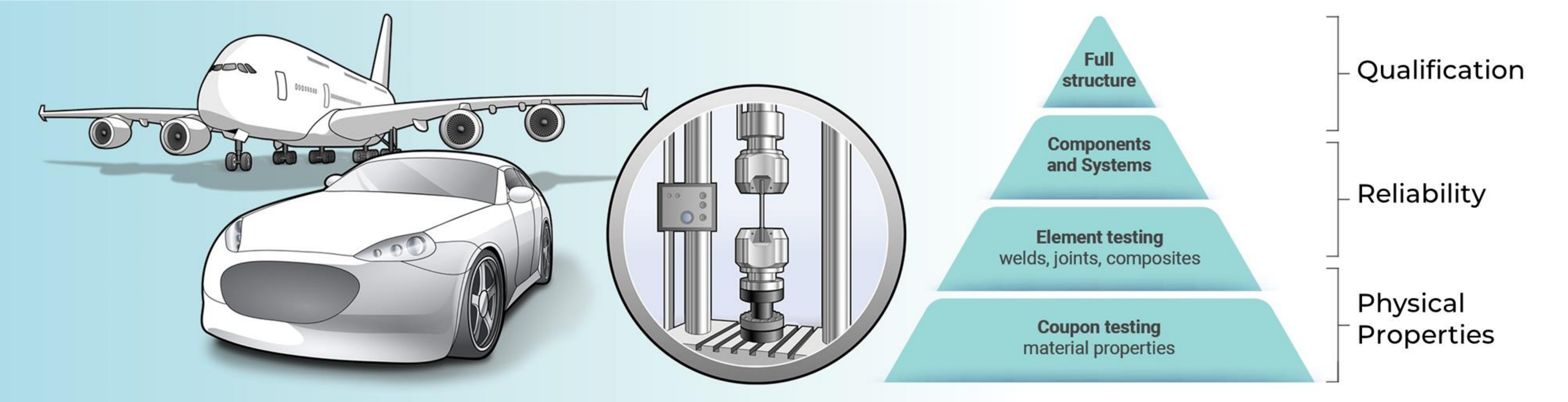
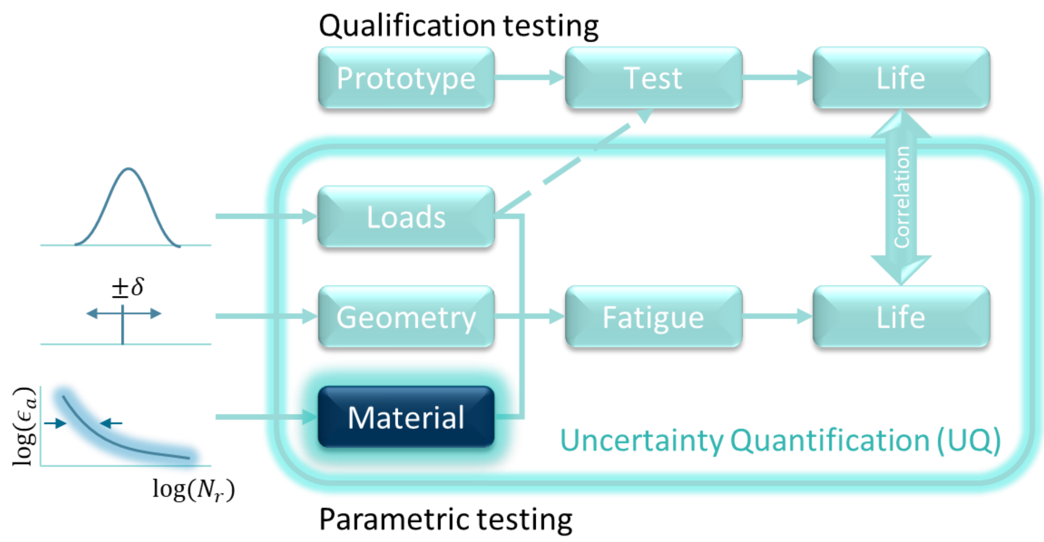


2023 HBK Technology Days

14 November 2023



- **Complementary material parametric testing and simulation for fatigue prediction**

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

Complementary material parametric testing and simulation for fatigue prediction

Abstract

- The structural design of mechanical systems is significantly enhanced by simulation. Fatigue simulation is conveniently divided into two stages:

1. Stress simulation (or constitutive modelling) is the transformation of loads, through displacements, to structural stresses. A structure may respond to these loads in either a static or dynamic fashion, and the response may be linear or non-linear in its nature. The Finite Element (FE) method is most commonly used for these simulations.
2. Materials simulation is the transformation of these structural stresses into a statistical likelihood of failure. There are often many possible failure modes, and these may be classified as either:
   - Ultimate Limit State (ULS): e.g. tensile failure or buckling.
   - Serviceability Limit State (SLS): e.g. material ageing or fatigue.

- This presentation addresses the characterisation of increasingly complex materials. It considers the simple strength and elastic modulus values, and extends this to include the non-linear, elastic-plastic behaviour. Parameters are shown for several mathematical models depending on the complexity of the stress analysis required.
- The presentation continues by covering ULS and SLS failure models. These range from traditional static failures to SN and EN fatigue models, and on to complex thermo-mechanical fatigue and creep models.

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Complementary material parametric testing and simulation for fatigue prediction

Abstract (continued)

- For one or more materials connected as a "joint" (bolts, rivets, welds, adhesives, etc.), mechanical testing alone is insufficient in determining their fatigue properties. In this case the term 'stress' will depend on the FE modelling strategy. Different strategies may result in different stress values. It is therefore essential that the test coupons are modelled using the same FE modelling strategy as the final components. This analysis is described in the presentation.
- Finally, it becomes necessary to consider the variability of material strength and how this affects the component design. The paper concludes by considering design parameters that are suitable for both traditional Deterministic designs (i.e. safe design curves), and parameters that are suitable for Stochastic design (i.e. simulating uncertainty).

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 material parametric testing and simulation for fatigue prediction

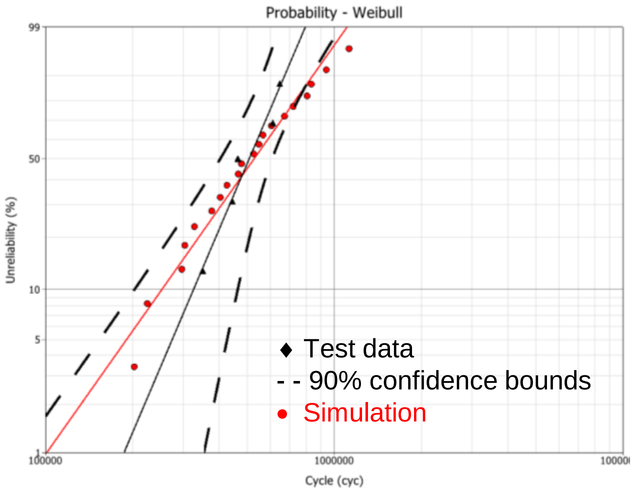
Presenter: Dr Andrew Halfpenny

Director of Technology – nCode Products

Motivation

Requirement:

*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%*

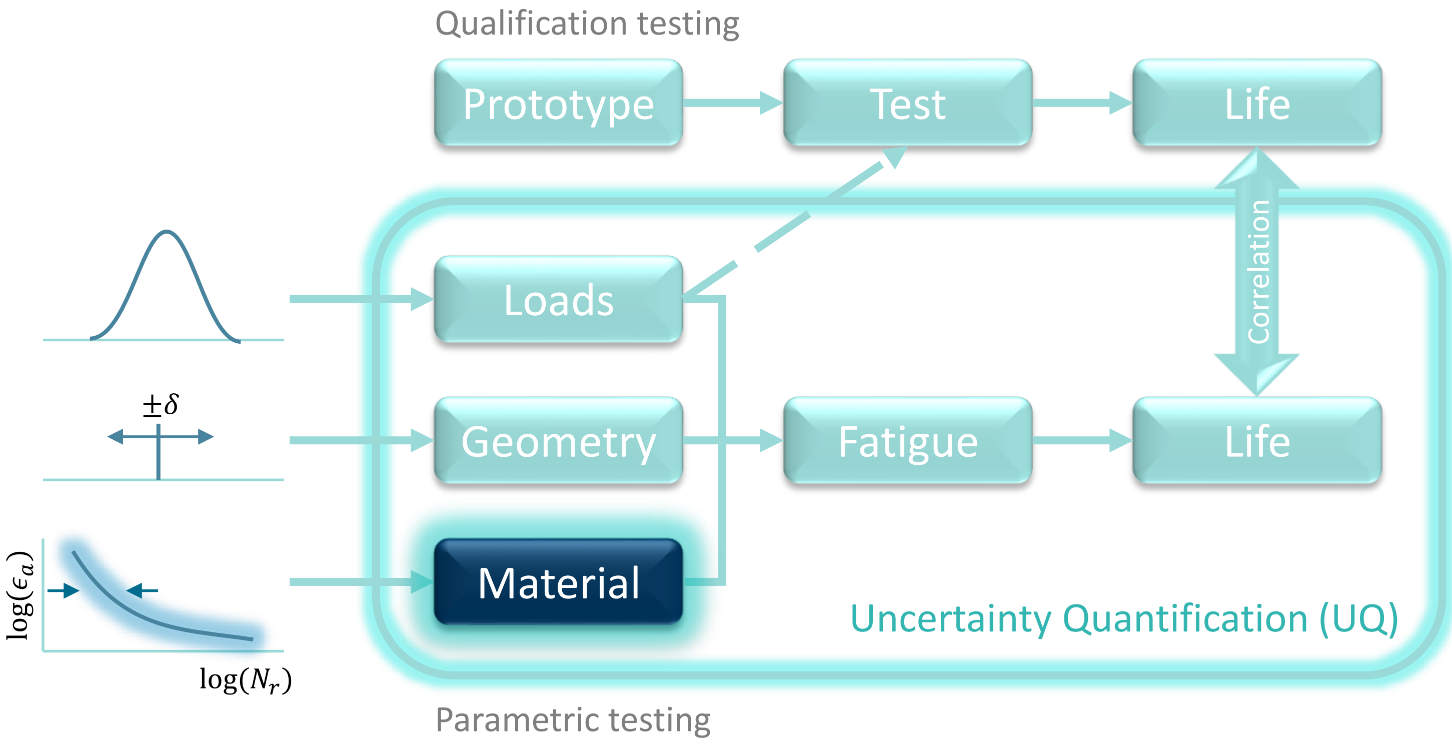


Challenge:

- How to validate requirement is met considering high degree of uncertainty implicit in fatigue ageing?

Solution:

- We must simulate the uncertainty too.



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Agenda

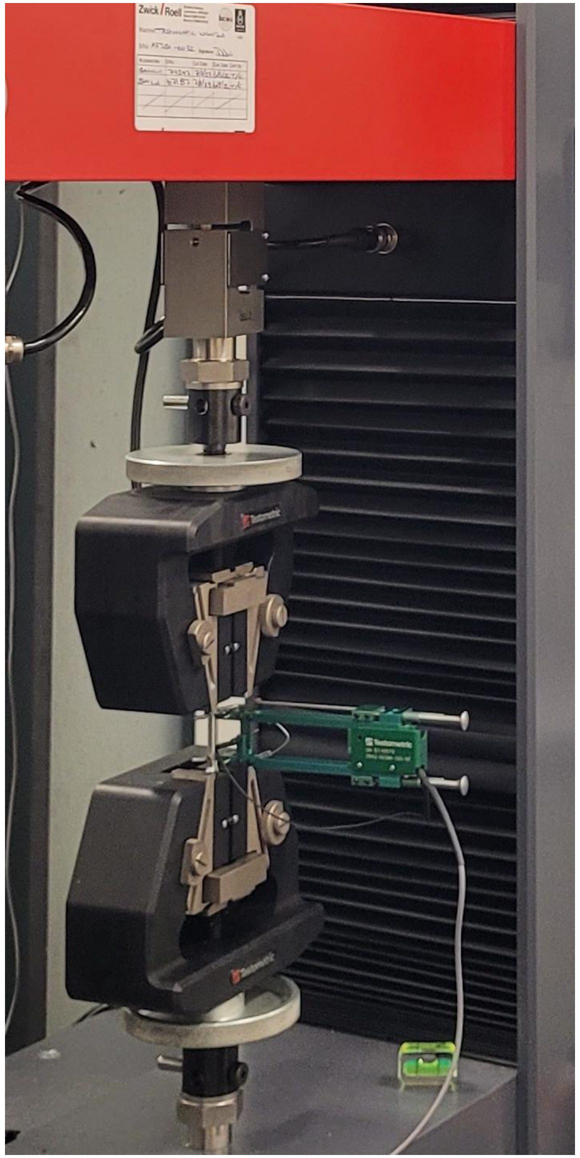
1. **Strength** – Monotonic tensile parameters
   - Strength & ductility
   - Non-linear Isotropic hardening
   - Uncertainty
2. **Ageing** – Cyclic & fatigue parameters
   - Strain-controlled testing
   - Non-linear Kinematic hardening
   - Strain-Life (EN) fatigue
   - Uncertainty
3. Today's challenges

New IMechE student members

Alex – Graduate *Degree-level apprentice. Just starting his MSc in Materials Science.*

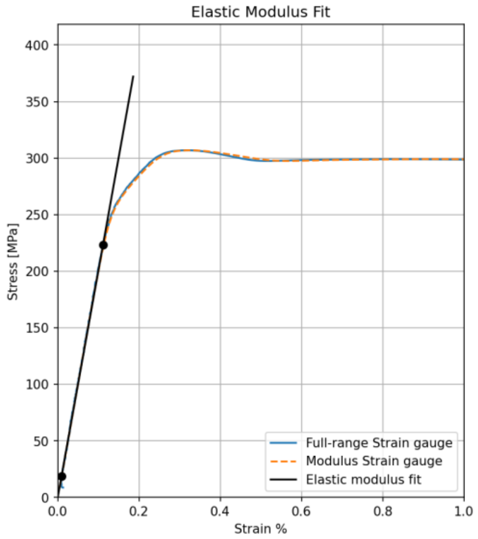
Rebecca – *new Degree-level apprentice.*

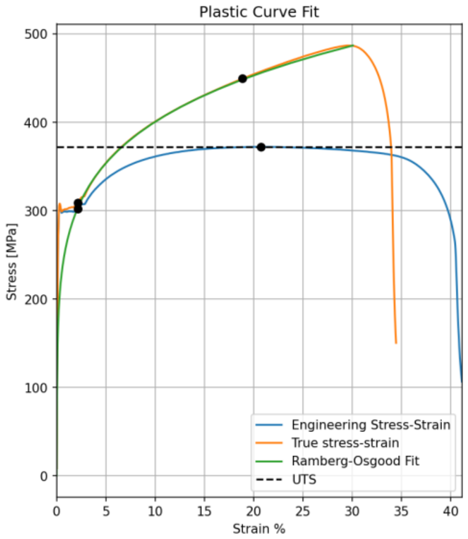
Monotonic Tensile Parameters

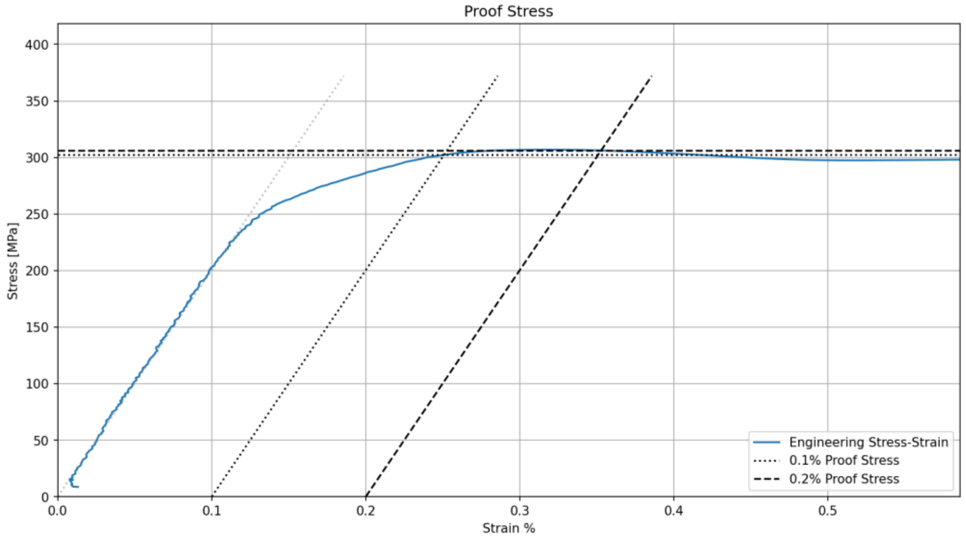


Tensile Test Report

Job reference:	C12345	Test number:	T02
Test date:	04/10/2022	Software version:	3.0.0
Material:	Sample Material	Customer:	HBK AMCT
Engineer:	AP	Test rig / temp:	Kestrel (W+B) at Room Temperature
Condition:	As Received	Elastic strain rate:	0.00274 % strain/s







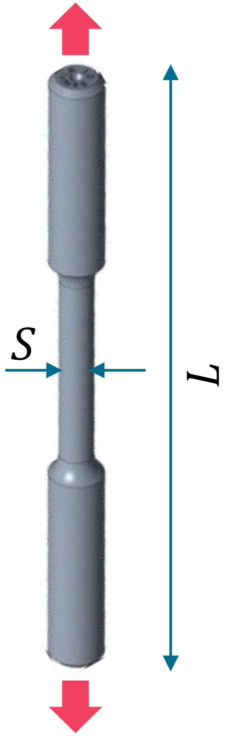
E	E_c	σ_u	$\sigma_{0.1\%}$	$\sigma_{0.2\%}$	K	n	$A\%$	$Z\%$
200,459.3 MPa	197,962.6 MPa	372.1 MPa	302.2 MPa	306.1 MPa	601.8 MPa	0.1754	41.43 %	80.75 %

Monotonic Tensile Parameters – *Strength & Ductility*

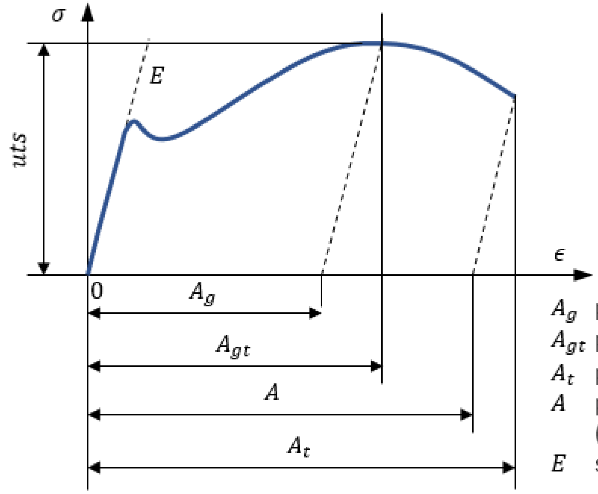
Ductility – from specimen dimensions:

- $A = \frac{L_u - L_o}{L_o}$: elongation %,
  L_o : original gauge length
  L_u : final gauge length after fracture

- $Z = \frac{S_o - S_u}{S_o}$: reduction in area %
  S_o : original cross-sectional area
  S_u : final cross-sectional area after fracture

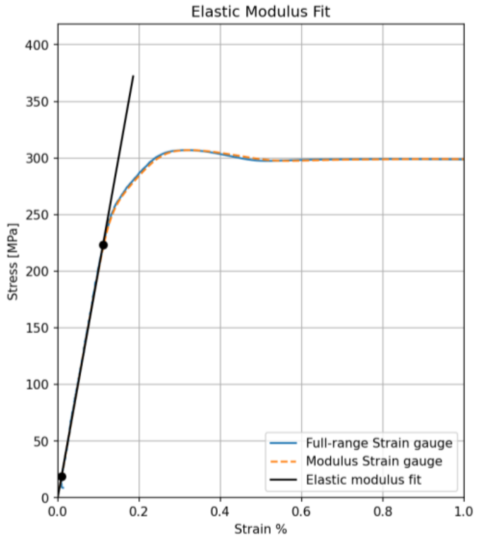


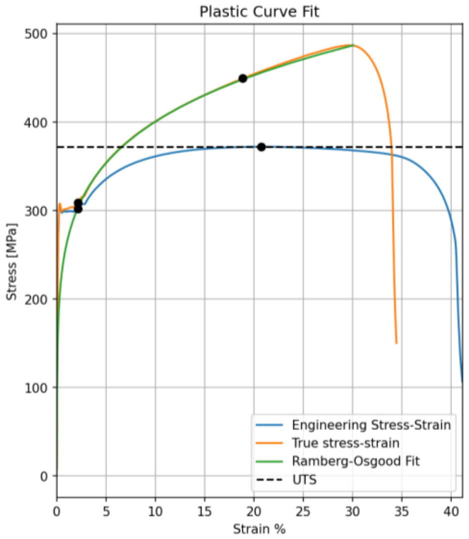
Ductility – from measurement curves:



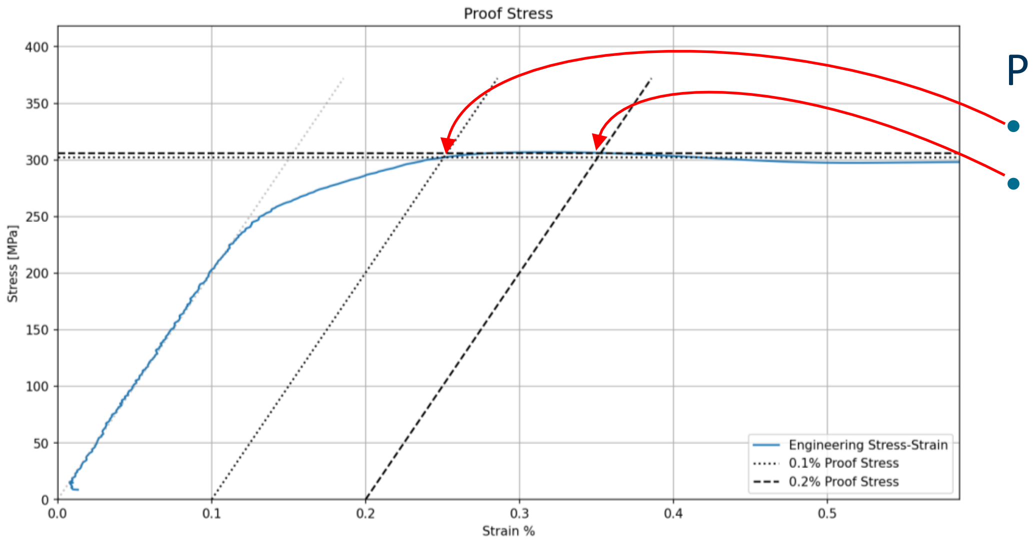
A_g percentage plastic extension at maximum force
A_{gt} percentage total extension at maximum force
A_t percentage total extension at maximum fracture
A percentage elongation after fracture (determined by clipper measurement or from curve)
E slope of the elastic part of the curve

Strength:





σ_u : Ultimate Tensile Strength



Proof strength:

- $\sigma_{0.1\%}$
- $\sigma_{0.2\%}$

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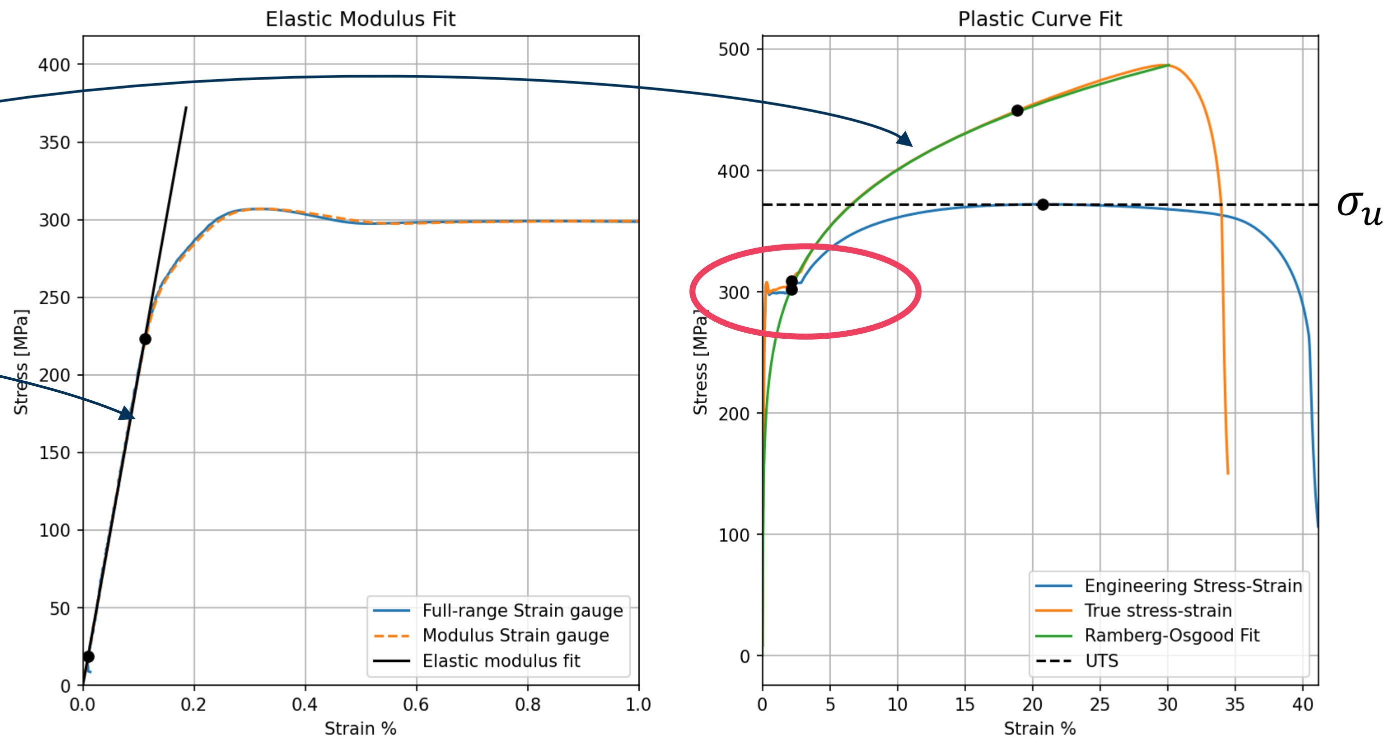
Monotonic Tensile Parameters – *Isotropic Hardening*

Ramberg-Osgood (RO) isotropic hardening model:

$$\epsilon_T = \underbrace{\frac{\sigma_T}{E}}_{\text{Elastic}} + \underbrace{\left(\frac{\sigma_T}{K}\right)^{\frac{1}{n}}}_{\text{Plastic}}$$



Elastic:

- E obtained through linear regression of σ and ϵ
- $E_c = \frac{\Delta\sigma}{\Delta\epsilon}$: chord modulus between 2 points

Plastic:

- RO curve based on log regression through *True Stress* σ_T vs. plastic *True Strain* ϵ_T

$$\sigma_T = \sigma(1+\epsilon)$$
$$\epsilon_T = \log(1+\epsilon)$$
$$\epsilon_{T_{plastic}} = \log\left((1+\epsilon) - \frac{\sigma}{E}\right)$$

Other Isotropic hardening models:
- Chaboche
- Piecewise linear interpolation

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Monotonic Tensile Parameters – *Uncertainty*

Min 3x as received:

- Used for quality control of supplied material before fatigue testing.

Min 3x cyclically stabilised:

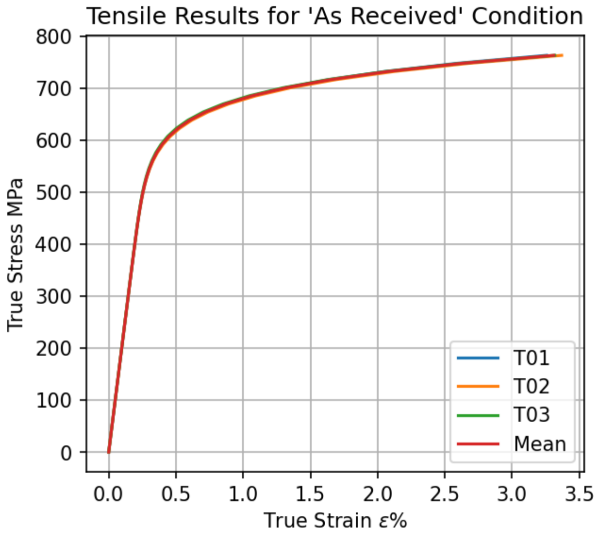
- Cycled for ~100 – 2000 cycles in strain control close to plastic limit prior to tensile testing.
- Used for cyclically stabilised static parameters in fatigue analysis.

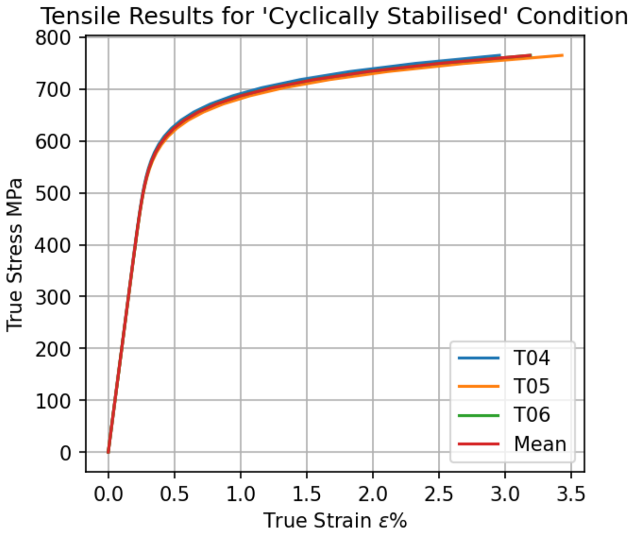
Uncertainty on fatigue life relatively insensitive to uncertainty on tensile parameter, ∴ 3 tests usually satisfactory for fatigue analysis.

But, if ultimate strength is a design-limiting factor, then suggest full statistical analysis based on ≥15 specimens.

		T04	T05	T06	Mean
Strength	UTS	770.0	761.0	764.7	765.3
	Elastic modulus E	197,635	196,240	196,030	196,635
	0.1% proof stress	679.3	664.1	674.4	672.6
	0.2% proof stress	688.1	675.2	683.9	682.4
Plasticity	K	1,001.3	993.2	995.0	996.5
	n	0.0734	0.0746	0.0734	0.0738
Ductility	Elongation A%	24.4%	25.6%	24.7%	24.9%
	Reduction of area Z%	72.1%	74.1%	70.5%	72.2%

Parameters for elastic and elastic-plastic analysis with isotropic hardening





Agenda

1. Strength – Monotonic tensile parameters
   - Strength & ductility
   - Non-linear Isotropic hardening
   - Uncertainty
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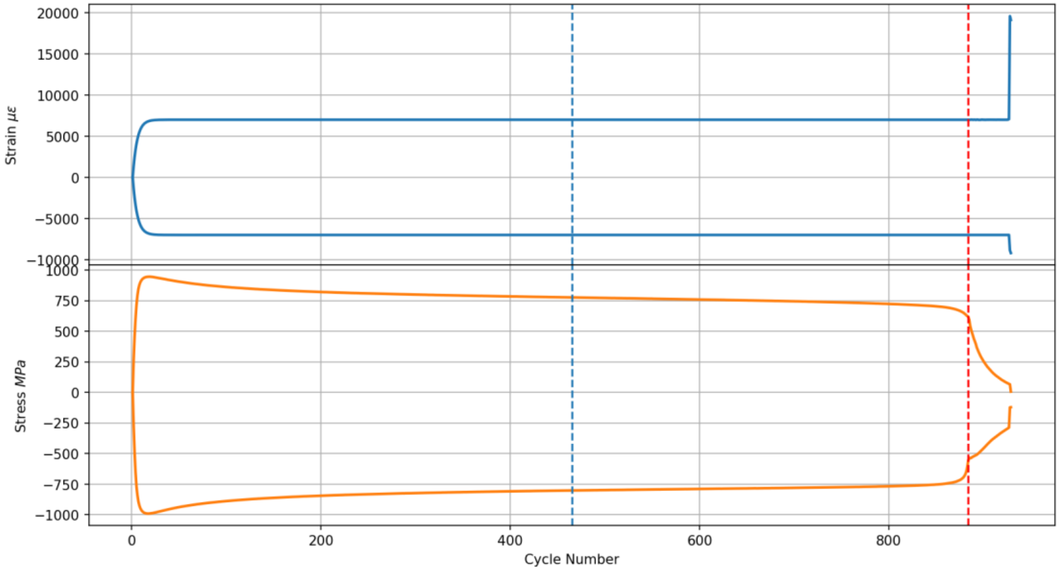
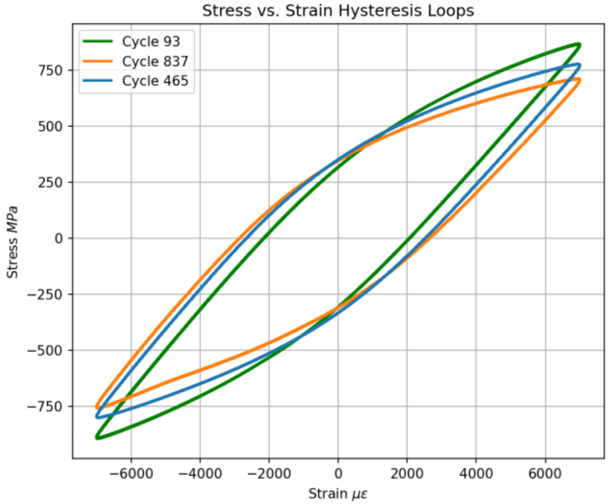
Cyclic & Fatigue Parameters

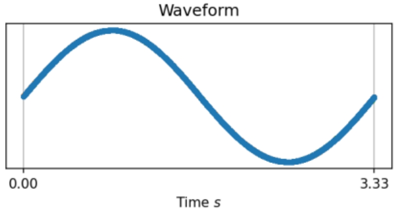
Strain Controlled Fatigue Test Report

Job reference:	C12345	Material:	Sample Material
Test number:	11	Customer:	HBK AMCT
Test date:	21/10/2020	Engineer:	MC
Software version:	3.0.1	Test rig:	Emily (Tiab)



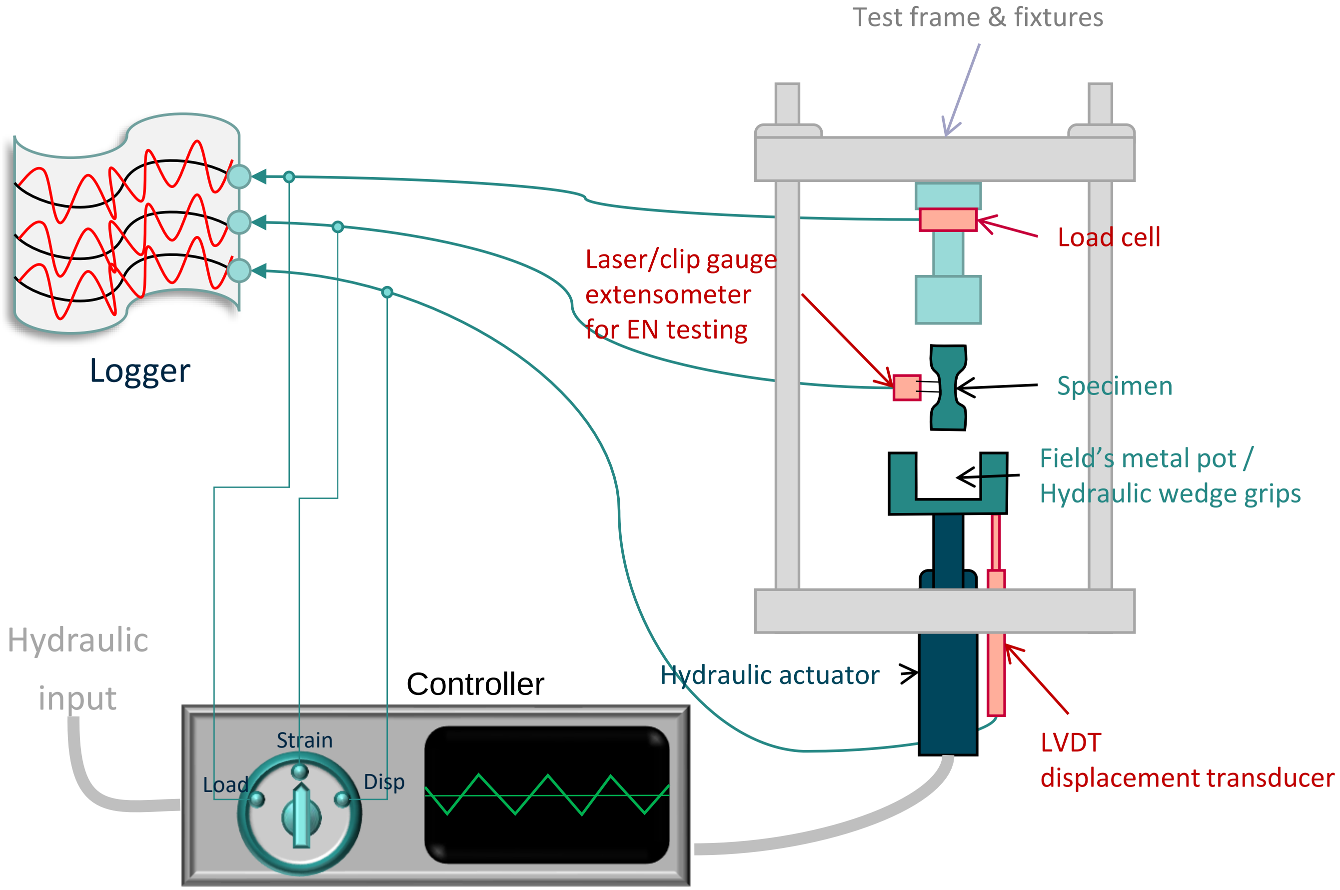


Cross sectional area:	16.100 mm^2
Test temperature:	Ambient
Test frequency:	0.3 Hz
Stable loop:	465
Cycles to separation:	929
5% load drop:	740
10% load drop:	858
20% load drop:	884
50% load drop:	893



Cycle No.	Total Stress	Total Strain	Elastic Strain	Plastic Strain
93	1758.5 *MPa*	14000	9780	4220
465	1577.1 *MPa*	13999	8817	5182
837	1468.4 *MPa*	14000	8496	5504

Cyclic & Fatigue Parameters



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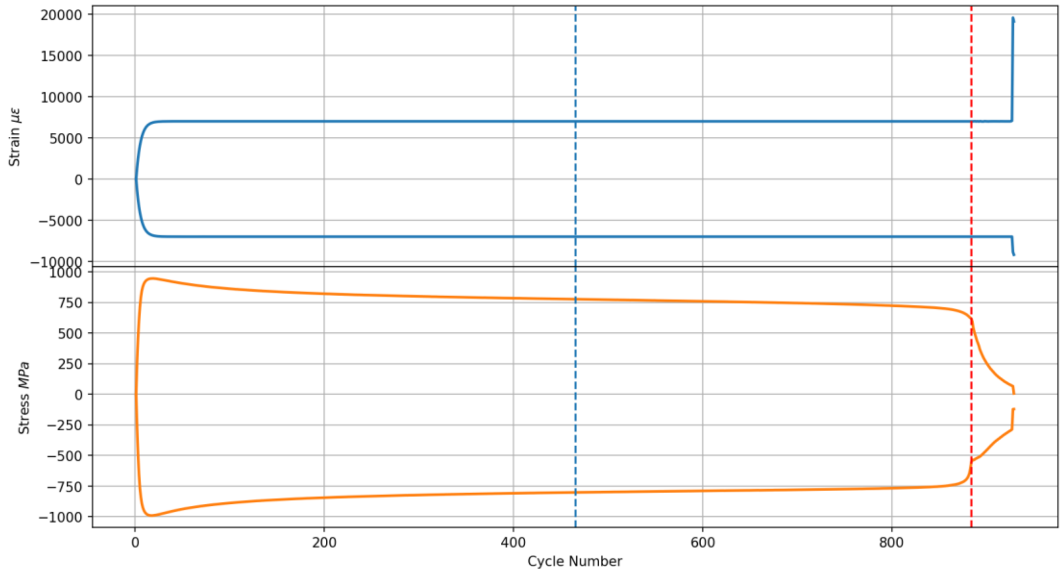

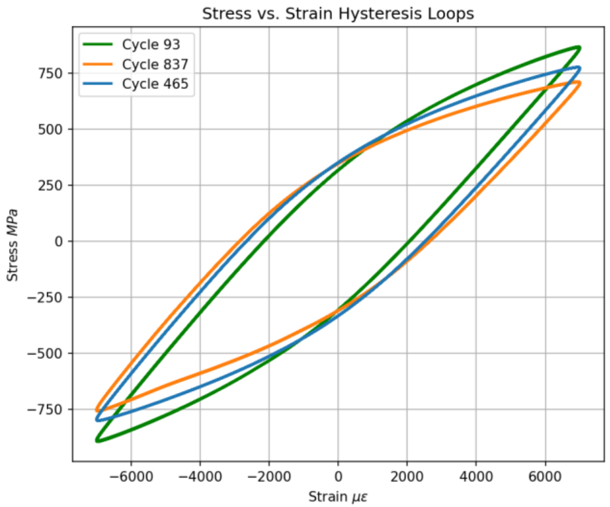

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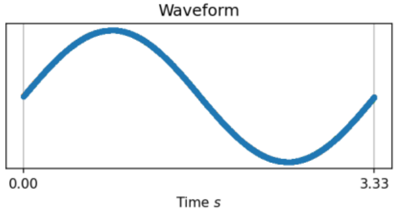

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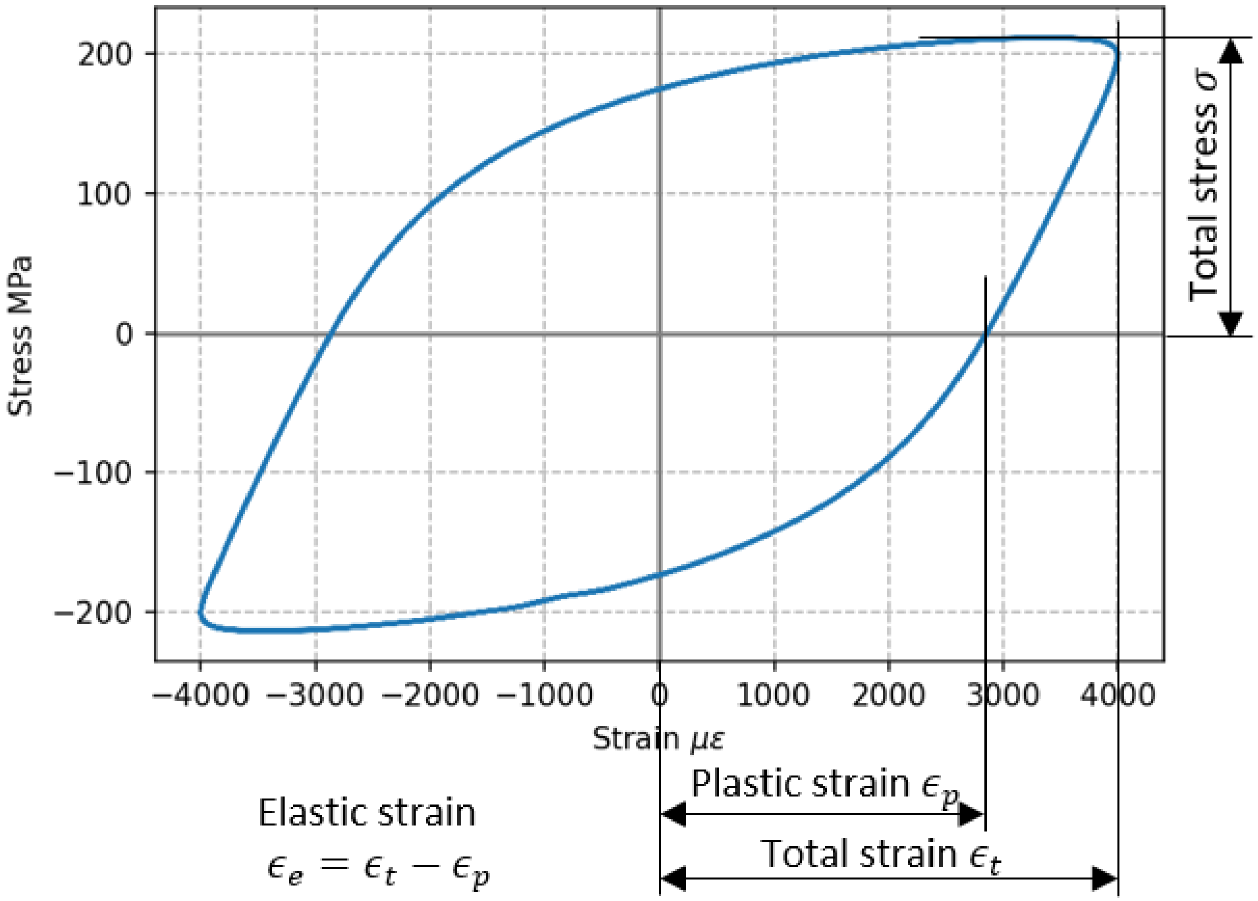

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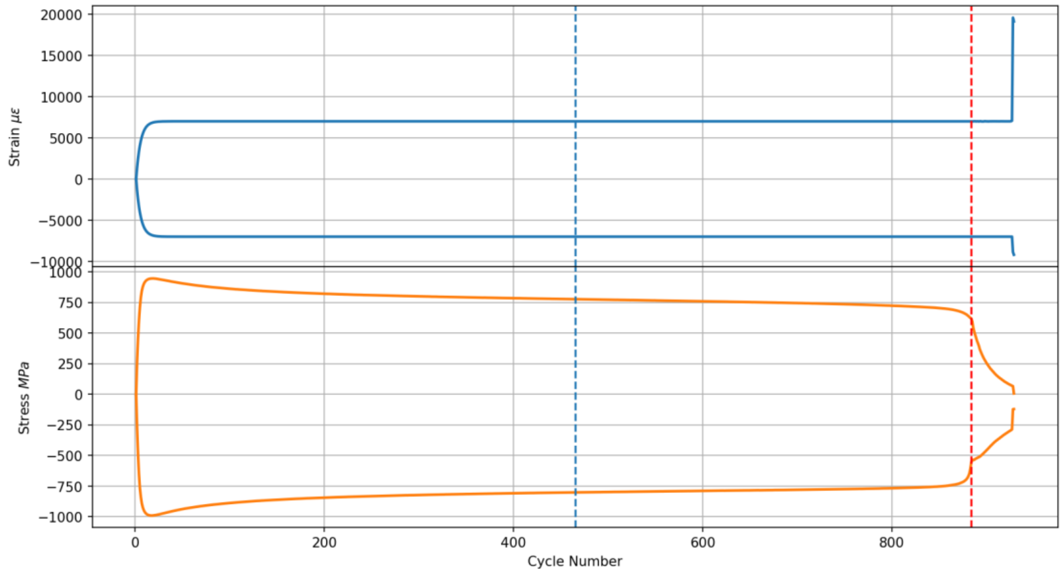

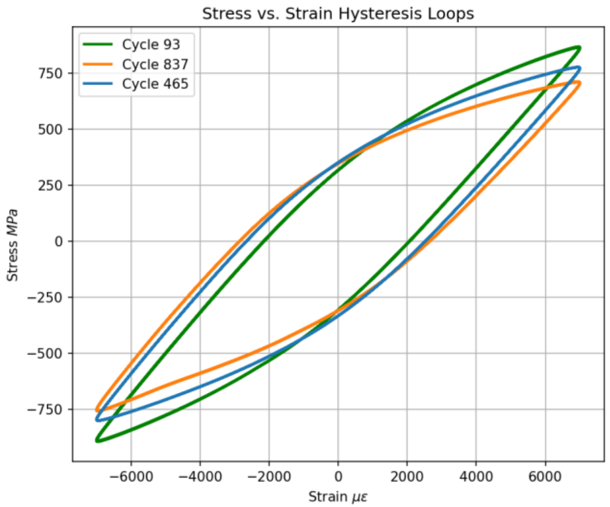

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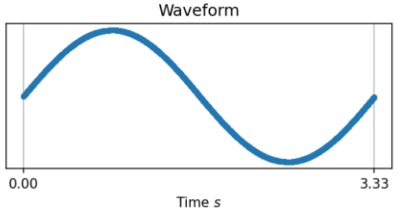

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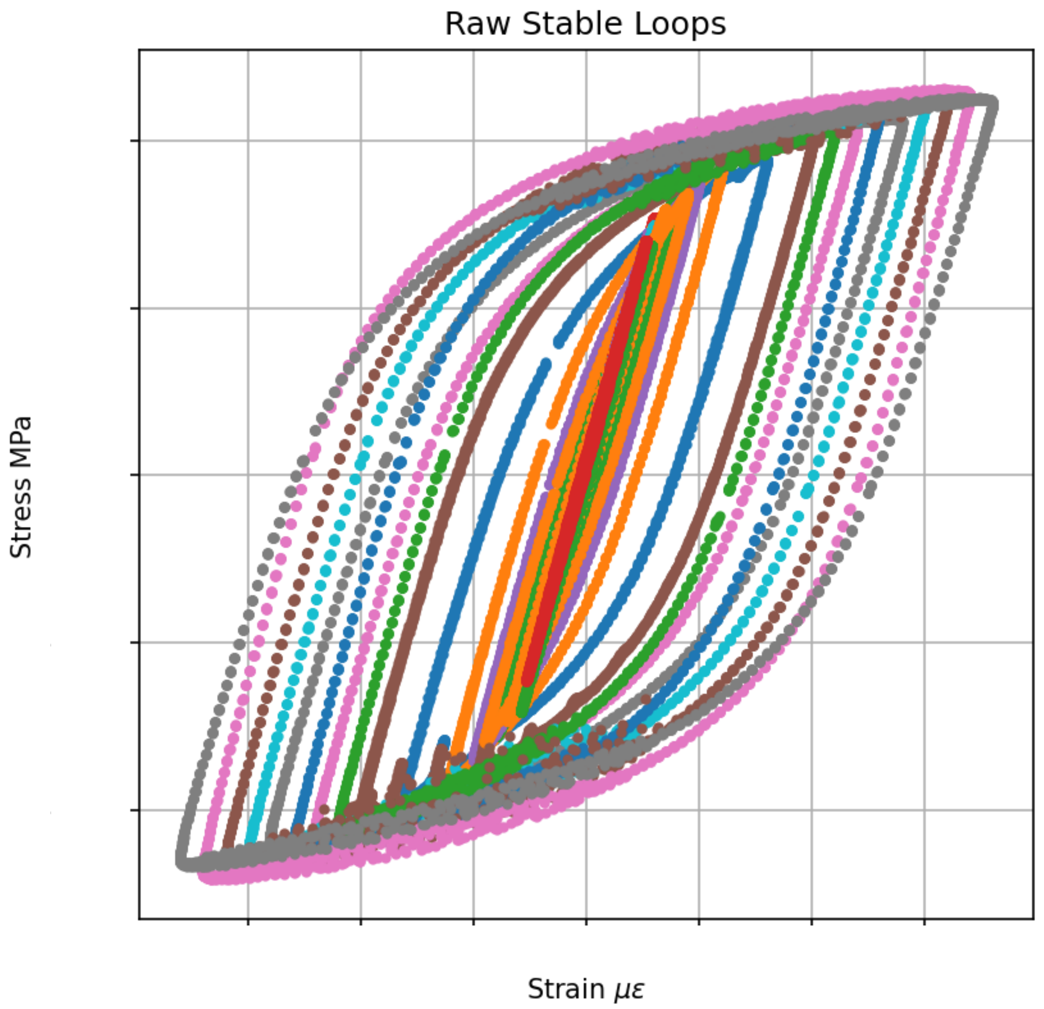
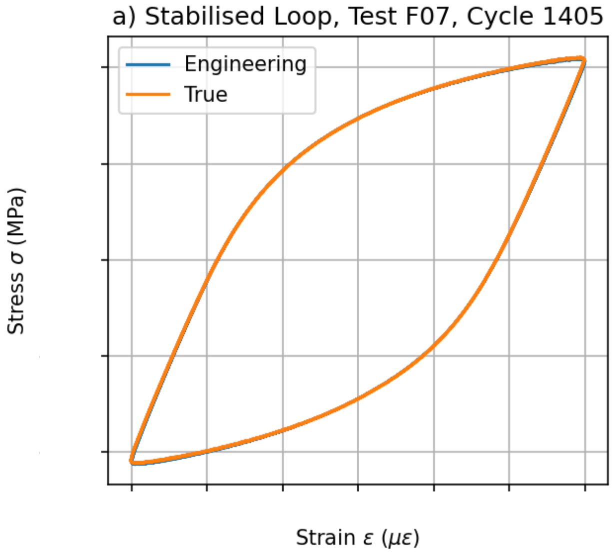
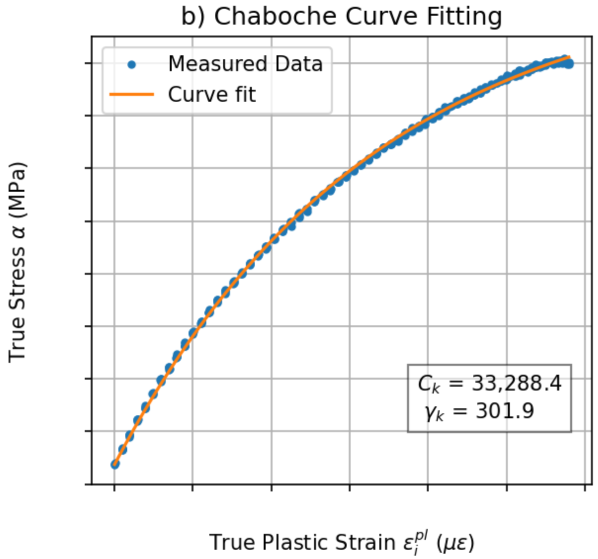
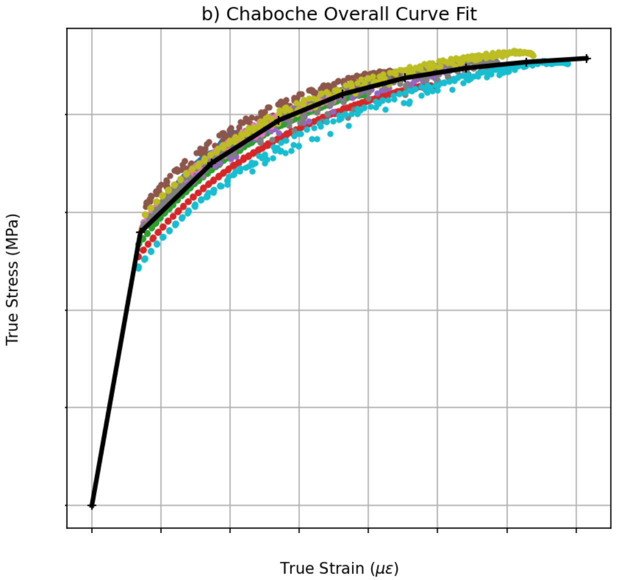
Cyclic & Fatigue Parameters – *Kinematic hardening*









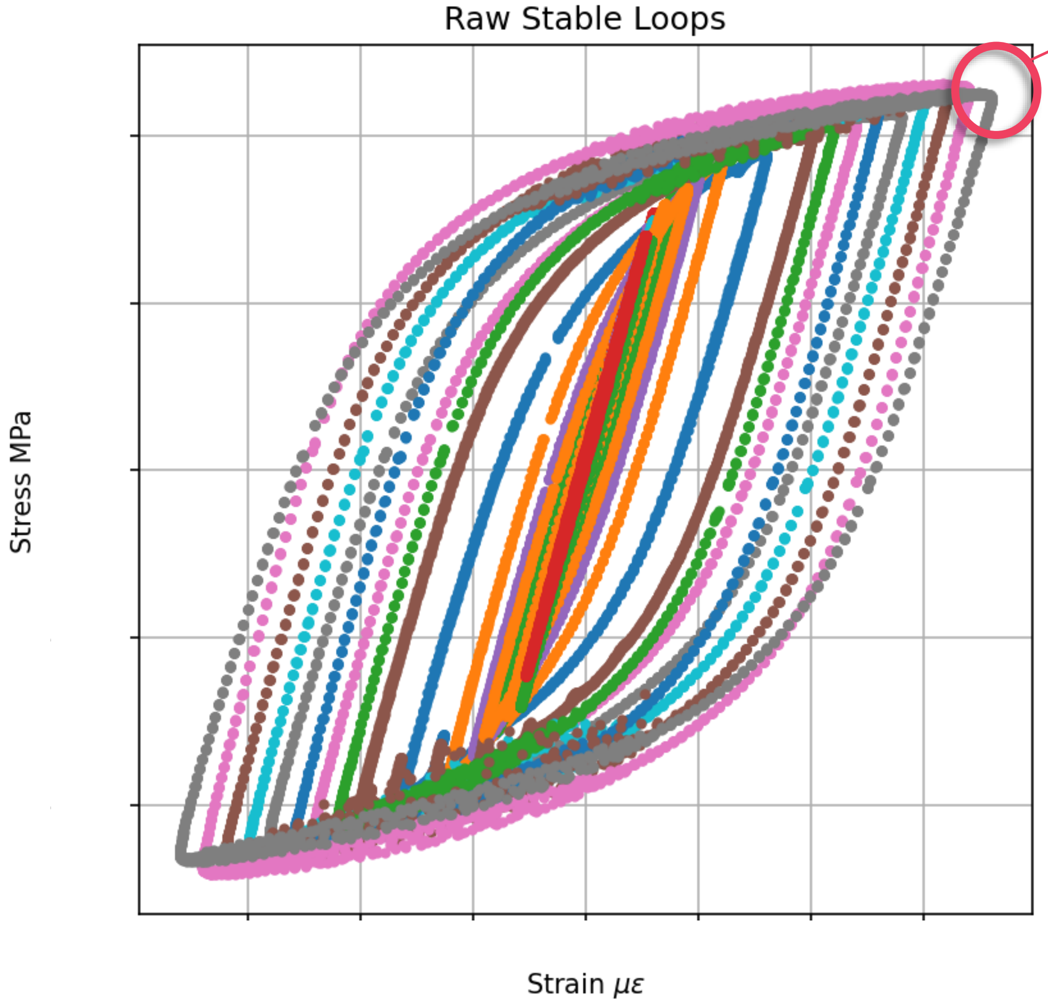
Kinematic hardening models:

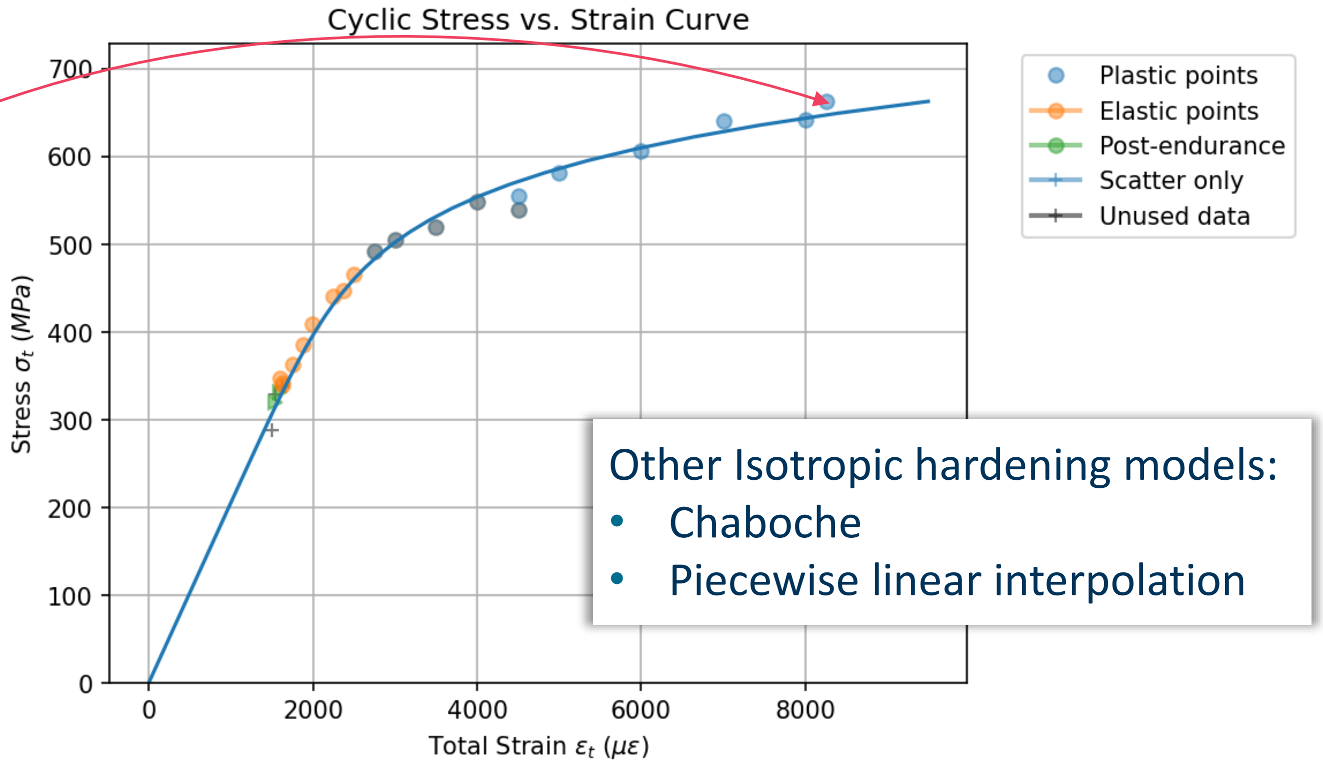
- Ramberg-Osgood-Neuber
- Chaboche

Challenge:

- How to determine an average curve

Cyclic & Fatigue Parameters – *Kinematic hardening*





Other Isotropic hardening models:

- Chaboche
- Piecewise linear interpolation

Plot peak Total stress σ vs. peak Total strain ϵ_t for all tests, and fit Ramberg-Osgood equation

$$\epsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$

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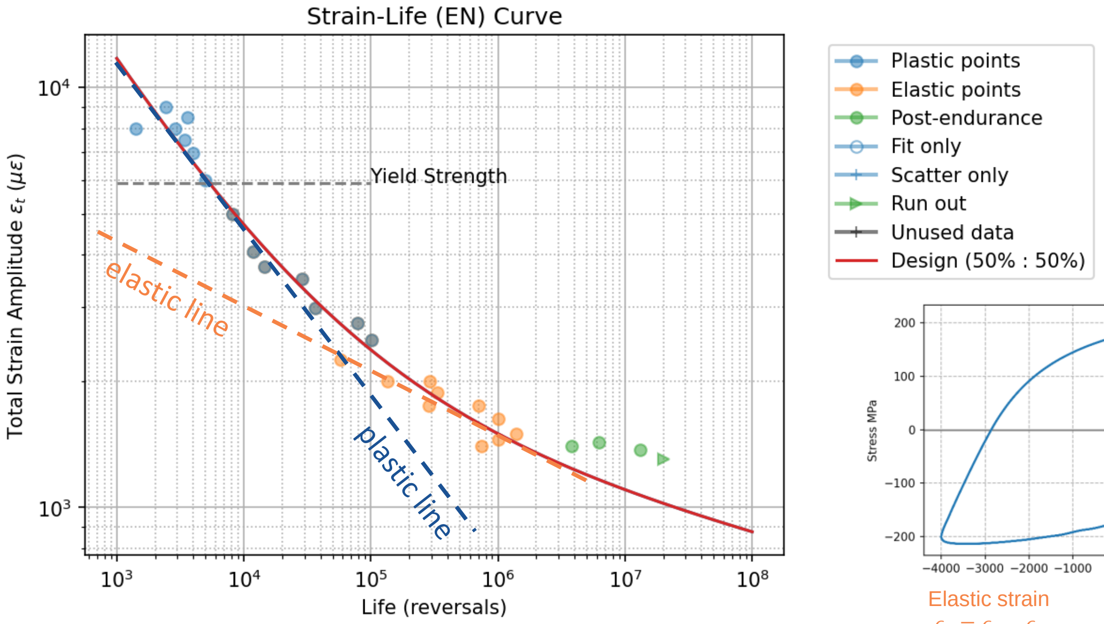
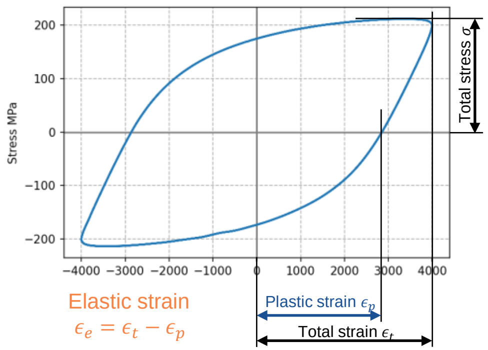
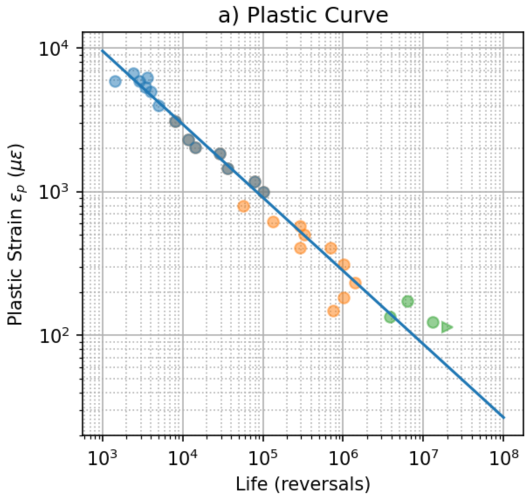
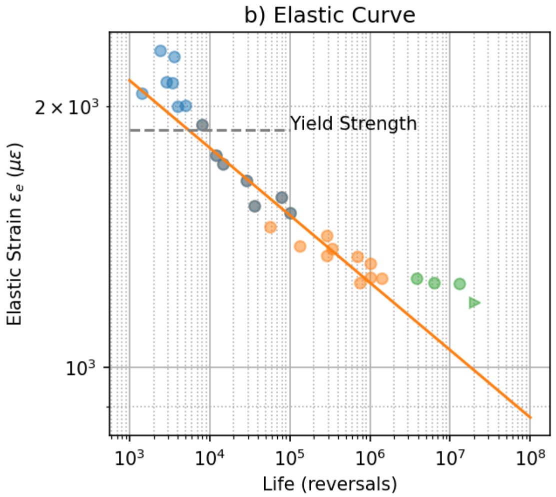
Cyclic & Fatigue Parameters – *EN characterisation analysis*









1. Plot Total strain amplitude ϵ_t vs. reversals to failure N_r for the specified load-drop.
2. Fit **plastic line** using plastic strain ϵ_p

$$\epsilon_p = \epsilon_f' N_r^c$$

3. Fit **elastic line** using elastic strain

$$\epsilon_e = \frac{\sigma_f'}{E} N_r^b$$

4. Parameter re-optimisation

$$\epsilon_t = \frac{\sigma_f'}{E} N_r^b + \epsilon_f' N_r^c$$

5. Outlier analysis

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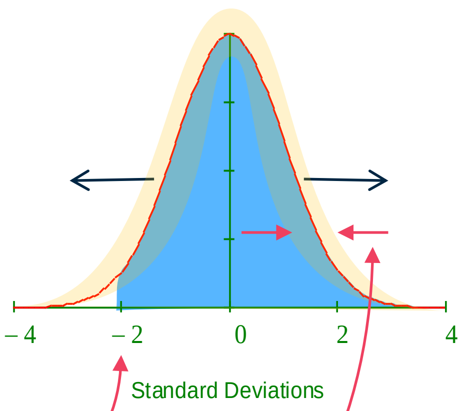
Cyclic & Fatigue Parameters – *Uncertainty Quantification*

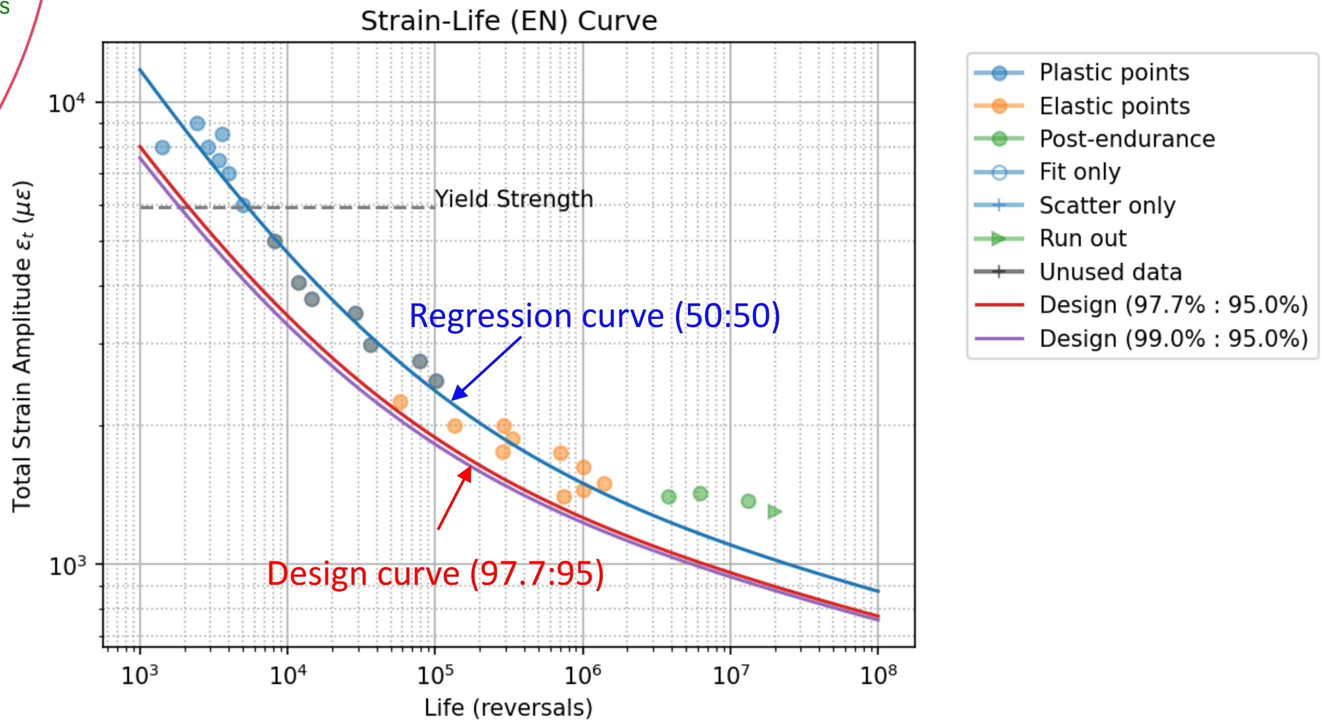
Deterministic design approach:

Design curve(reliability % : confidence %)



*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%*

- Reliability statistic:
  (acceptable number of failures)
  - 50% (mean expected life)
  - 95% (5 failures in 100)
  - 97.7% (2 sigma)
  - 99% (1 failure in 100)
- Confidence statistic:
  (sensitivity to sample size)
  - 50% (mean expected life)
  - 90 – 95% (typical design curves)



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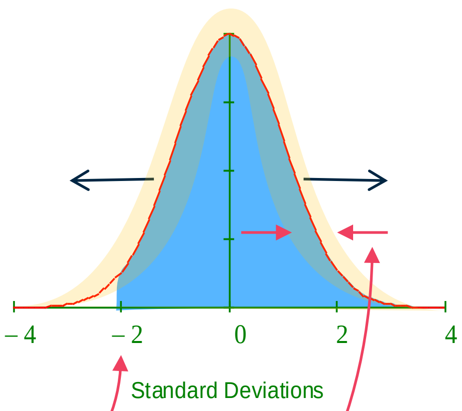
Cyclic & Fatigue Parameters – *Uncertainty Quantification*

Deterministic design approach:

Design curve(reliability % : confidence %)

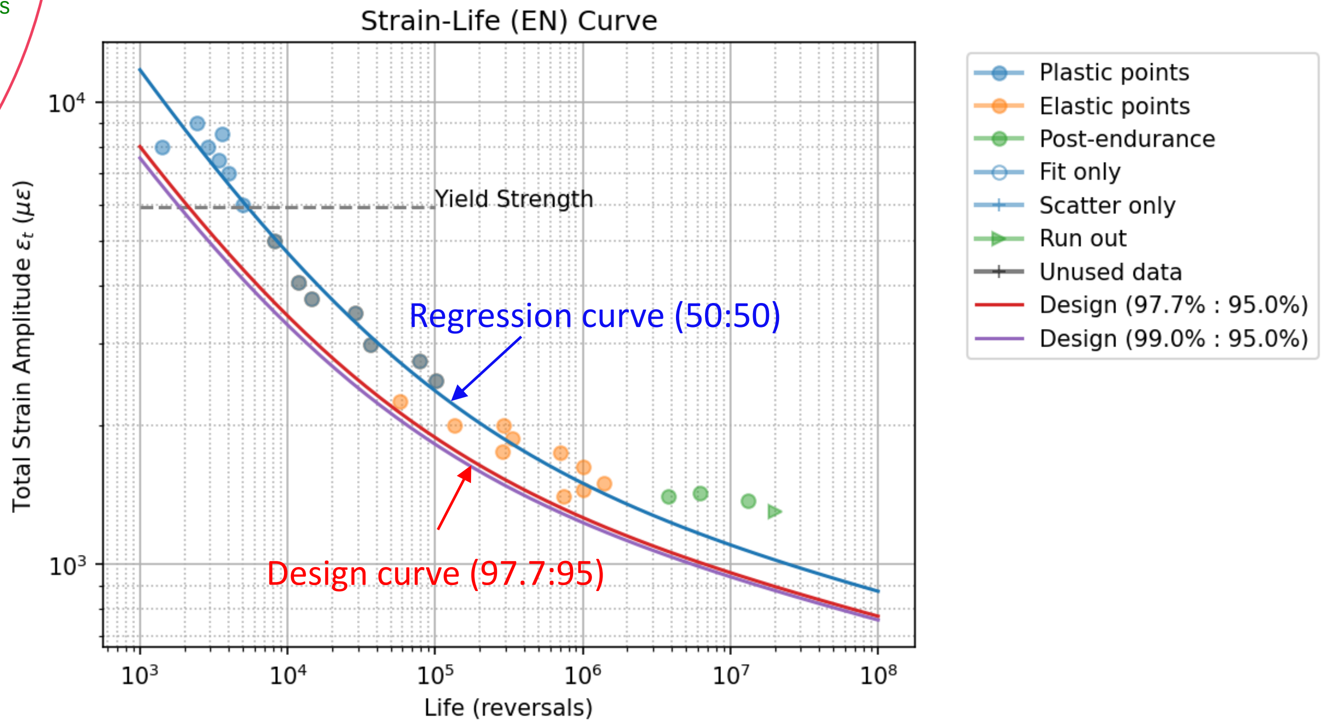


$$\epsilon_t = \frac{\sigma'_f}{E} 10^{k_{Ue} \cdot SEe} N^b + \epsilon'_f 10^{k_{Up} \cdot SEp} N^c$$

$$k_U = \frac{z_\rho + \frac{z_\gamma}{\sqrt{n}} \sqrt{1 - \frac{z_\gamma^2}{2(n-1)} + \frac{n z_\rho^2}{2(n-1)}}}{1 - \frac{z_\gamma^2}{2(n-1)}}$$

- Reliability statistic:
  (acceptable number of failures)
  - 50% (mean expected life)
  - 95% (5 failures in 100)
  - 97.7% (2 sigma)
  - 99% (1 failure in 100)

- Confidence statistic:
  (sensitivity to sample size)
  - 50% (mean expected life)
  - 90 – 95% (typical design curves)



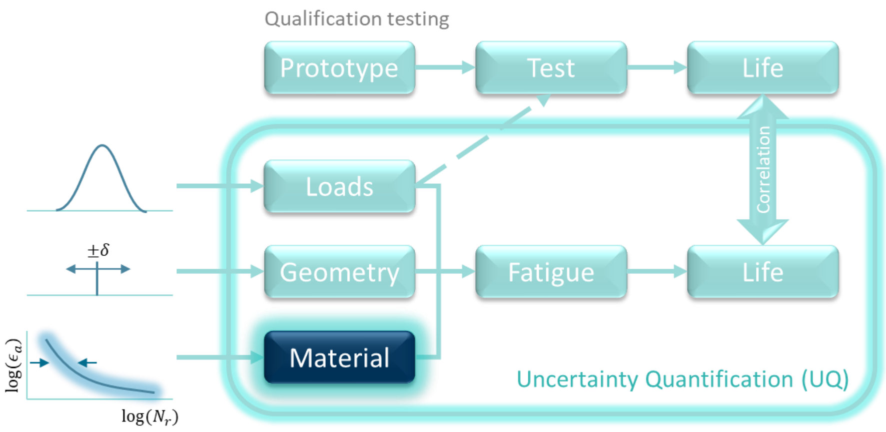
Cyclic & Fatigue Parameters – *Uncertainty Quantification*

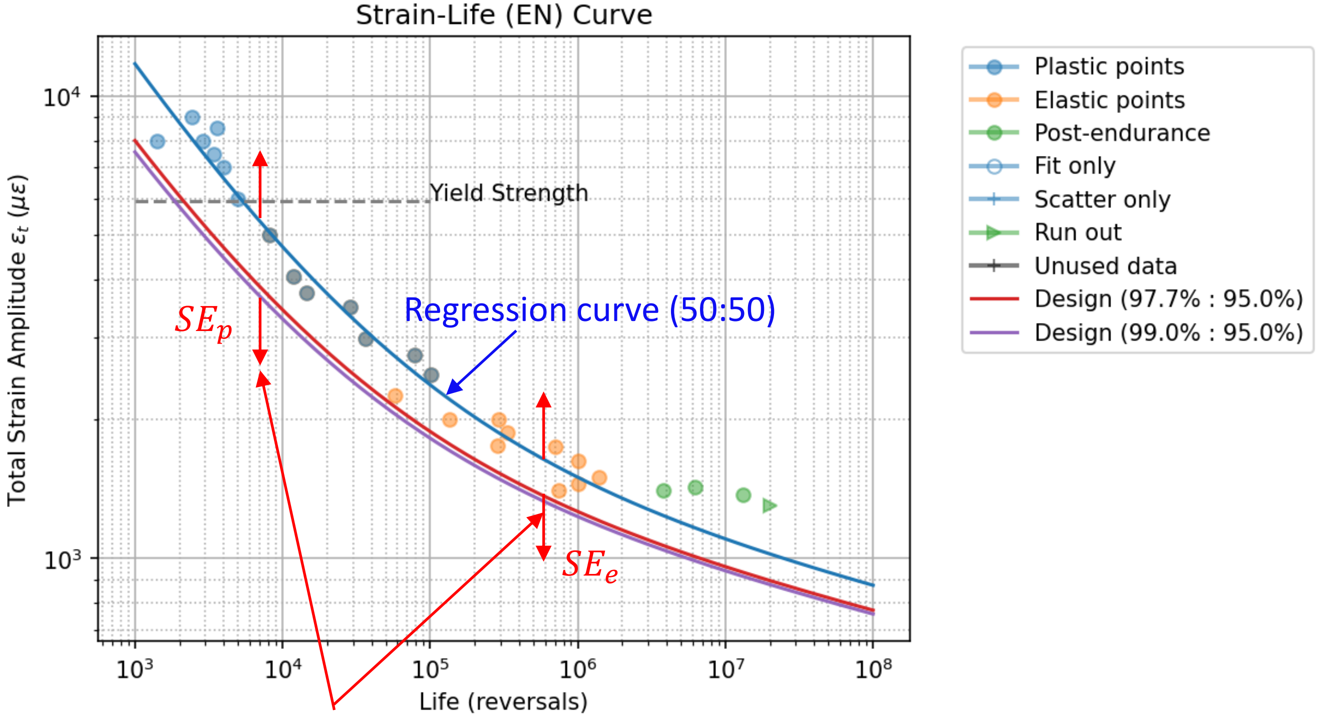
Stochastic design approach:

- Montecarlo uncertainty simulation using standard error values.

$$\epsilon_t = \frac{\sigma_f'}{E} 10^{u \cdot SE_e} N^b + \epsilon_f' 10^{u \cdot SE_p} N^c$$

u is the random number of standard deviations (DesignLife %age Certainty of Survival)





Plastic & elastic lines have different SE values (SE_p and SE_e)

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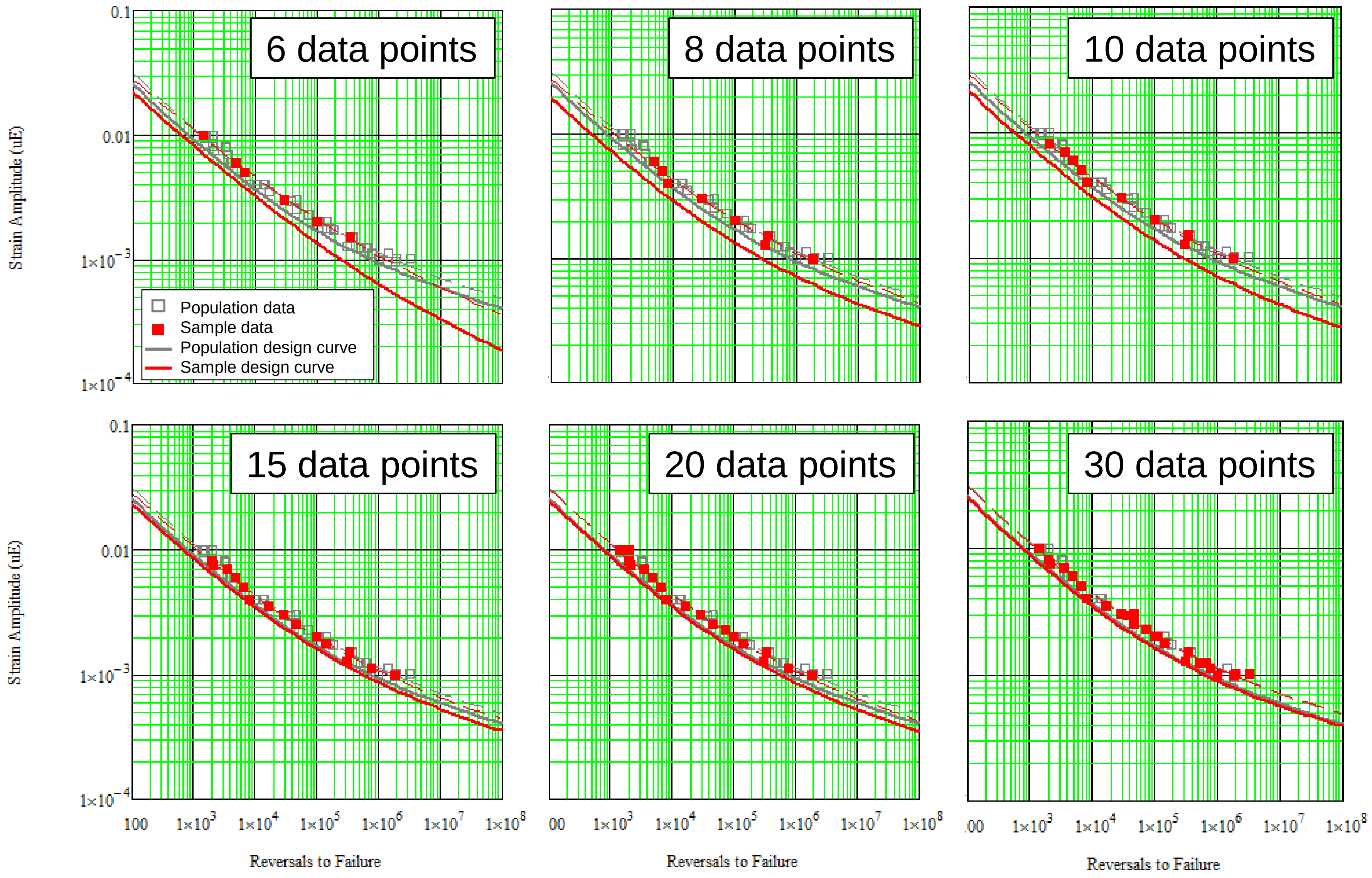
UNRESTRICTED

Cyclic & Fatigue Parameters – *Uncertainty Quantification*



6 – 10 samples
- Inadequate for EN
- Absolute minimum for SN

15 - 20 samples
- Absolute minimum for EN
- Usually adequate for SN

20 - 30 samples
- Good quality SN & EN design curve (97.5 : 95)

Agenda

1. Strength – Monotonic tensile parameters
   - Strength & ductility
   - Non-linear Isotropic hardening
   - Uncertainty
2. Ageing – Cyclic & fatigue parameters
   - Strain-controlled testing
   - Non-linear Kinematic hardening
   - Strain-Life (EN) fatigue
   - Uncertainty
3. Today's challenges

New IMechE student members

Alex – Graduate *Degree-level apprentice. Just starting his MSc in Materials Science.*

Rebecca – *new Degree-level apprentice.*

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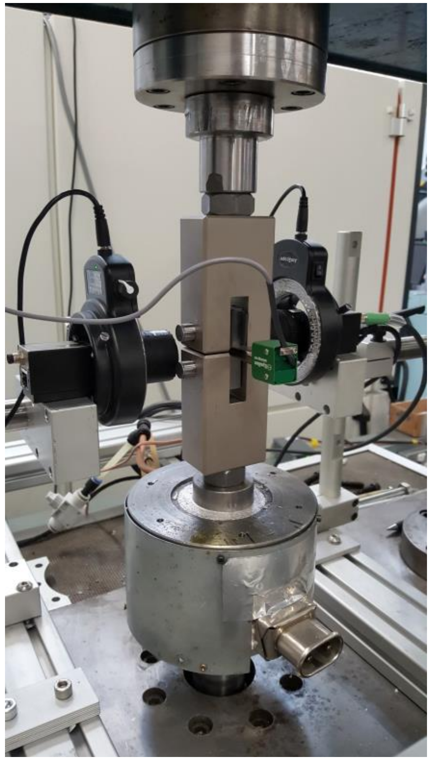
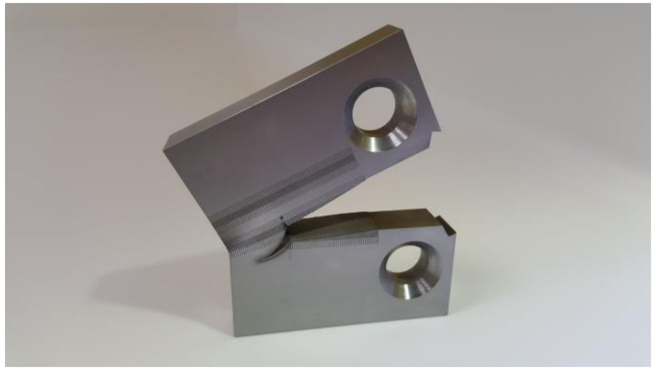
Challenges – *Driven by Environmental Sustainment*

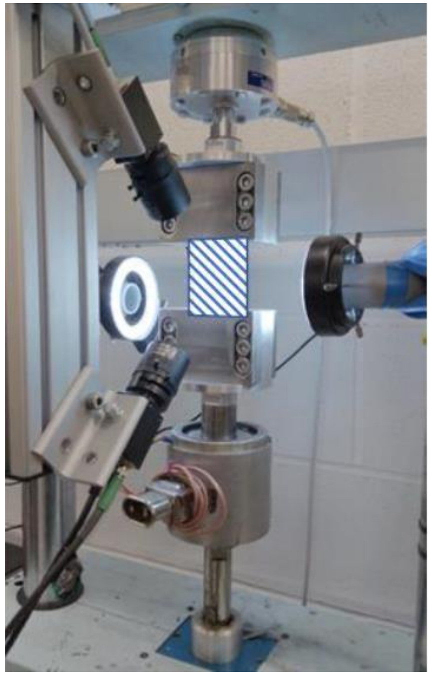
- New high-performance, light-weight materials:
  - Wider range of materials:
    'exotic' metals, polymers, composites, laminates…
  - Jointing of dissimilar materials
    - Continuous joints: *welds, adhesives…*
    - Discrete fasteners: *spot welds, rivets, SPR, adhesive hybrids…*
  - New production techniques:
    Additive Manufacturing, sintering, casting…

- Improved materials models to reduce epistemic uncertainties:
  - R ratio (mean stress sensitivity) modelling
  - Surface finish / treatment modelling
  - High (& low) temperature, thermo-mechanical
  - Reuse & life extension of ageing materials
  - Load sequence effects modelling
  - Crack growth and progressive failure modes





Crack growth & progressive failure modes



Adhesive lap-shear & coach-peel

Thermo-mechanical fatigue

Thank You

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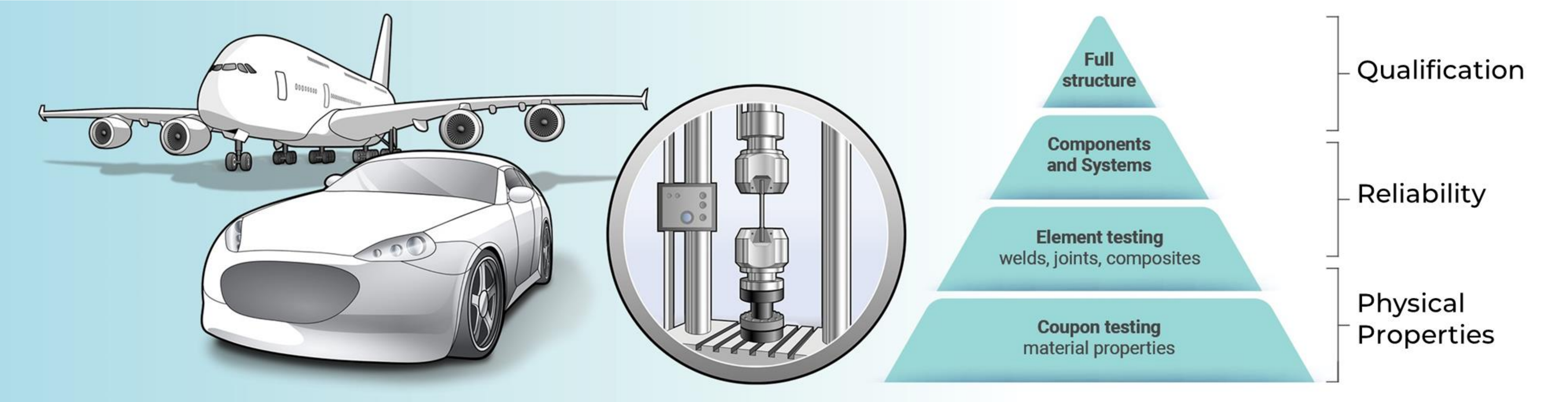
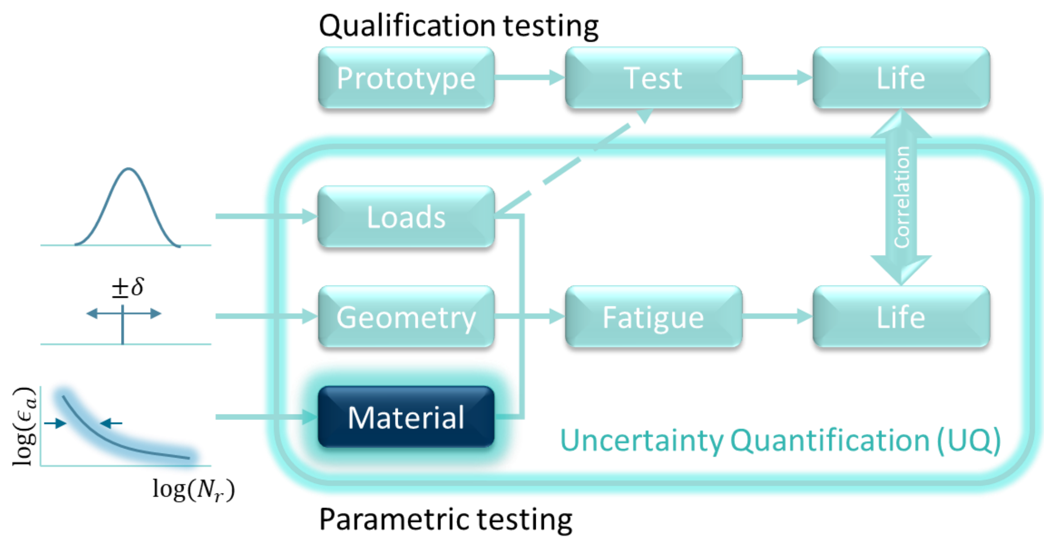


2023 HBK Technology Days

14 November 2023



- **Complementary material parametric testing and simulation for fatigue prediction**

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