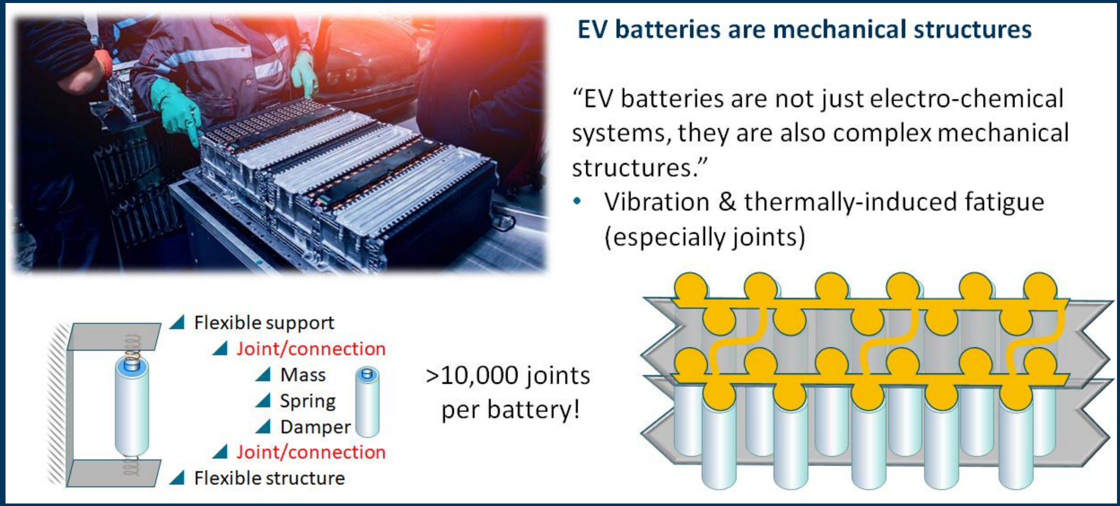
Virtual Seminar Series – Tuesday 2, 9, 16 November



Durability and Reliability of Electric Vehicle Battery Structures

Presented by Dr. Andrew Halfpenny
Director of Technology
Prenscia (HBK)

Tuesday, November 16, 2021

Durability and Reliability of Electric Vehicle Battery Structures

Abstract

<u>Battery Structural Durability</u>

Like their thermal-engine counterparts, electric vehicles are susceptible to structural fatigue failures. The mechanical complexity of the battery structure and its mountings also give rise to significant additional fatigue failure issues. Insights into these structural and vibration-induced failures enable engineers to eliminate the risk of fatigue failure, improve the durability of electric vehicle batteries, and increase vehicle reliability. This presentation considers:

- Fatigue design of battery packs
- Accelerated vibration testing of battery packs
- Fatigue analysis of battery structures

<u>Battery Reliability</u>

All electric vehicle batteries degrade overtime. Their performance, however, varies by model and external conditions such as usage, temperature, and charging methods. To improve the overall reliability of the battery system and avoid excessive warrantee exposure, it is important to understand both the mean life and the statistical distribution of lives for the battery. Furthermore, understanding how the battery degrades over time will lead to significant improvements in battery design, reliability, and vehicle efficiency. This presentation considers how Prenscia experience with mechanical fatigue testing, material characterisation, fatigue modelling and analyses are applicable to battery reliability:

- Battery life analysis
- Battery performance degradation modelling and analysis
- FMEA for new failure modes

About the presenter, Dr. Andrew Halfpenny, Chief Technologist, Prenscia (HBK)

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.

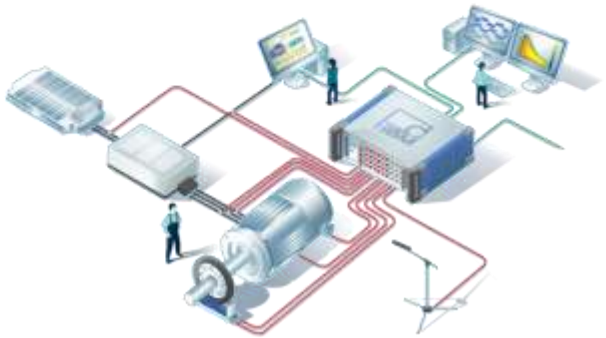
Durability and Reliability of Electric Vehicle Battery Structures

Dr. Andrew Halfpenny
Director of Technology – nCode Products

PUBLIC

Development

eDrive Test Systems



VI-Grade Noise & Ride Simulators

VI-GRADE

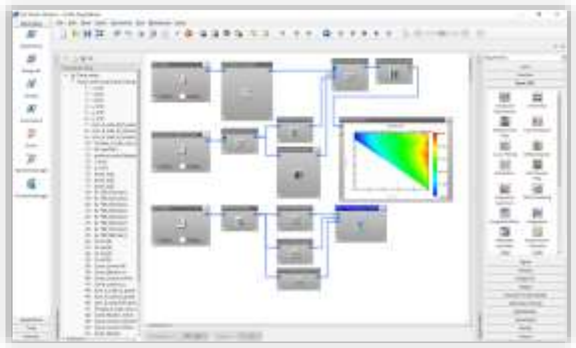
Qualification

LDS Shaker Systems

Analysis Software

nCode

ReliaSoft



Quality Assurance

DISCOM Production Line Quality Assurance

DISCOM

B&K Sound & Vibration Measurement & Analysis

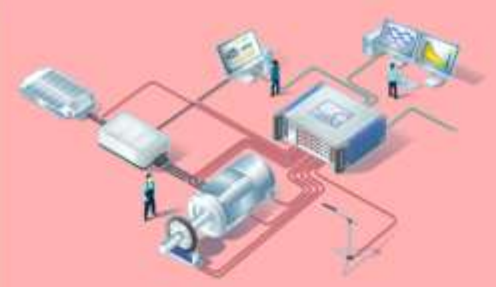
B K

HBK

HOTTINGER BRÜEL & KJÆR

Challenges

Vehicle Electrification
Challenges & Solutions



Performance

- Bench testing
  - Better vehicle range
  - Better energy density
  - Better thermal performance
- Power measurement & analysis
  - Better accuracy
- Real-world usage & efficiency assessment
  - Better understanding of real customer usage
- **Digital Twin**
  - Early detection of anomalies
  - Continual through-life improvements

IOT

Durability

- Fatigue design of battery packs
  - *"Batteries are mechanical structures"*
  - Reduce battery degradation
- Accelerated vibration testing of battery packs
  - Better understanding of thermal & vibration loads
  - More representative vibration tests
- Fatigue of light-weight structures
  - Lighter, more durable vehicles
  - Lighter, more compact batteries
- **Digital Twin**
  - Avoid in-service failure

IOT

Reliability

- FMEA for new failure modes
  - Identify potential risks earlier
  - Capture best practice
- Battery life & reliability growth analysis
  - Reduce warranty exposure
  - Analyze reliability, availability, and maintainability
  - Promote continual reliability growth
- System of Systems modelling
  - Optimize complex battery systems for reliability
- **Digital Twin/FRACAS**
  - Reduce lifetime warranty costs

Challenges

Vehicle Electrification
Challenges & Solutions

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  - **Better vehicle range**
  - **Better energy density**
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IOT

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  - **Lighter, more durable vehicles**
  - **Lighter, more compact batteries**
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IOT

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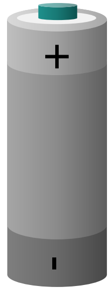
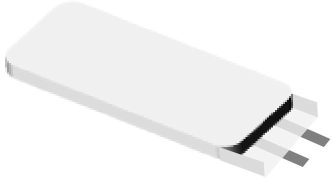
  - **Reduce lifetime warranty costs**

Batteries are mechanical structures

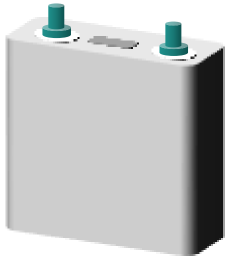


Laminated foil pouch



2.8< 3.7v <4.2

Hard case



C-cells

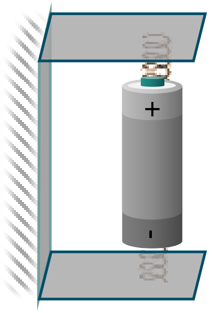
Prismatic cells

Battery Pack

- Vibro-thermal fatigue of cells & joints
- Progressive failure → battery degradation

- Broad range frequency input & response
- Highly variable damping

Battery Modules

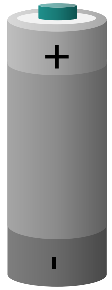


- Flexible structure
  - Joint
    - Mass
    - Spring
    - Damper
  - Joint
- Flexible structure

>10,000 joints per battery!

- Battery enclosure part of vehicle structure
- Both inertially and structurally loaded
- Transfer road loads & crash protection
- Structural fatigue & adhesive/hybrid joints
- Structural light-weighting

Batteries are mechanical structures



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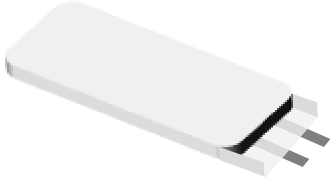

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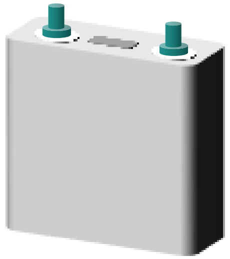

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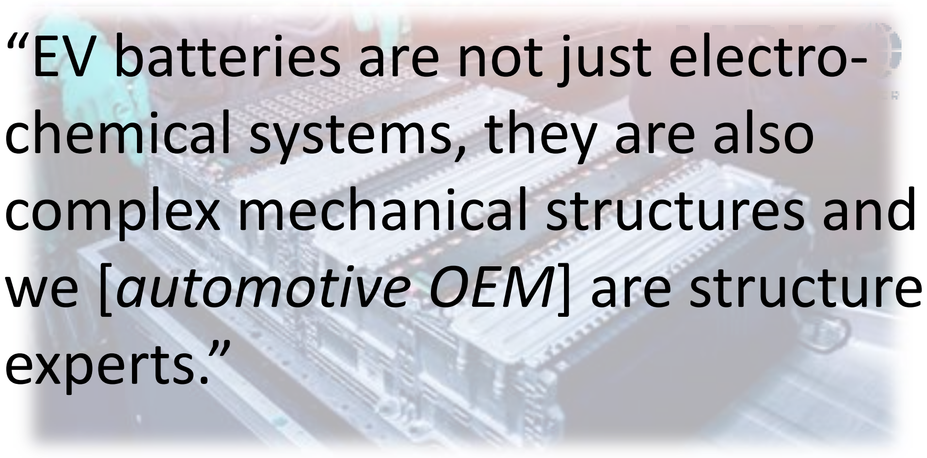

“EV batteries are not just electro-chemical systems, they are also complex mechanical structures and we [*automotive OEM*] are structures experts.”

Battery Pack

- Vibro-thermal fatigue of cells & joints
- Progressive failure → battery degradation

- Broad range frequency input & response
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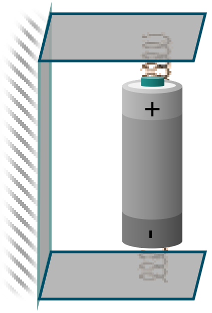
Battery Modules



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    - Mass
    - Spring
    - Damper
  - Joint
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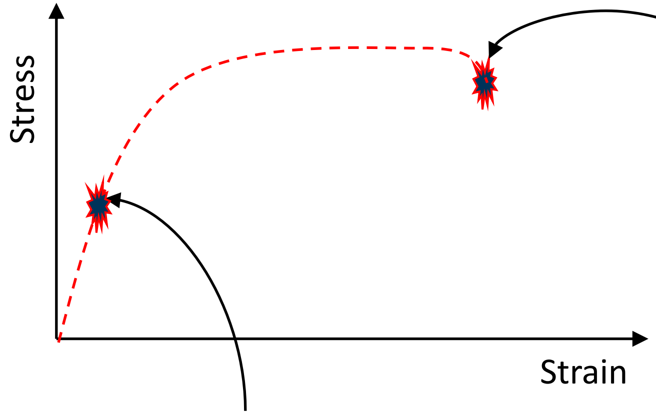
What is fatigue?

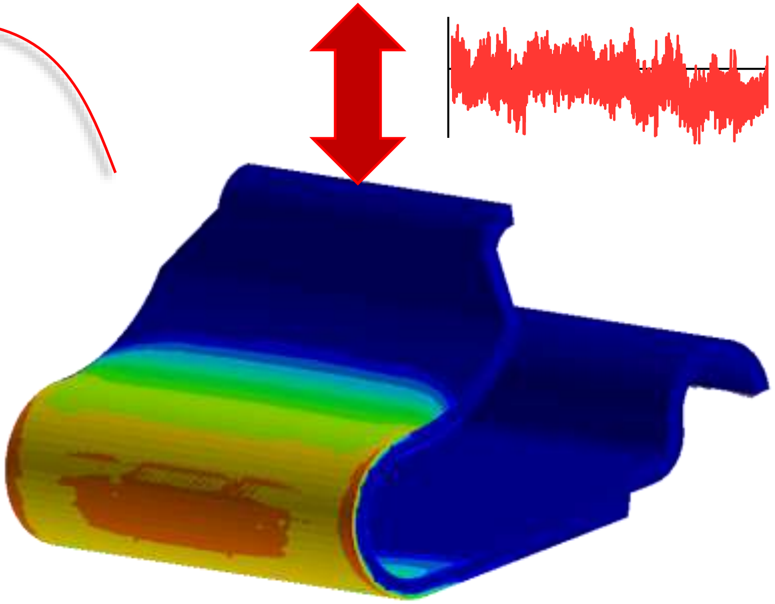
Stress V’s Strain Plot

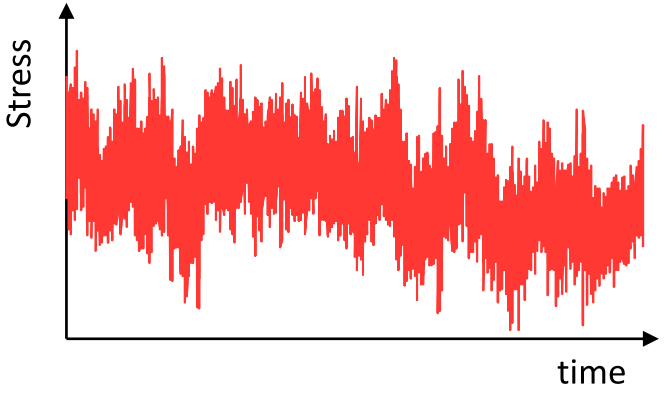


Apply cyclic load
at low stress level

STATIC failure:

Failure when stress exceeds UTS in a single pass





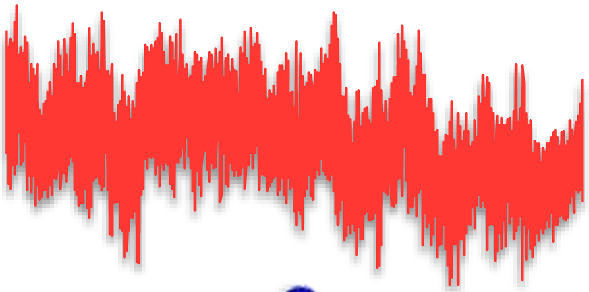
FATIGUE failure:

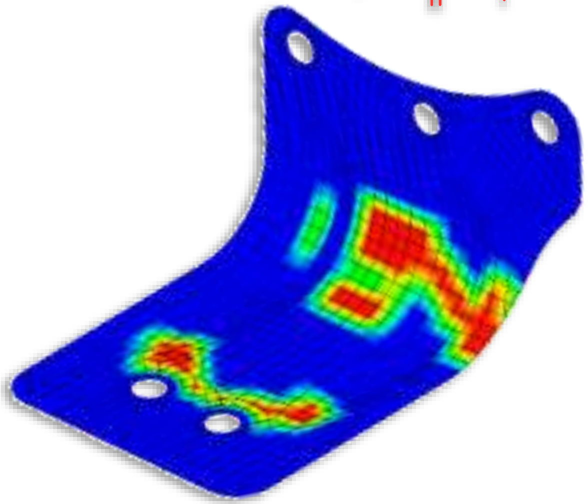
Fatigue is the progressive weakening of a material caused by varying loads, even though the resulting stresses are well within the static strength limits.

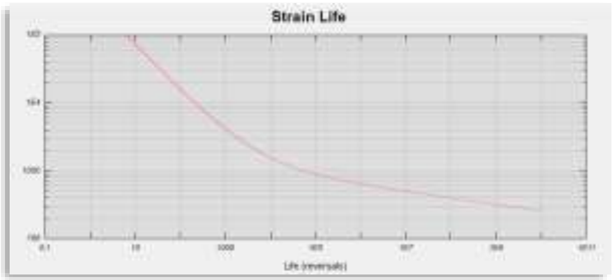
The component seems to get ‘Tired’, hence the name FATIGUE

Fatigue analysis roadmap

- Measure **vibration** input to the battery pack/modules
- Measure **temperature**
  - thermo-mechanical fatigue
  - constrained thermal expansion







Loading

Geometry

Materials

Fatigue analysis

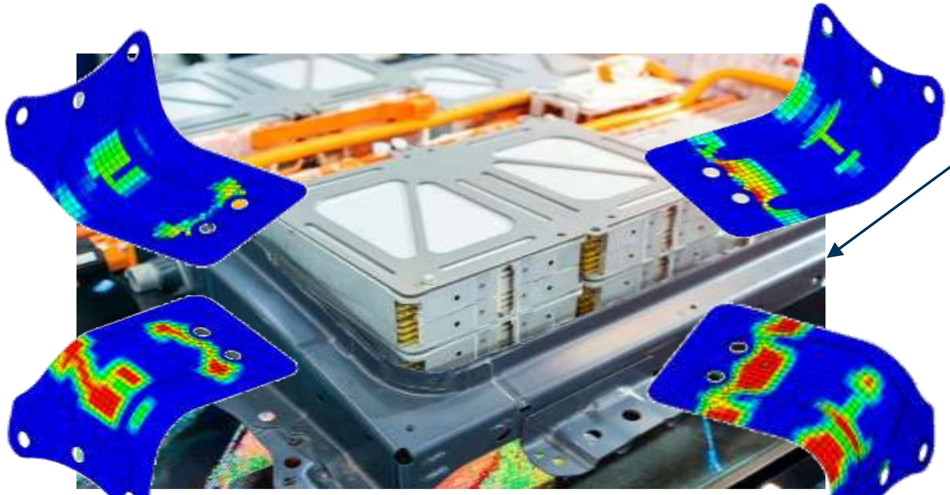
Fatigue life

How do we find the loads?

1. Statistical target customer analysis

2. Make it scientifically reproducible

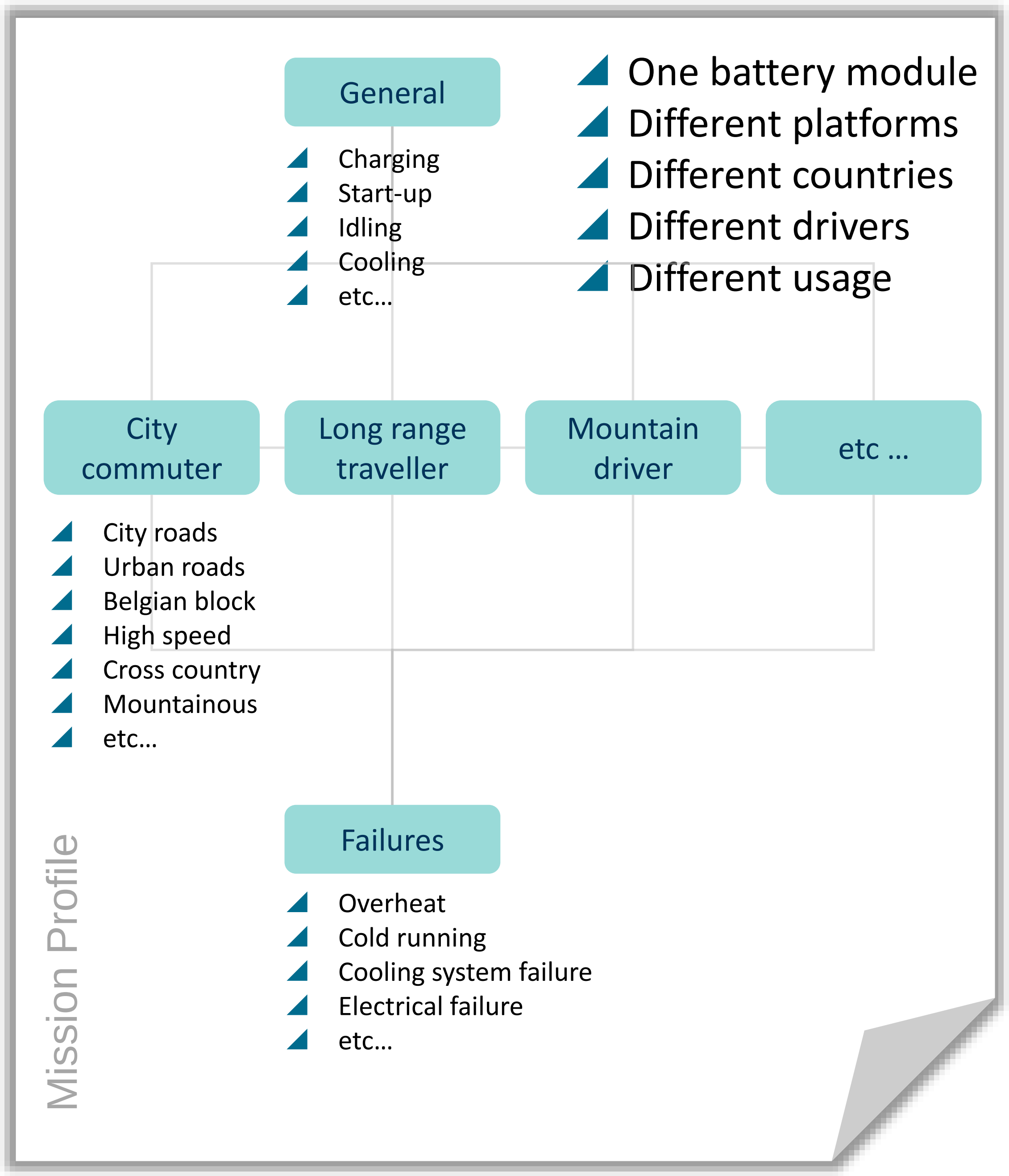
3. Accelerated qualification testing



4. Simulate the qualification test

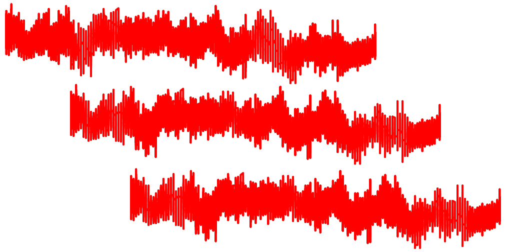
Mission Profiling & Test Synthesis – what is it?

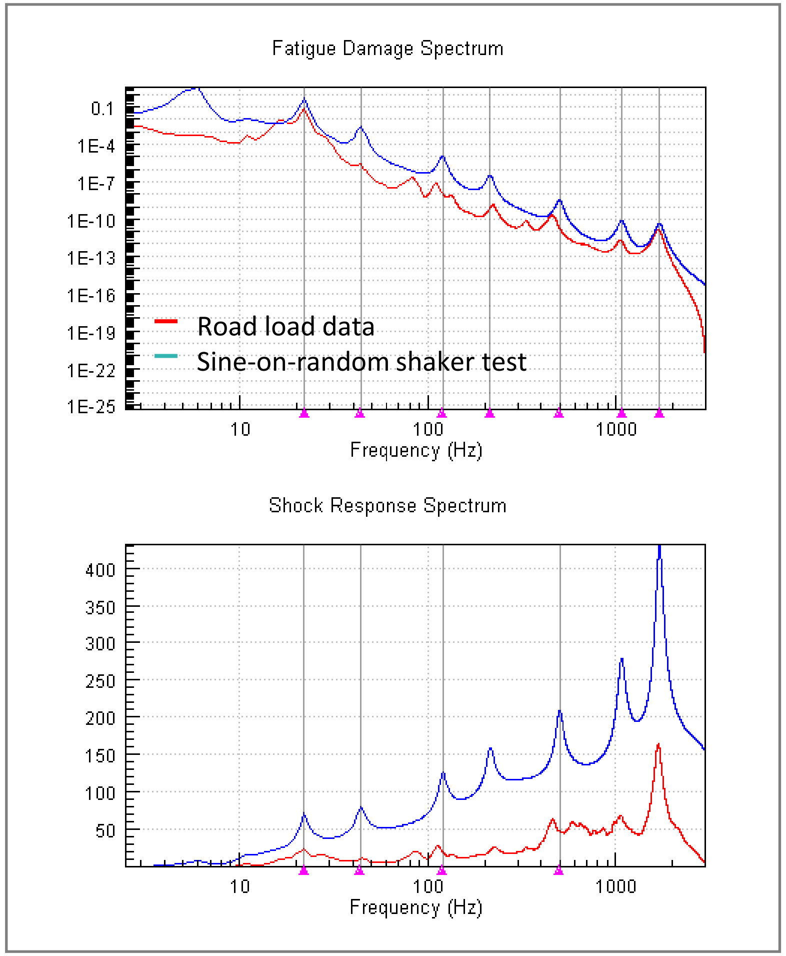
Requirement:
1. Shaker/thermal test spec ✓
2. Statistically worst-case world-wide damage content ✓
3. Accelerated (250,000 km → 150 hours test) ✓
4. Same failure modes as in-service (no over-acceleration) ✓



Mission Profiling & Test Synthesis – how?

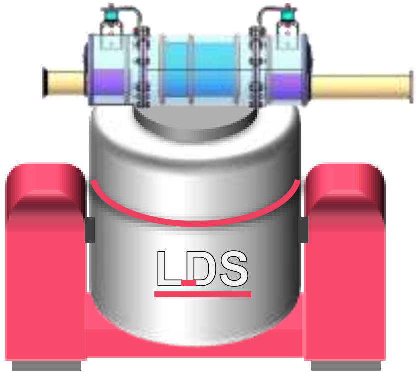
1. Proving ground road load data test – measure vibration levels for each surface/event

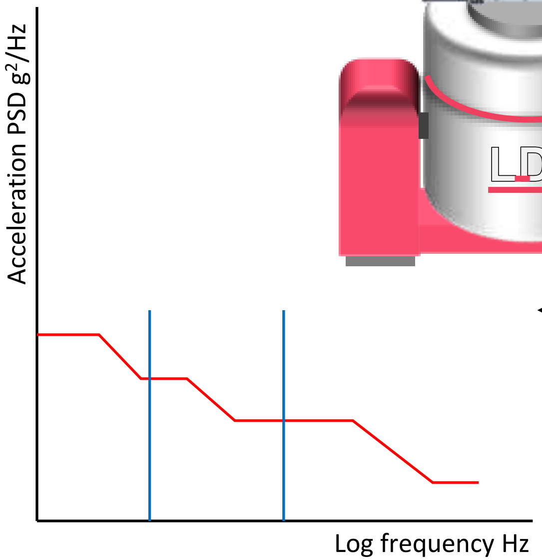




2. Characterise event data (*Fatigue Damage & Shock Spectra*)

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
- …

Fatigue analysis roadmap

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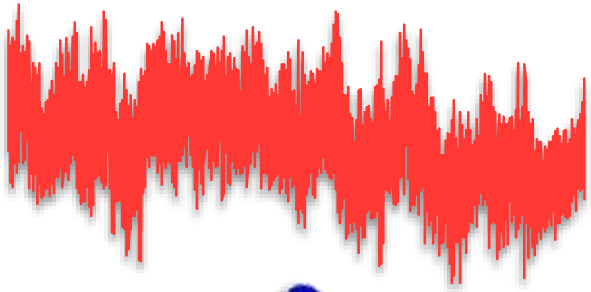

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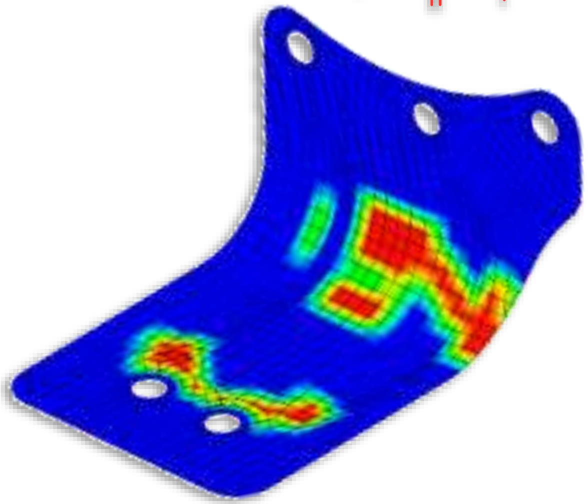

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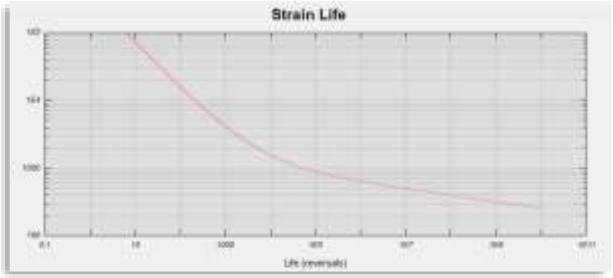


Materials

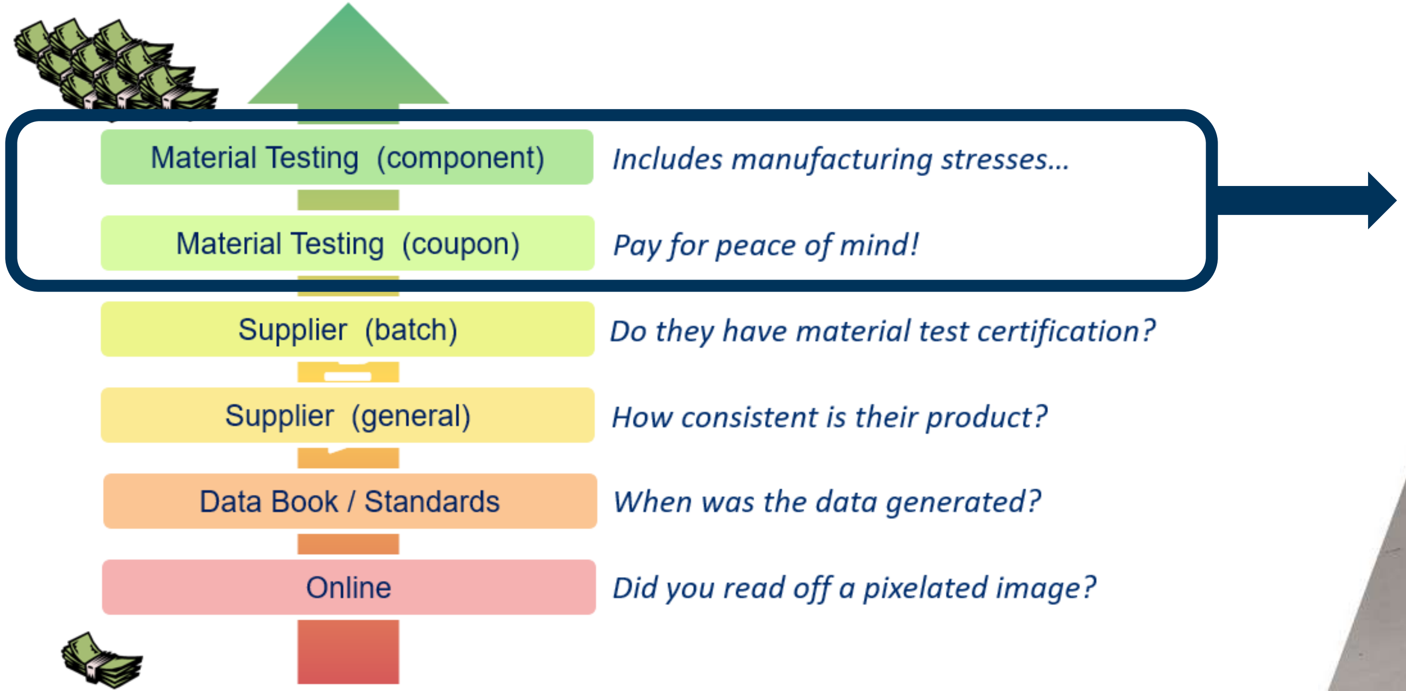
Fatigue analysis

Fatigue life

AMCT
Advanced Materials Characterisation and Testing

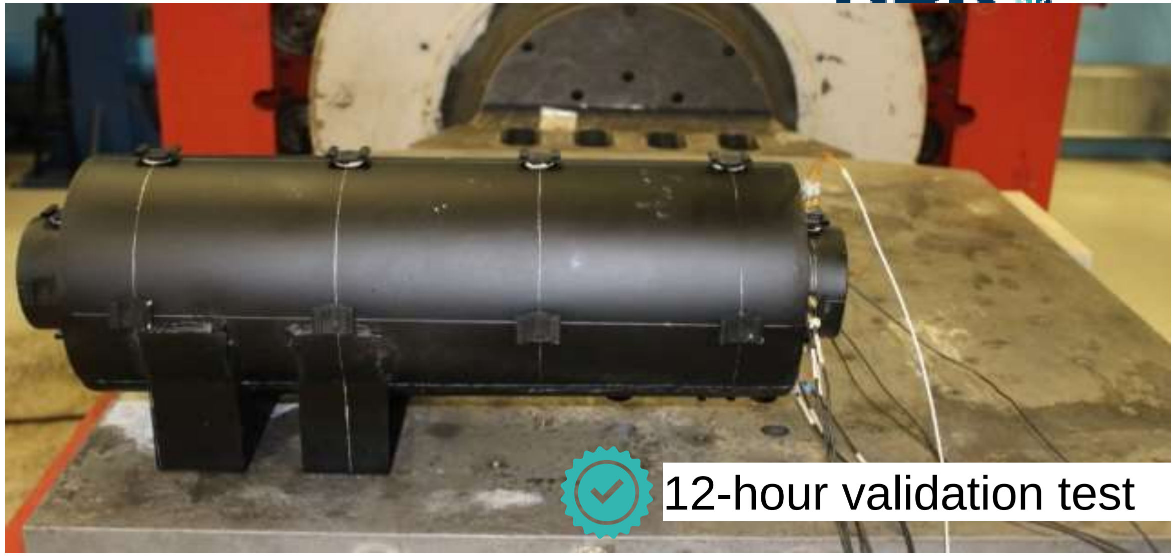
Understand the fatigue performance of the materials used for your products.

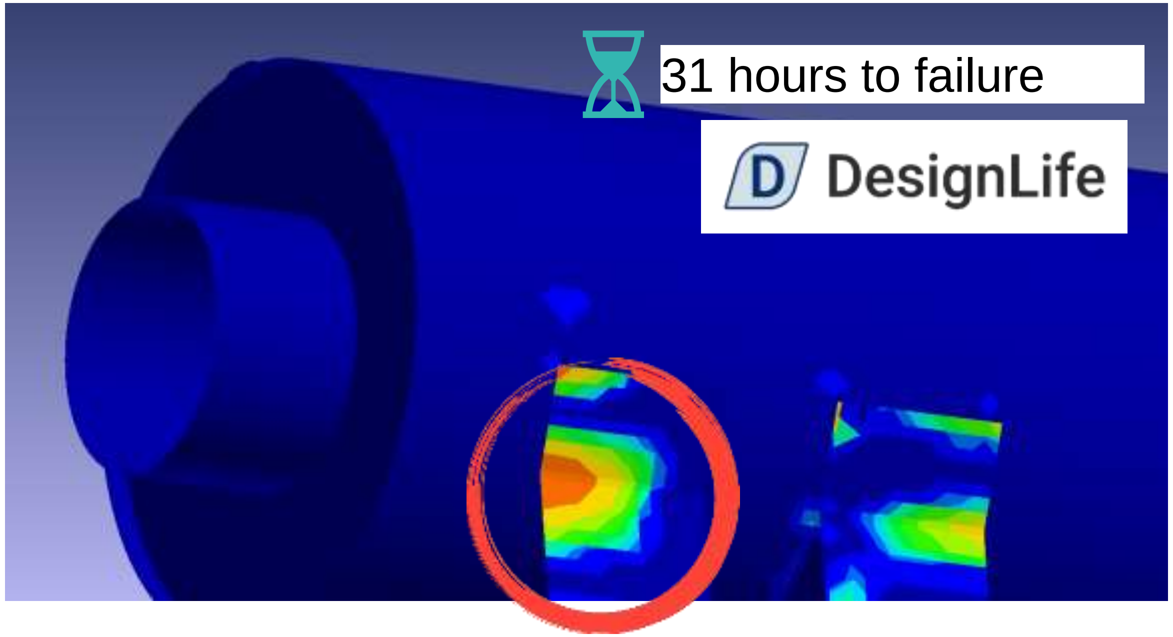
Increase the accuracy of fatigue calculations in order to predict and improve product lifecycles.



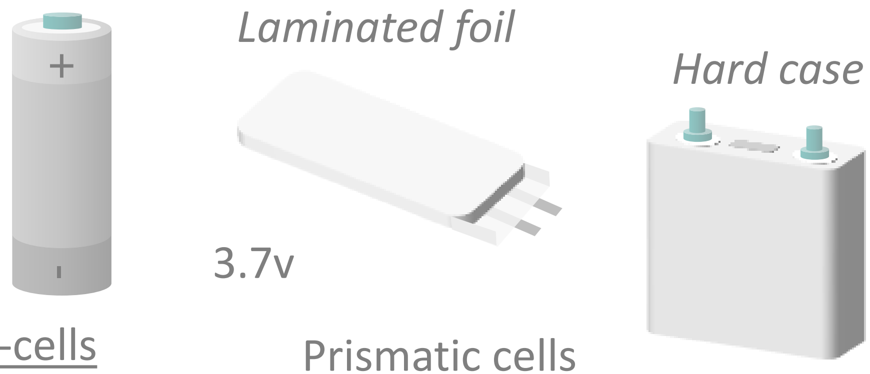
Virtual fatigue life prediction

- Simulate the fatigue life of the test article for trouble shooting & “what-if” games
  - ✓ Virtually test before committing to building and testing prototypes
  - ✓ Modal testing used to update the simulation
  - ✓ Predict design margins
  - ✓ Investigate failure modes and avoid them next time





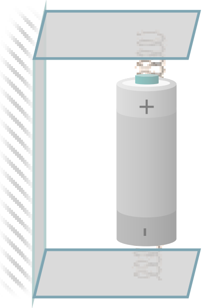
Conclusion



C-cells

Prismatic cells

Battery Modules



- Flexible structure
  - Joint
    - Mas
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    - Dam
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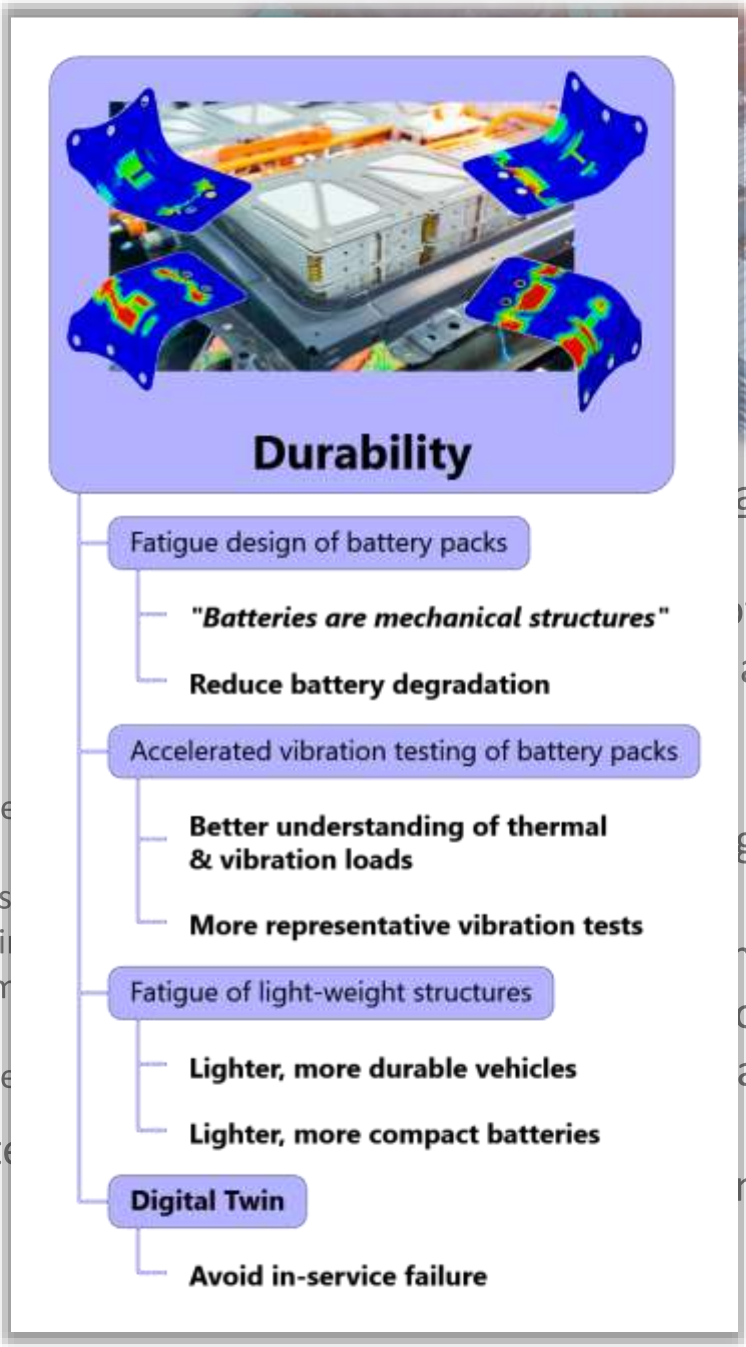
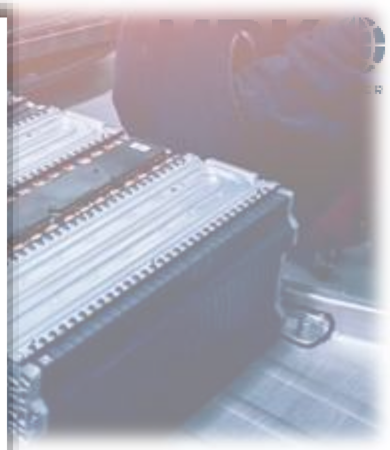
>10,000 joints per batt





ack

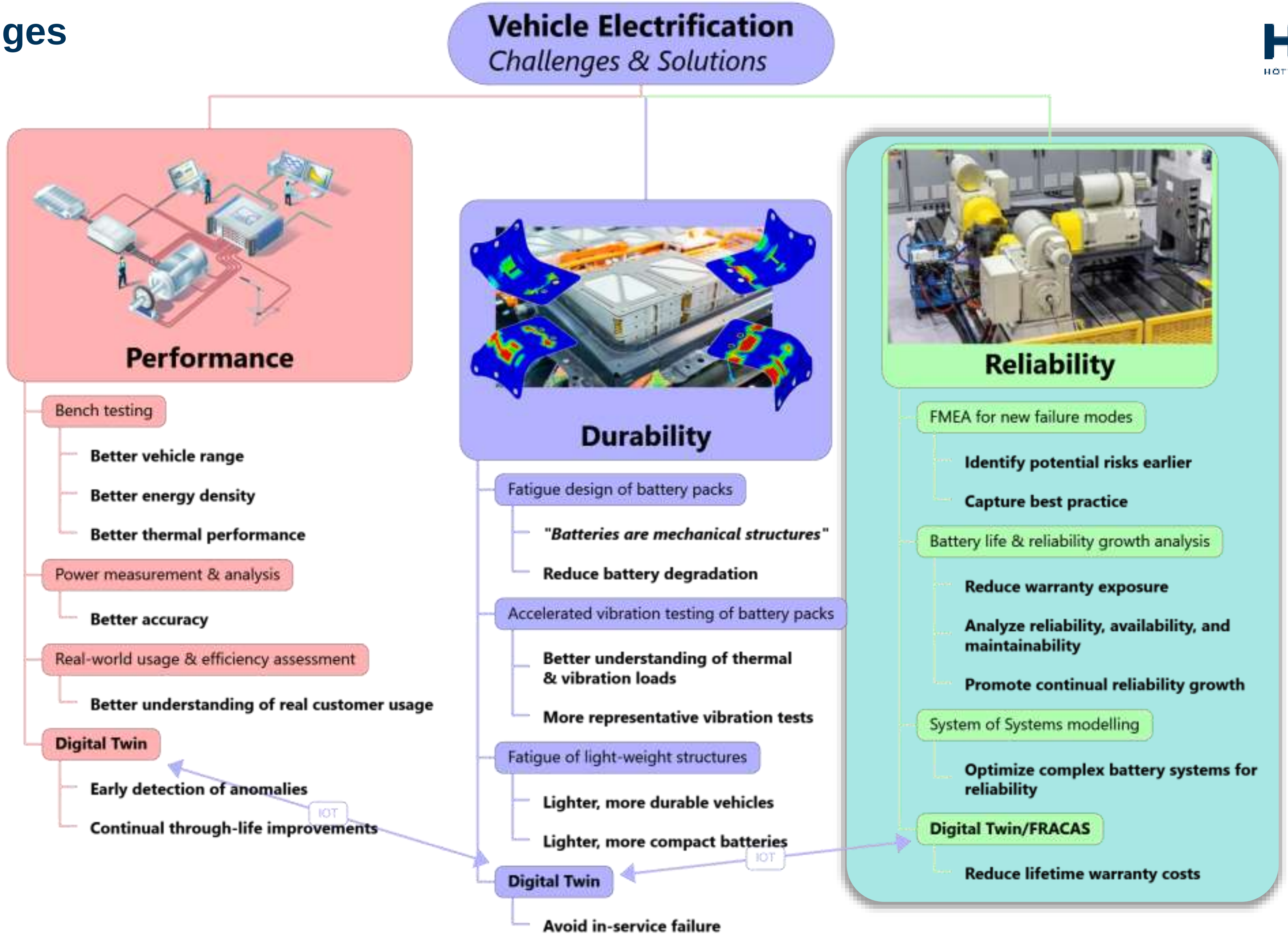
f joints
attery degradation

input & response
g

esive/hybrid joints
of vehicle structure
ash protection

ng

Challenges



Vehicle Electrification
Challenges & Solutions
Performance
Bench testing
Better vehicle range
Better energy density
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Capture best practice
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Promote continual reliability growth
System of Systems modelling
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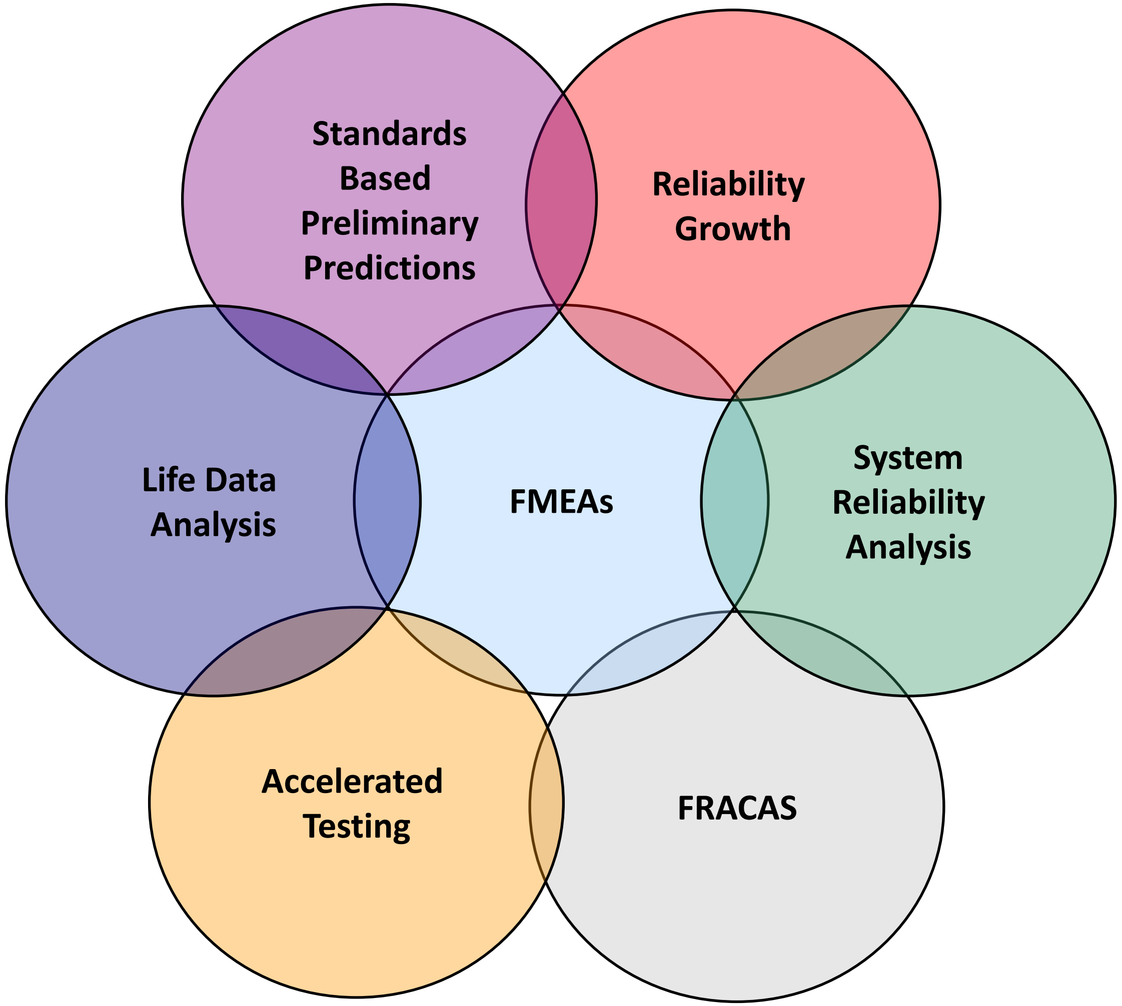
Reliability Engineering Tools

Goal: “to ensure that our product will:
a) perform its intended function adequately
b) for a specified period of time
c) in a defined environment
without failure”



Different failure modes

Mechanical failures

- Battery pack fatigue
- Vehicle structure fatigue

Thermal runaway

- Internal short circuit
- External short circuit or mechanical abuse

Capacity loss

- Capacity loss due to charge-discharge cycles
- Capacity loss due to calendar aging

Auxiliary systems

- Cooling
- Controls, BMS

Reliability Engineering Tools

Reliability

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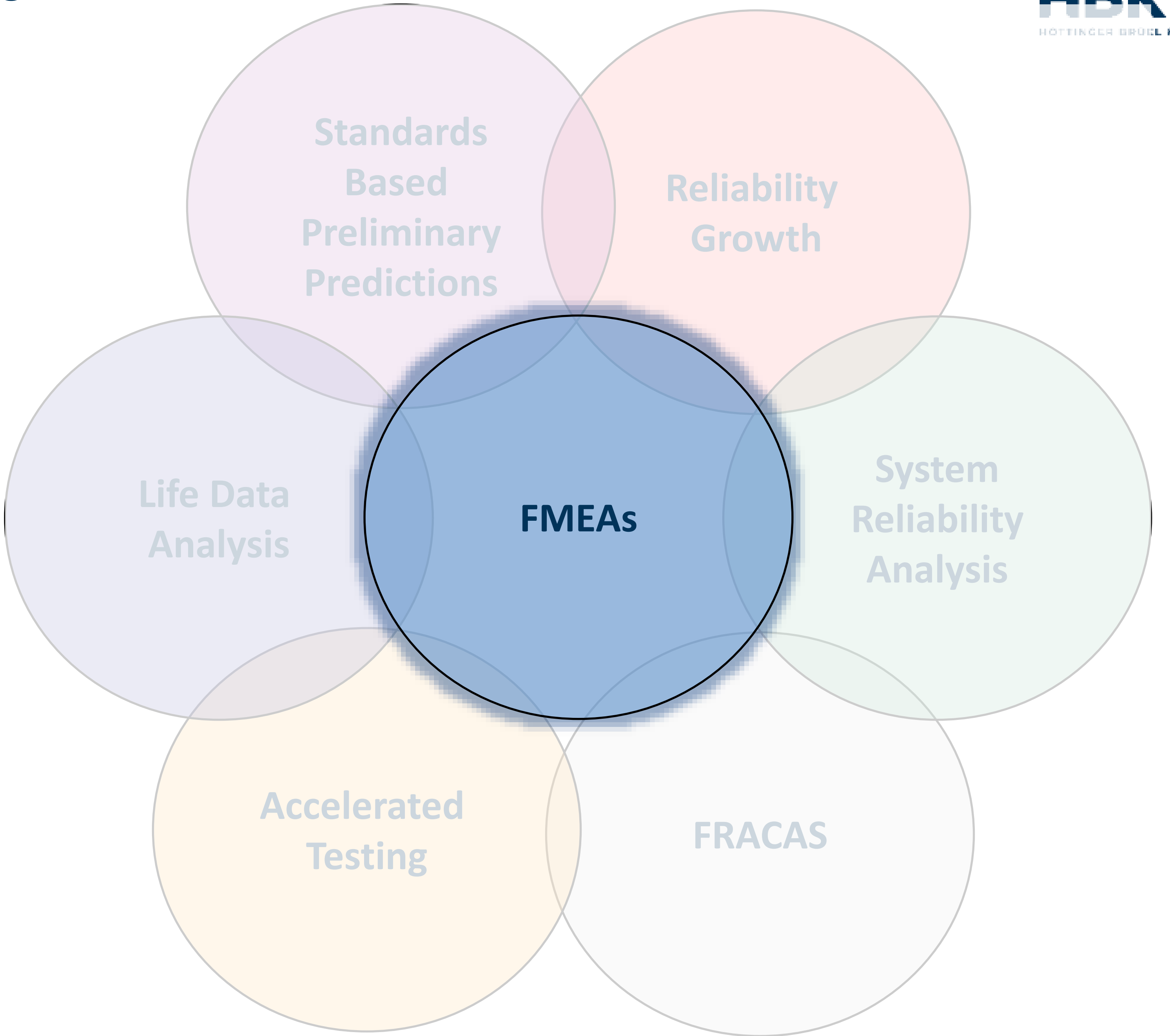
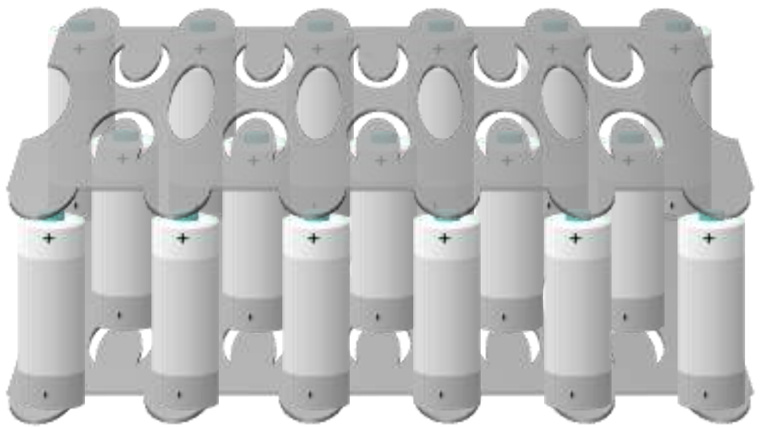


FMEA – Failure Modes and Effects Analysis

"A structured and methodical approach to identifying & mitigating risk & warranty exposure"

- Identify potential failure modes
- Assess risk
- Rank issues
- Decide corrective actions



- Team-work – more knowledge in a team

- Reliability
- Design
- Test
- Maintenance
- SMEs

FMEA – System Hierarchy and Risk discovery

System Hierarchy | FMRA

Reference Number	Name			F
	LFP Battery			F
	29Cell Module (34.8v)			
	Single Cell Assy			
	Welded End Cap -ve		1	F
	Welded End Cap +ve		1	F
	Cell Outer Metal Tube		1	F
	Damper		2	F
	Cell (1.2V 85Ah)		3	F
	BMS		2	
	Bus Bar Assy			F
	Weld Tab		1	F
	Upper Structure		4	F
	Bus Bar		4	F
	Lower Structure		4	F

Properties | Risk Discovery | FMEA

Label	Question	Response
New Technology	Will the design involve new technology?	Yes
New Application	Will the design apply existing technology in a new way?	No
Historical Problems	Is there a history of problems for a similar design?	Yes
Safety Issues	Is there a potential for safety-related issues?	No
Regulation Issues	Is there a potential for regulation-related issues?	No
Mission-Critical	Is this a mission-critical item?	Yes
Supplier Capability	Are there concerns about the supplier's capability?	No

FMEA – Procedure

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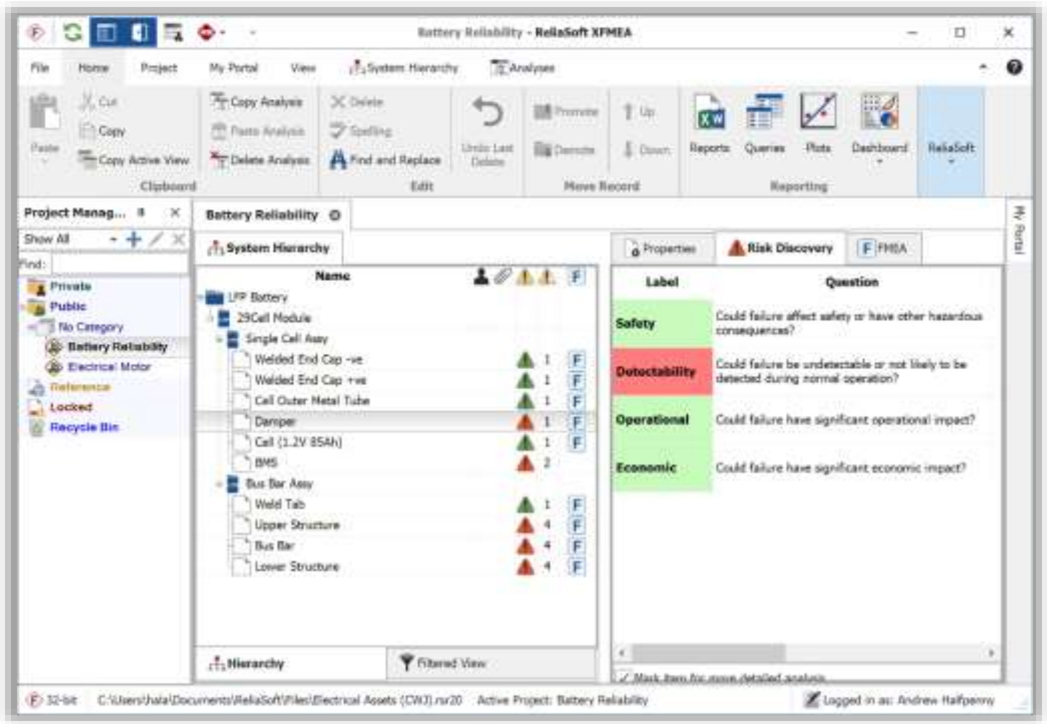
	Function	Potential Failure Mode	Potential Effect(s) of Failure	SEVi	Potential Cause(s) of Failure	OCCi	Current Design Controls	DETi	RPNi	Recommended Action(s)
1	Supply Voltage 1.2v for 85Ah	Thermal runaway	Lost of primary function for a single cell (7,-) Propagation beyond individual cell, catastrophic failure of the entire pack and potential damage to surroundings (9,-)	9	Short circuit due to overcharge or overdischarge	3	Current limiting by fuse	2	54	
2					Internal short circuit due to battery recharging in low temperature	2	Module temperature monitoring	2	36	
3					Electrolyte vaporization due to high storage temperature	3	Pressure detection	4	108	
4					Failure of the separator due to repeated charge-discharge cycling	4	Charge discharge current monitoring	2	72	
5					External short circuit	4		2	72	
6					External mechanical abuse	3		4	108	
7					Aging due to electrochemical cycling	2	SOH monitoring	2	36	
8		Does not supply specified voltage of 1.2v	Sub optimum performance (7,-)	7	Aging due to degradation of electrode properties caused by electrochemical cycling	6	SOH monitoring	2	84	
9					Accelerated degradation due to trace contaminants	2	Quality control	5	70	
10					Residual mechanical stress induced by the packaging the cell	5	Durability test	3	105	

FMEA – Failure Modes Effects Analysis

- Power of FMEA is in knowledge capture and recycling
- Items/Systems reusable between different vehicle/battery platforms – saves time!
- Central shared database of FMEA sheets
- Link with FRACAS – update FMEA using warrantee data
- Link with numerical analysis
  - Life Data Analysis
  - RCM (Reliability Centred Maintenance)
  - etc…



Reliability Engineering Tools

Reliability

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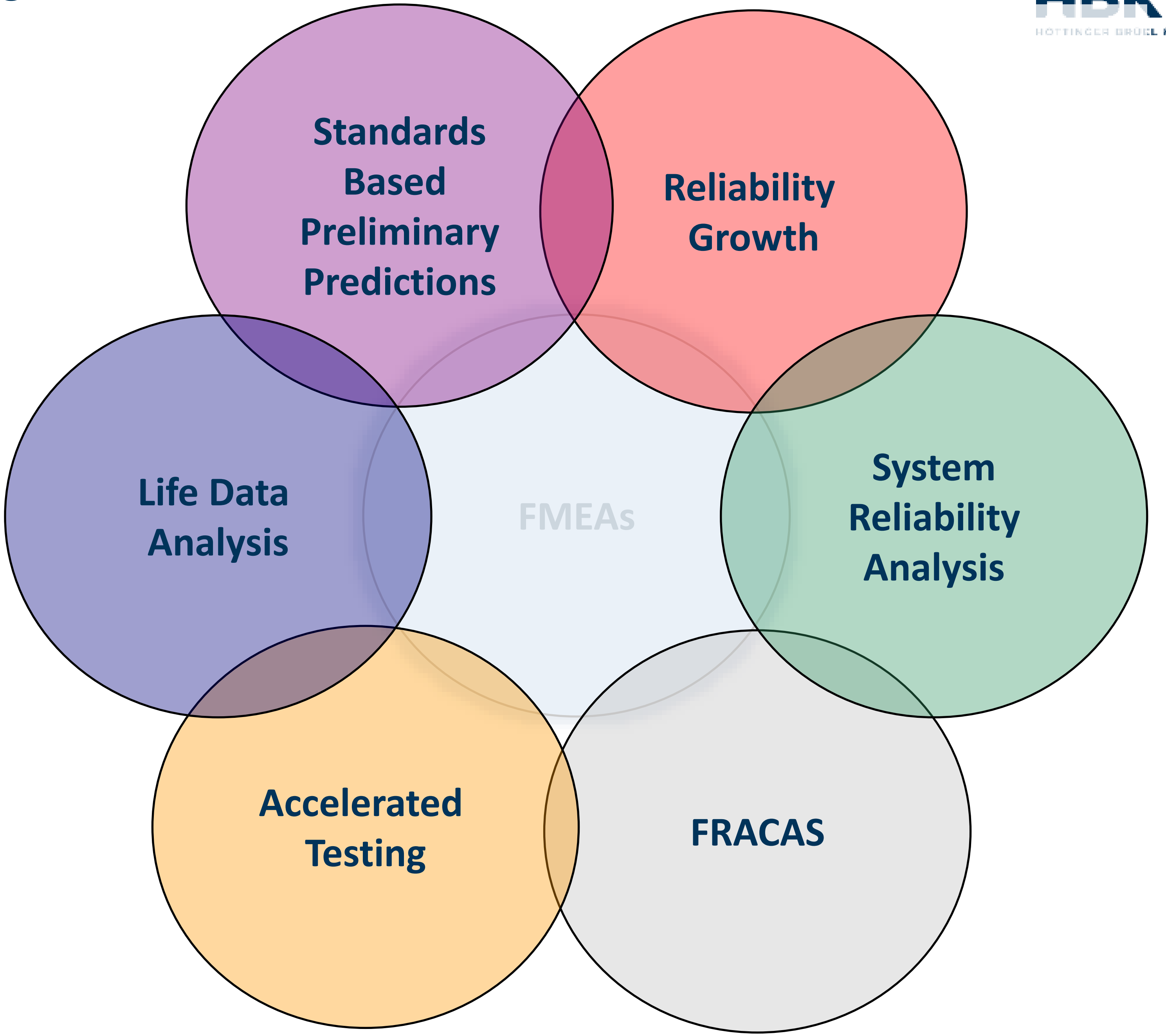
  - Optimize complex battery systems for reliability
- Digital Twin/FRACAS
  - Reduce lifetime warranty costs



Battery reliability target

- EVs are sold with battery pack guarantees
- 8 years / 100,000 miles
- Replacement is very expensive
- How many do failures are expected within the warrantee period?
- How to improve this?

Different failure modes & modelling

- Capacity loss
  - Cycle life
  - Calendar fade
- Mechanical failures
  - Battery pack fatigue
  - Vehicle structure fatigue
- Auxiliary systems
  - Cooling
  - Controls

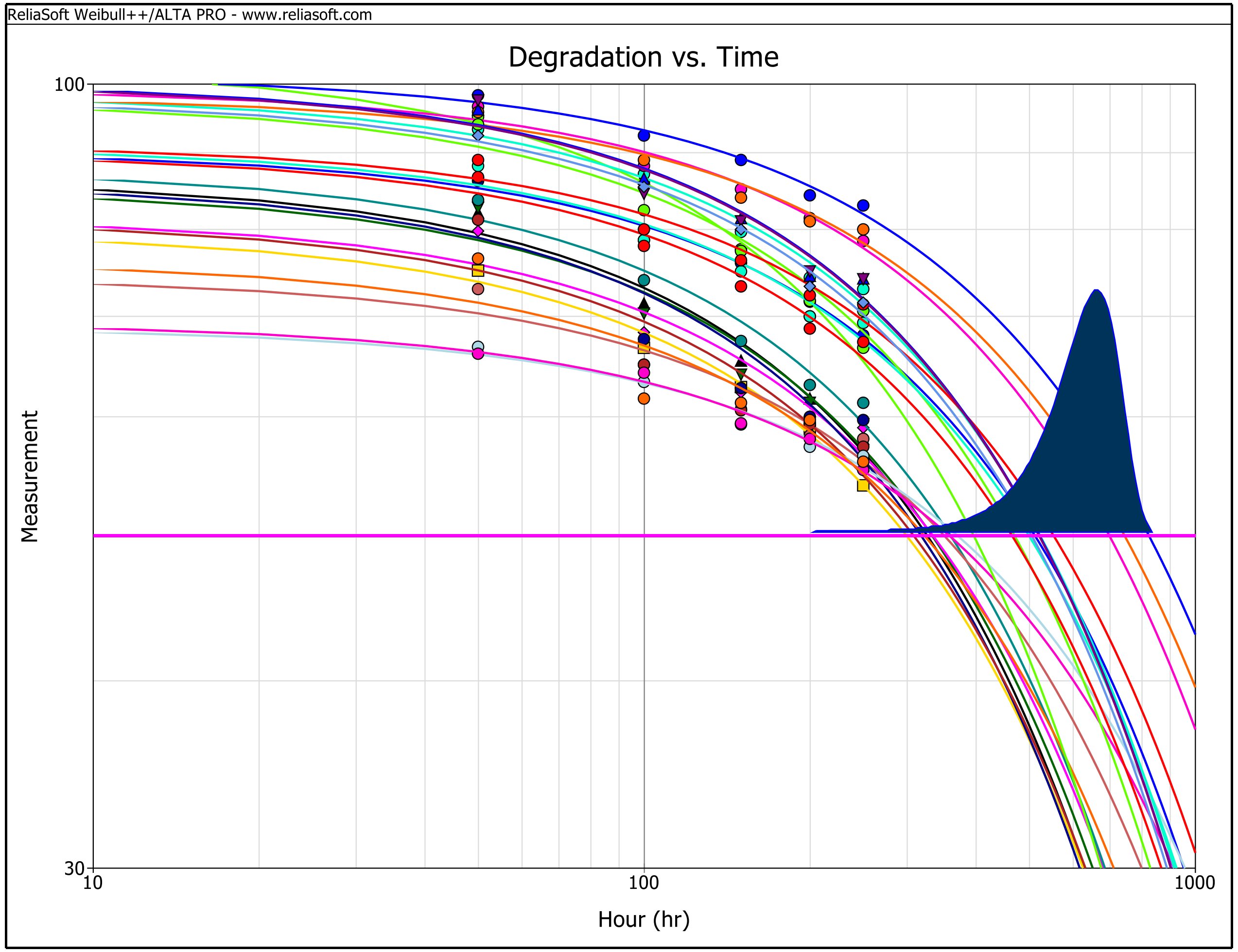
Phenomenological (statistics) models

Engineering design models

Constitutive (physics) models

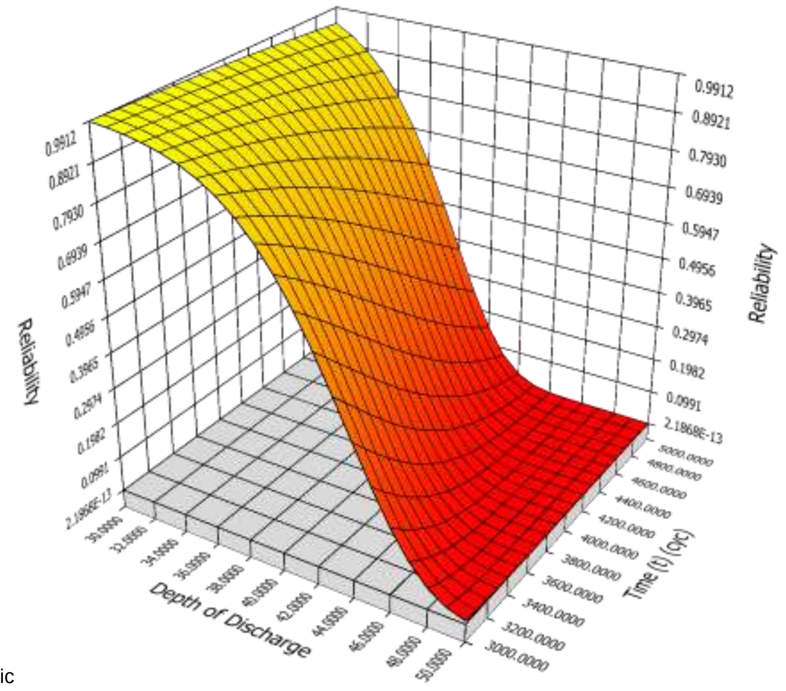
Life testing

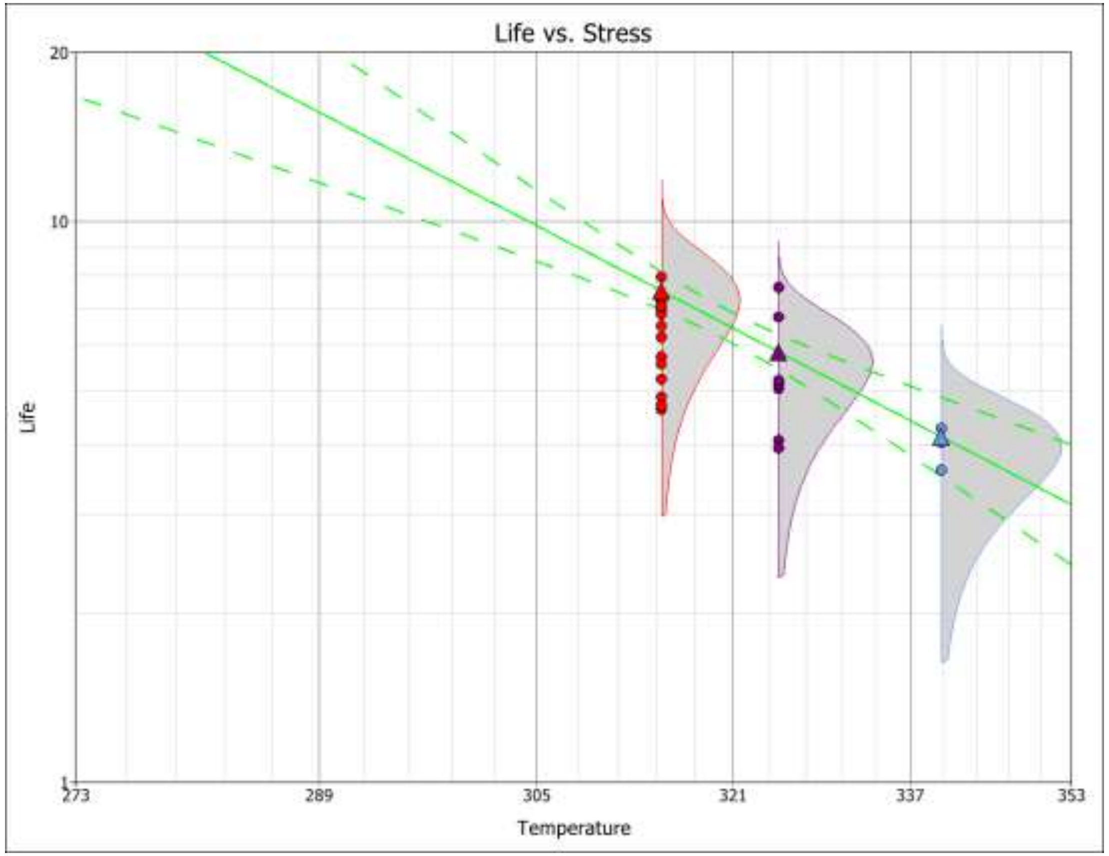
- Test and record time or cycles to failure or success, fit distribution
- Go from life estimate to reliability estimate
  - “91% to 99% reliability at 8 years”
  - “B5 life of 8.5 years”
  - “>90% reliability at 90% confidence”
- Requires failures, but there are workarounds



Accelerated life testing

- Physics models tell us how life changes with several factors
  - Arrhenius with temperature
  - Power-law with DoD
  - Generalized Eyring for both
- Can get failures faster and extrapolate to use condition

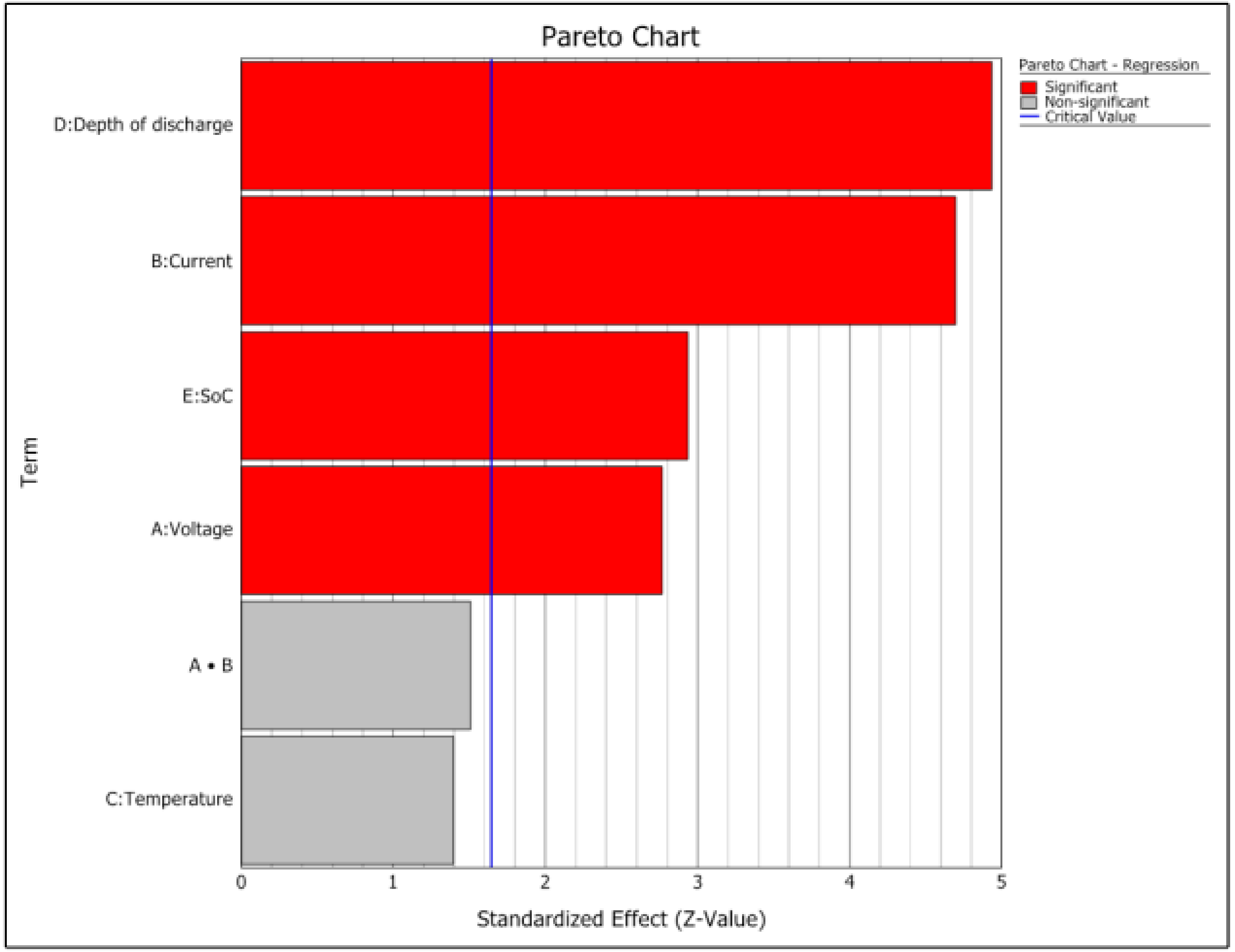




Quantify effect of stresses

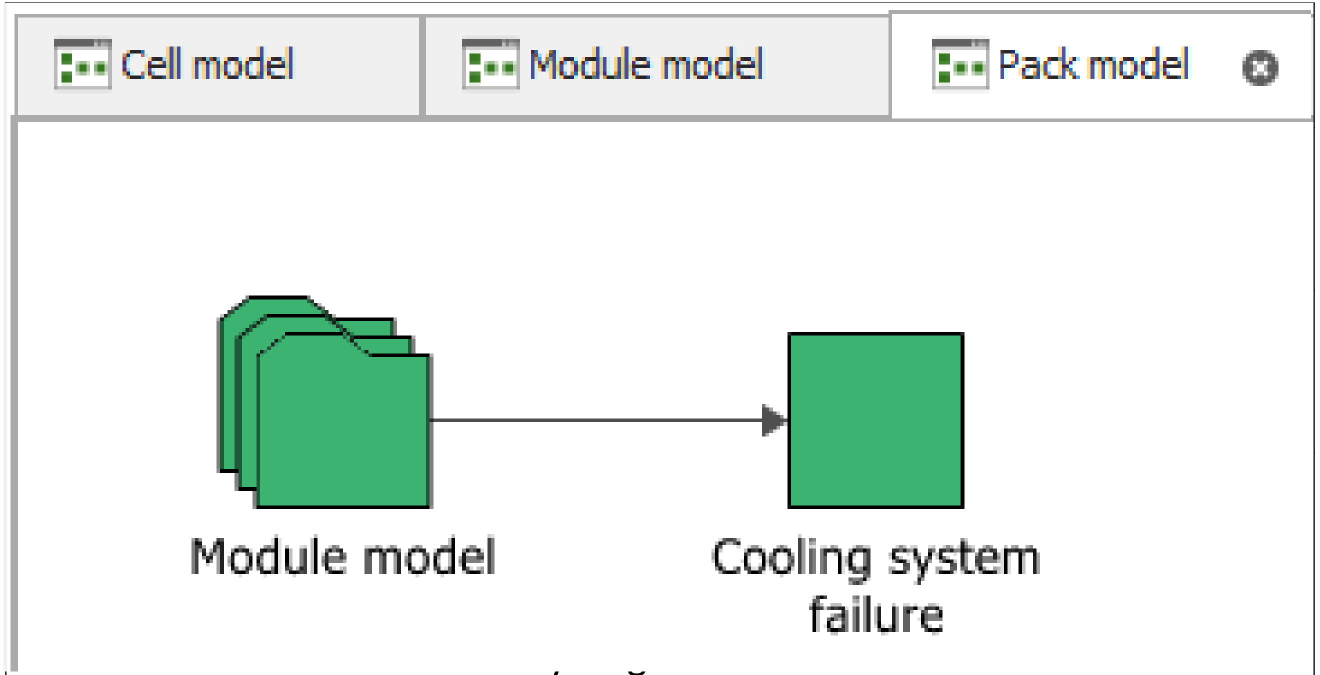
- Identify important stressors using DOE

- Use primary effects for accelerated test with more extrapolation



System reliability

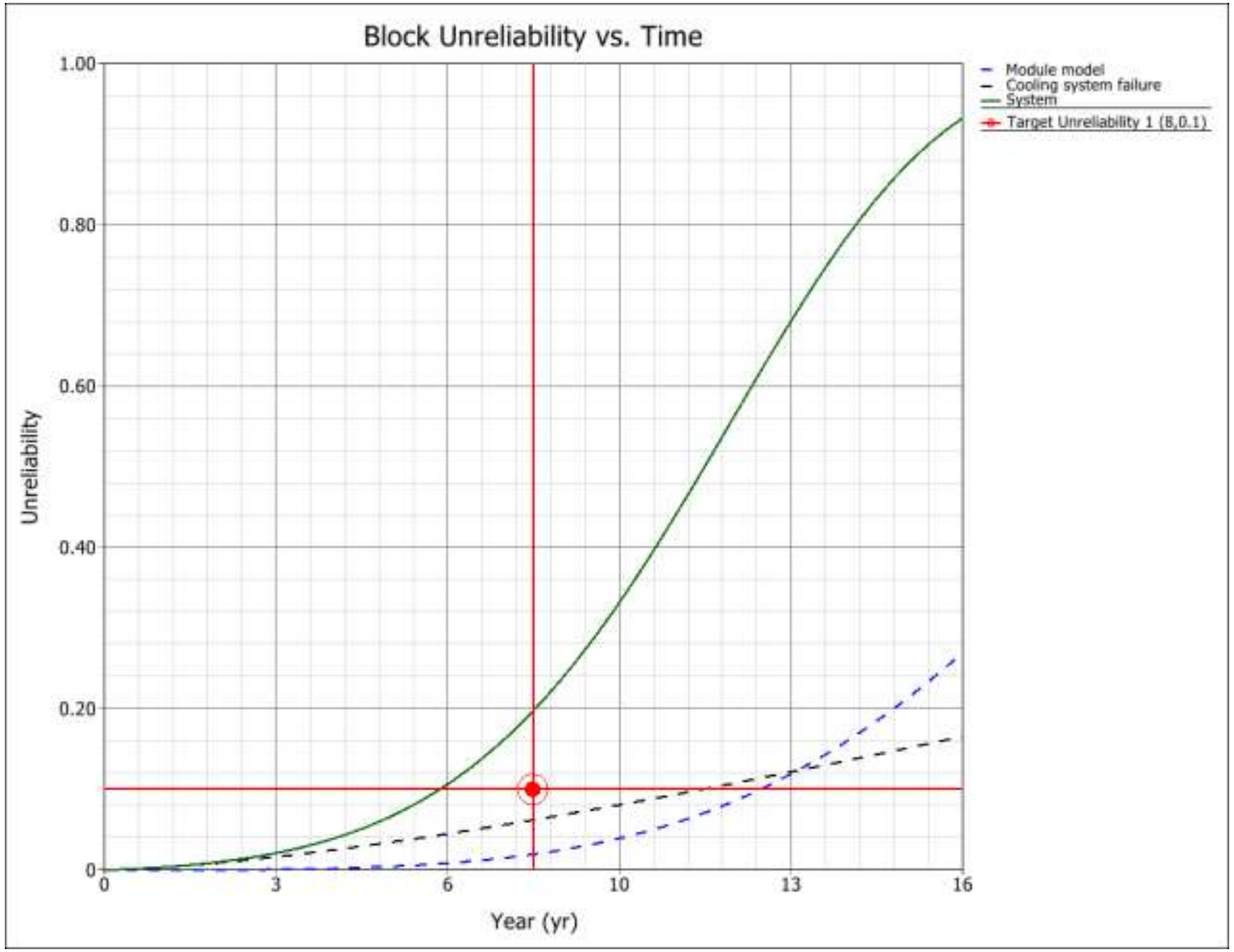
- Combine failure modes to see overall reliability
- Roll up cell level, module level and pack level models



Pack	Structural fatigue	Stress range, strain range	CAE Fatigue prediction	DesignLife

System reliability

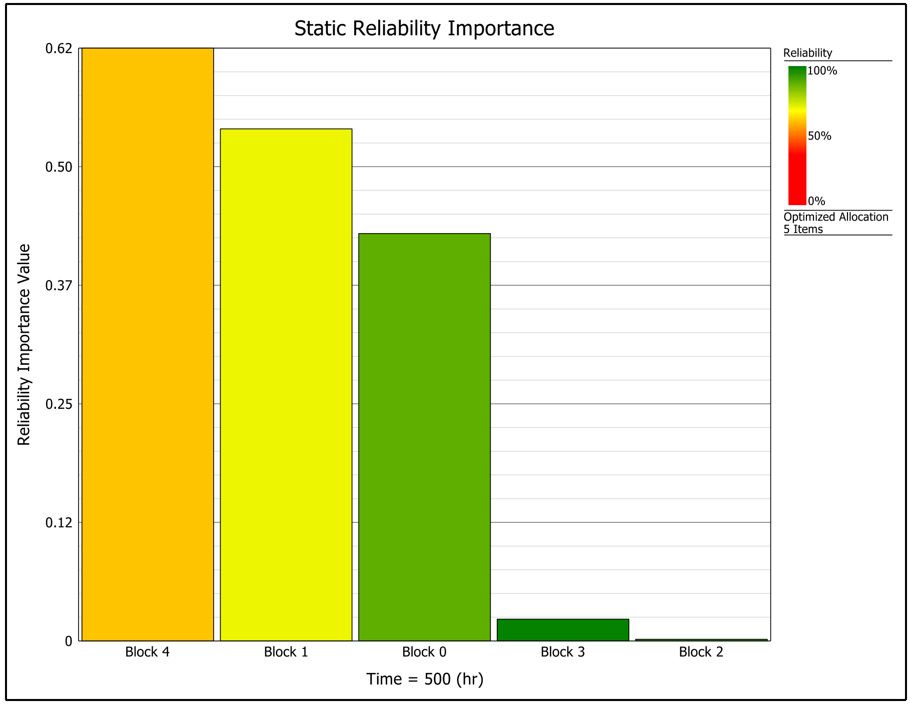
- Do we meet our target?
- If not, what should we do about it?



Public

Identify critical failure mechanisms

- Find which failure modes drive system reliability
- Allocate component reliability targets based on system target



	Block Name	Reliability Importance	Current Reliability	Maximum Achievable Reliability	Feasibility	Target Reliability	Equivalent Parallel Units
☑	Block 4	0.9581	0.9048	1	Easy (3)	0.9757	1.5801
☑	Block 1	0.8948	0.9689	1	Moderate (6)	0.9834	1.1814
☑	Block 0	0.8767	0.9889	1	Hard (9)	0.9901	1.0258
☑	Block 2	3.2108E-05	0.9975	1	Easy (1)	0.9975	1.0000
☑	Block 3	0.0022	1.0000	1	Easy (1)	1.0000	1.0000

Reliability Engineering Tools

HBK
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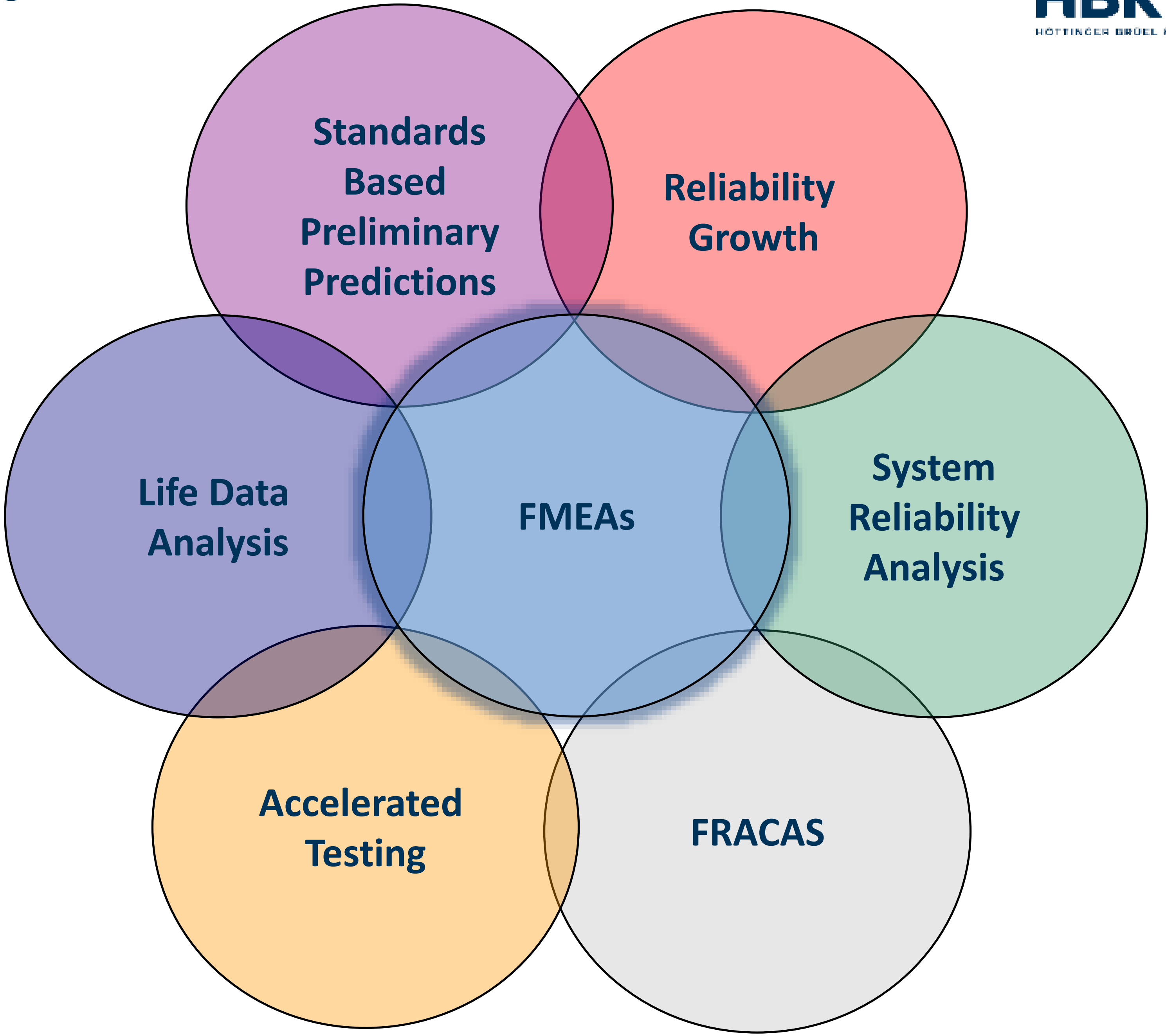
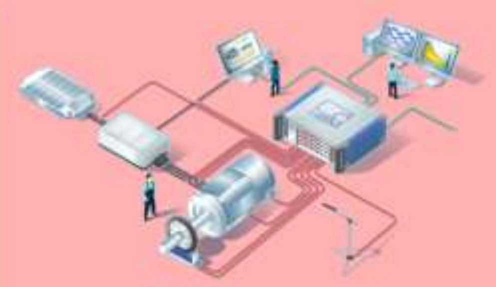
Reliability

- FMEA for new failure modes
  - **Identify potential risks earlier**
  - **Capture best practice**
- Battery life & reliability growth analysis
  - **Reduce warranty exposure**
  - **Analyze reliability, availability, and maintainability**
  - **Promote continual reliability growth**
- System of Systems modelling
  - **Optimize complex battery systems for reliability**
- **Digital Twin/FRACAS**
  - **Reduce lifetime warranty costs**



Challenges

Vehicle Electrification
Challenges & Solutions



Performance

- Bench testing
  - Better vehicle range
  - Better energy density
  - Better thermal performance
- Power measurement & analysis
  - Better accuracy
- Real-world usage & efficiency assessment
  - Better understanding of real customer usage
- **Digital Twin**
  - Early detection of anomalies
  - Continual through-life improvements

IOT

Durability

- Fatigue design of battery packs
  - ***"Batteries are mechanical structures"***
  - Reduce battery degradation
- Accelerated vibration testing of battery packs
  - Better understanding of thermal & vibration loads
  - More representative vibration tests
- Fatigue of light-weight structures
  - Lighter, more durable vehicles
  - Lighter, more compact batteries
- **Digital Twin**
  - Avoid in-service failure

IOT

Reliability

- FMEA for new failure modes
  - Identify potential risks earlier
  - Capture best practice
- Battery life & reliability growth analysis
  - Reduce warranty exposure
  - Analyze reliability, availability, and maintainability
  - Promote continual reliability growth
- System of Systems modelling
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- **Digital Twin/FRACAS**
  - Reduce lifetime warranty costs

Development

eDrive Test Systems

VI-Grade Noise & Ride Simulators

VI-GRADE

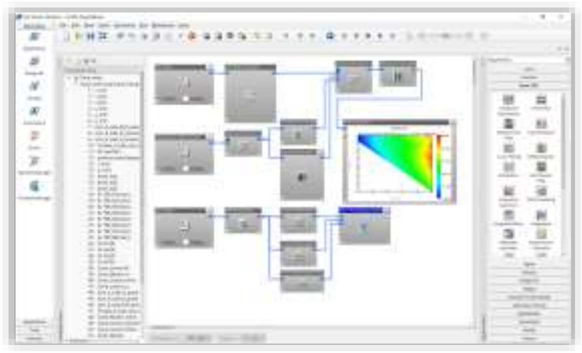
Qualification

LDS Shaker Systems

Analysis Software

nCode

ReliaSoft



Quality Assurance

DISCOM Production Line Quality Assurance

DISCOM

B&K Sound & Vibration Measurement & Analysis

HBK

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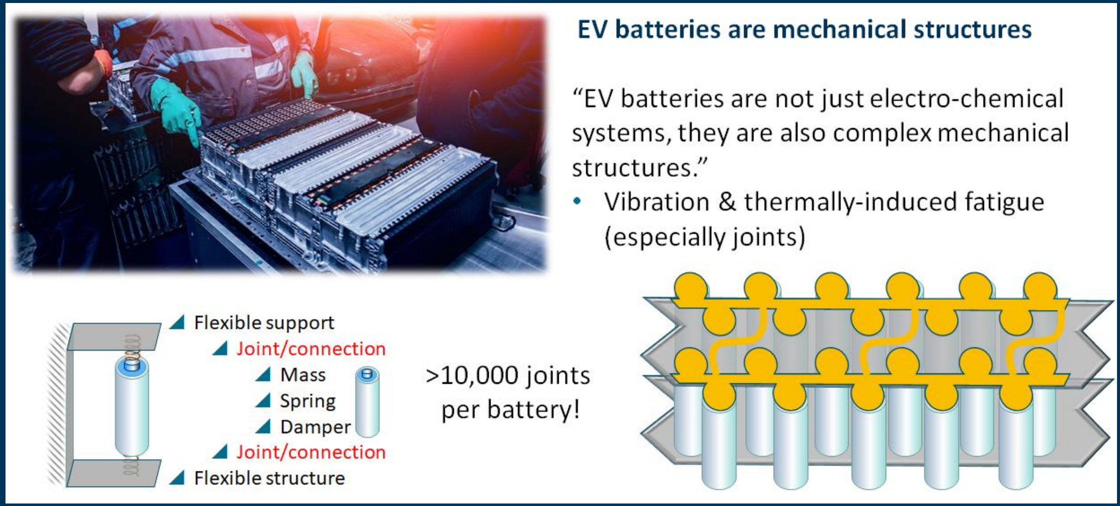
Thank You

PUBLIC

Virtual Seminar Series – Tuesday 2, 9, 16 November



Durability and Reliability of Electric Vehicle Battery Structures

Presented by Dr. Andrew Halfpenny
Director of Technology
Prenscia (HBK)

Tuesday, November 16, 2021