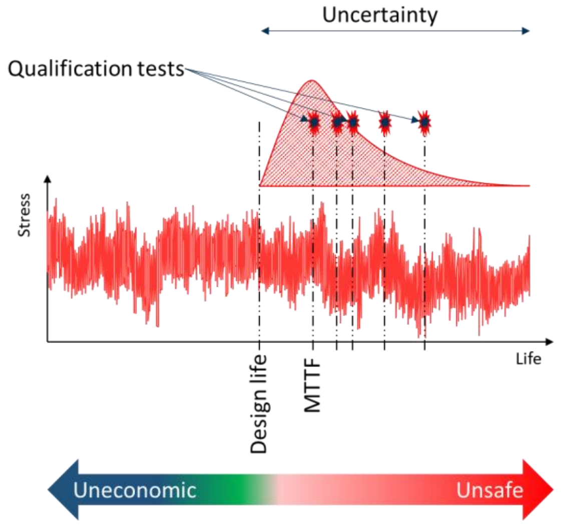
HBK Technology Days – Virtual Seminar Series

Tuesday, November 22, 2022



Statistical and Reliability Aspects of Electric Vehicles

Presented by Dr. Andrew Halfpenny,
Director of Technology, HBK nCode Products

Statistical and Reliability Aspects of Electric Vehicles

Abstract

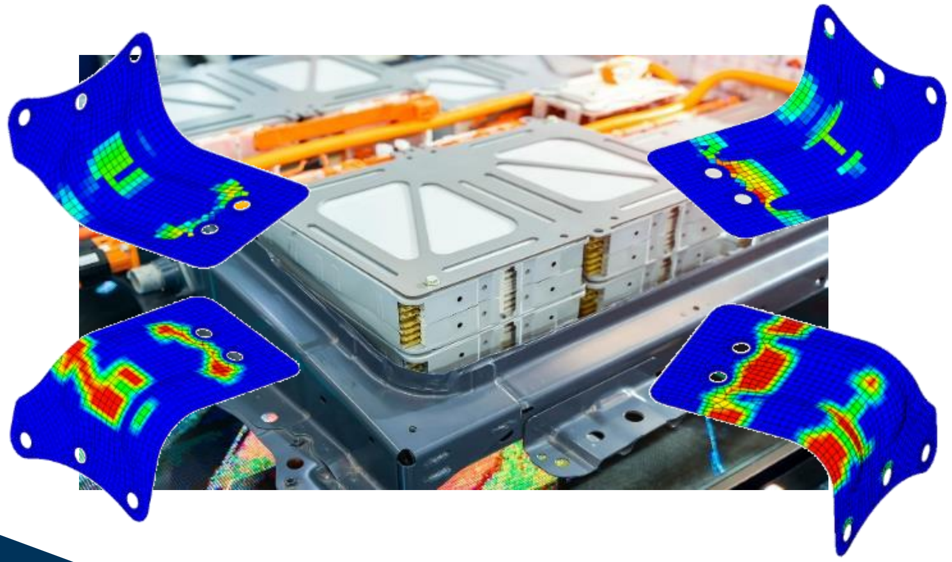
The automotive industry is mobilizing at a rapid pace to meet the demands and challenges presented by the shift to more widely accepted battery-powered electric vehicles. The rapid pace of innovation can expose manufacturers to potentially expensive warranty claims. This presentation addresses techniques to quantify and minimize reliability exposure for structural EV battery systems. It covers the following topics:

- Understanding the impact of mechanical shock, vibration, and thermal stresses, on the durability and reliability of EV batteries.
- Obtaining statistically representative loading spectra, and deriving vibration test profiles.
- Using a combination of physical vibration testing with CAE simulation to better understand component reliability and the impact of uncertainty on risk exposure.

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

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 is a founding member of NAFEMS PSE Certification scheme and sits on the NAFEMS committee for Dynamic Testing. He is a visiting lecturer on structural dynamics with The University of Sheffield.

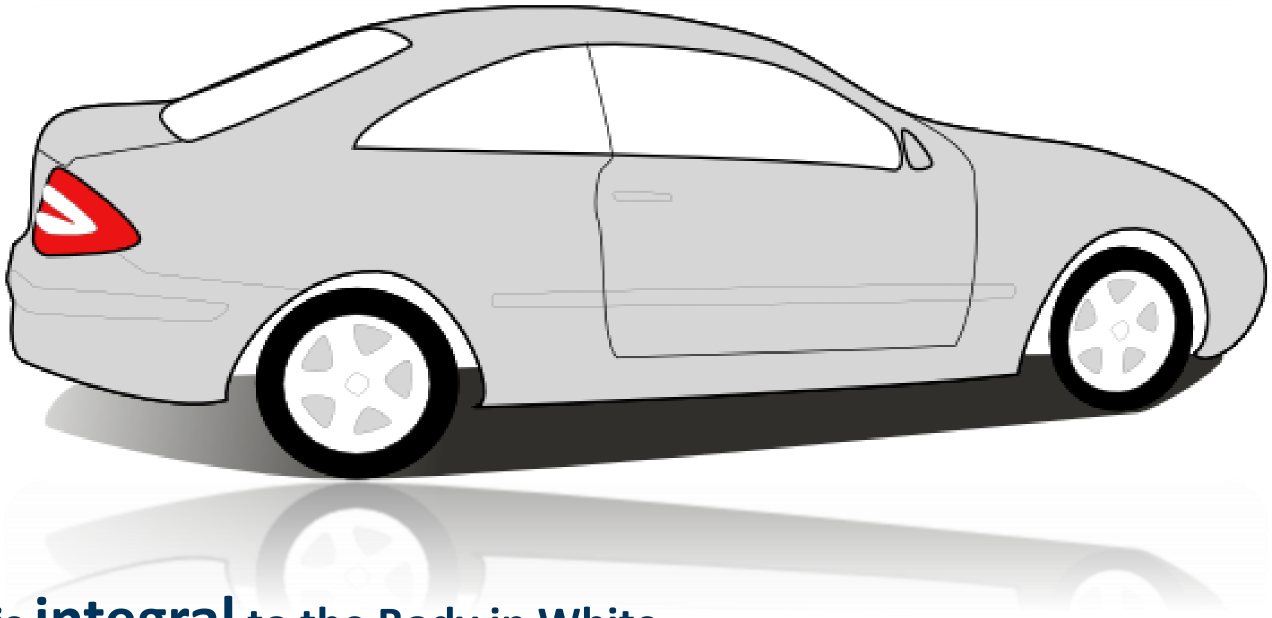
Statistical and Reliability Aspects of Electric Vehicles



Dr. Andrew Halfpenny

Director of Technology – HBK nCode Products

Challenge – *not just a bigger 12v battery*



Traditional battery
- Light-weight
- Small size

Attached to the Body in White

BEV battery is integral to the Body in White
- Comparable weight to Body in White
- Affects dynamic response of vehicle and structure
- Transfers road loads and affords crash protection
- Transfers inertial loads from heavy cells
- Physically large
- Internally complex – load-bearing chassis and joints (welds, adhesive, etc.)

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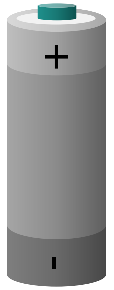
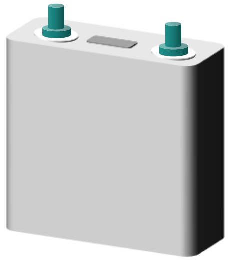
Batteries are mechanical structures



Laminated foil pouch

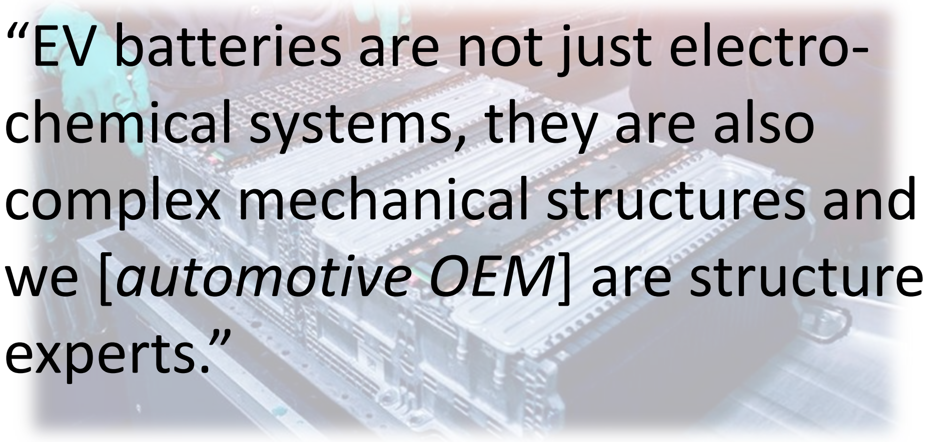
2.8< 3.7v <4.2

Hard case



C-cells

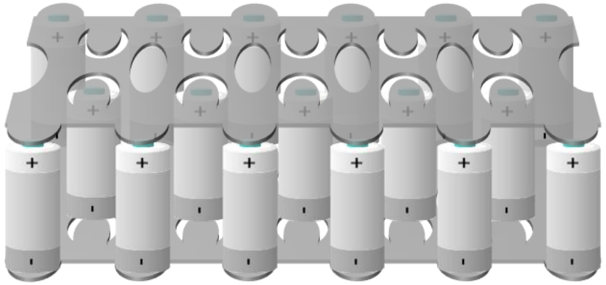
Prismatic cells

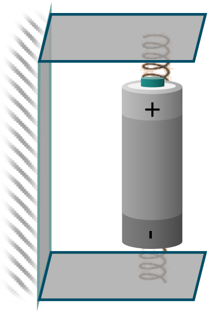


"EV batteries are not just electro-chemical systems, they are also complex mechanical structures and we [*automotive OEM*] are structures experts."

Battery Pack

Battery Modules





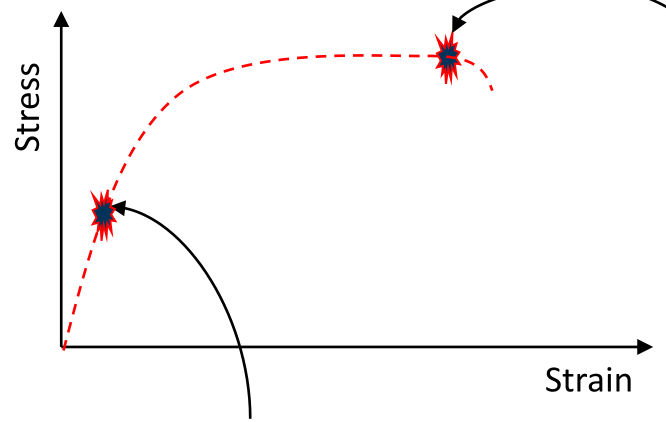
- Flexible structure
  - Joint
    - Mass
    - Spring
    - Damper
  - Joint
- Flexible structure

>10,000 joints per battery!

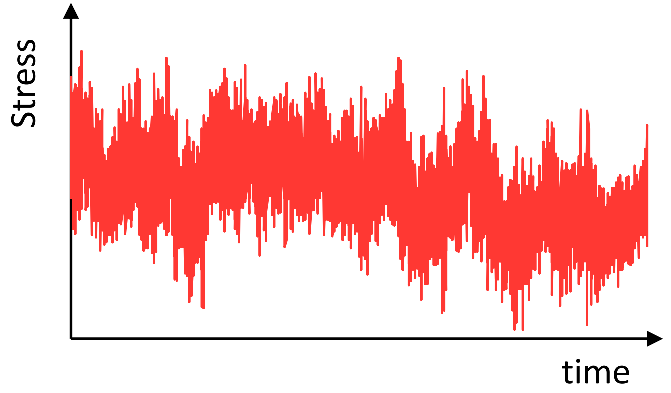
- Vibro-thermal fatigue of cells & joints
- Progressive failure → battery degradation
- Structural and inertial loads
- Broad range frequency input & response
- Highly variable damping

Structural durability and fatigue?

Stress V's Strain Plot

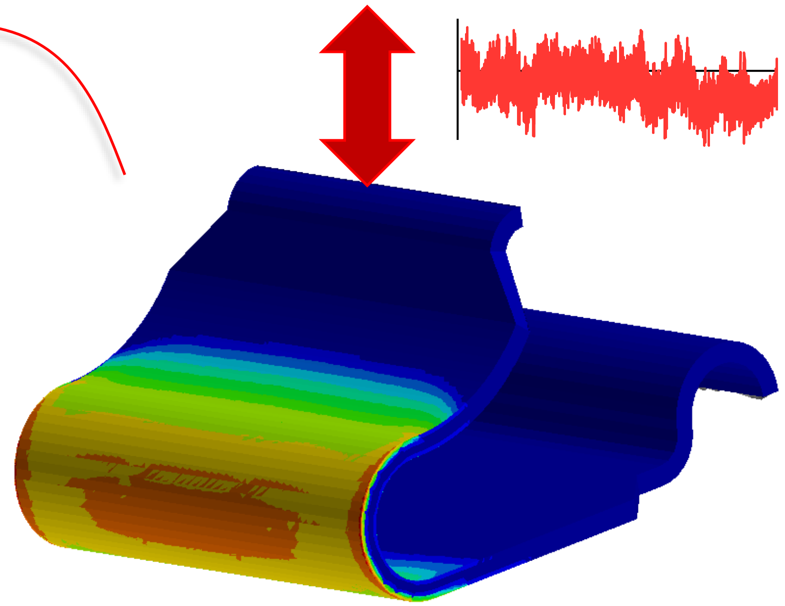


Apply cyclic load
at low stress level



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* ***low stresses*** *are well within the static strength limits.*

The component seems to get 'Tired', hence the name FATIGUE

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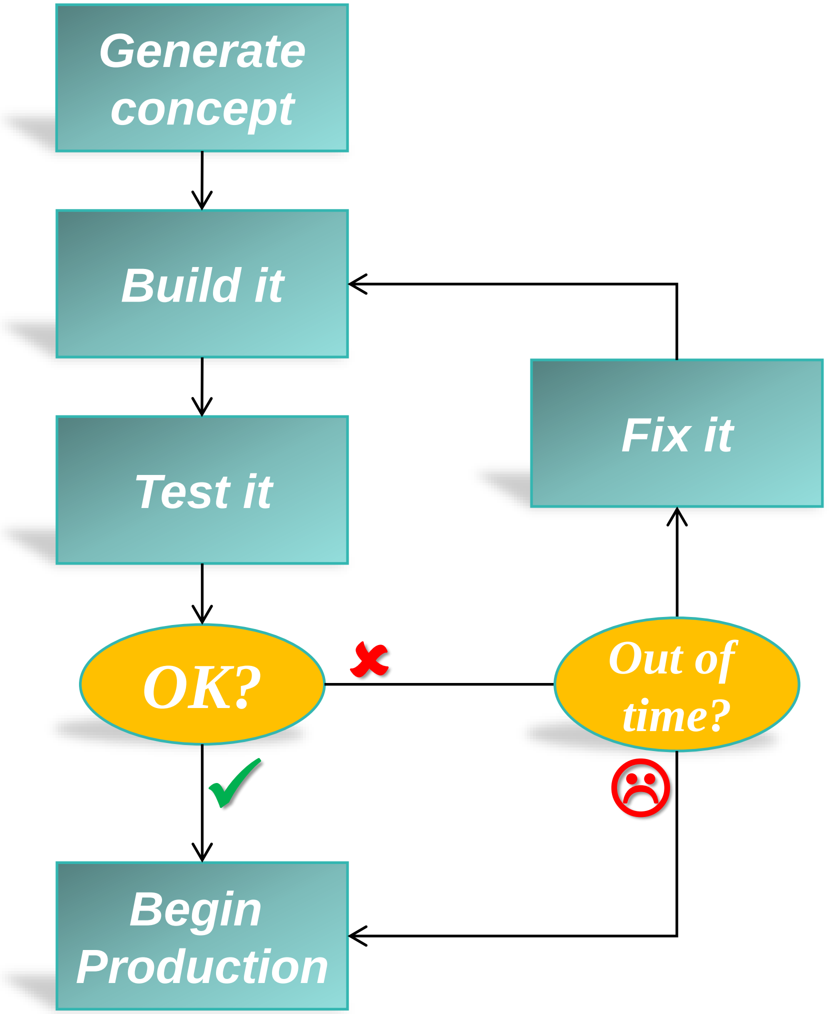
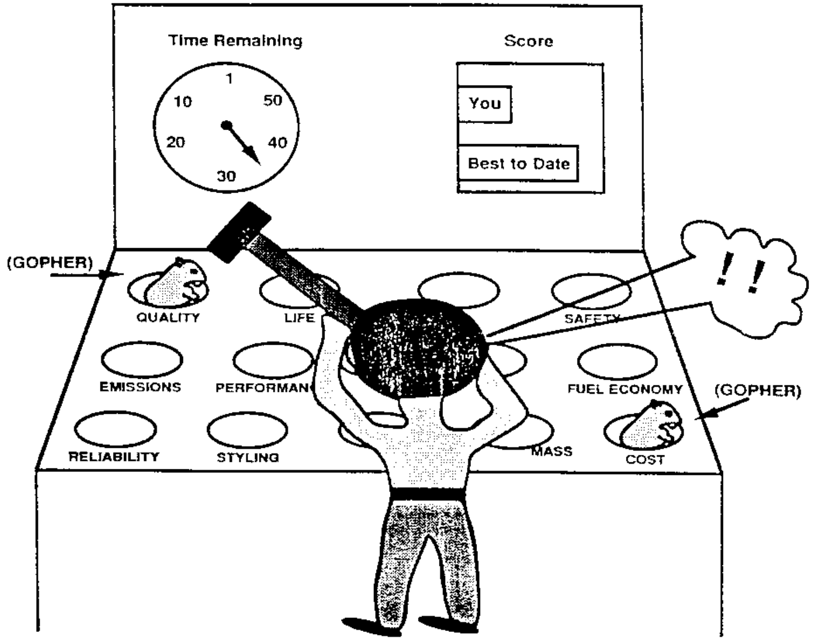
Fatigue design before simulation



GET THE GOPHER [ONE-AT-A-TIME]



- 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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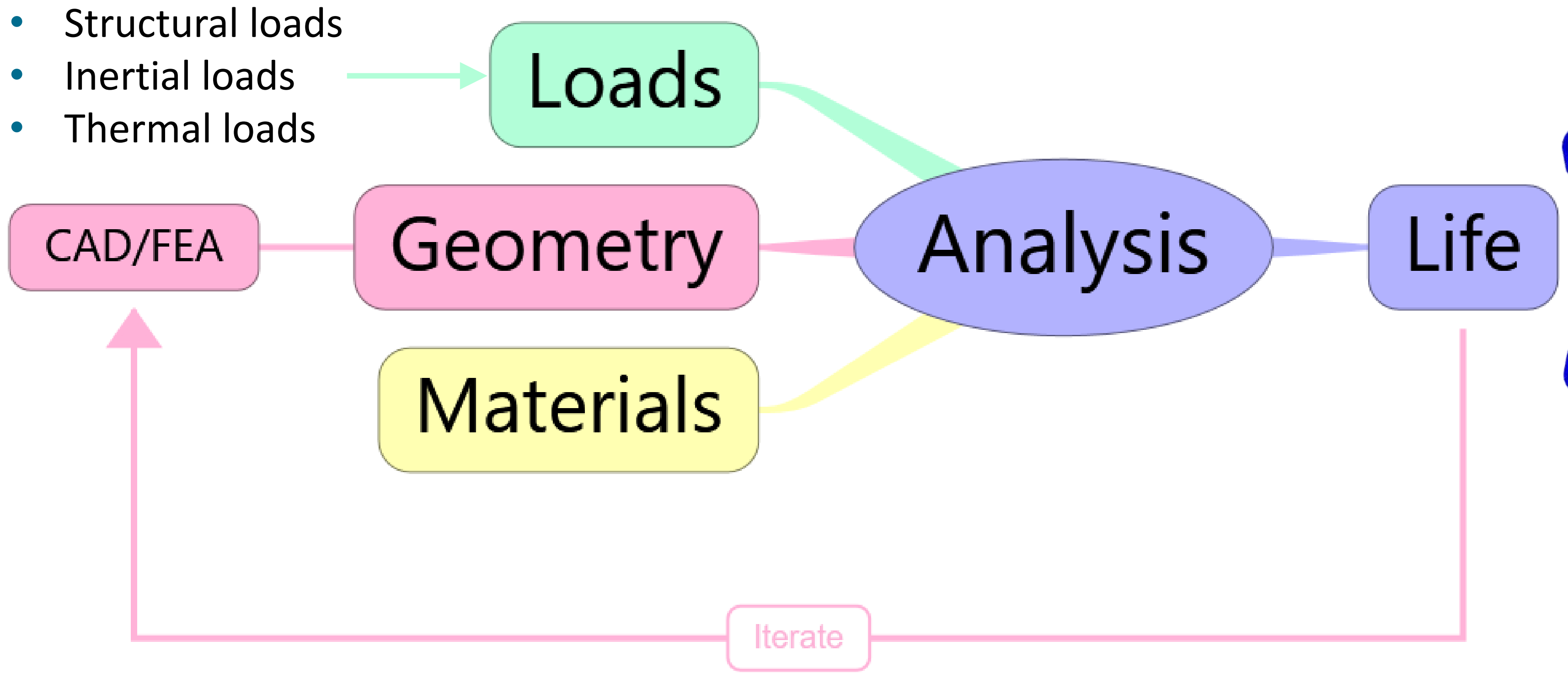
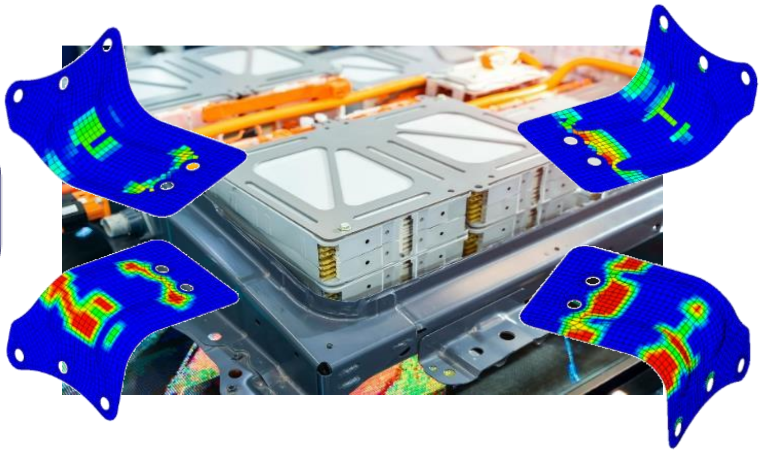
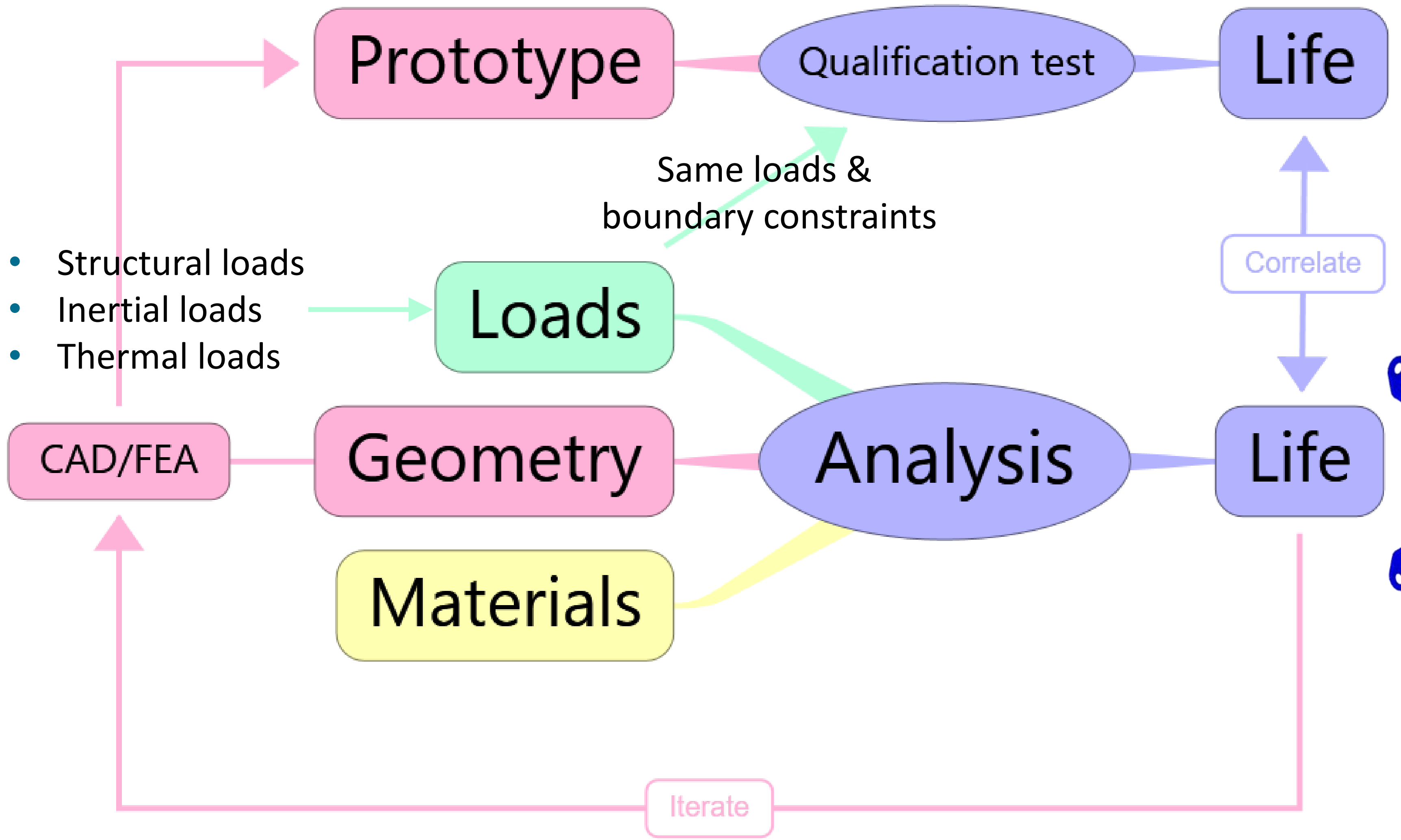
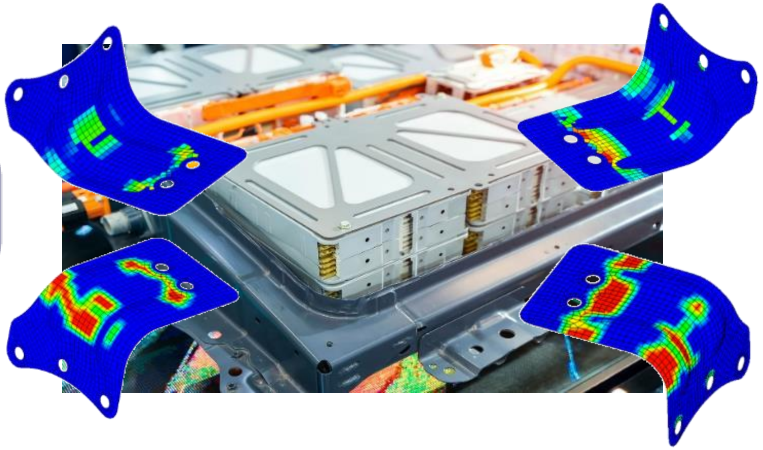
Fatigue Simulation





Fatigue Simulation, Verification & Validation





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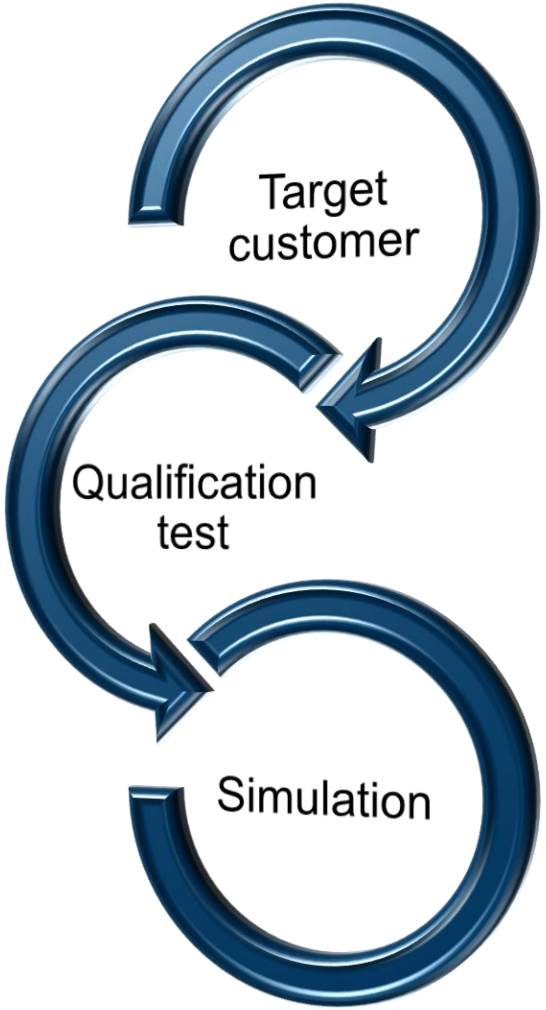
How do we find the loads?



2. Make it scientifically reproducible

1. Statistical target customer analysis

3. Accelerated qualification testing

4. Simulate the qualification test

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CONFIDENTIAL - EXTERNAL

How do we find the loads? *– Vibration Profile Design*

Requirement:
1. Shaker/thermal test spec ✓
2. Statistically worst-case world-wide damage content ✓
3. Accelerated (250,000 km → 48 hours test) ✓
4. Same failure modes as in-service (no over-acceleration) ✓

Mission Profile

- One battery module
- Different platforms
- Different countries
- Different drivers
- Different usage

General
- Charging
- Start-up
- Idling
- Cooling
- etc…

City commuter
- City roads
- Urban roads
- Belgian block
- High speed
- Cross country
- Mountainous
- etc…

Long range traveller

Mountain driver

etc …

Failures
- Overheat
- Cold running
- Cooling system failure
- Electrical failure
- etc…

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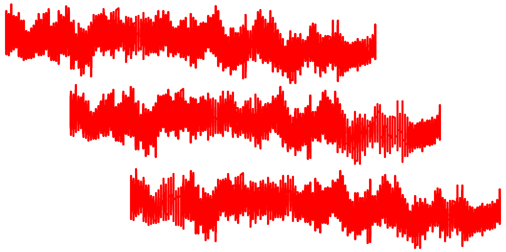
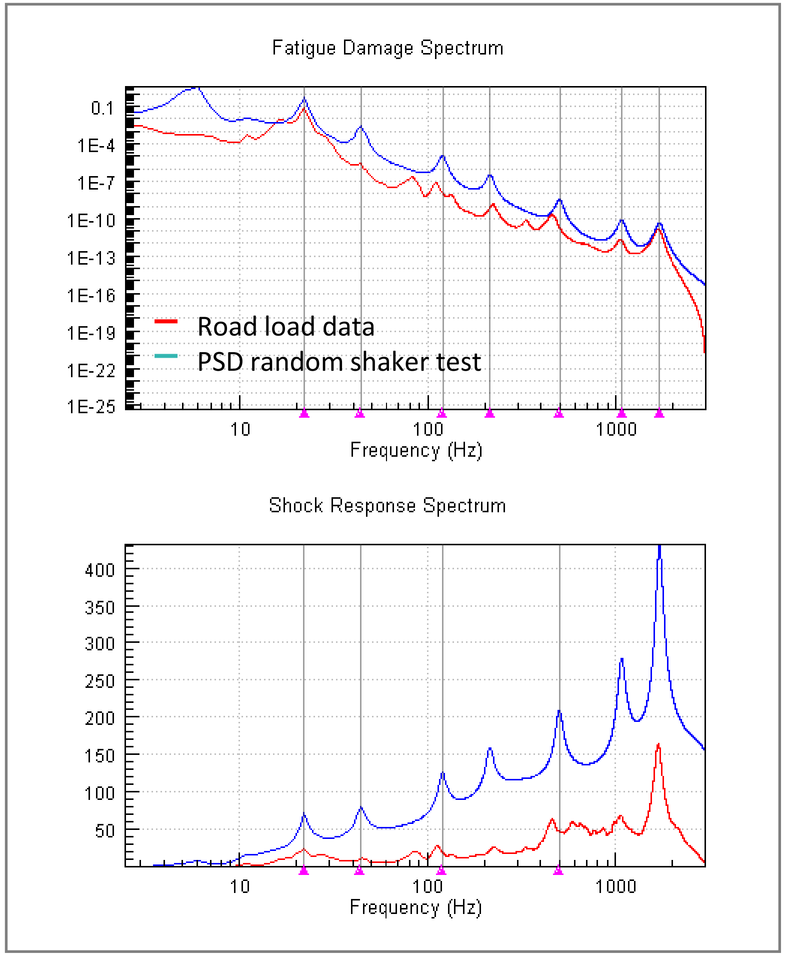
How do we find the loads? *– Vibration Profile Design*

1. Proving ground road load data test – measure vibration levels for each surface/event



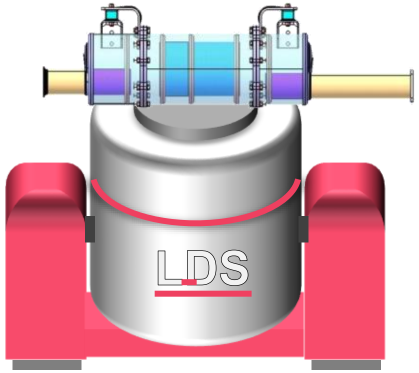
2. Characterise event data (*Fatigue Damage & Shock Spectra*)

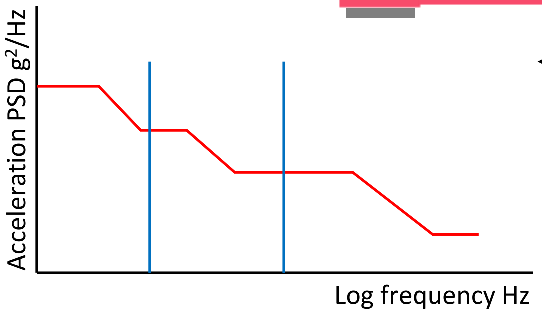


3. Combine damage over all mission profiles

4. Synthesize a tailored shaker test
   - Same damage content ✓
   - Same failure modes ✓

- Sine sweep & dwell
- PSD random
- Sine on random
- Swept sine on random
- Shock on random
- …





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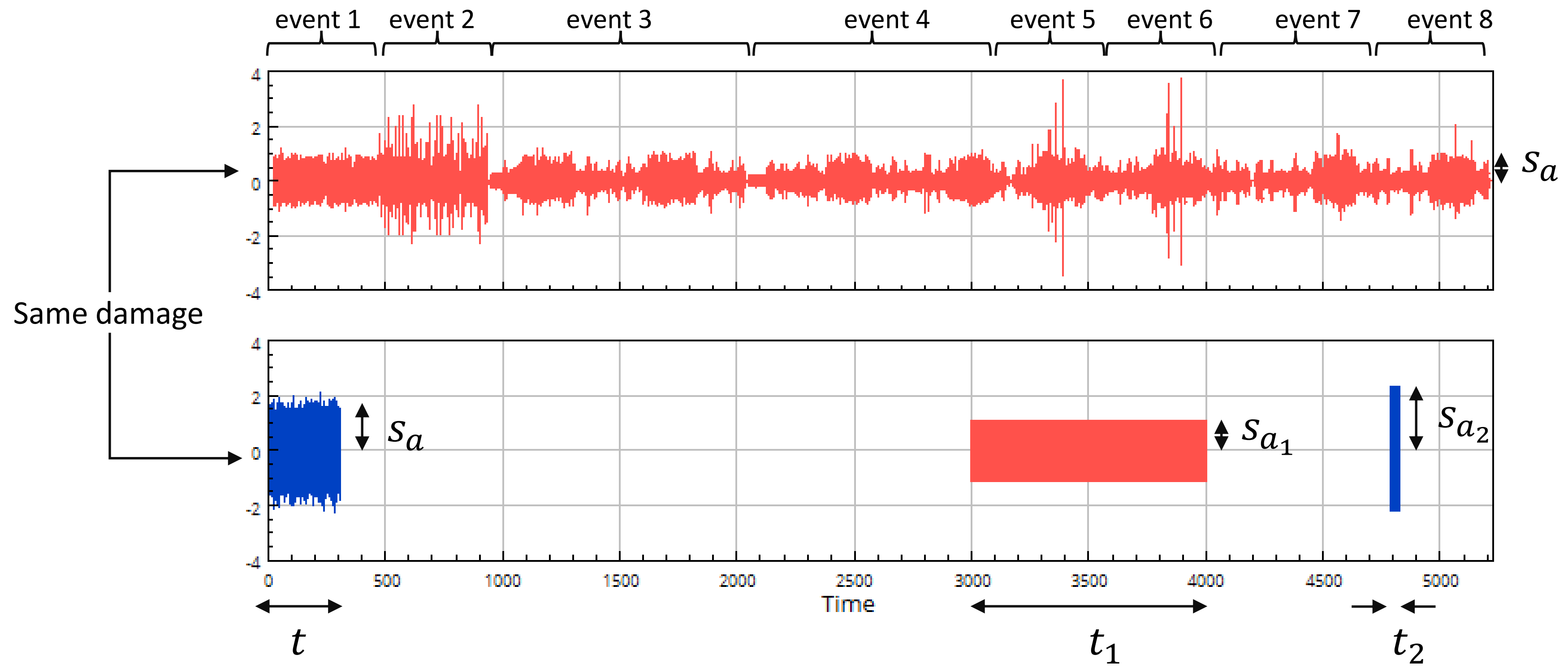
How do we accelerate the tests?

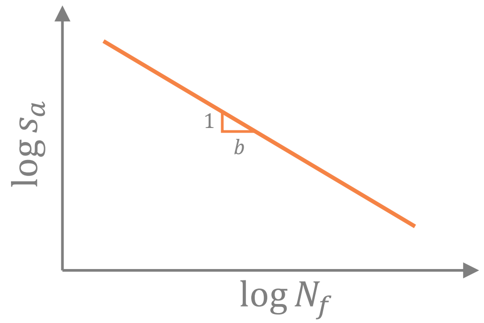


Original vibration signal
weighted mean $s_a \approx 0.88g$
max range $\pm 3.5g$

Accelerated test signal
weighted mean $s_a \approx 1.8g$
max range $\pm 2.2g$

$$D = t_1\left(s_{a_1}\right)^b = t_2\left(s_{a_2}\right)^b$$

Wöhler (SN) curve



Small load increase → exponentially shorter test time
Optimise test time without overloading component or shaker table

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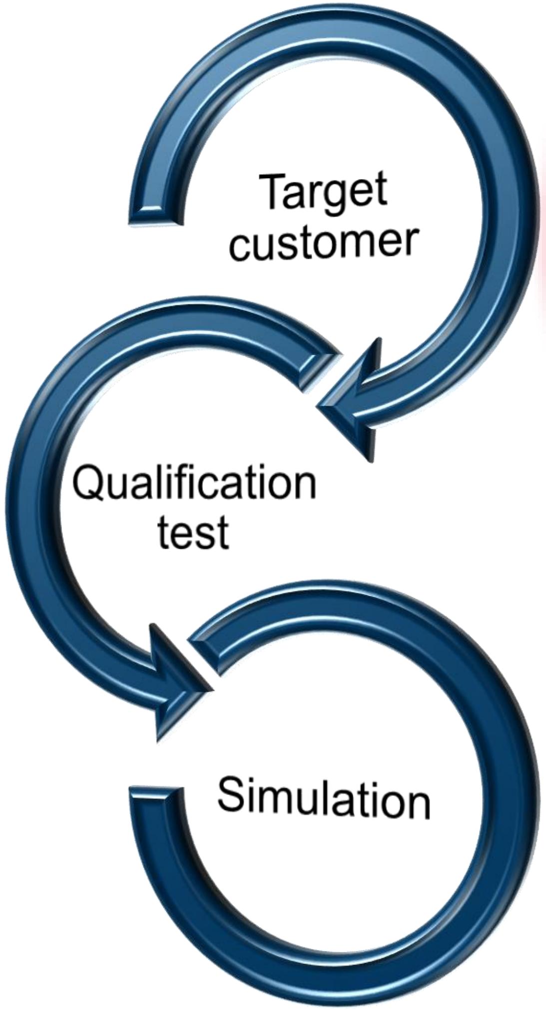
How do we find the loads?



1. Statistical target customer analysis

2. Make it scientifically reproducible

3. Accelerated qualification testing

4. Simulate the qualification test

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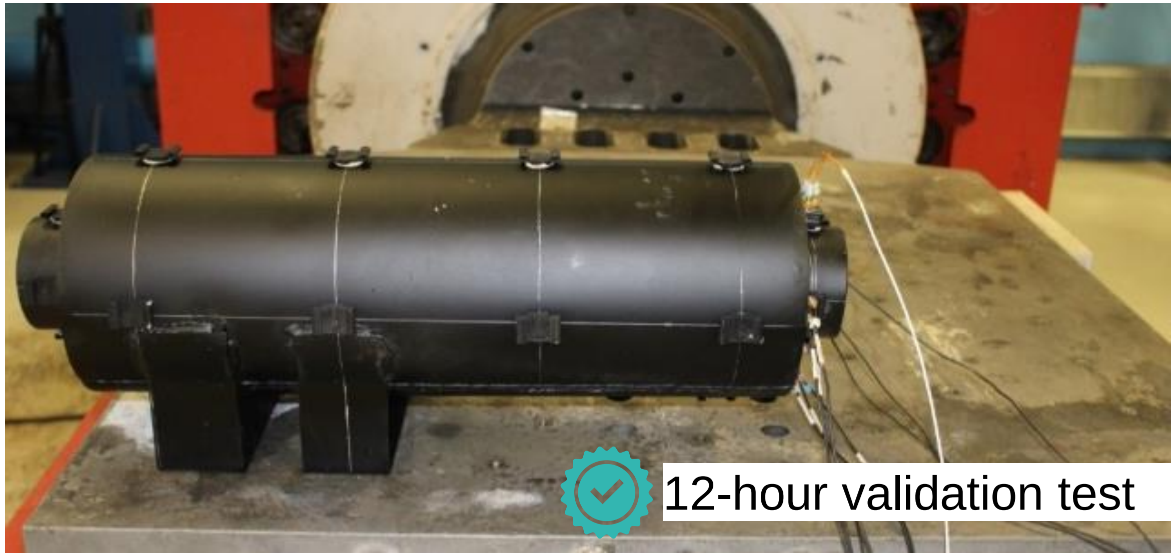
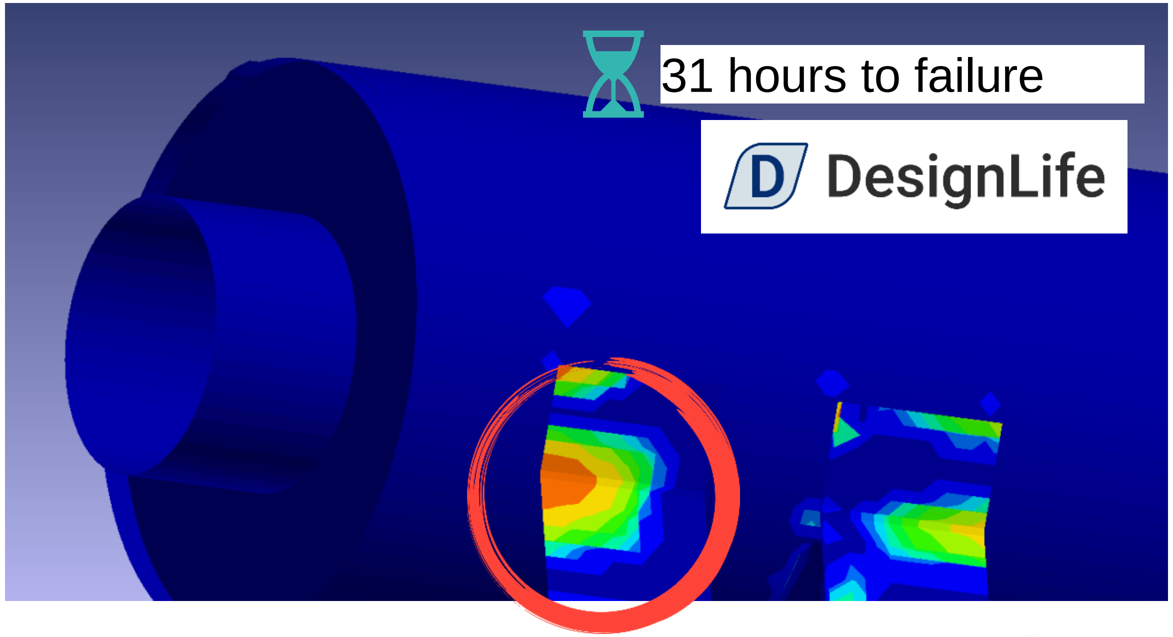
Simulation 🤝 Qualification Test

- ✓ **Simulation before the test –**
- ✓ **Simulation during the test –**
- ✓ **Simulation after the test –**





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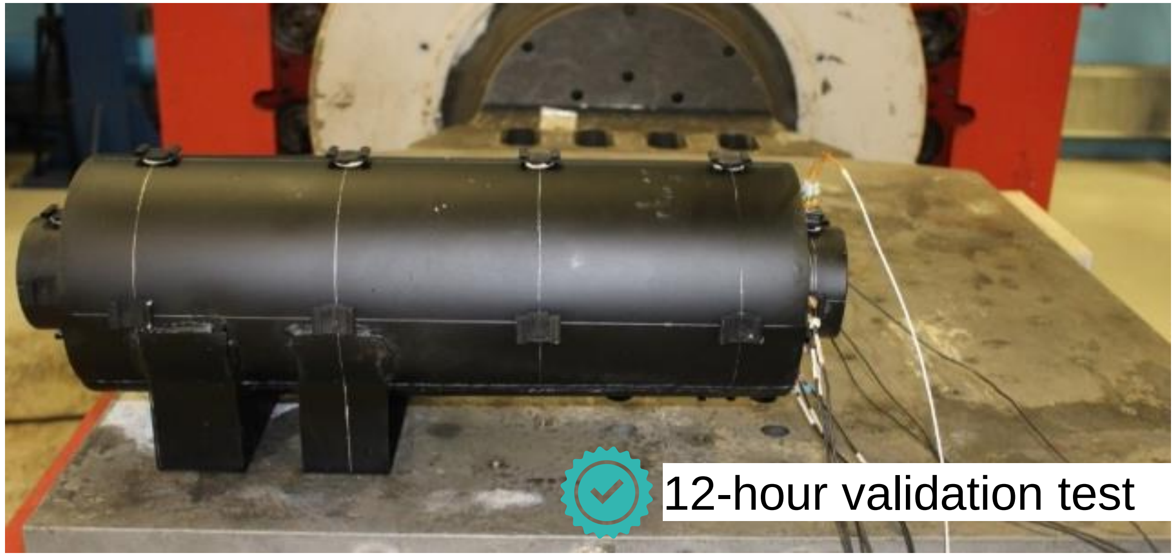
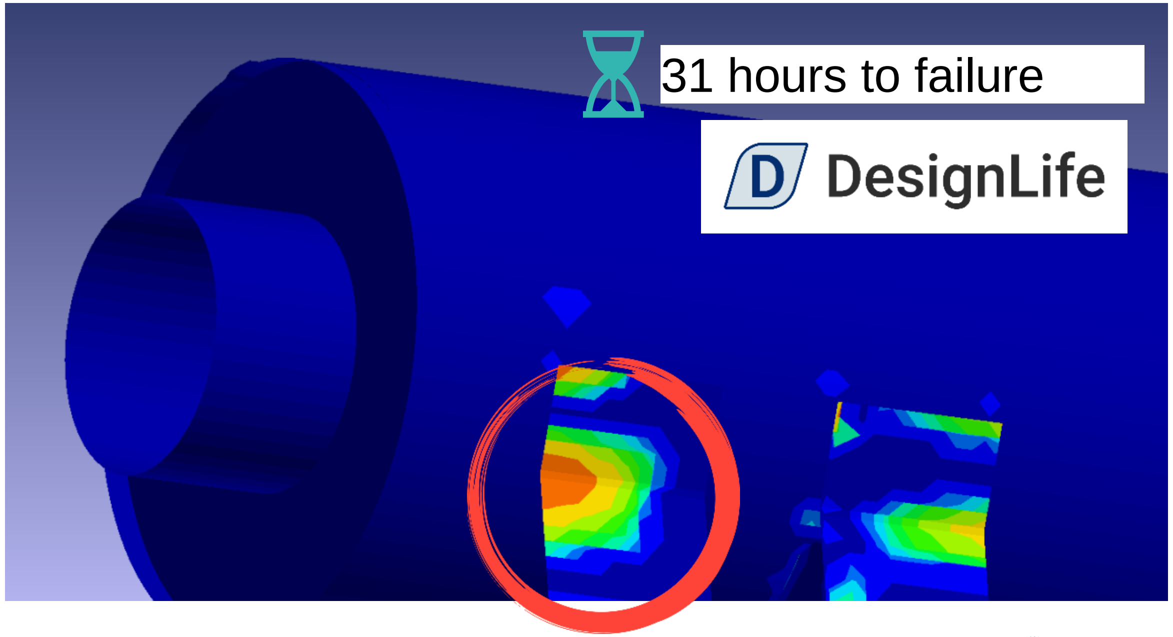
Simulation 🤝 Qualification Test

✓ **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 use a single axis test? Which axis is critical?</u>
  - ✓ Do I still get the correct failure modes?
  - ✓ How does it affect life?
  - ✓ Do I need supplemental axes (x, y & z)?





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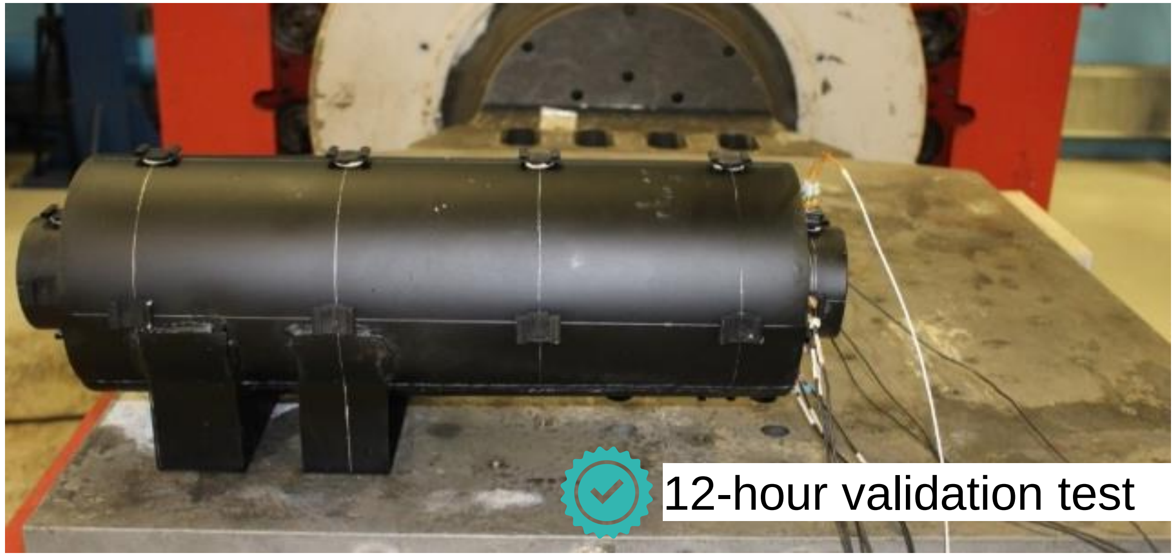
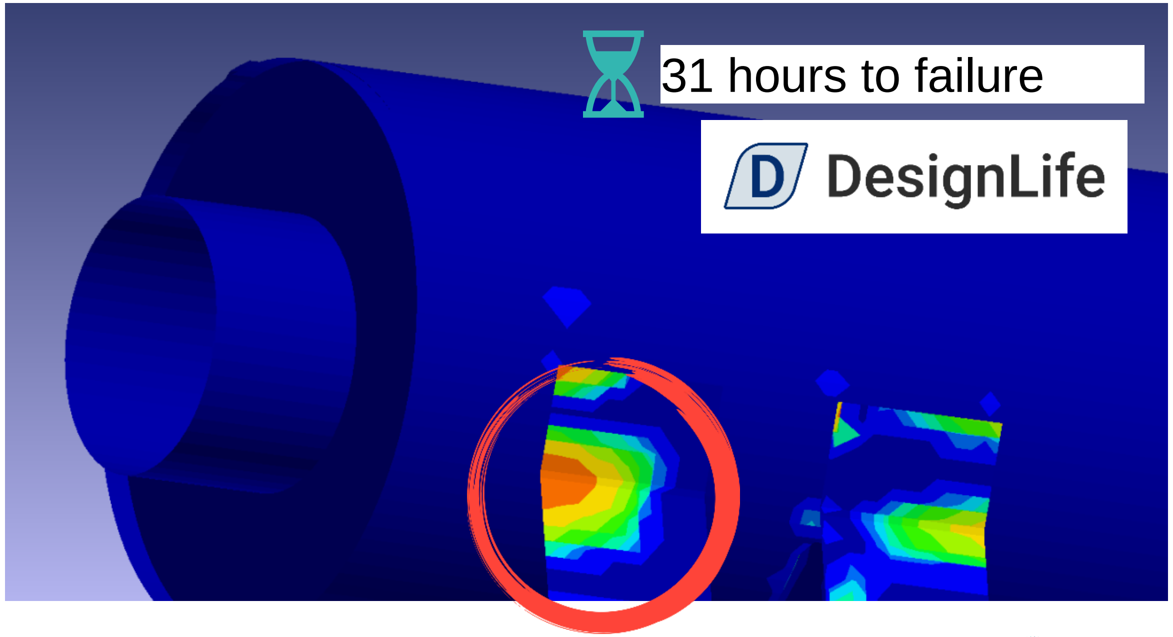
Simulation Qualification Test

- ✓ **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 using modal analysis?
    - ✓ ODS to compare natural frequencies & mode shapes
    - ✓ EMA or OMA to calculate damping parameters
    - ✓ MAC analysis to compare model with test article





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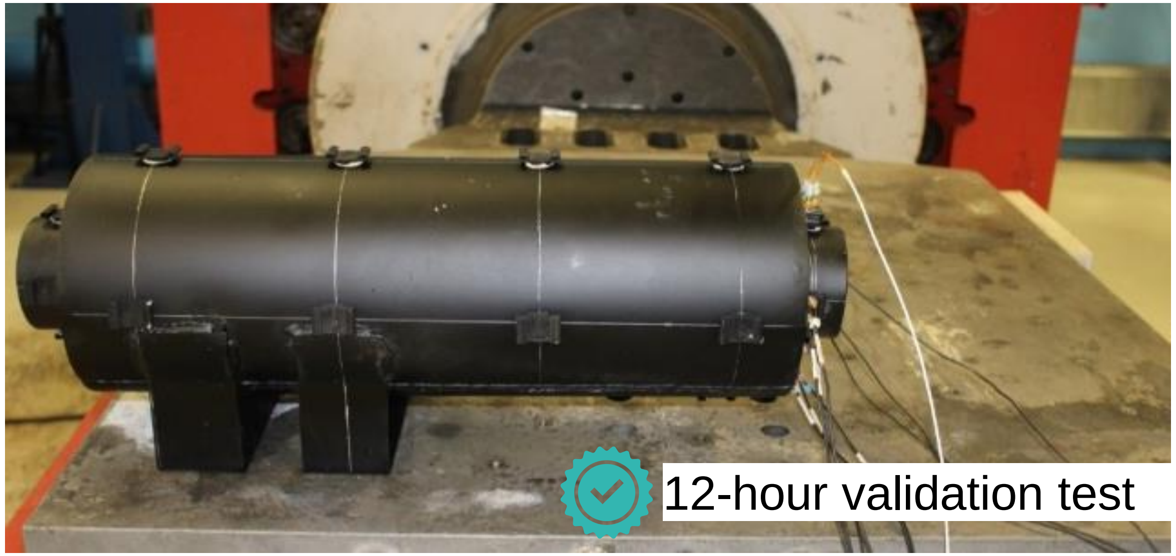
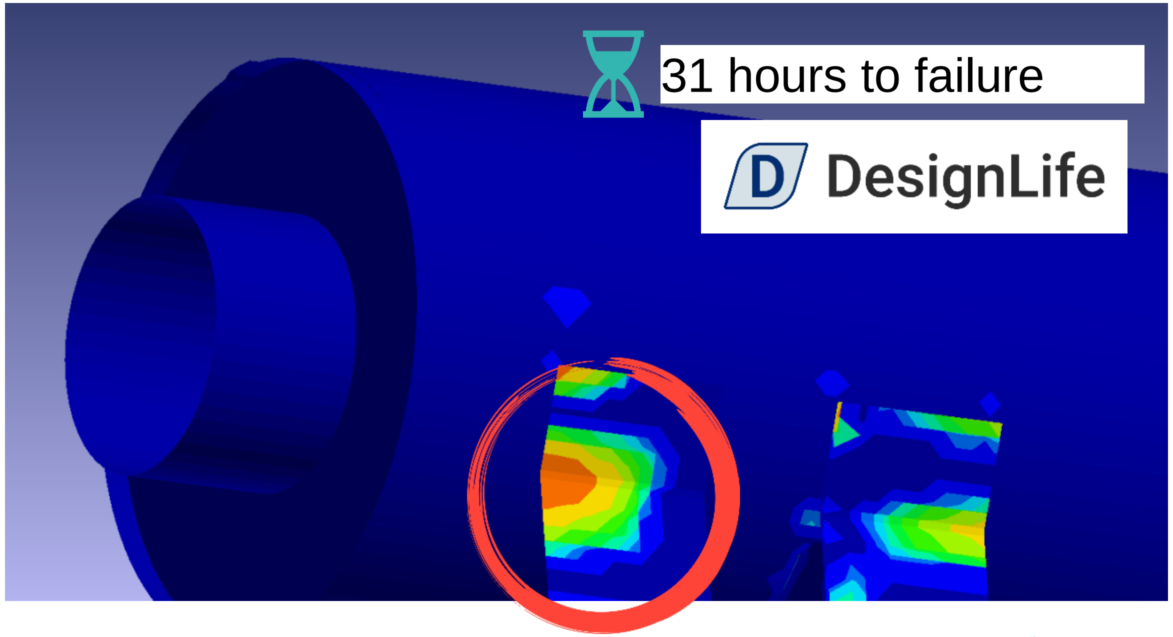
Simulation 🤝 Qualification Test

- ✓ **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?





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Simulation 🤝 Qualification Test

- ✓ **Simulation after t**
  - ✓ What shoul
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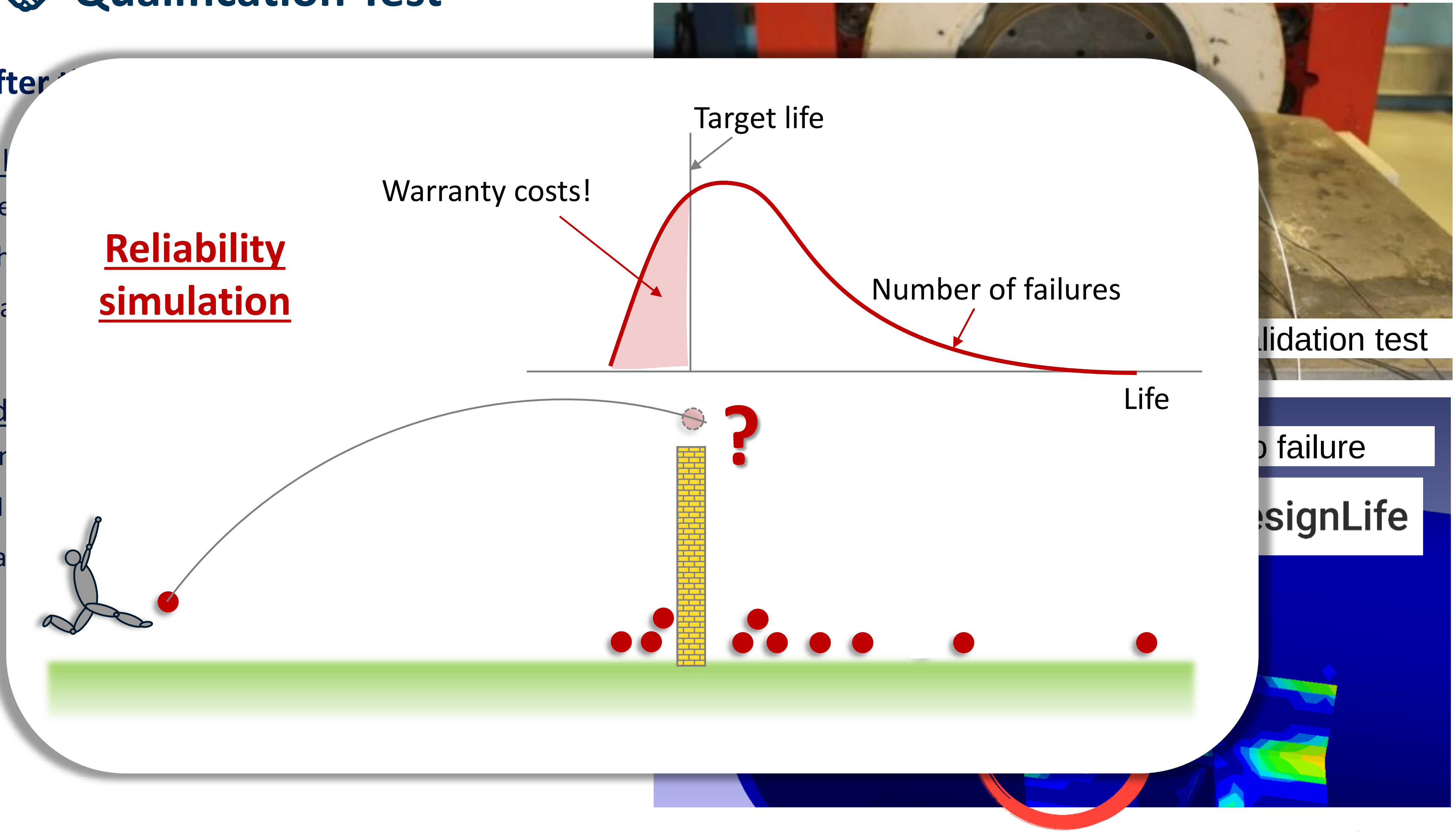
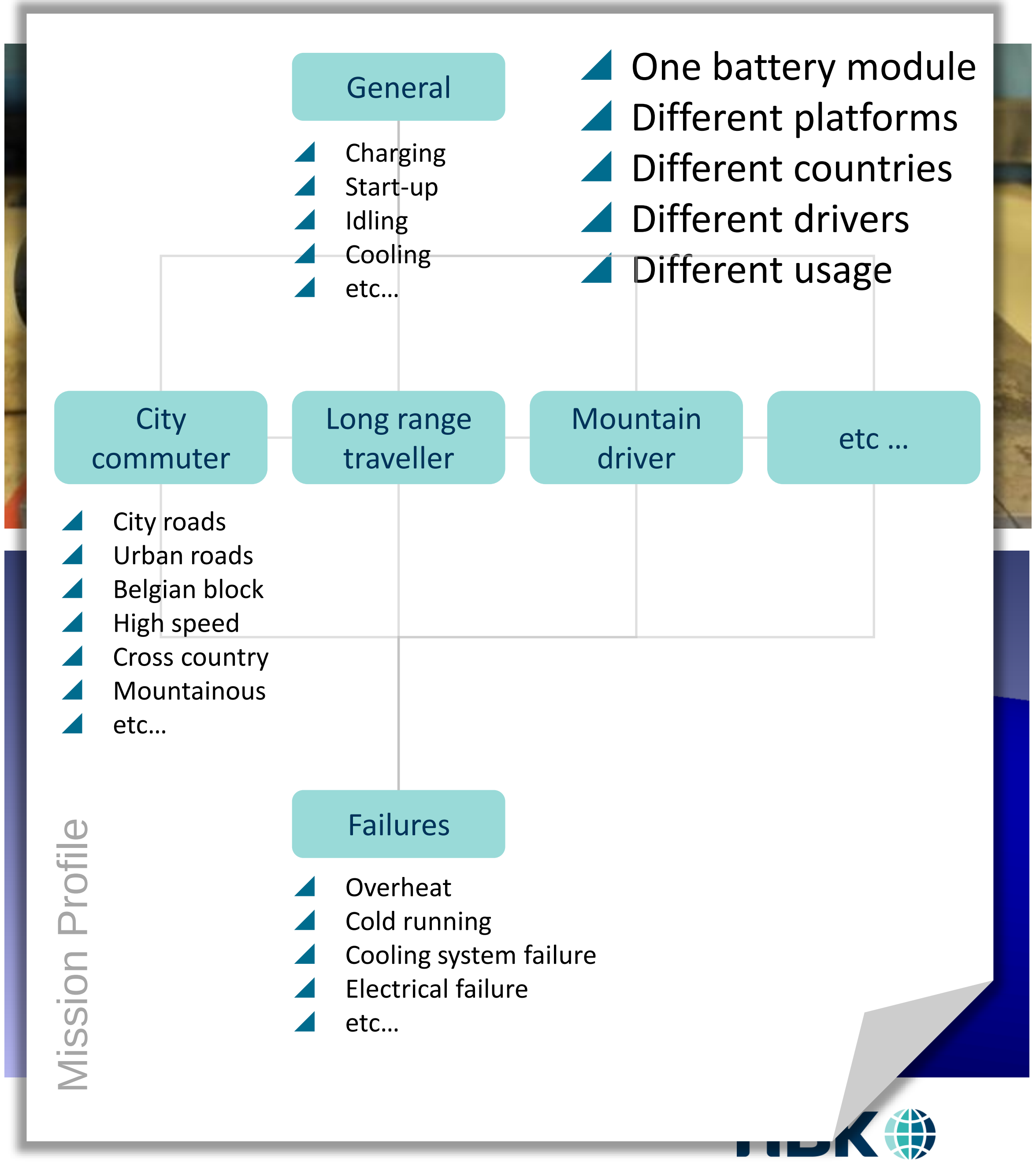


Simulation Qualification Test

✓ **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?
  - ✓ Who are my critical users?



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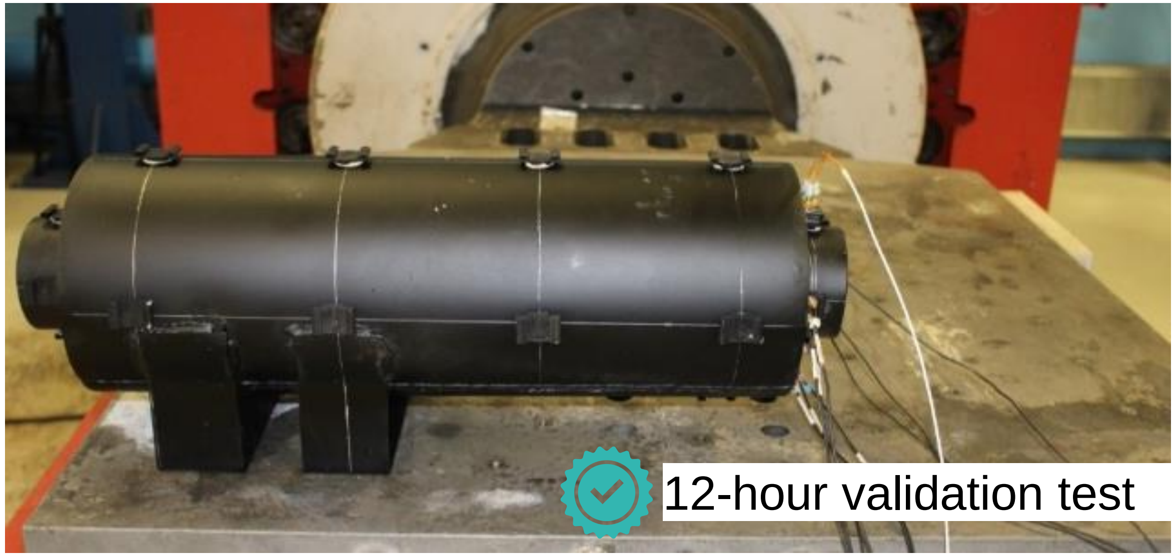

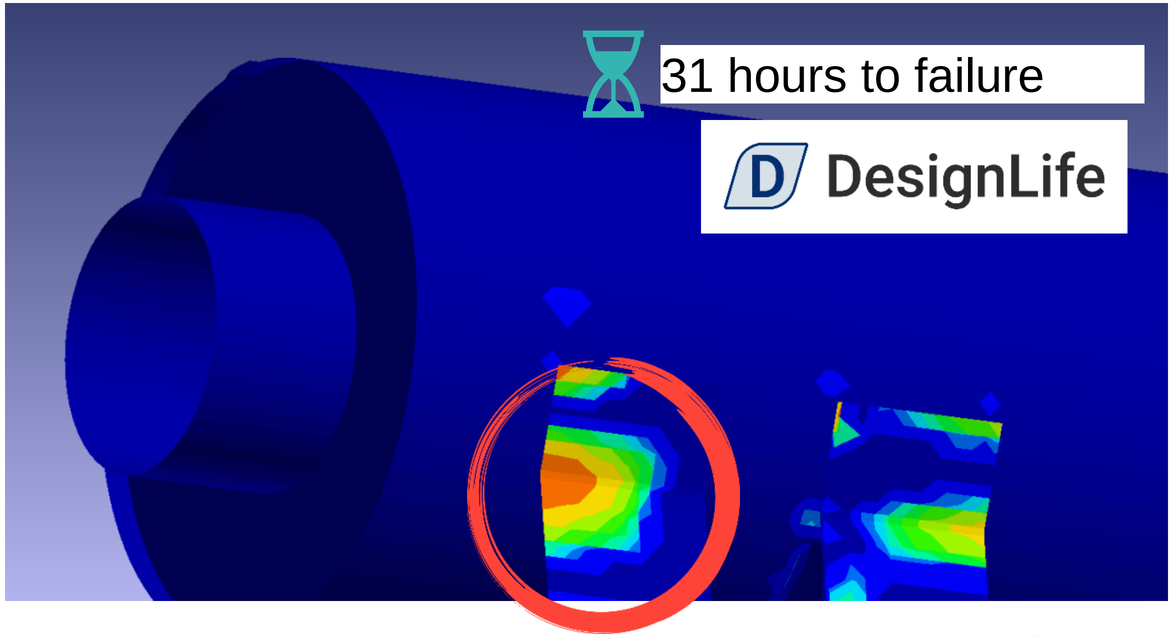

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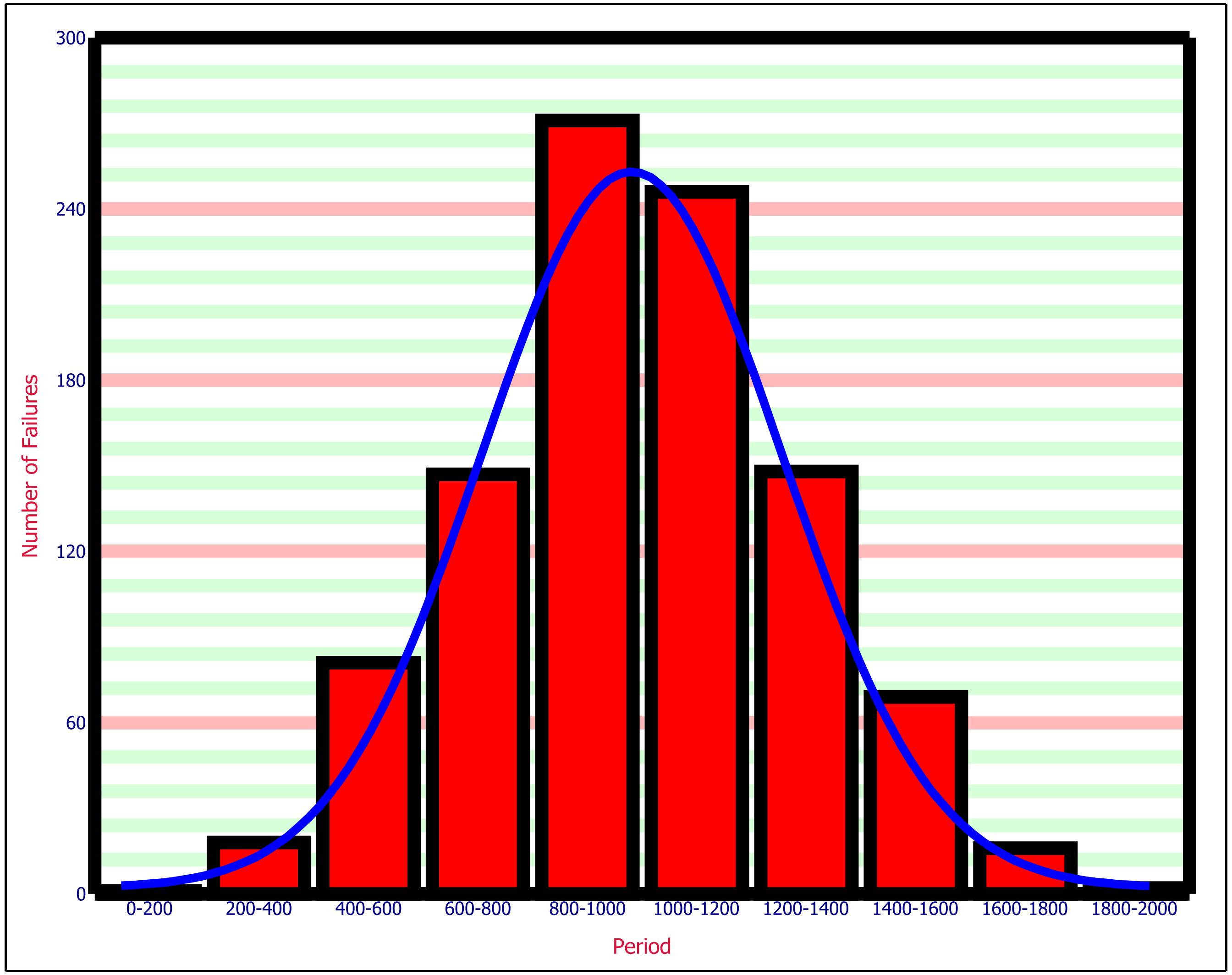
Product reliability estimation

Go from pass/fail to:

- “I want to be 90% confident that I will have less than 5% failures over a service life of 8 years”



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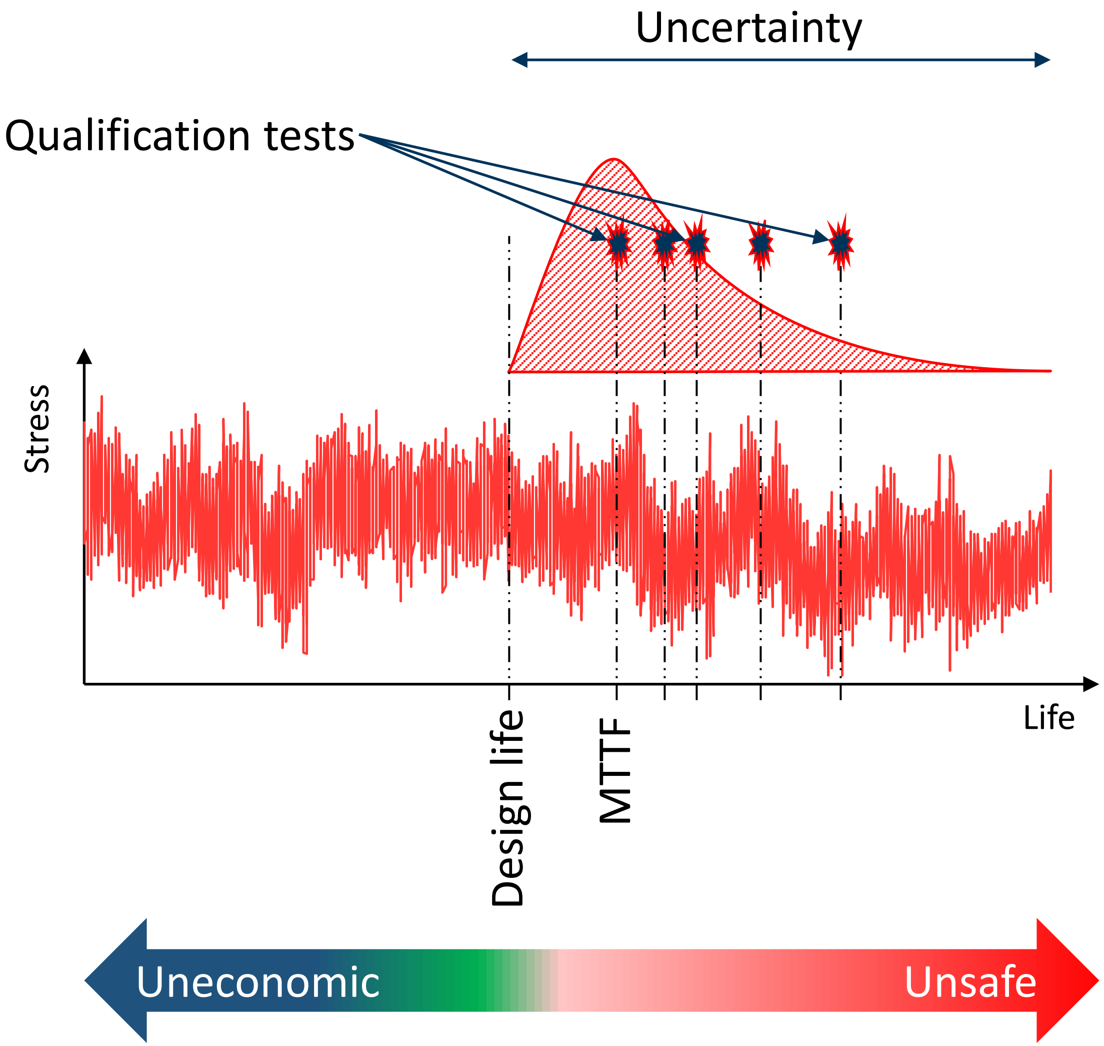
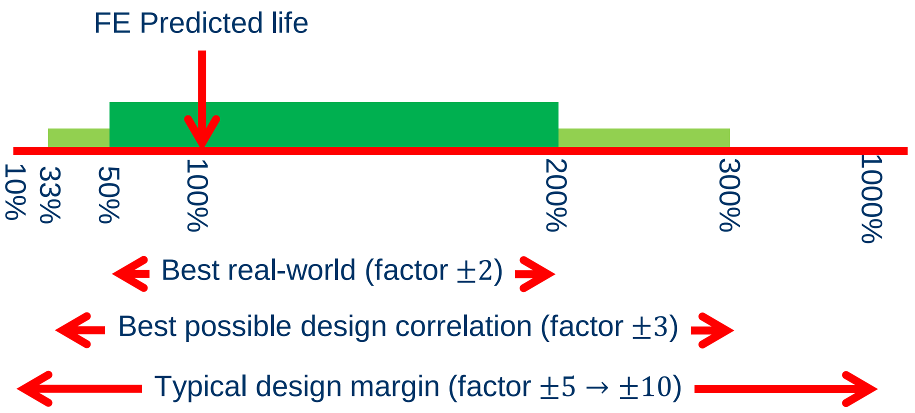
Product reliability estimation – the challenge!





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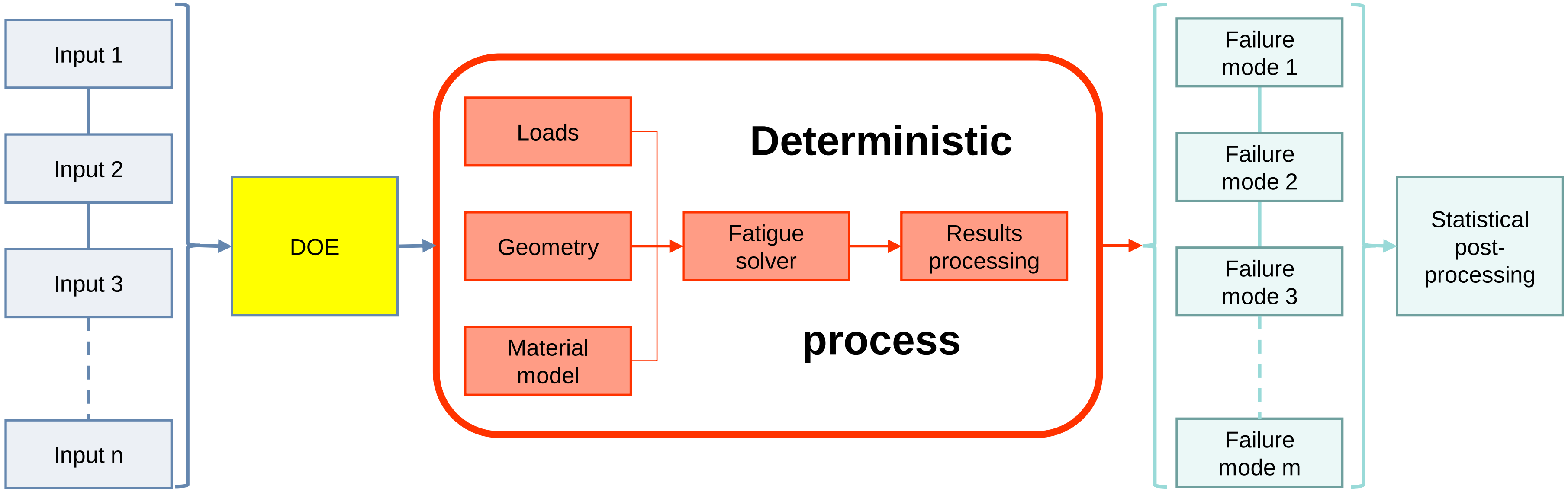
Probabilistic Design Simulation Method



Measurement Uncertainties

- mean values & probability distributions

DOE (Design of Experiments)
– Design space optimization

- Design for Reliability
  - Latin Hypercube Method
- Design for Robustness (extreme edge cases)
  - Factorial Methods
  - Response Surface Methods

Monte Carlo

- wrapper around an existing deterministic fatigue analysis
- multiple runs using different input values for each run

ROM (Reduced Order Model)

- reduce FEA processing load

Statistical Reliability Analysis

- Collate results
- Bayes-Weibull analysis
  A priori assumption on fatigue life distribution
  - log-normal
  - Weibull (assumed β)

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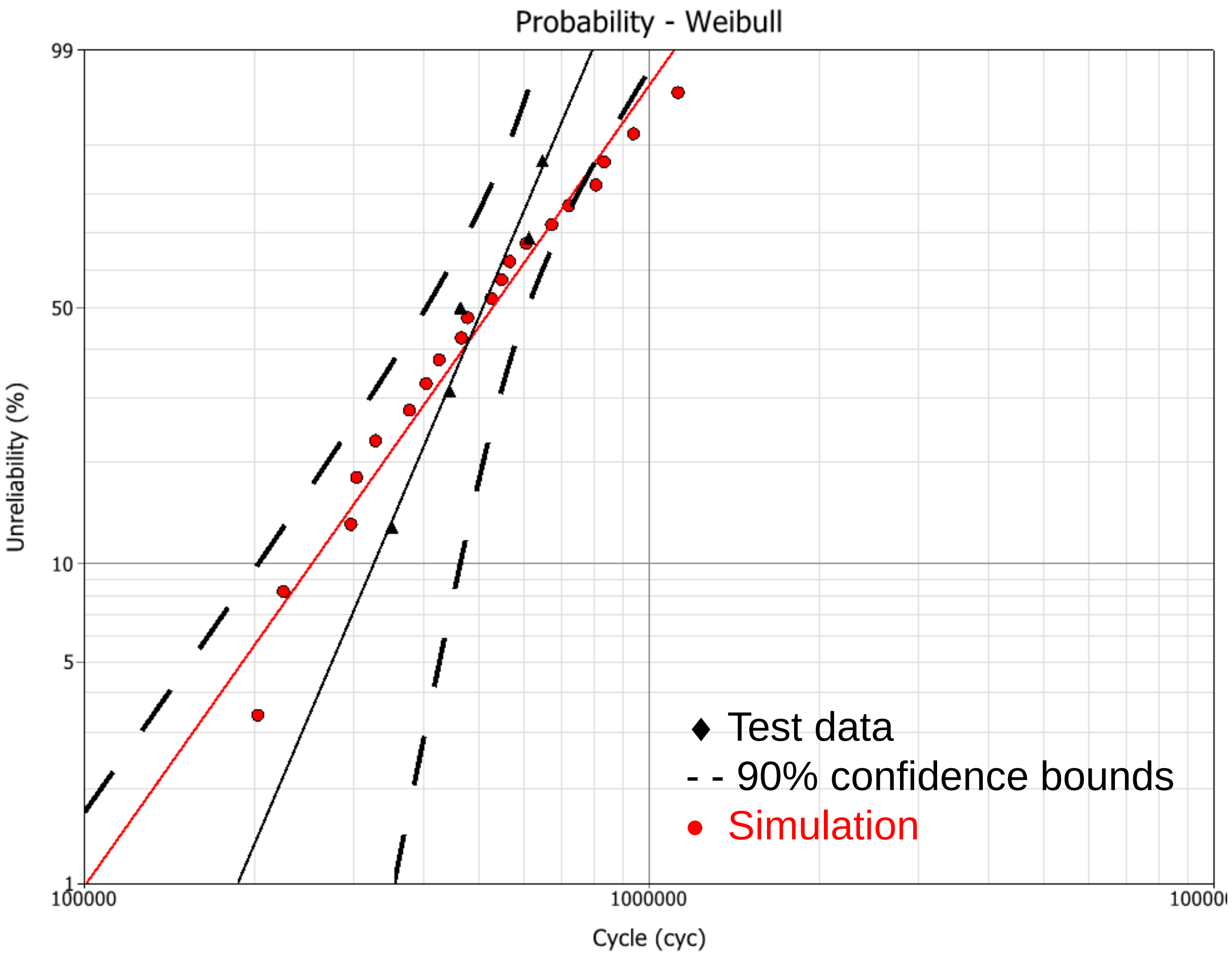
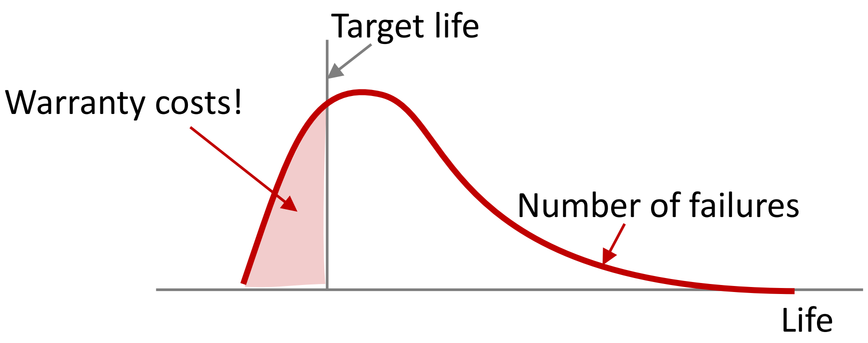
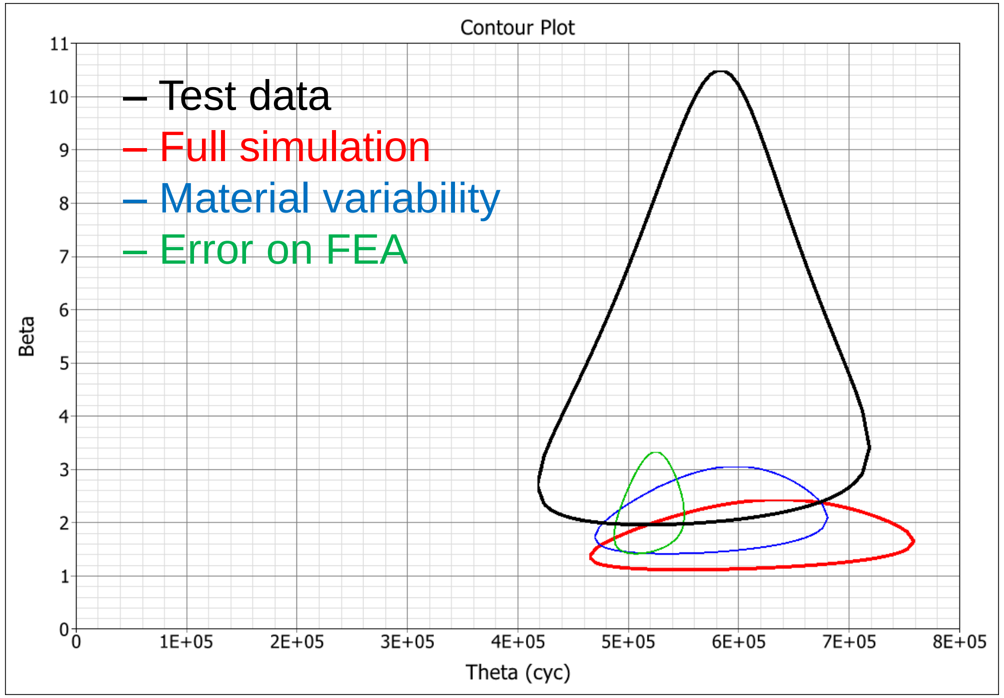
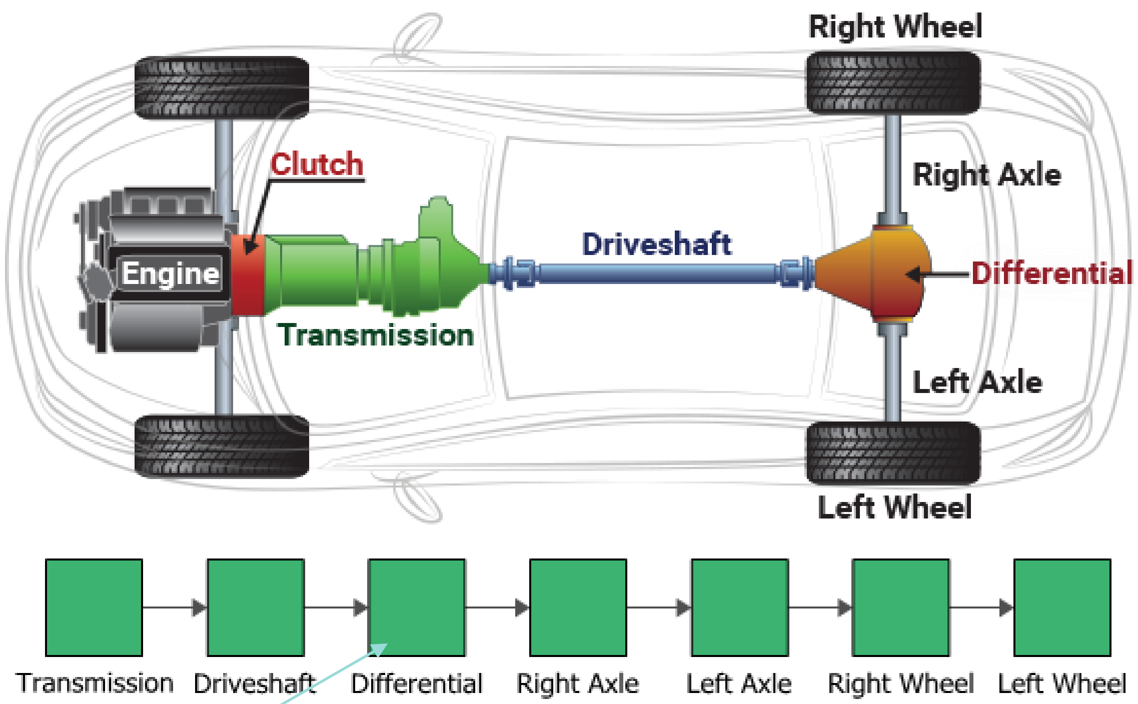
Statistical Correlation of Test and Simulation – *small sample sizes*

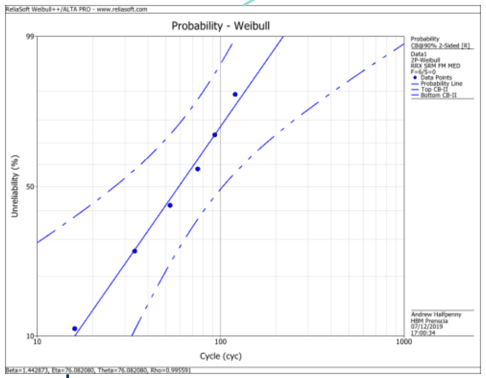






System-level Simulation

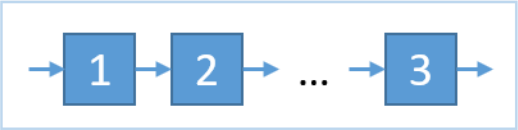




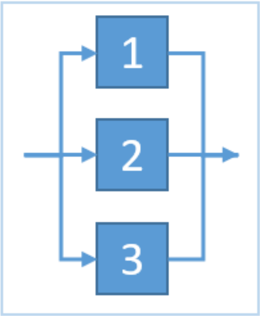
Reliability model for each failure mode is assembled into a “Block Diagram”

- Failure modes can be serial – one failure causes the entire system to fail
- or parallel – redundant failure paths or non-critical failures

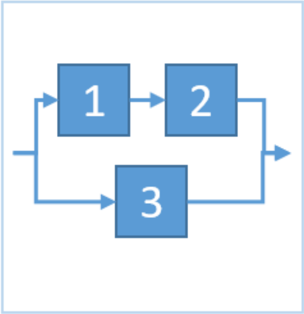
Allows reliability simulation of complex systems → Quantifiable Risk Exposure → Reliability Growth Analysis → Optimal Maintenance Planning → etc….



a) Series systems



b) Parallel systems



c) Combined systems

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Conclusion

Representing the target customer

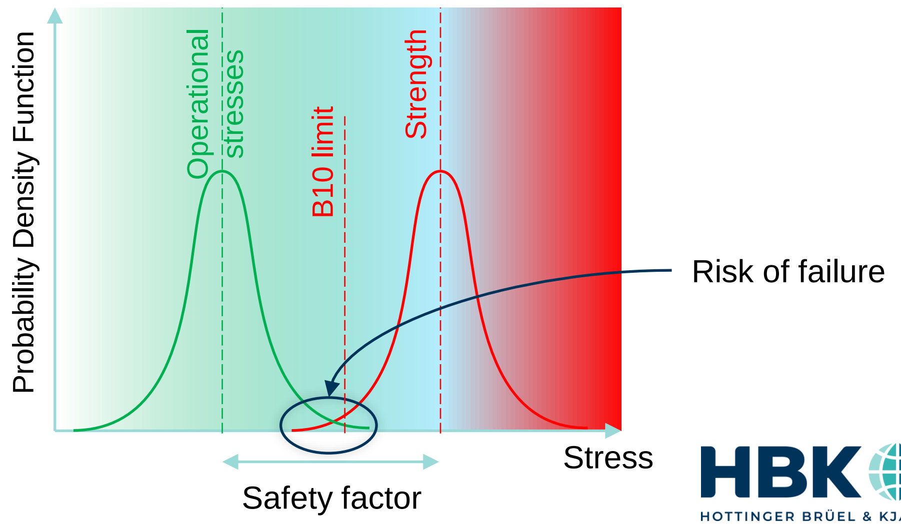
- Statistically the same damage content as the worst real-world conditions
- Accelerated to an optimum level without incurring overload
- Many different types of test ….

Simulation 🤝 qualification test

- Simulation before the test
  - Will it pass the test?
  - Where will it fail?
  - Is the test representative?
- Simulation during the test
  - Where is the best place to mount accelerometers?
  - How do test measurements compare with simulation?
  - Can I improve my Digital Twin using modal analysis?
- Simulation after the test
  - What should I do if it fails the test?
  - How confident am I?
  - Should I test to failure?
  - How is my reliability affected by different platforms, usage mix, country, etc.

Establishing product reliability

- Validate the simulation model
- System-level reliability simulation
- Ensure product reliability and quantify warranty exposure



Thank You

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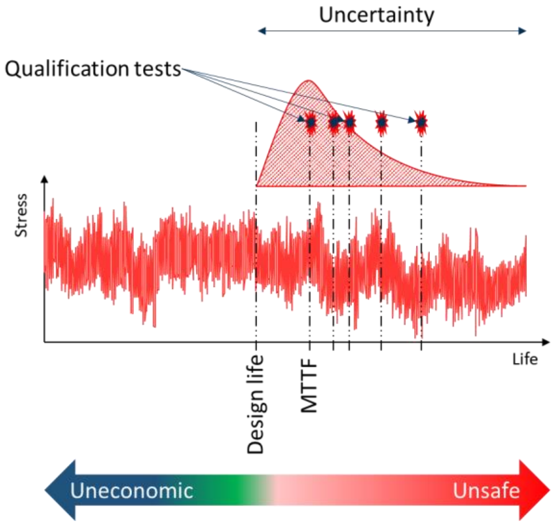
HBK Technology Days – Virtual Seminar Series

Tuesday, November 22, 2022



Statistical and Reliability Aspects of Electric Vehicles

Presented by Dr. Andrew Halfpenny,
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