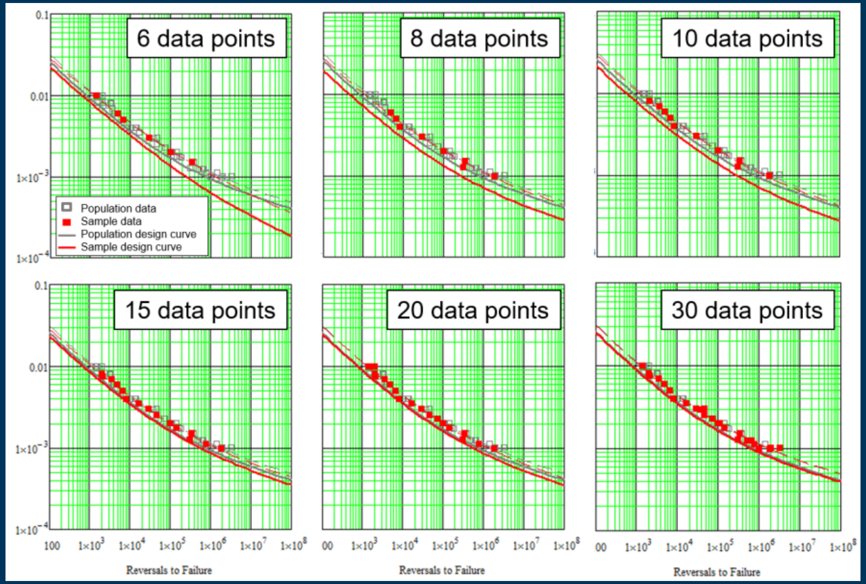

Virtual Seminar Series – Tuesday 2, 9, 16 November




# Fatigue Testing of Materials and Fatigue Characterisation

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

Tuesday, November 16, 2021

# Fatigue Testing of Materials and Fatigue Characterisation


## Abstract

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. In many cases, fatigue failures occur suddenly with little warning and so it is important to design structures to resist fatigue failure. While it can be technically challenging to simulate fatigue failure, it is possible to get accurate fatigue life calculations by using specific and reliable material data.

This presentation considers how material fatigue properties used in fatigue simulation are determined from laboratory tests. We will review the very first ‘rotating-bend’ test invented by August Wöhler through to the popular ‘load-control’ and ‘strain-control’ test procedures used today. Particular consideration is paid to ‘characterizing the material’ to derive a ‘design curve’ for use in component fatigue analysis.

Such material characterisation accounts for statistical reliability and confidence, enabling quantification of answers to questions such as:

- How many specimens to test?
- How to validate replacement materials?
- How to compare the performance of materials from different suppliers?


## 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.

# Fatigue Testing of Materials and Fatigue Characterisation

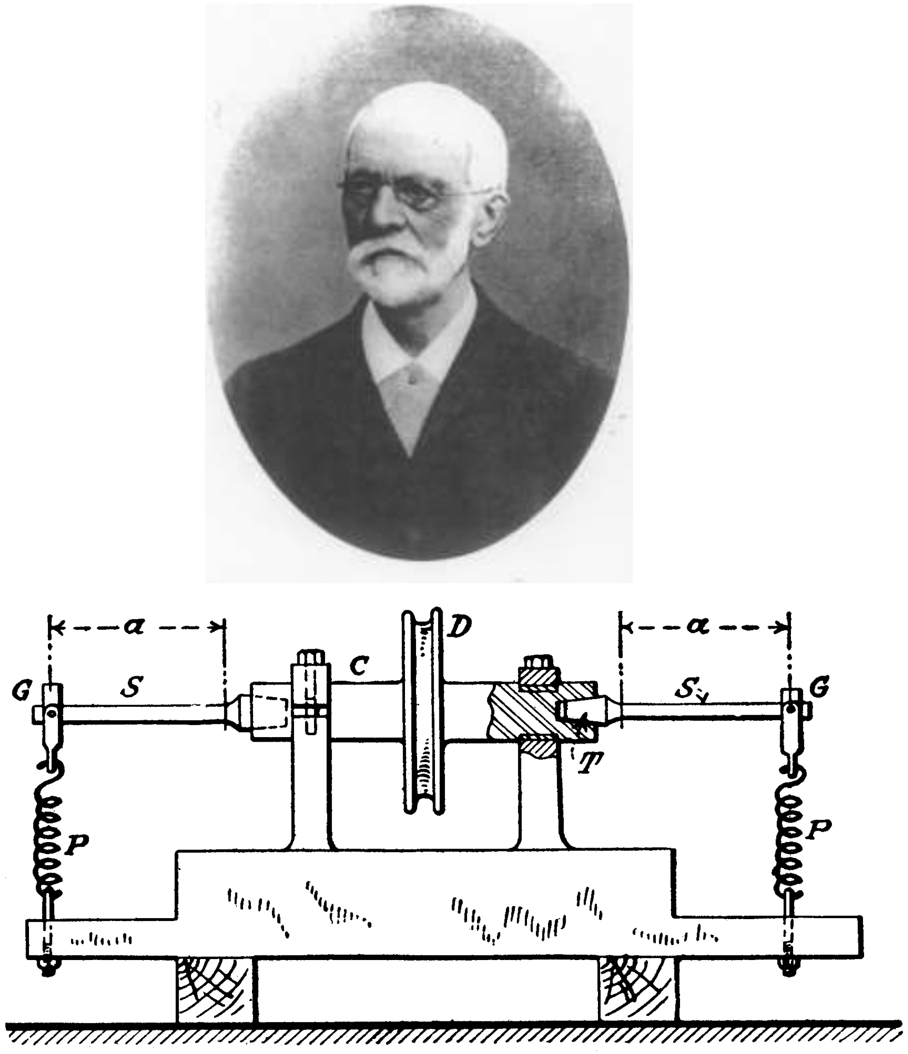
Dr Andrew Halfpenny
Director of Technology – nCode Products

# Agenda

1. Load-controlled (SN) fatigue testing
2. Strain-controlled (EN) fatigue testing
3. Conclusion
   - AMCT services & research activities

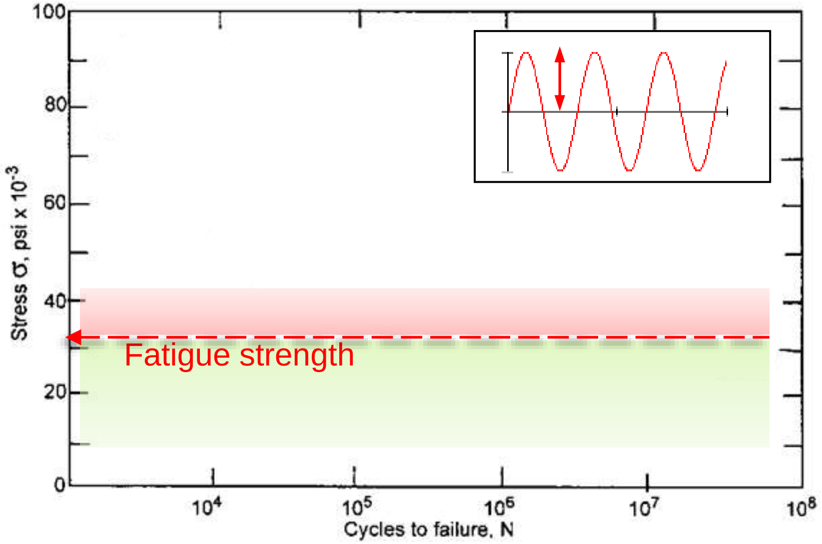
Advanced Materials Characterization & Testing (AMCT)

# Grandfather of Fatigue




**Wöhler circa 1850**

- 1852-70, August Wöhler studied progressive failure of railway axles
- Invented first fatigue test – *rotating bend test*
- Discovered concept of '*Fatigue Strength*'
- Basquin later plotted loglog relationship between stress and number of cycles to failure – *Fatigue Life Curve*



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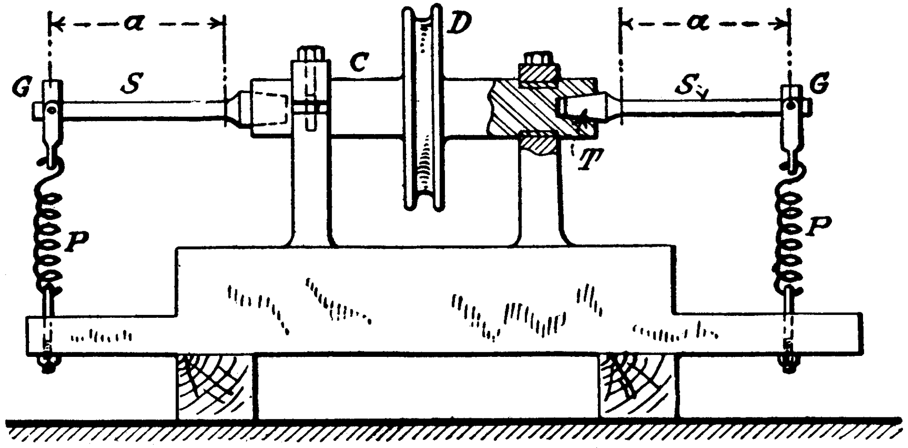
# Grandfather of Fatigue

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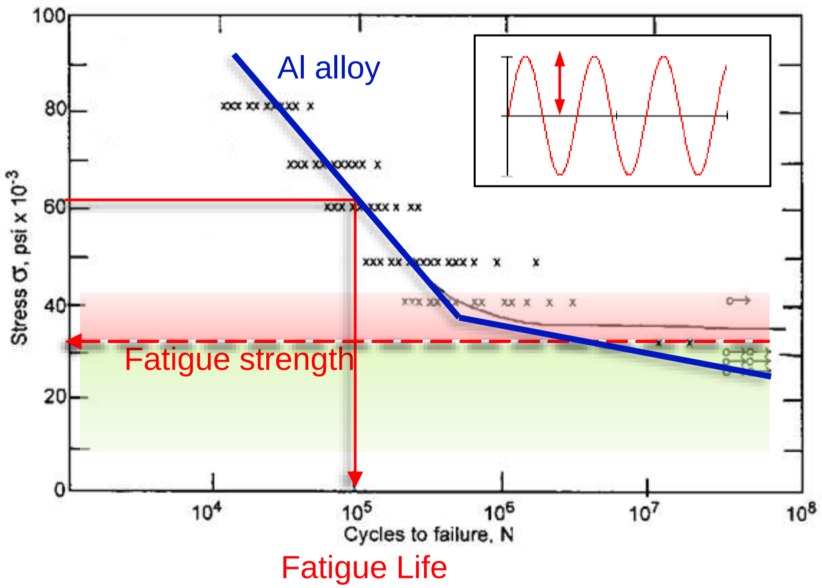




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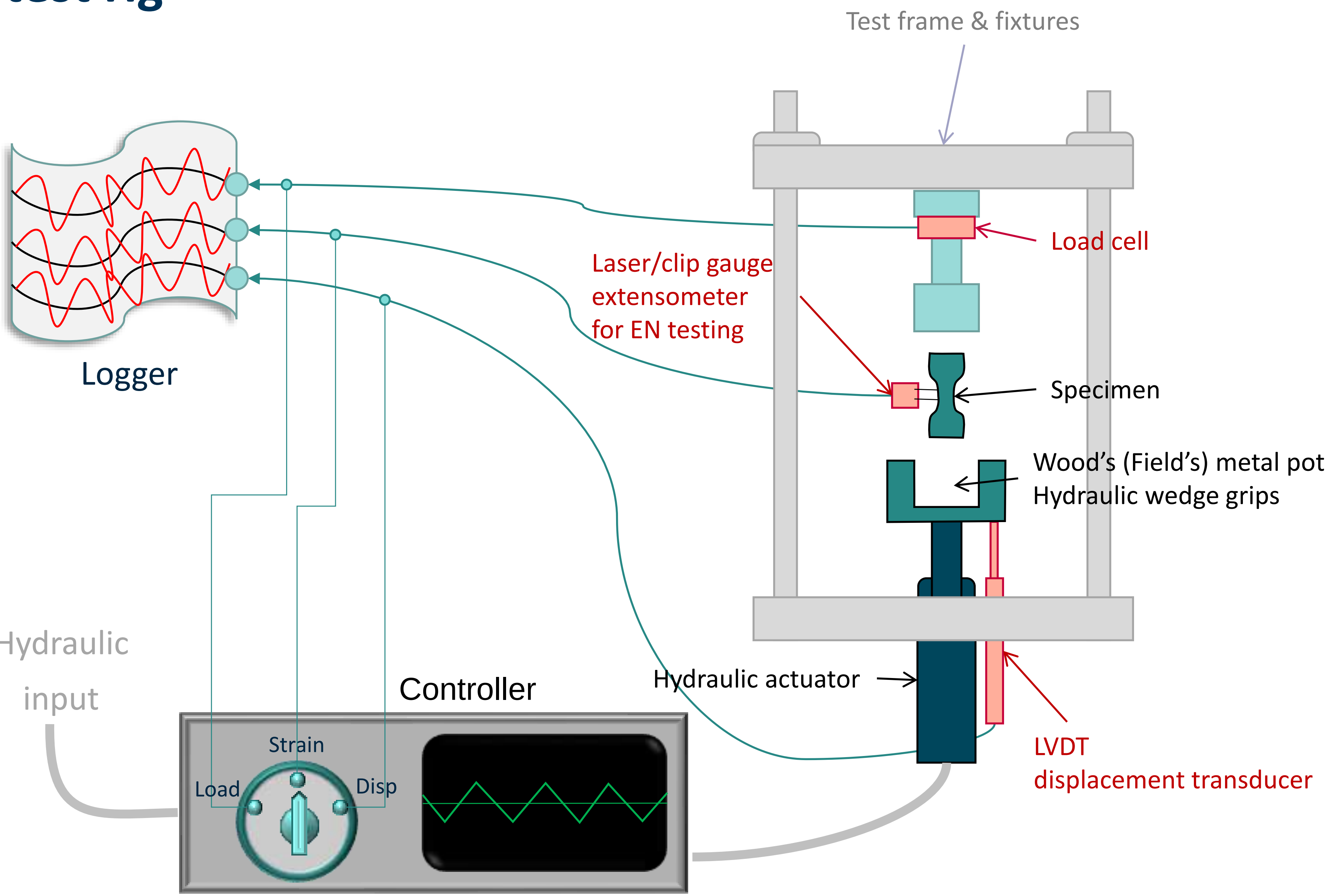
# AMCT – Typical fatigue test rig



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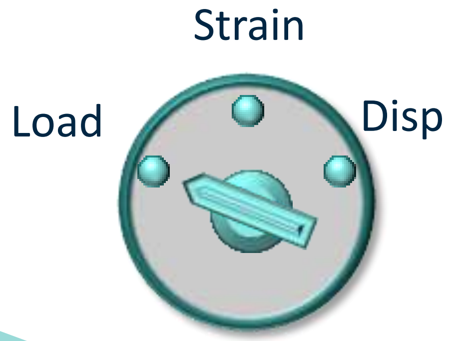
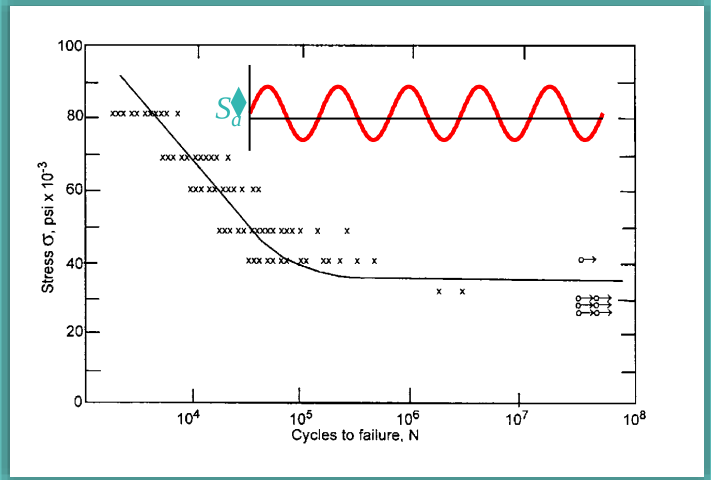



# SN Fatigue or ‘Load-Controlled’ Testing

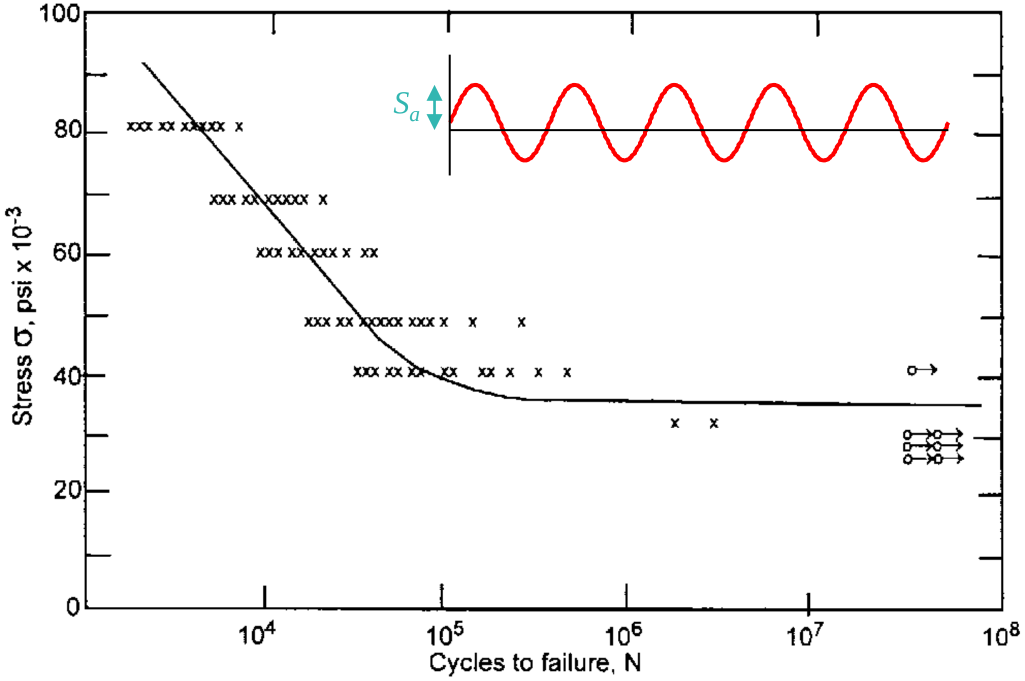


# SN Fatigue – *load-controlled test*

- Specimens subjected to constant amplitude loading – Load Controlled test
- log nominal elastic stress vs. log life
- log regression line

*Basquin's equation* $s_a = \sigma_{f'} (2N_f)^b$







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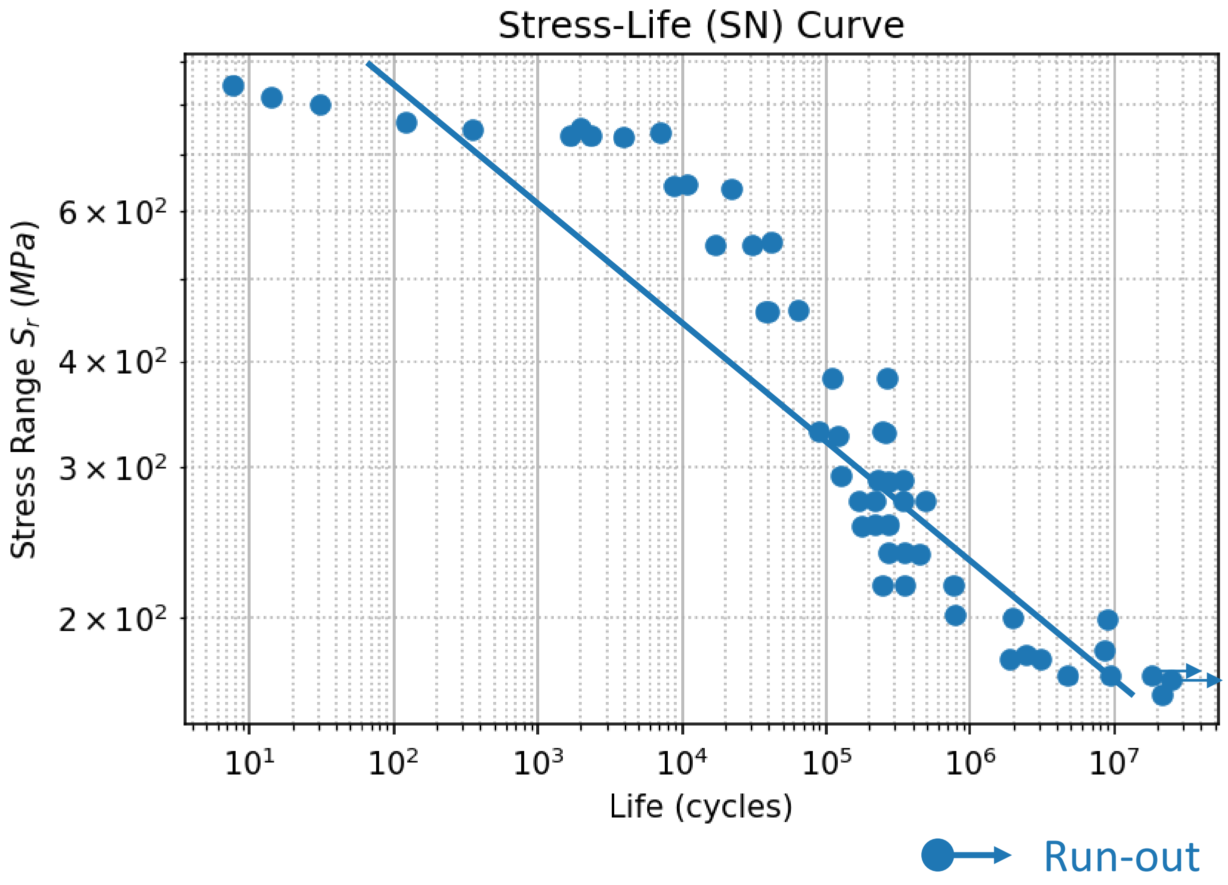
# Raw SN data for a Cast Aluminium

- Generally
  - an SN curve is not a straight line!
  - do not treat run-outs as ‘suspended tests’ when using MLE analysis!



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# SN Fatigue – *load-controlled test*

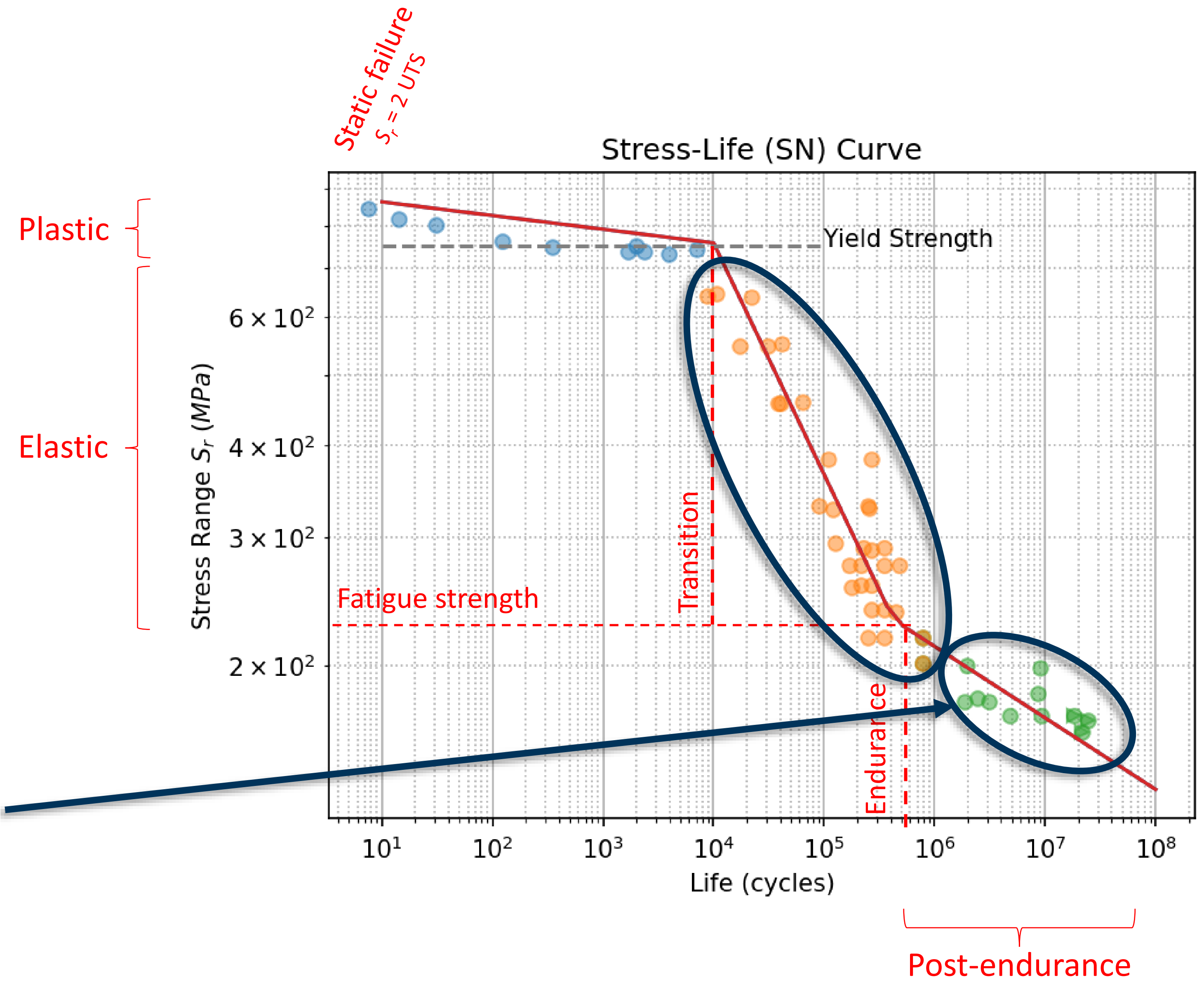
- Recognise 3 distinct regions
  - Plastic
  - Elastic
  - Post-endurance

transition ~$10^3$–$10^4$ cycles

transition ~$10^5$–$10^7$ cycles

- Post-endurance slope depends on material and loading history
  - Measure it – rotating SN, etc. 😊
  - Empirical assumptions 🤨
    1. Fatigue strength – Infinite life
    2. Continuous slope
    3. Empirical assumptions

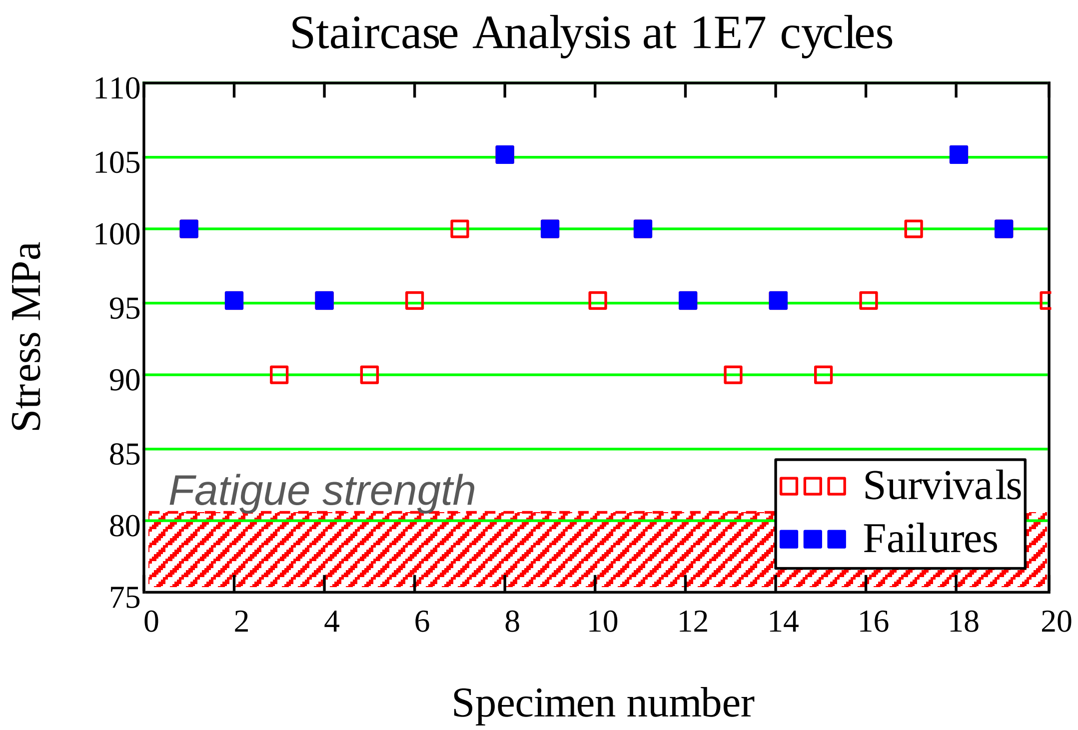
$$b_2 \approx \frac{b_1}{2 + b_1}$$ after Haibach



# Fatigue strength – staircase testing

- Set endurance limit
  (e.g. 1E7 cycles)
- Estimate fatigue strength s1
  (e.g. s1 = 100 MPa)
- Set stress interval $\Delta S$
  (e.g. $\Delta S = 5$MPa)

```
s₁ = 100
for i in range(20):
    if testᵢ survives then:
        sᵢ₊₁ = sᵢ+Δs
    else:
        sᵢ₊₁ = sᵢ-Δs
```




- Calculate safe fatigue strength using statistical survival analysis
  (e.g. Dixon-Mood, Svensson-Loren, etc.)



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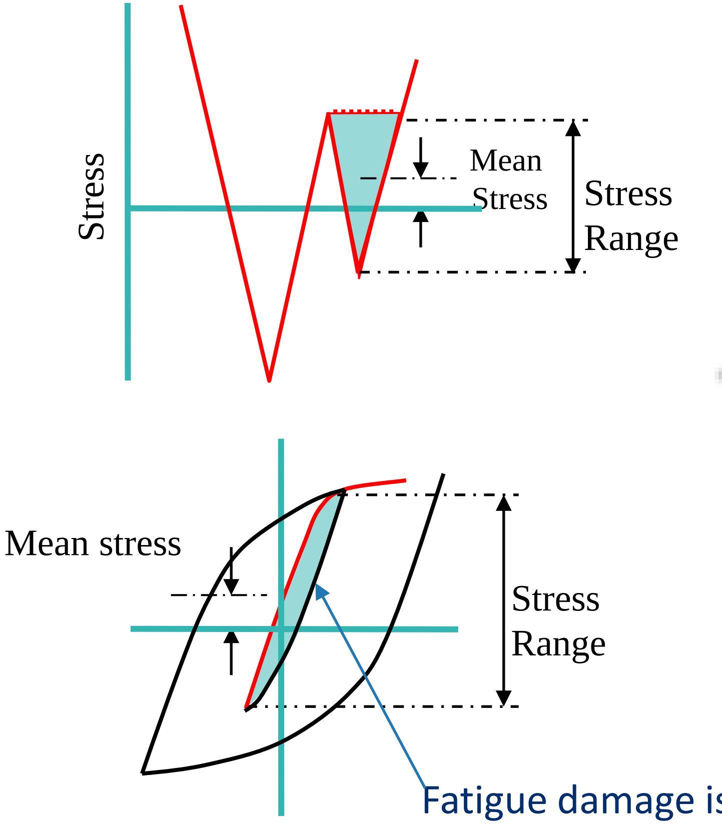
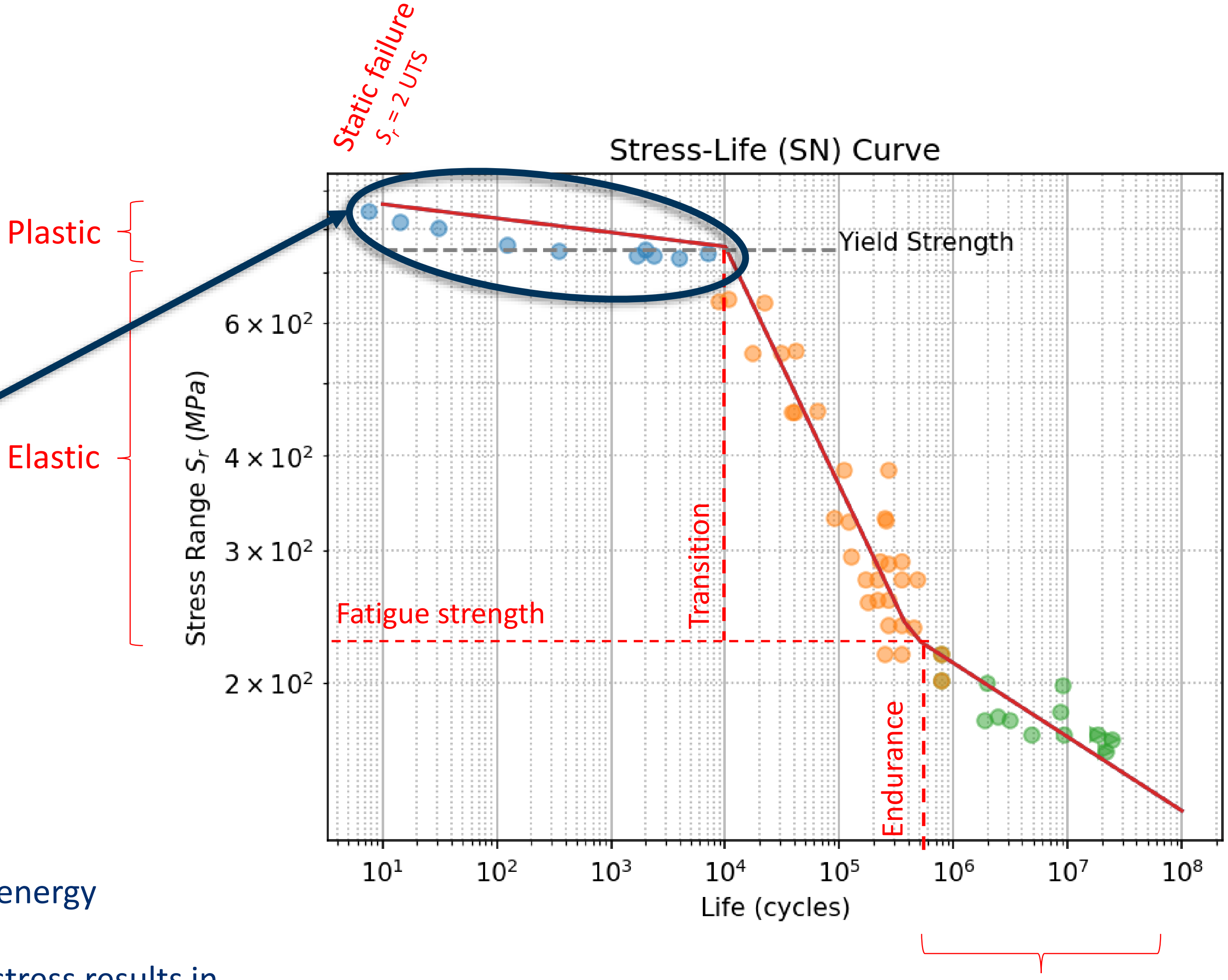
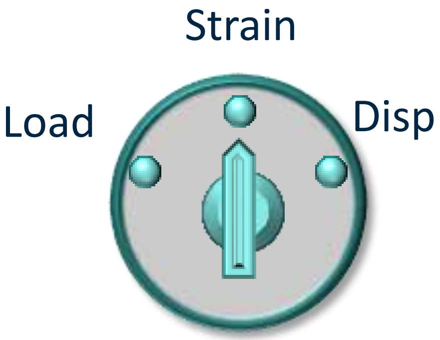
# SN Fatigue – *load-controlled test*

- SN doesn't work well for Plastic loads (Low-cycle fatigue)




Fatigue damage is proportional to energy (i.e. area of the hysteresis loop)
In plastic region a small change in stress results in a massive change in energy!

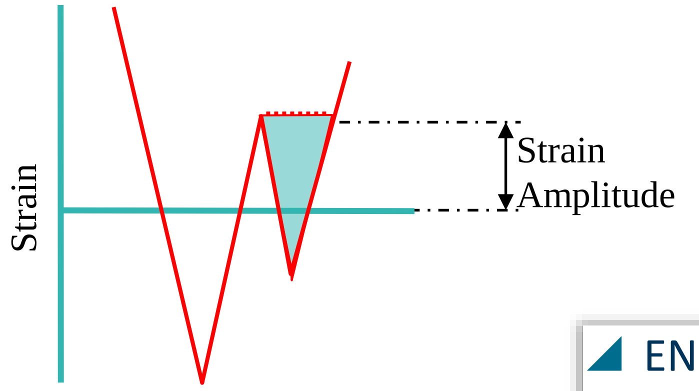


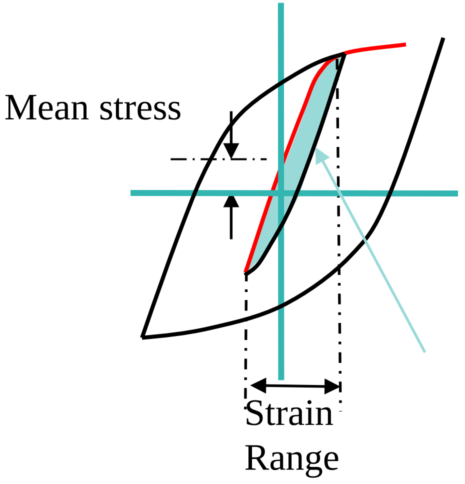

# EN Fatigue or ‘Strain-Controlled’ Testing

# EN Fatigue – *strain-controlled test*

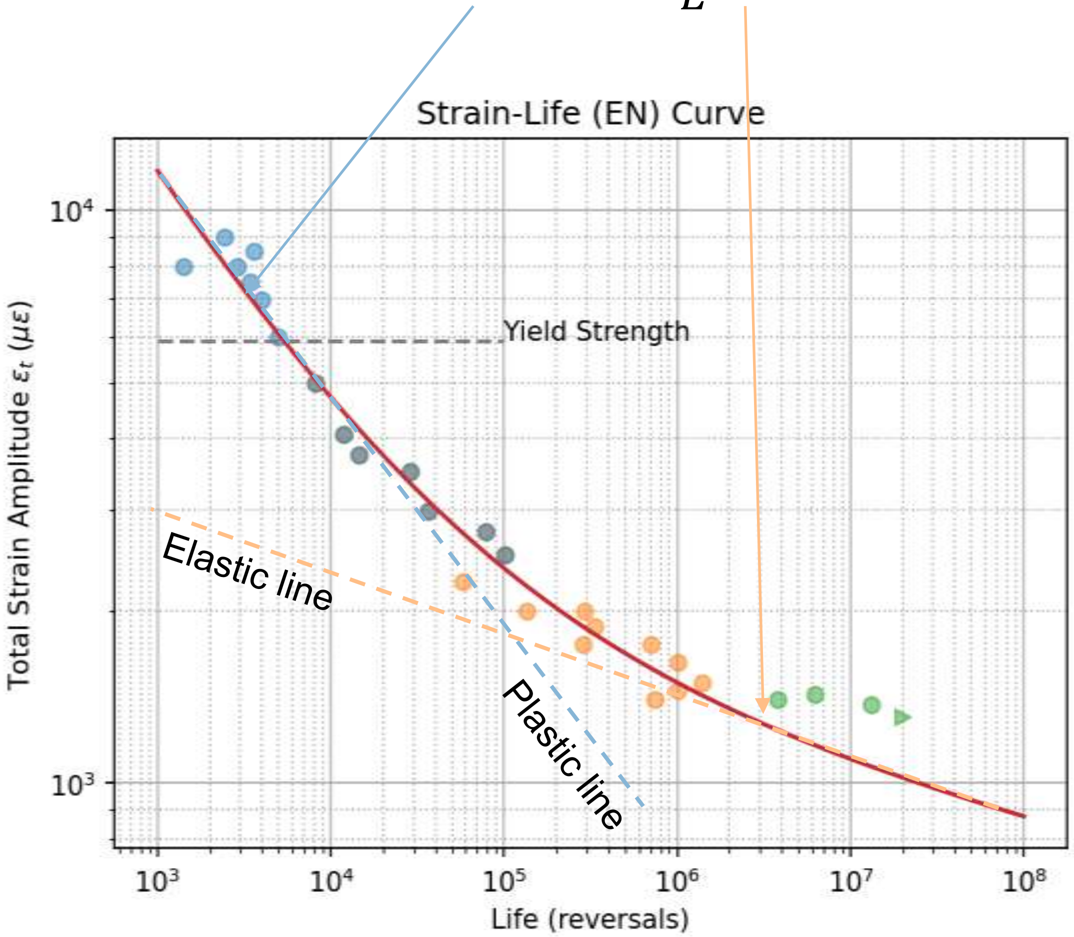
*Coffin-Manson-Basquin equation*

$$\varepsilon_a = \epsilon_{f'}(2N_f)^c + \frac{\sigma_{f'}}{E}(2N_f)^b$$




- EN method works for the whole range of the fatigue curve
- SN method only works in the high-cycle fatigue range




Fatigue damage is proportional to energy (i.e. area of the hysteresis loop)
A small change in strain is comparable to a small change in energy

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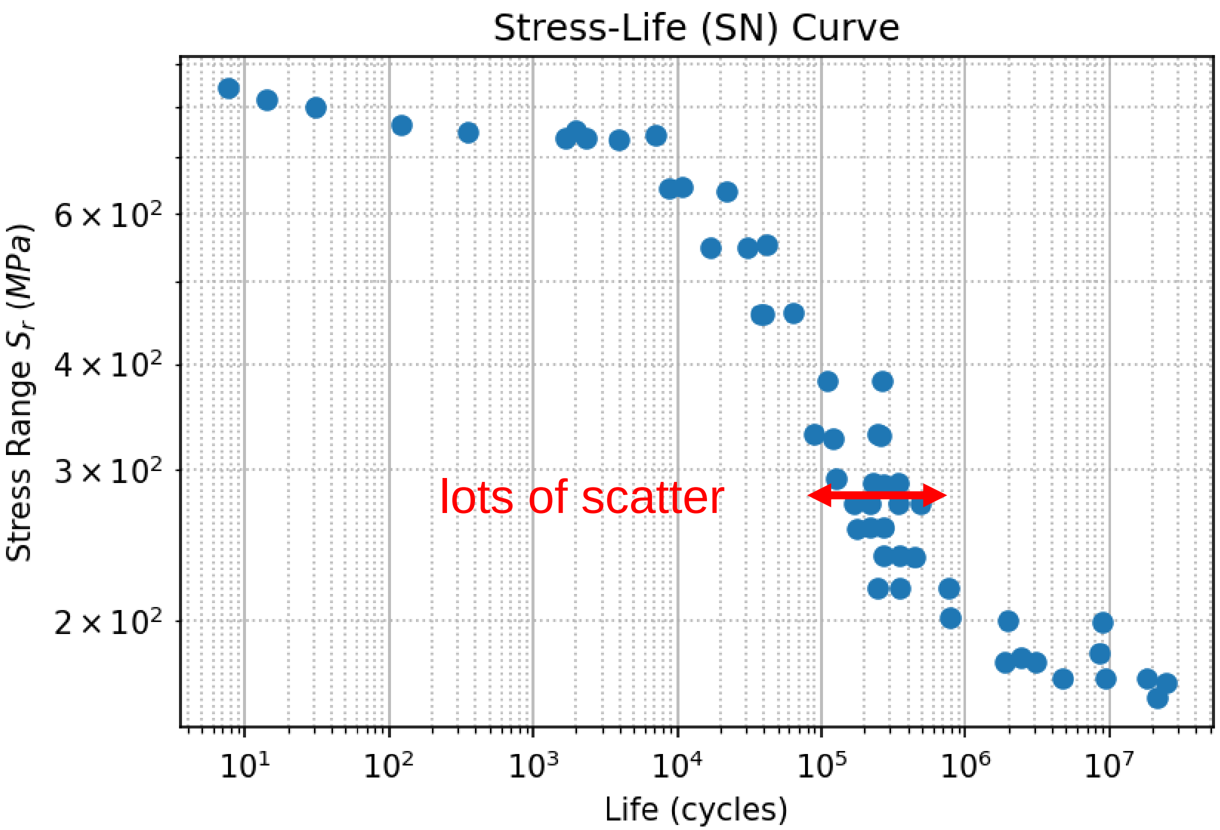
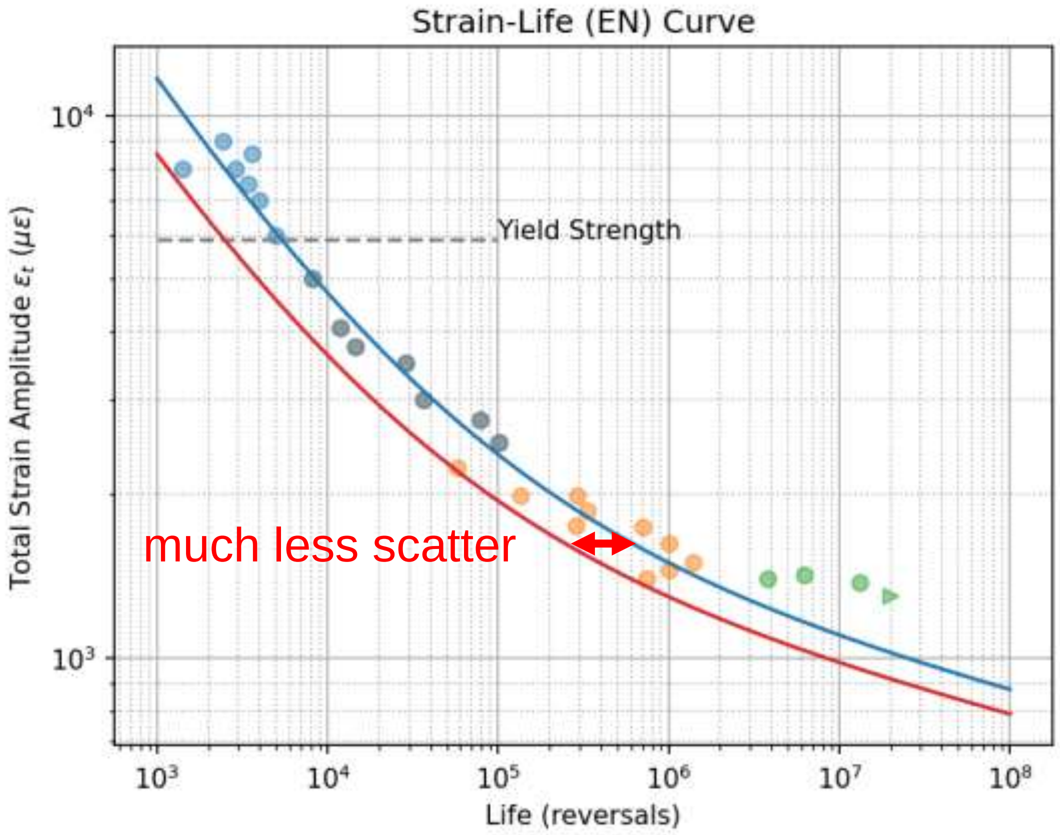
# EN Fatigue – *strain-controlled test*







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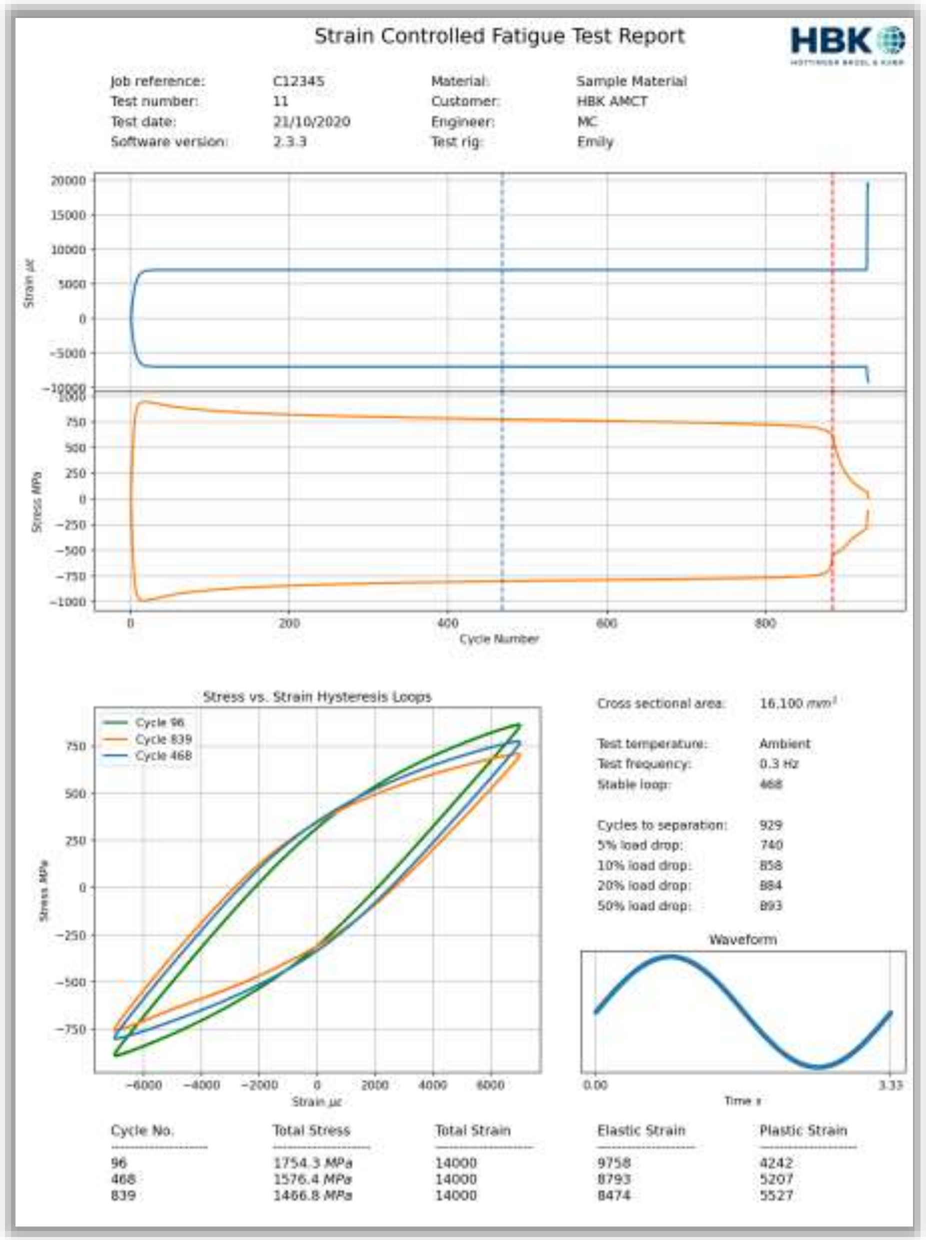
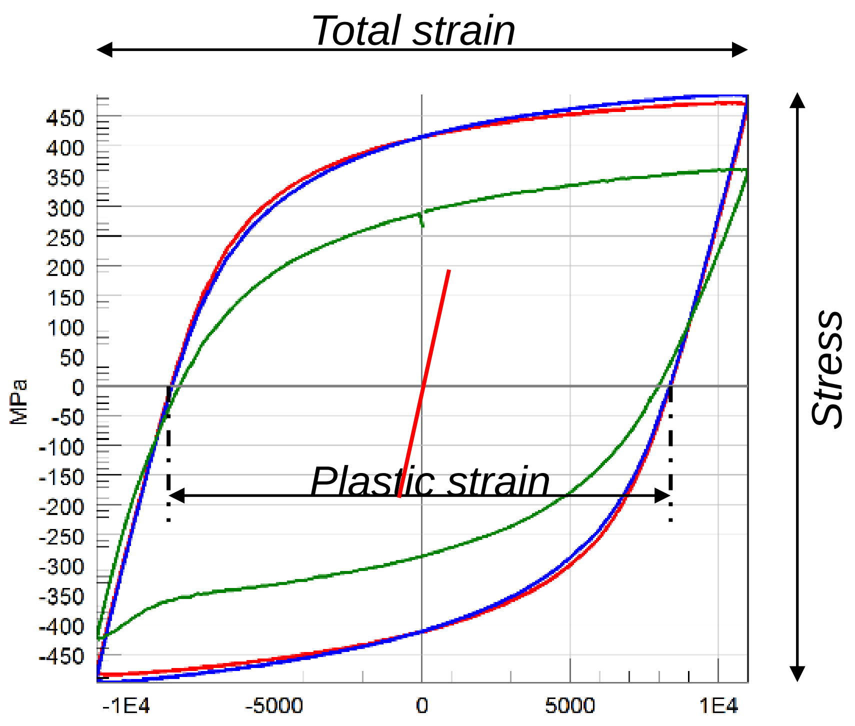
# EN Fatigue – *why does EN give less scatter?*

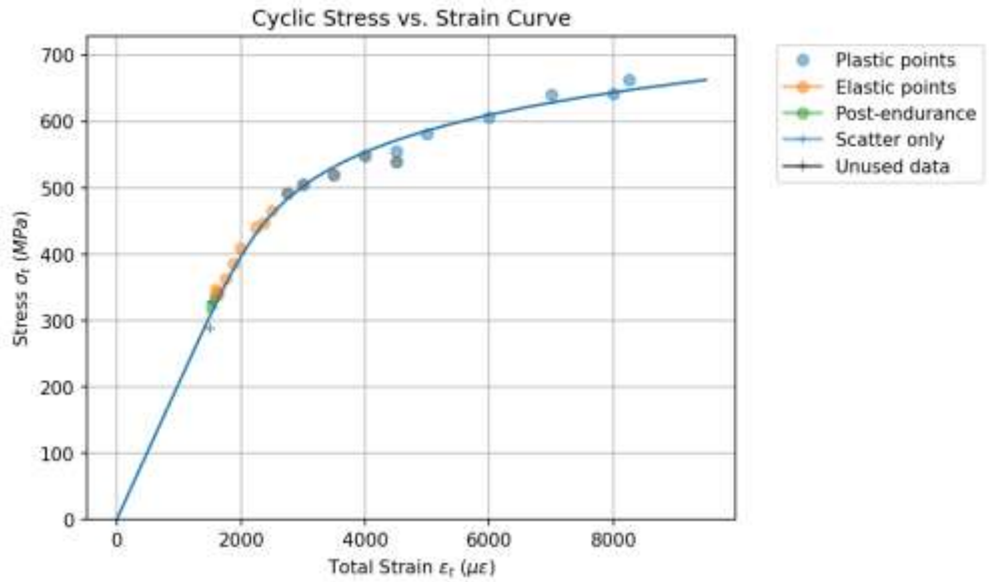


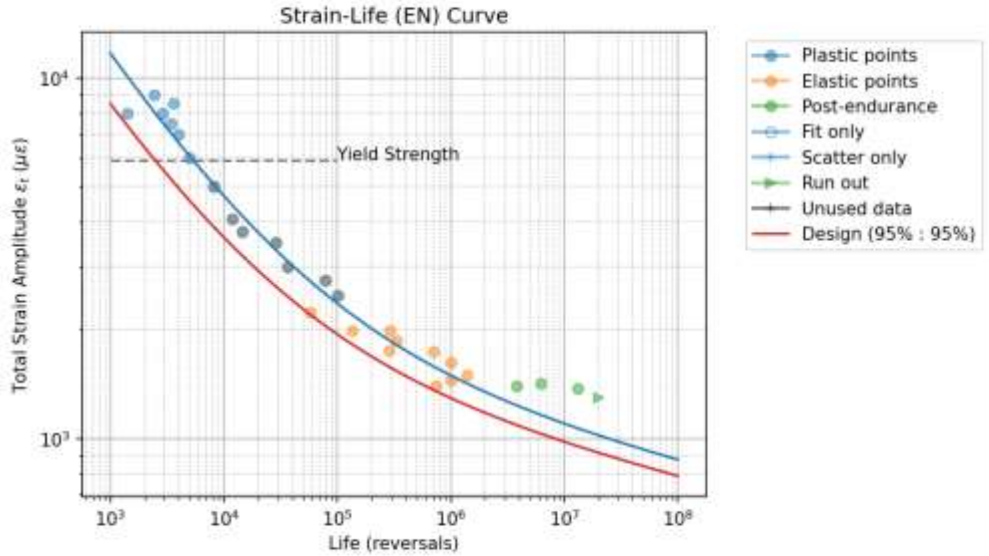

- EN controls the parameter of interest – *Strain energy*
- Better control of failure – separates crack initiation stage from growth stage
- Better representation of strain
  - Accurate strain measurements
  - Clear separation of elastic and plastic contributories

*Elastic strain = Total strain – Plastic strain*



# EN characterisation analysis




1. Plot stress vs. total strain for all tests and fit Ramberg-Osgood equation

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

2. Plot total strain amplitude vs. reversals to failure (load-drop)
3. Fit elastic line using elastic strain

$$\varepsilon_{elastic} = \frac{\sigma_{f'}}{E}(2N_f)^b$$

4. Fit plastic line using plastic strain

$$\varepsilon_{plastic} = \epsilon_{f'}(2N_f)^c$$

5. Parameter re-optimisation

$$\varepsilon_a = \epsilon_{f'}(2N_f)^c + \frac{\sigma_{f'}}{E}(2N_f)^b$$

6. Outlier analysis
7. Calculate statistical design curves



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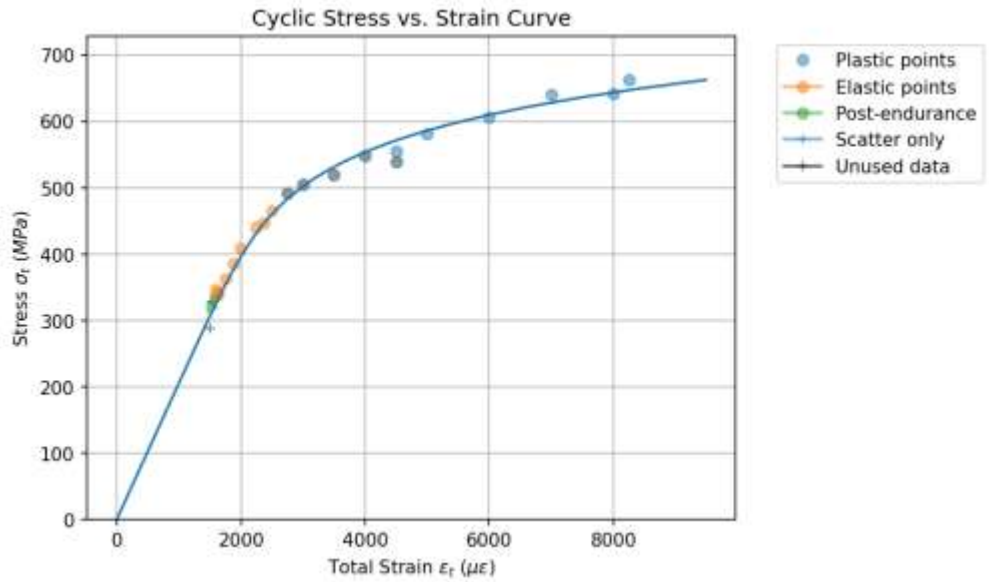


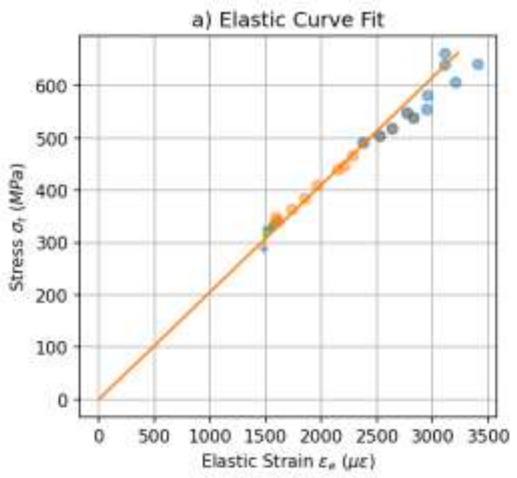


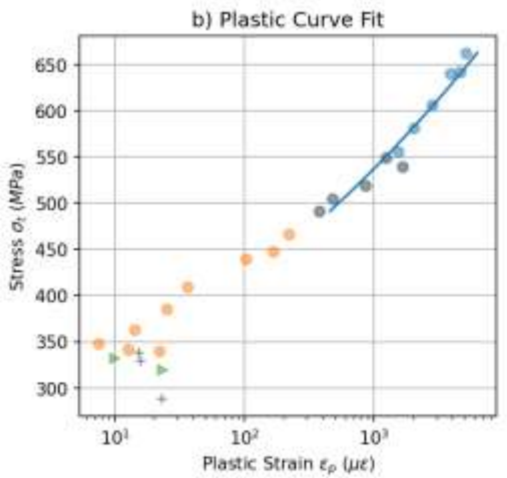


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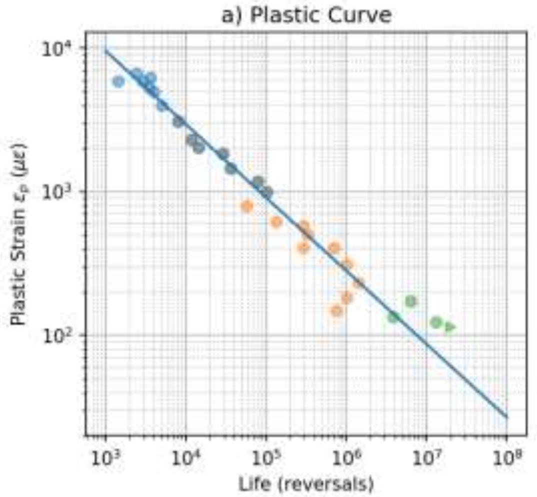


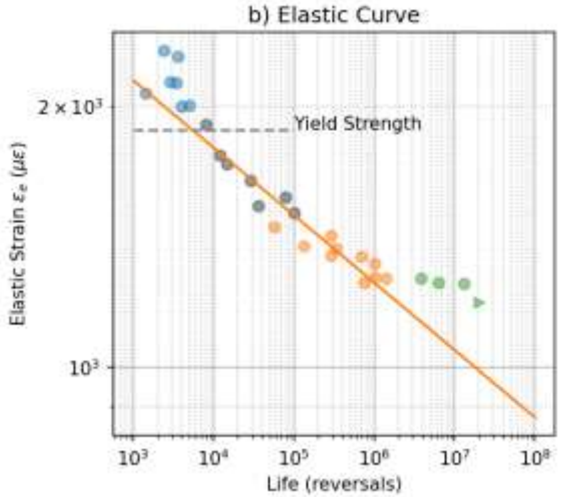


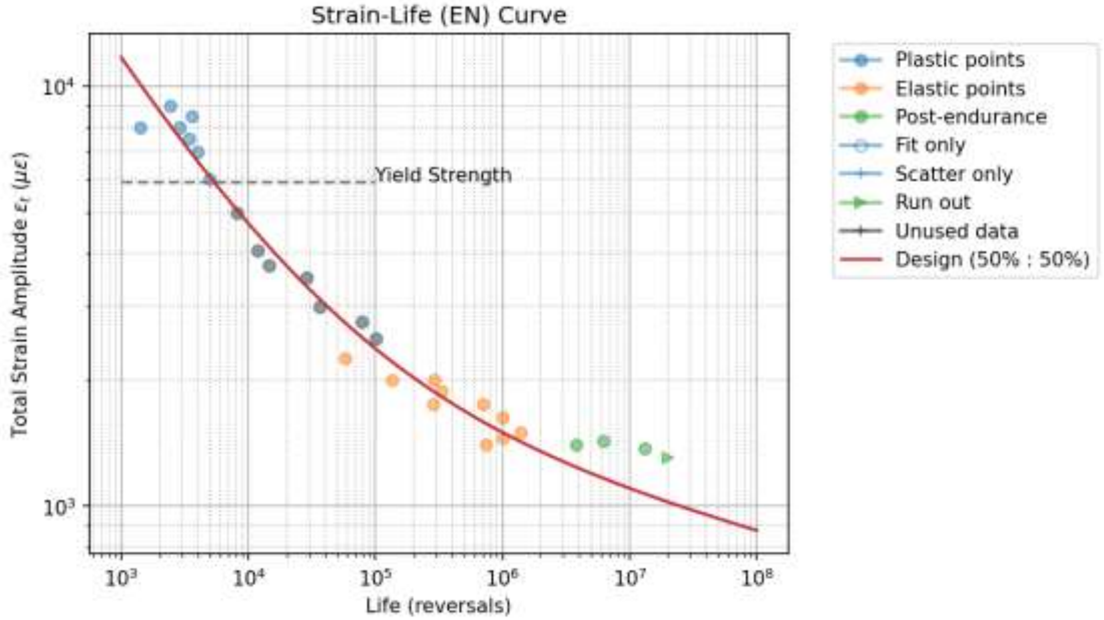


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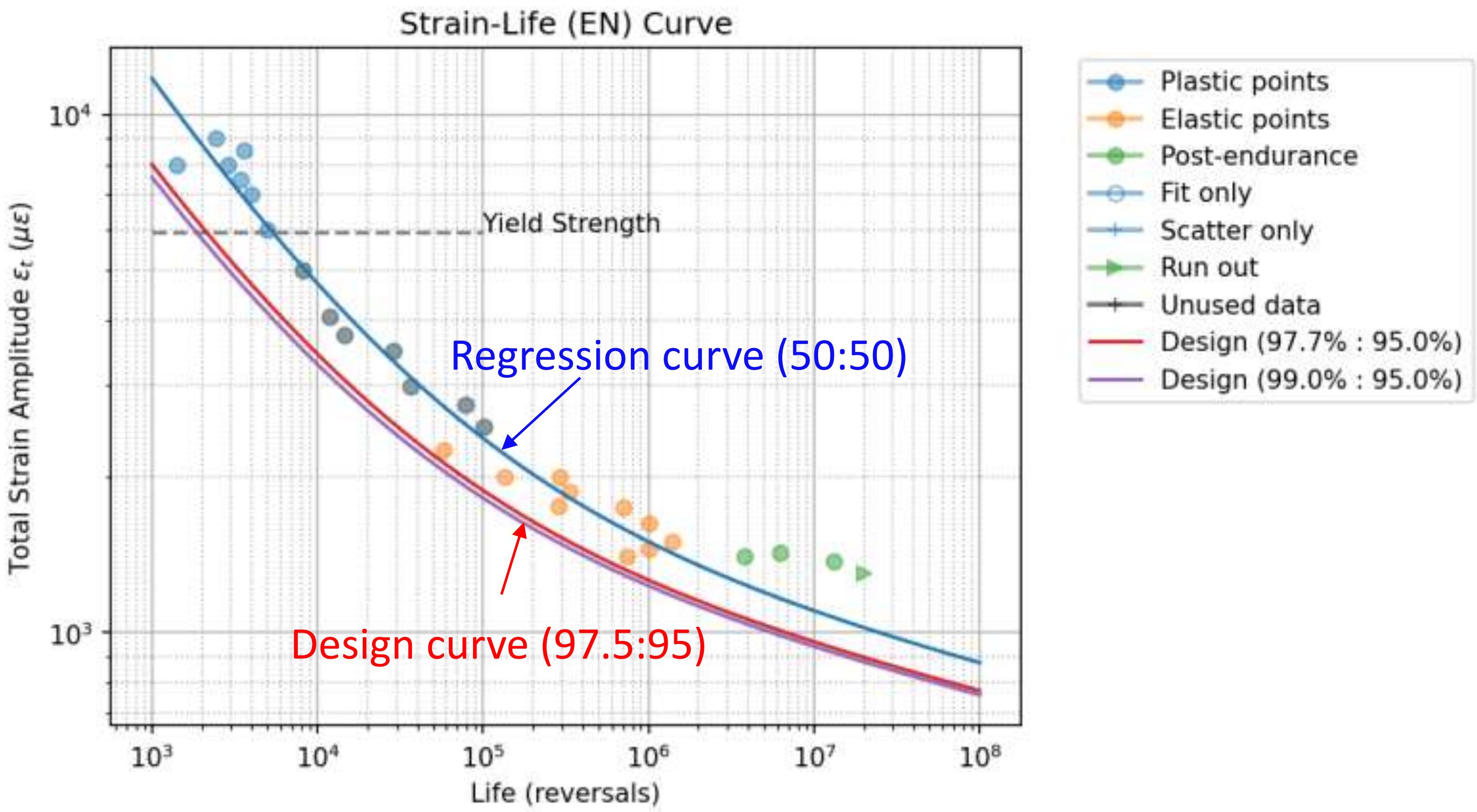
# What is the Design Curve?

- Regression curve represents life at which 50% of samples have failed
  i.e. 50% of manufactured components will fail by this time!

- Design curves often use:
  - 95% (5 failures in 100)
  - 97.5% (2.5 failures in 100)
  - 99% (1 failure in 100)
  - 99.87% (3 sigma)
    (13 failures in 1000)
  - 99.9997% (4.5 sigma)
    (3.4 failures in 1 million)
  - 6 sigma (1 failure in 1 billion)



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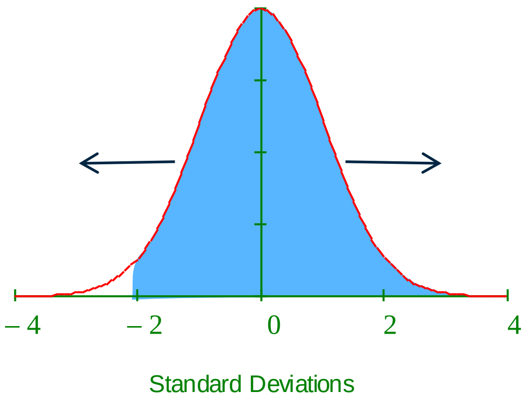
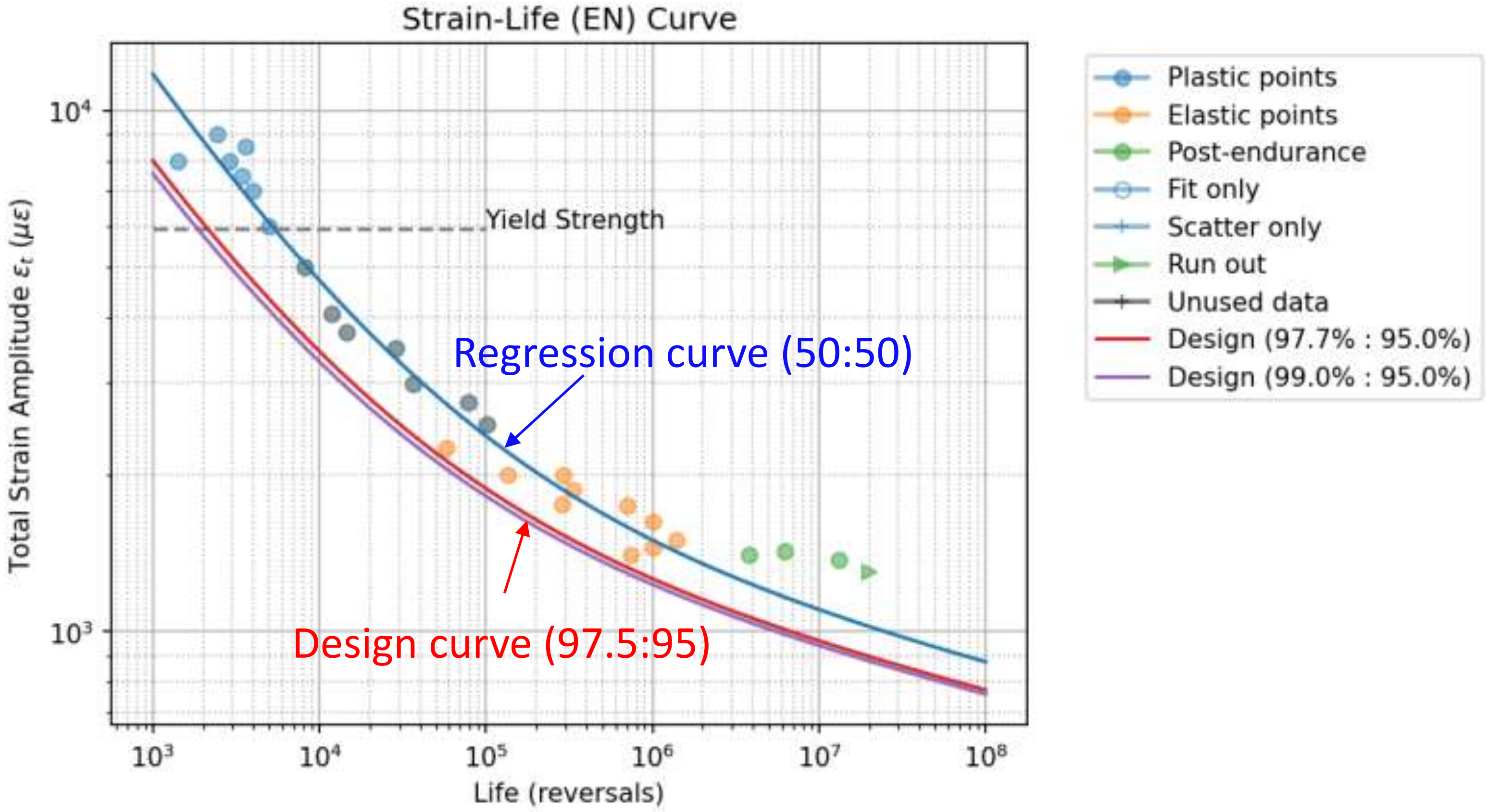
# What is the 97.5 : 95 Design Curve?

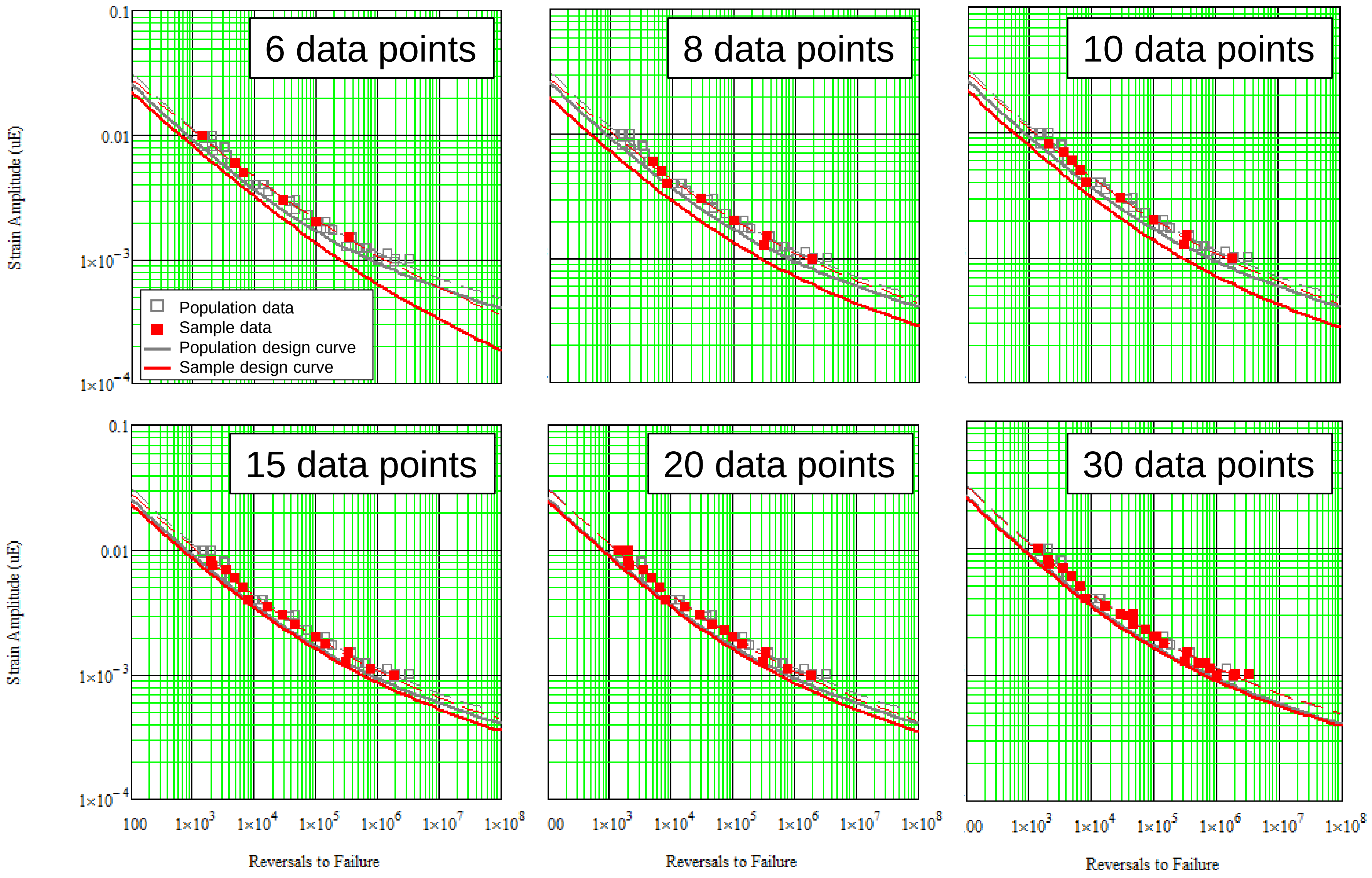
- 97.5% Reliability with a 95% Confidence
- The more samples you test the more confident you are about the scatter

*Scatter band increases with fewer data points*



# How many tests do we need?



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# How many tests do we need?

- 6 – 10 samples
  - 6 sample is absolute minimum for SN characterisation
  - SN design curve very conservative

- 15 - 20 samples
  - Minimum practical sample size for SN characterization
  - Absolute minimum for EN characterization
  - EN design curve very conservative

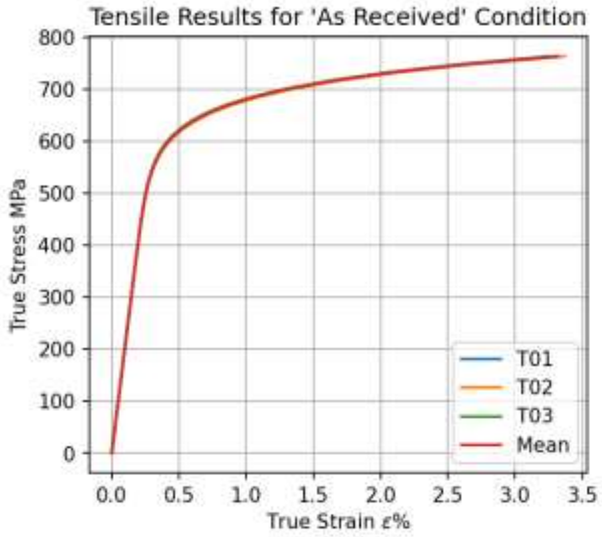
- 20 - 30 samples
  - Minimum practical sample size for EN characterization
  - Good quality design curve (at 97.5 : 95)
  - 30+ samples required as confidence / reliability requirements increase

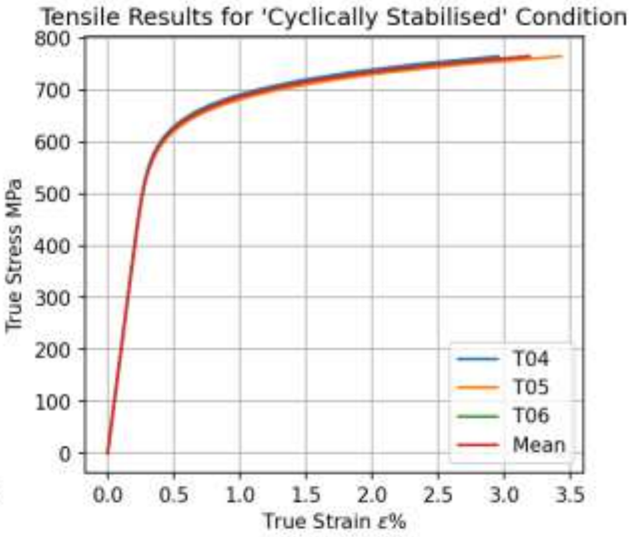
# Tensile Testing

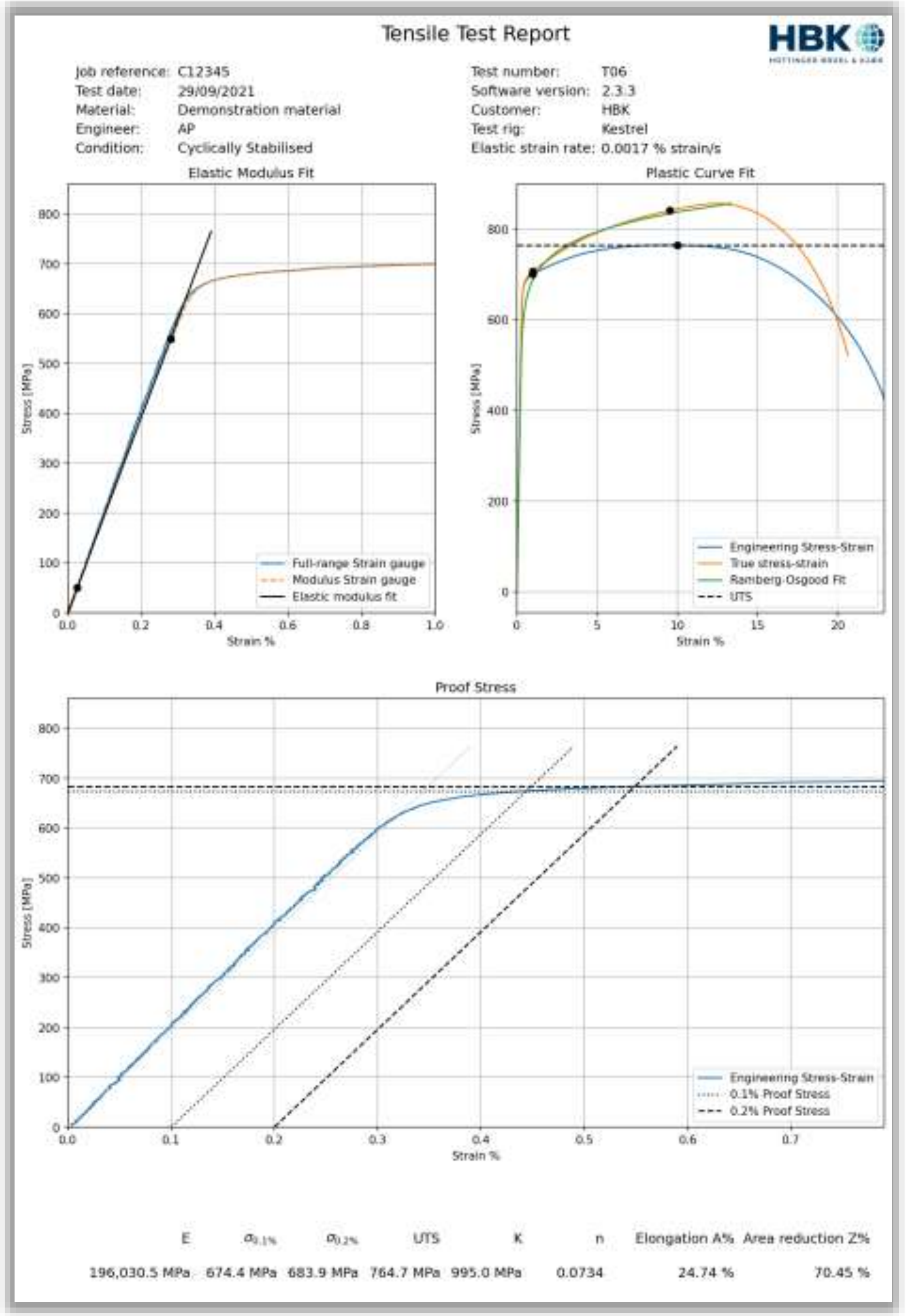
# Tensile Tests – *As Received/Cyclically Stabilised*

| | | T04 | T05 | T06 | Mean |
|---|---|---|---|---|---|
| Static | 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 |
| Ramberg-Osgood | 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% |

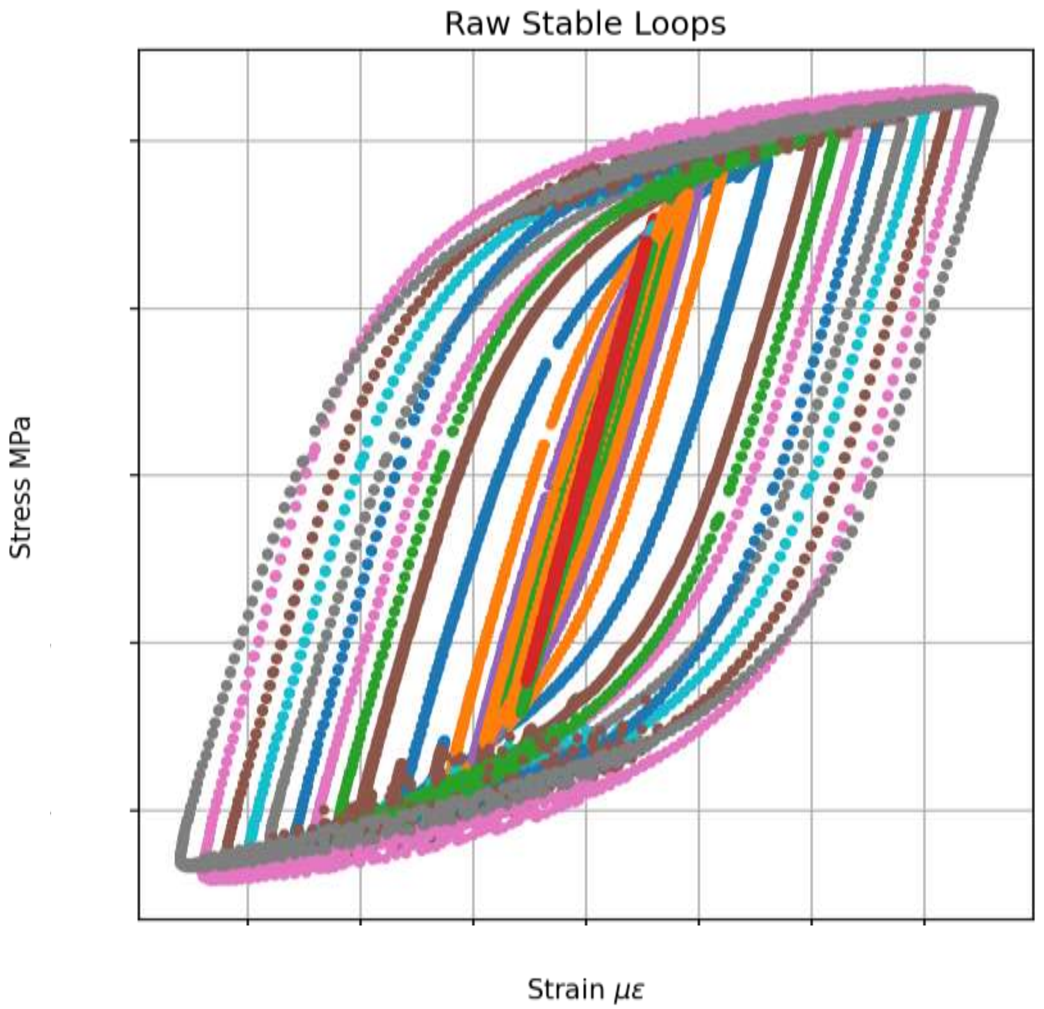
*Parameters for elastic and elastic-plastic analysis with isotropic hardening*

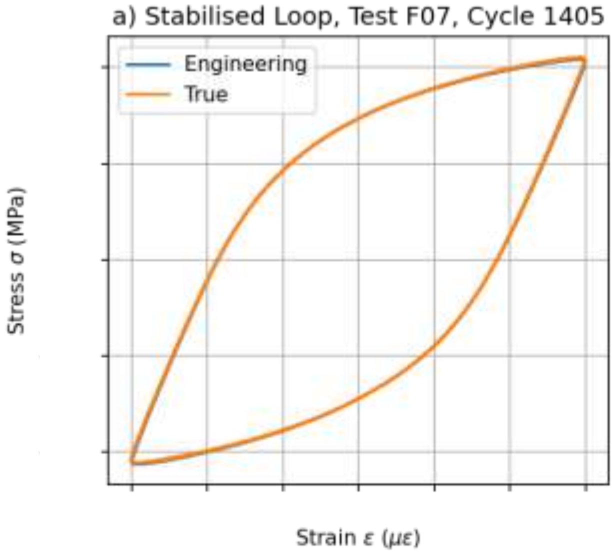


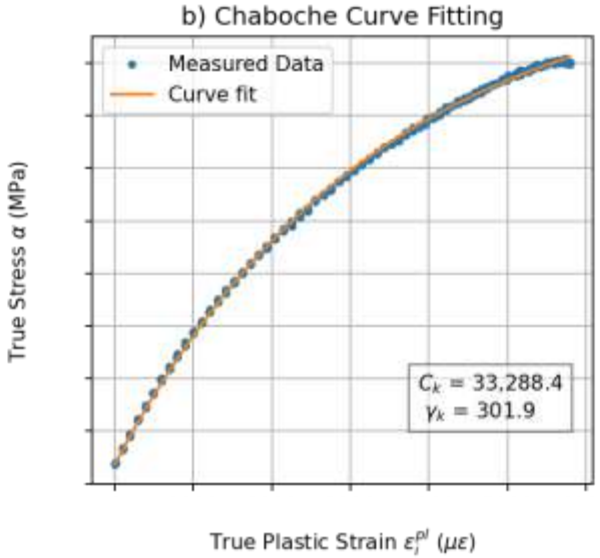



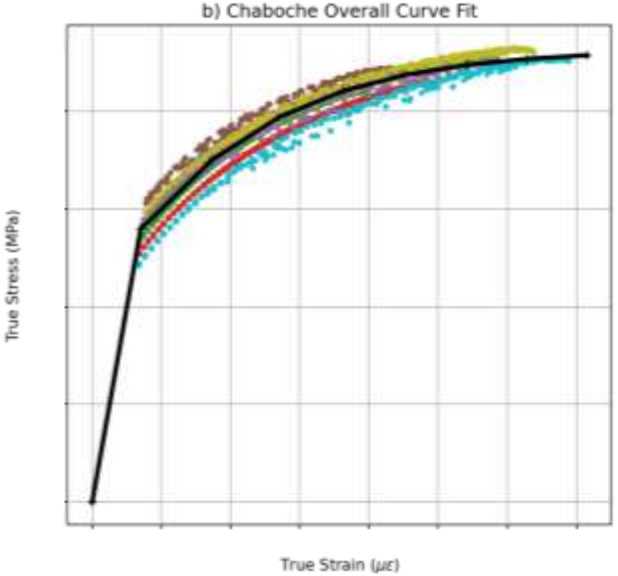



# Kinematic hardening – *post processing EN fatigue loops for ABAQUS*



# AMCT Services & Research Activities

# AMCT – Customer Services

## Materials Characterisation

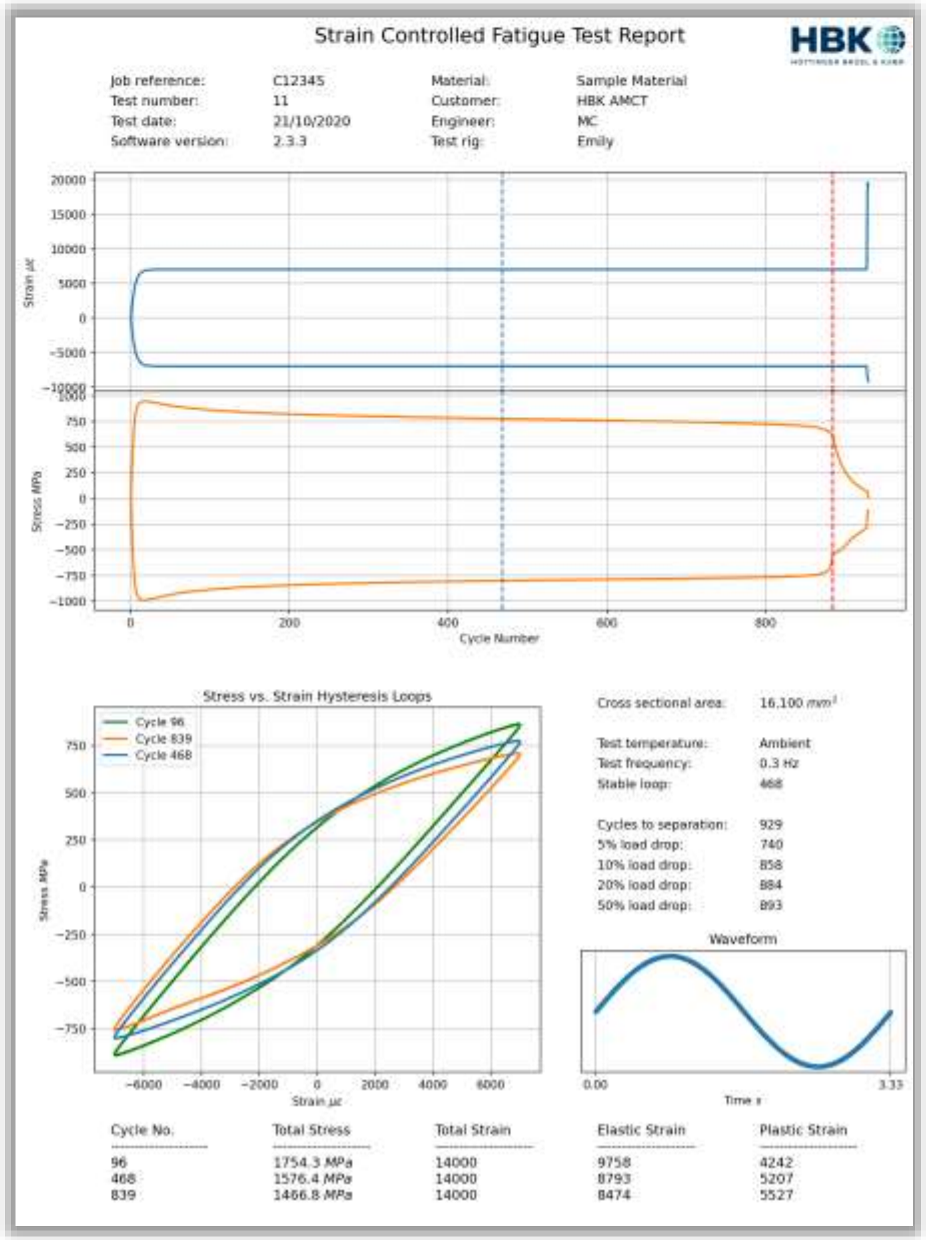
- Deriving parameters for various material models: *Tensile, SN, EN, TMF, crack growth, WholeLife, Welds, Joints, Haigh models, …*
- Characterising material improvements: *Heat & surface treatments, weld improvements*
- Characterising production processes: *Surface finishes, thin-sheets, brazing and jointing …*

## Materials Testing

- Specimen/component
- Durability certification

## Materials Assurance

- Quality assurance
- Supplier comparisons
- Material comparisons and short-listing



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# Thank You

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Director of Technology – nCode Products
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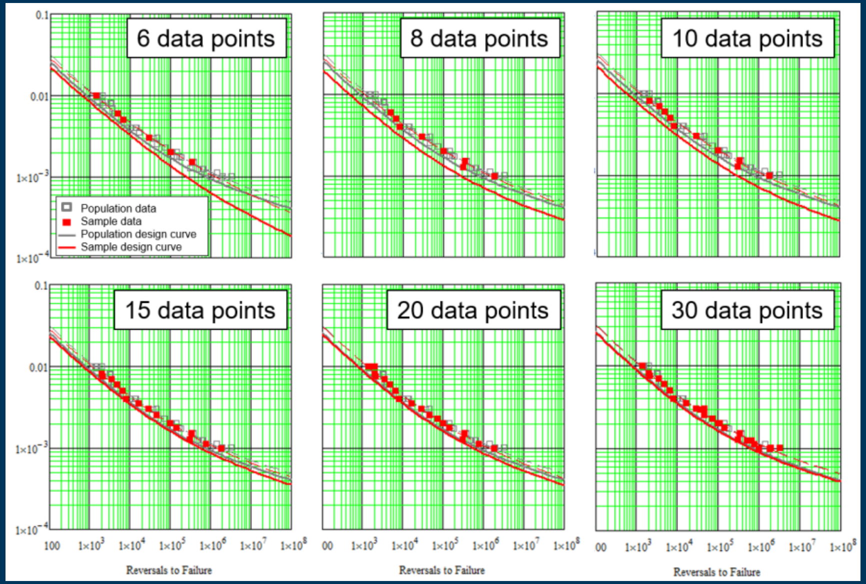
Virtual Seminar Series – Tuesday 2, 9, 16 November

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