High Frequency Testing

D-STANDART Technical Workshop

08/02/23 - Delft (NL)

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Funded by
the European Union

Contents

DIMAIO

- ❑ Brief background.
- ❑ Why did we change the test standard?
- ❑ The sensitivity of the transfer function phase to damage onset.
- ❑ Identification of critical event or delamination critical size.
- ❑ Modelling the phase and temperature curves.

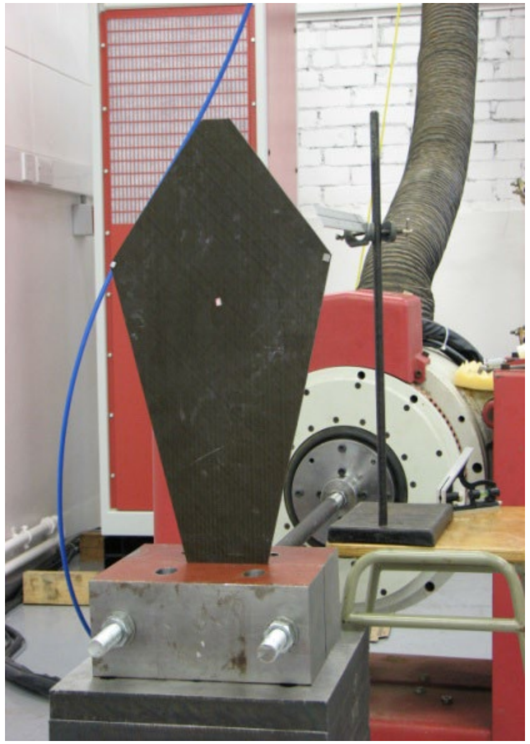
LASEN

- ❑ Fatigue damage growth of Zoltec samples.

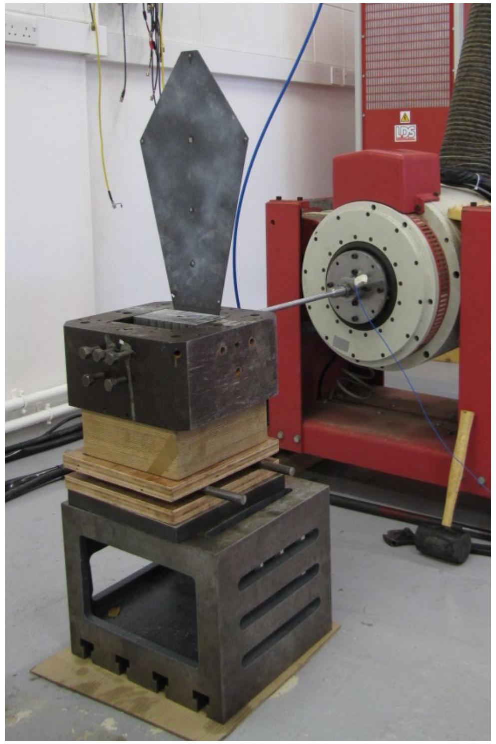
Will ever fatigue?

The drama unfolded!

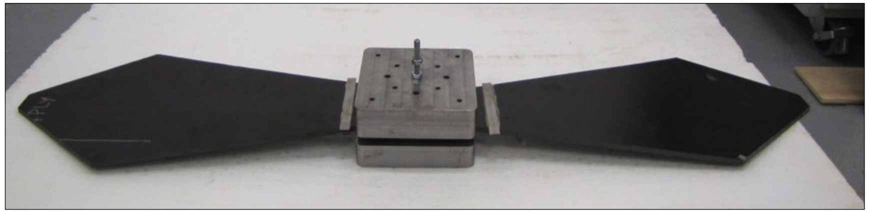
Observation n.1



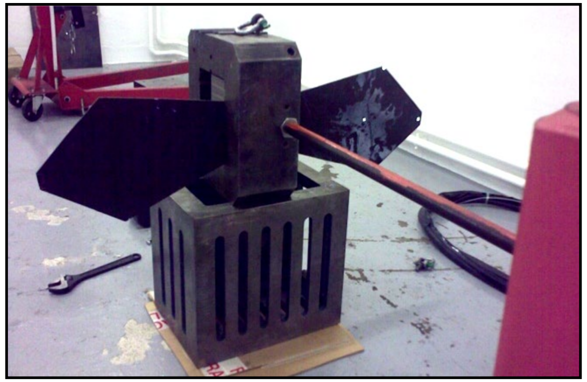
Observation n.2



Observation n.3



Observation n…



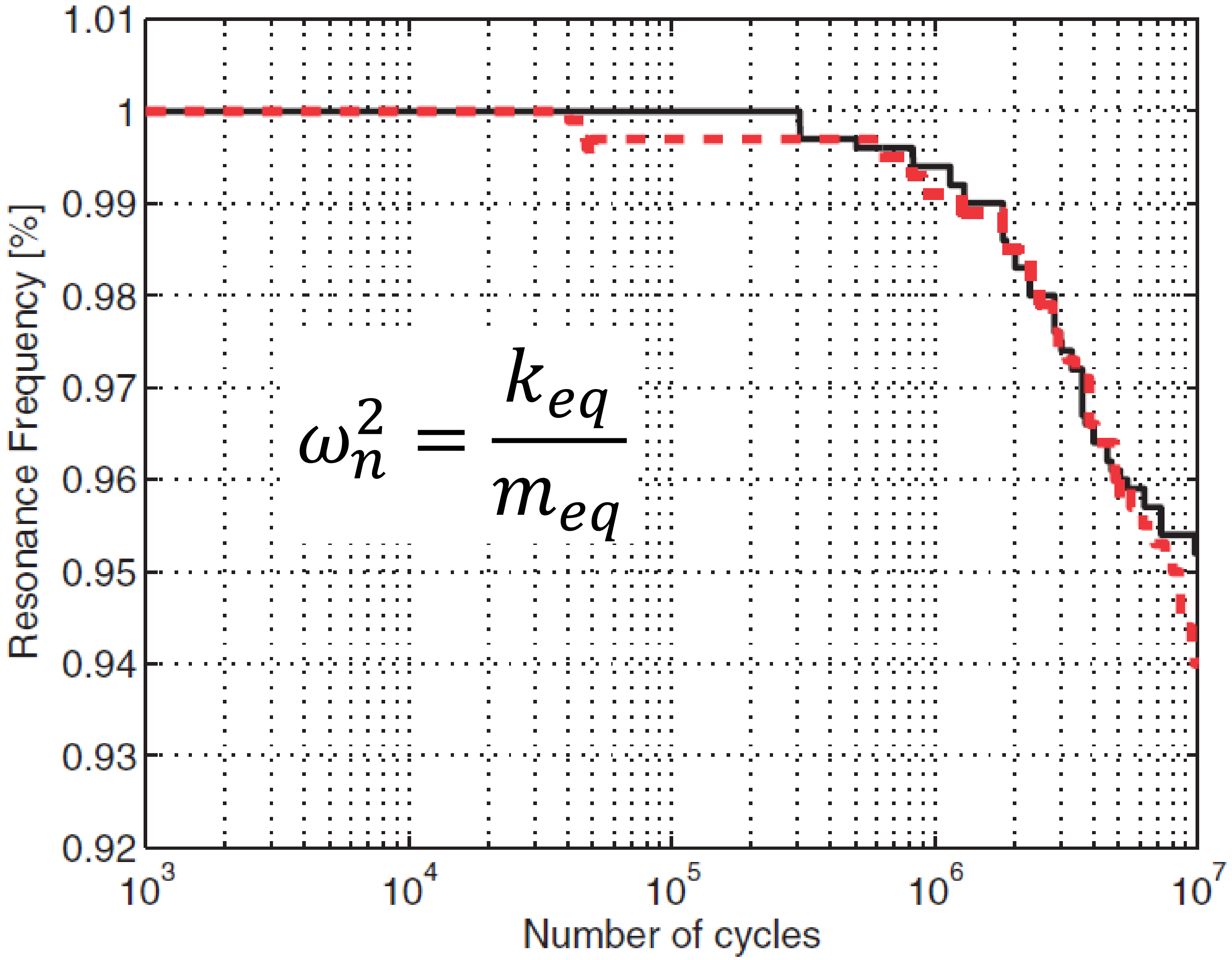
Experiments*: use of measurements to* ***observe*** *(and then to understand and explain) physical phenomena*

The Pulsed air-jet

- Fatigue test of a component made by quasi-isotropic stacking sequence (T700/M21).
- The plate was held by two wire ropes along the nodal lines.
- Maximum vibration displacement 50mm at approx. 140Hz.
- The frequency was tracked by changing the rotational speed of the pulsed air-jet system.
- Max pressure in the plenum chamber with full nozzle open 6bar.
- Estimated excitation force approx. up to 30 N with no mechanical impedance.

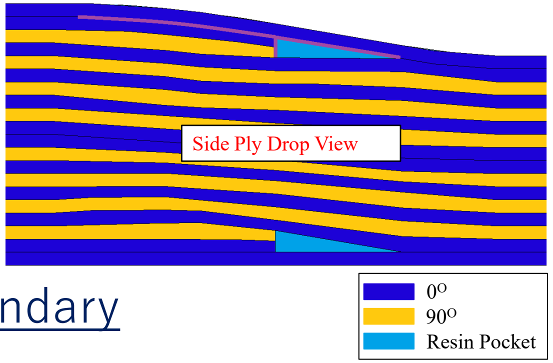
Frequency tracking

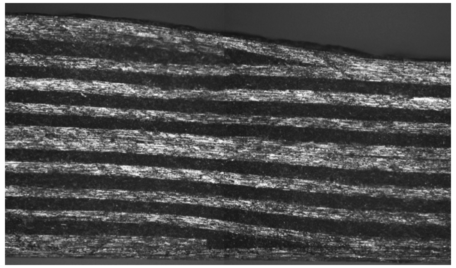
- The testing method followed the standard used for metals/alloys.
- Frequency is proportional to the compliance of the structure.
- The problem is that the compliance of composite structures can drop endlessly without giving any insight on damage propagation, and failure.
- When do we stop the test?
- And if we stop, what do we know about of the damage?
- Why quasi-static S-N curves do not align with fatigue caused by vibrations?



$$\omega_n^2 = \frac{k_{eq}}{m_{eq}}$$

Test setup evolutions

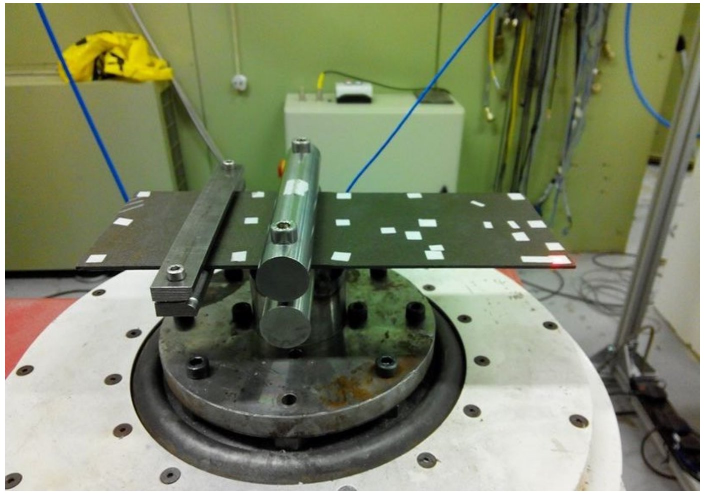




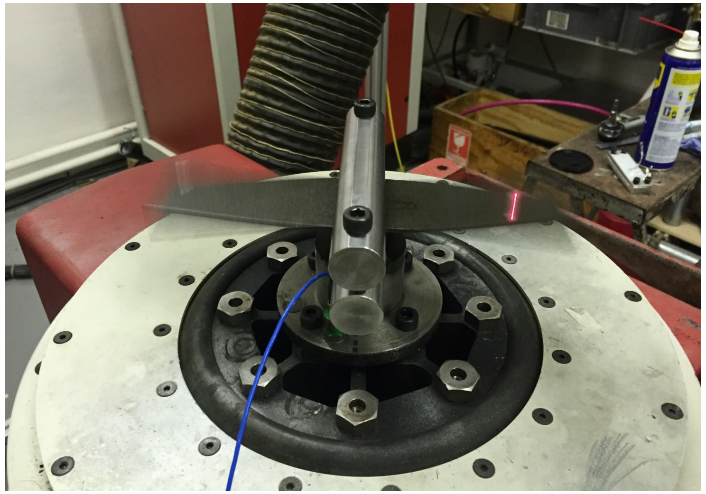
OBJECTIVE: create high stress conditions away from the boundary constraints of test setups.

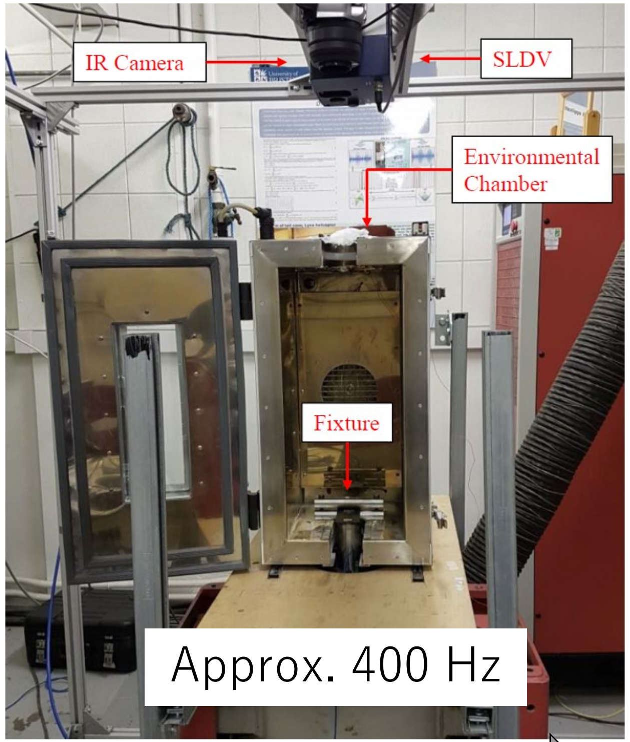
A strain gauge calibrates the severity measured by a laser vibrometer (as means of displacement) and the response is referenced by a stimulus acceleration.

Approx. 133Hz



Approx. 266 Hz

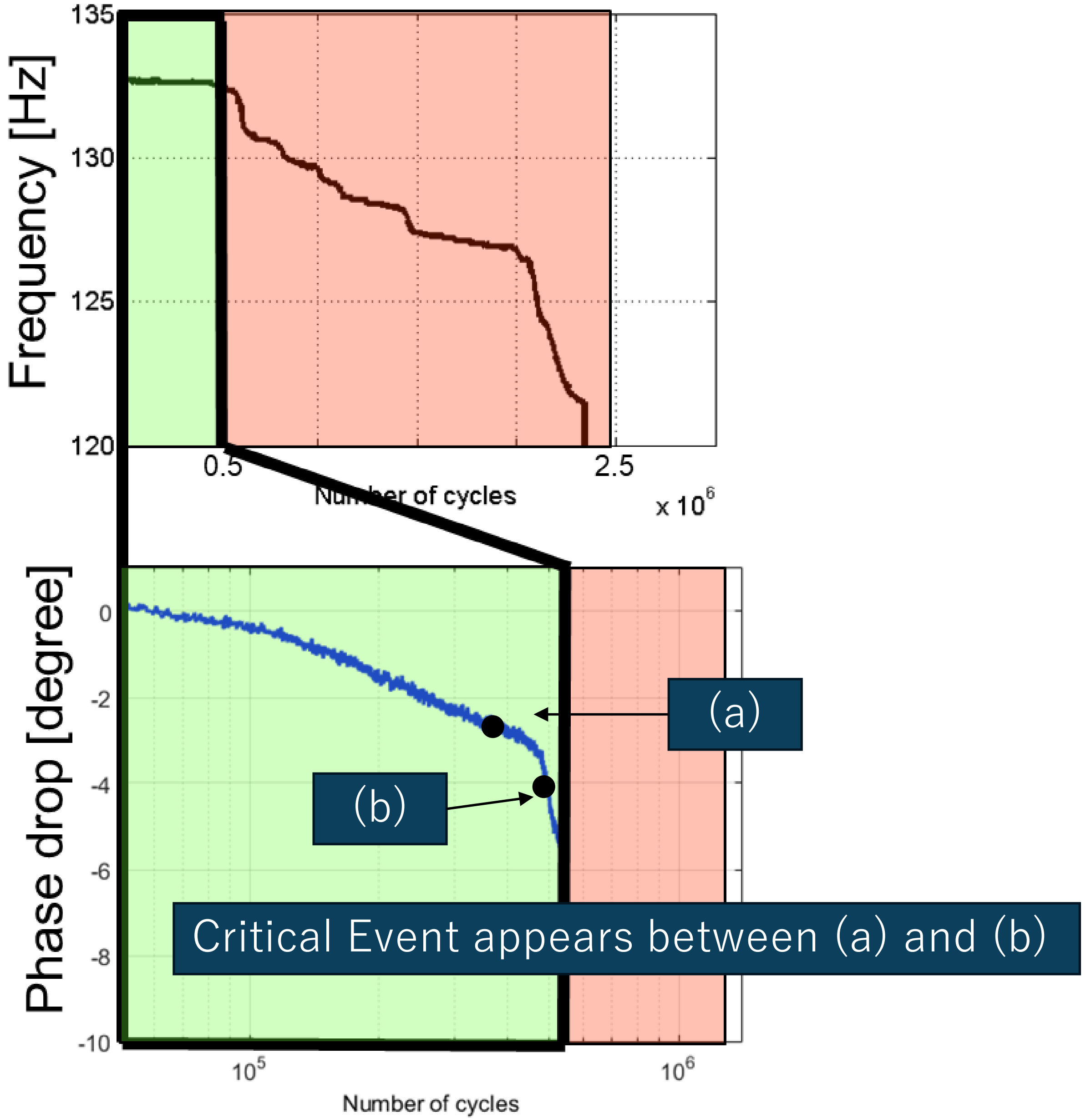




Frequency Vs Phase tracking

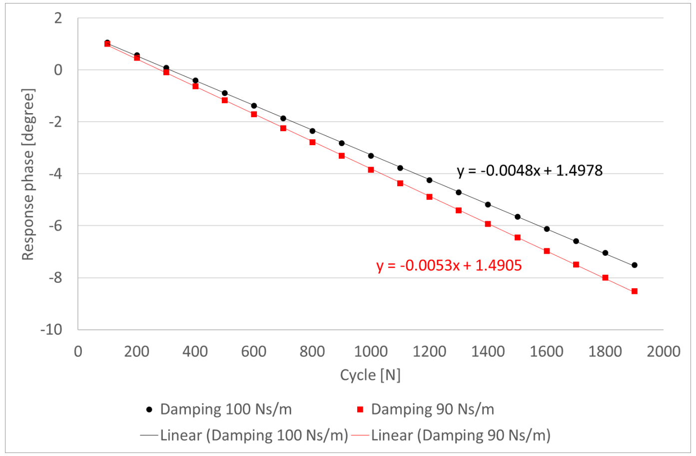
- It was discovered that by fixing the excitation frequency ($\omega_{Exct.}$) and the strain severity (ε) the transfer function phase $\left(\Phi(\omega_{Exct.})\right)$ showed a constant decline up a critical event, seen as an elbow of the phase curve.
- Frequency curve (obtained from the standard test) showed insignificant or no changes while the phase dropped.
- Transfer Function is the ratio between the response and the stimulus

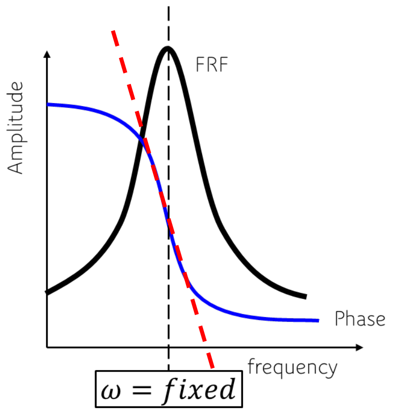
$$H(\omega) = \frac{X}{F}(\omega)$$

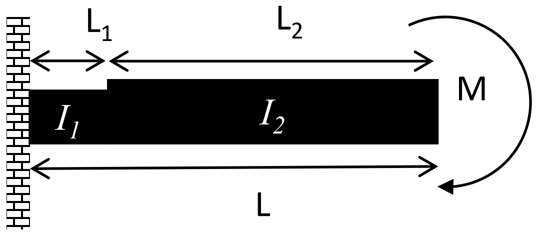


Phase of the Transfer Function

- For a simple case, one degree of freedom system, the transfer function phase measured at constant excitation frequency is proportional to the delamination length.
- Hence, the phase constantly drops as soon as the delamination appears. The process is irreversible!
- The phase also changes because of sources of nonlinearity, but the process is reversible.
- Why is the elbow appearing after a while?



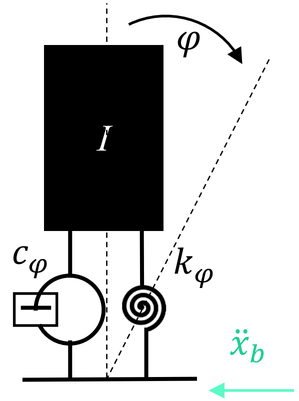




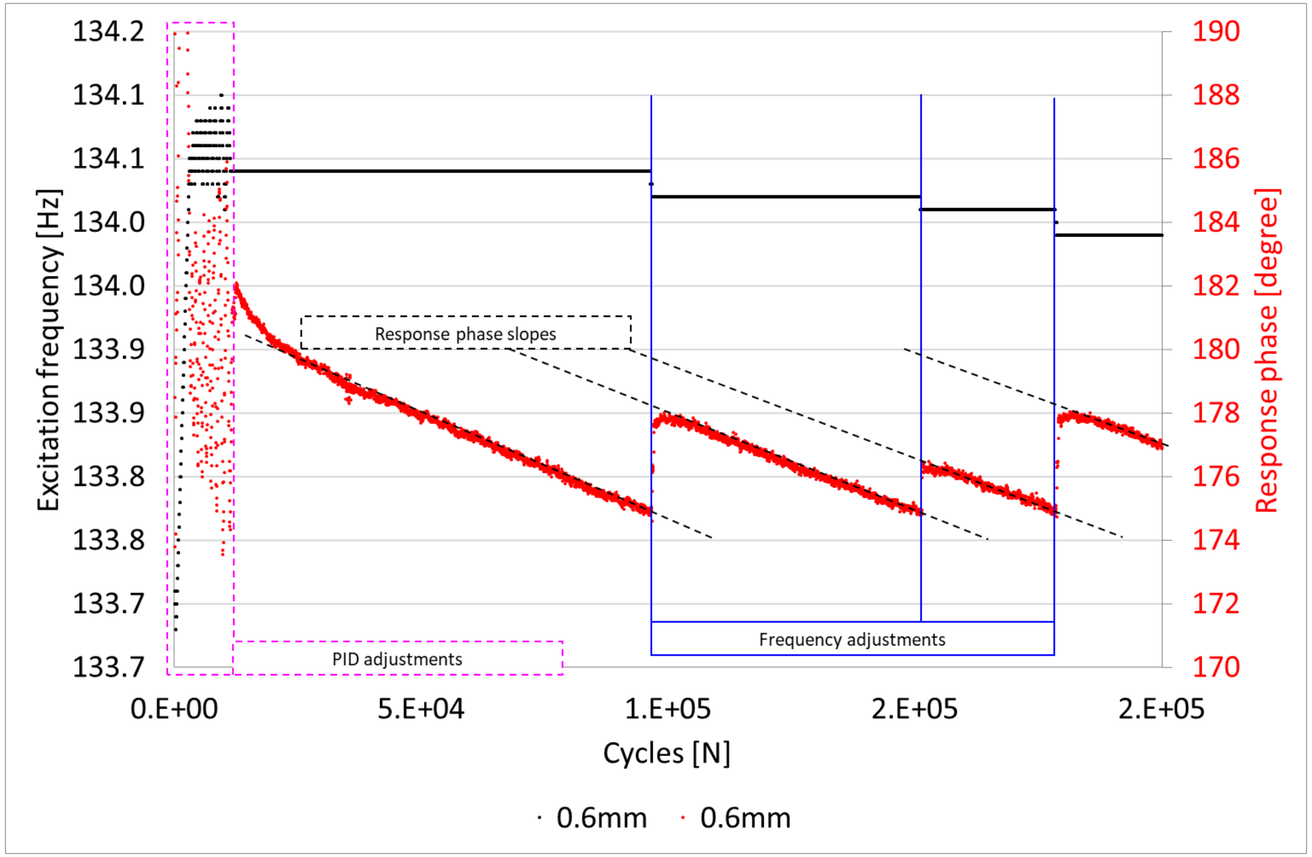
$$a = L_1 \text{ and } L_2 = L - a \quad (1)$$

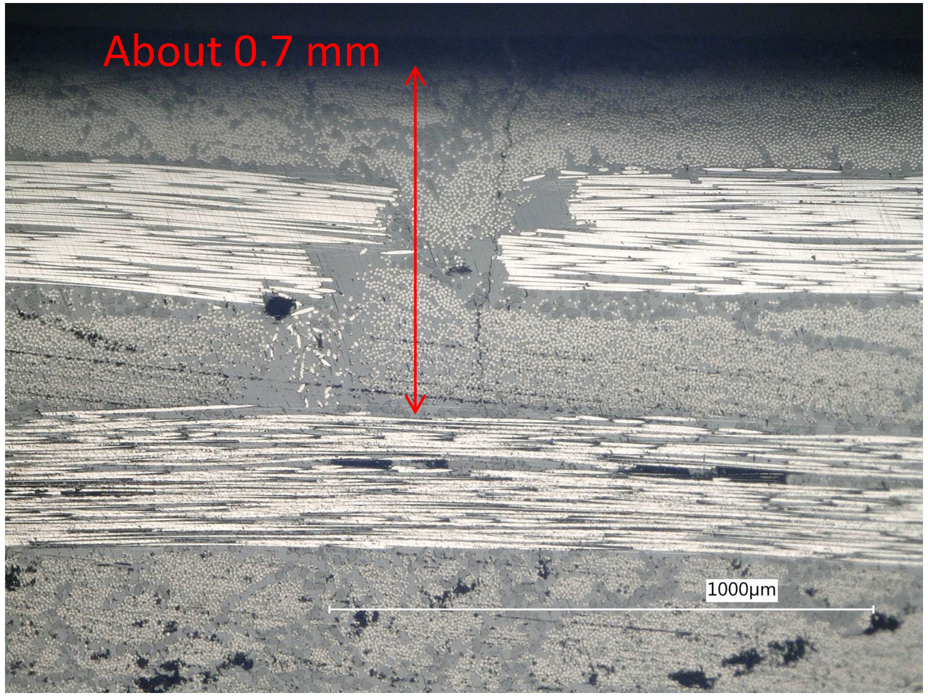
$$k_\varphi = \frac{M}{\varphi} = \frac{EI_1 I_2}{(I_2 - 2I_1)a + LI_1} \quad (2)$$

$$\Phi(\omega) = \tan^{-1}\frac{I\omega}{c_\varphi} + \frac{I^2\omega(k_\varphi - I\omega^2)}{c_\varphi{}^3 + c_\varphi I^2\omega^2} + \mathcal{O}\left(\left(k_\varphi - I\omega^2\right)^2\right) \approx A + B\left(\frac{EI_1 I_2}{(I_2 - 2I_1)a + LI_1}\right) \quad (3)$$



Sensitivity of phase to damage onset

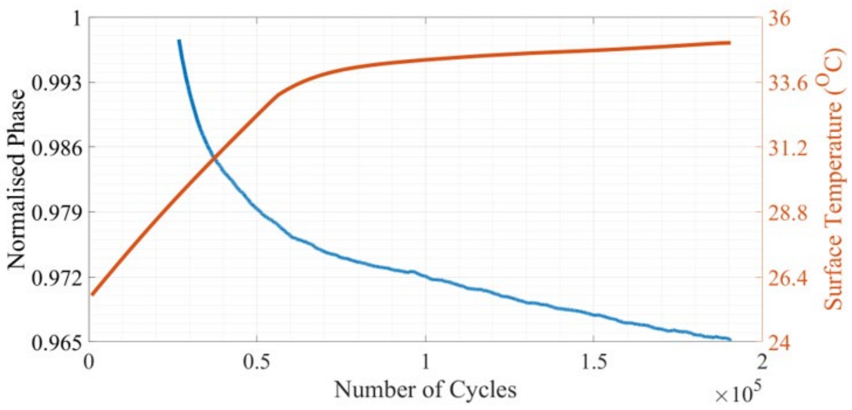


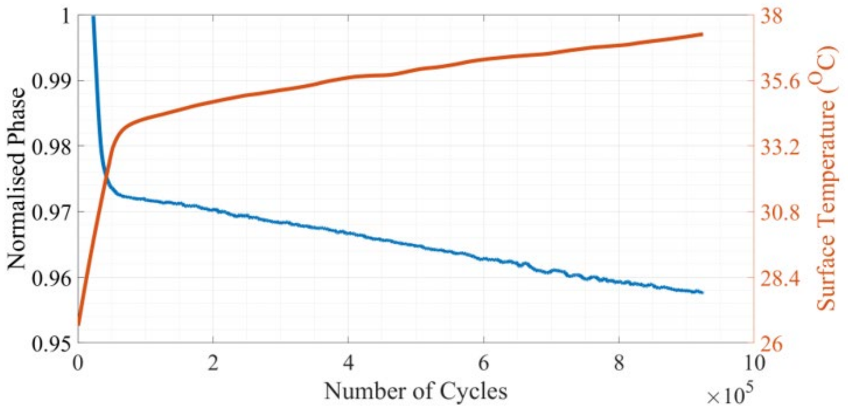


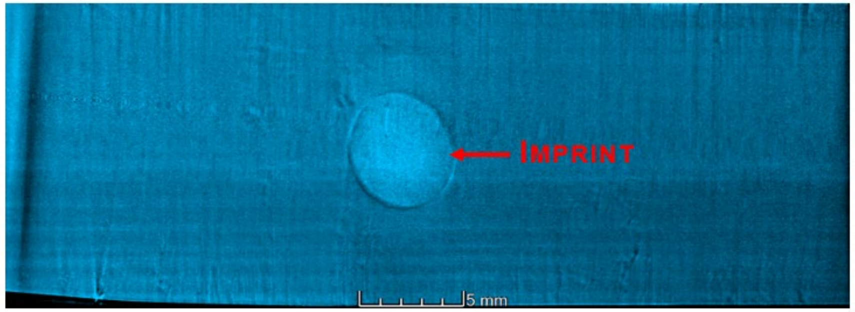
$$\frac{\Delta a}{\Delta N} = \frac{0.7}{200k} = \frac{\Delta \varphi}{\Delta N} = \frac{12}{200k}$$

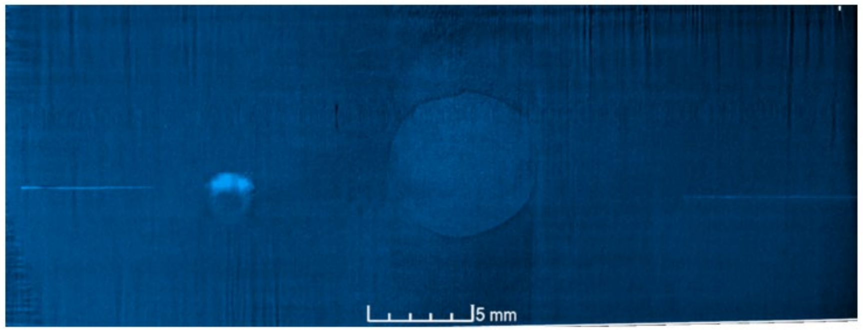
The phase curve and damage evolution

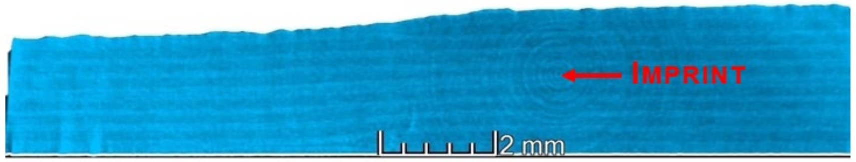
- As soon after the settling conditions (caused by sources of nonlinearity) the phase starts consistently declining,
- Micro damage develops and CT picks damage onset.

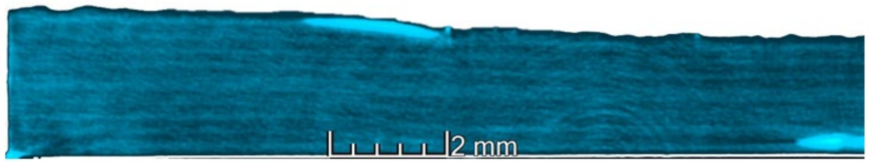






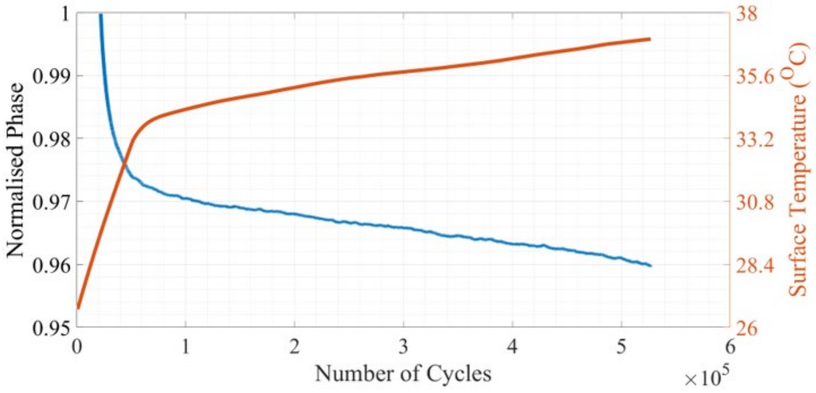


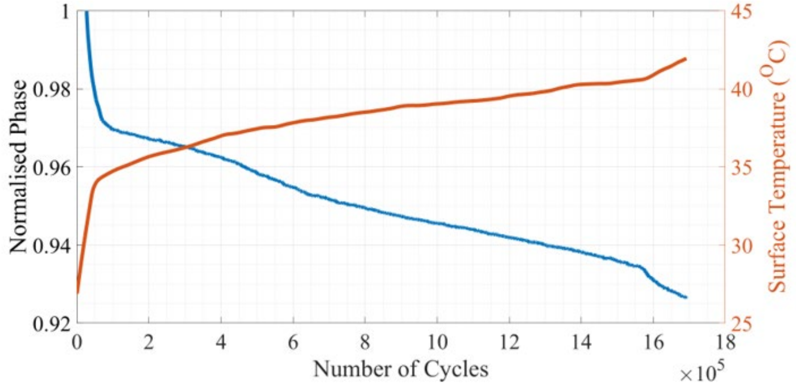


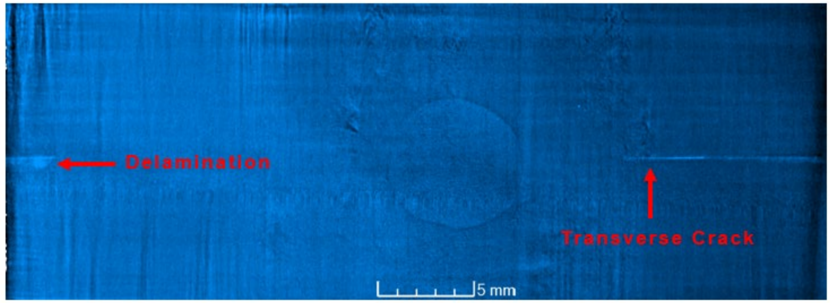


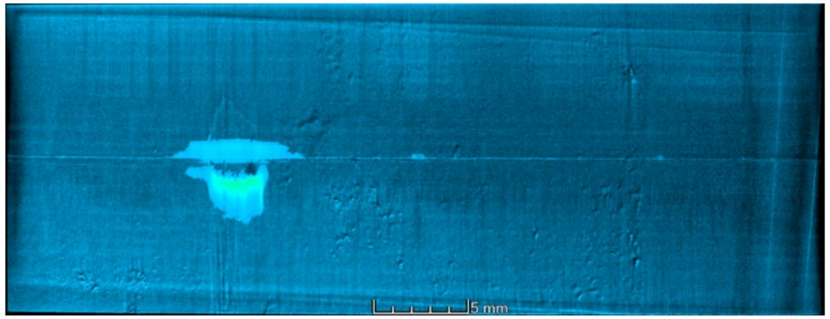
The phase curve and damage evolution

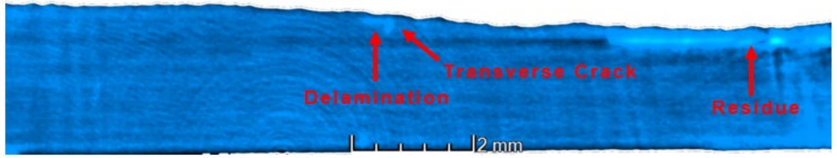
- The phase keeps dropping until the critical event appears.
- The component reached the failure criterion, which is a repeatable feature observed in all samples tested.
- What is the critical event?

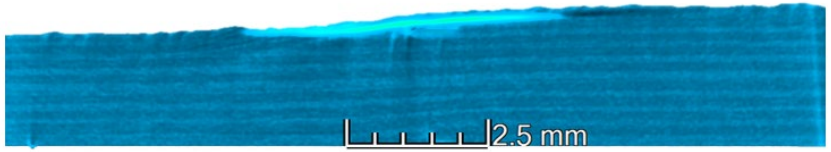






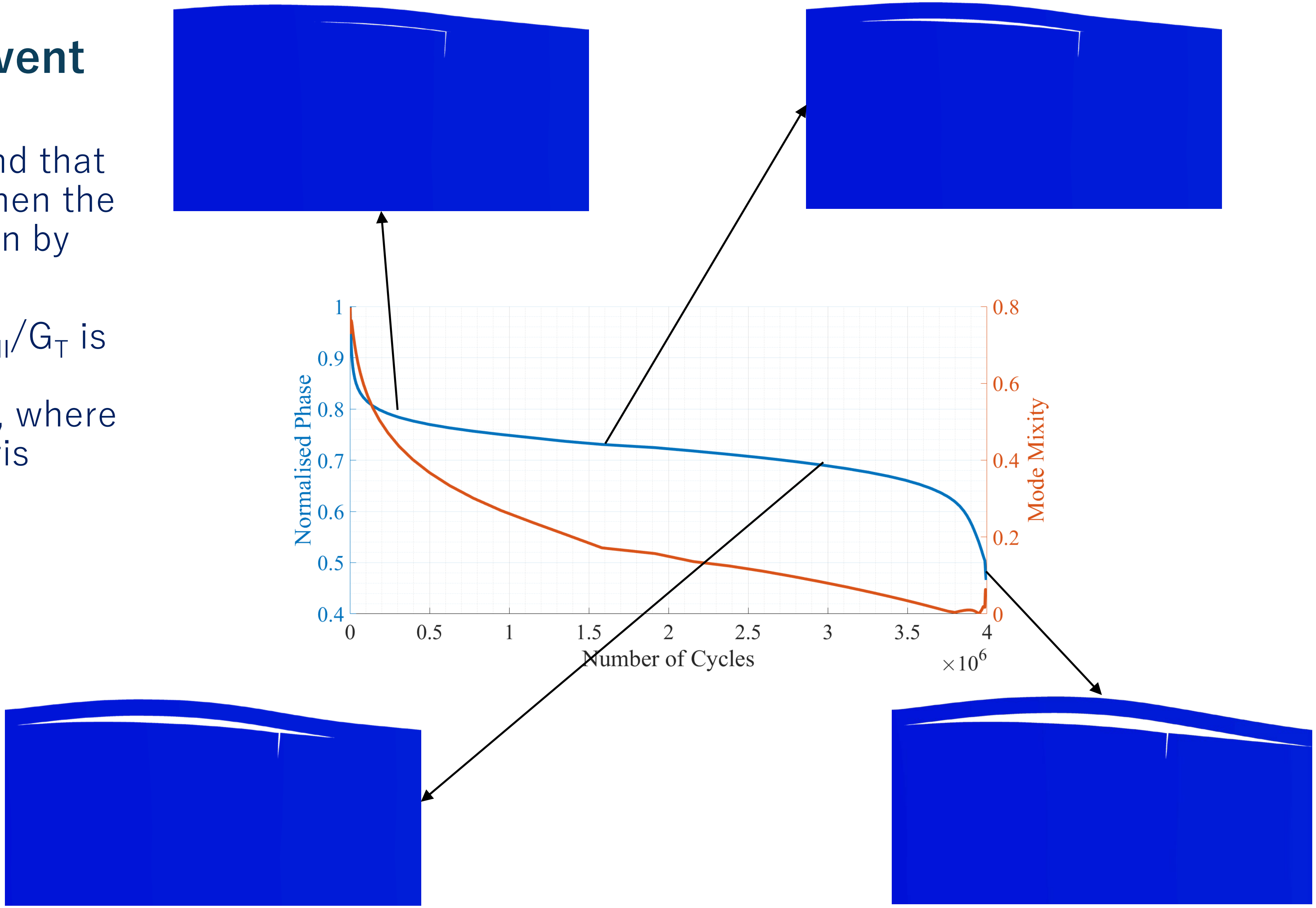




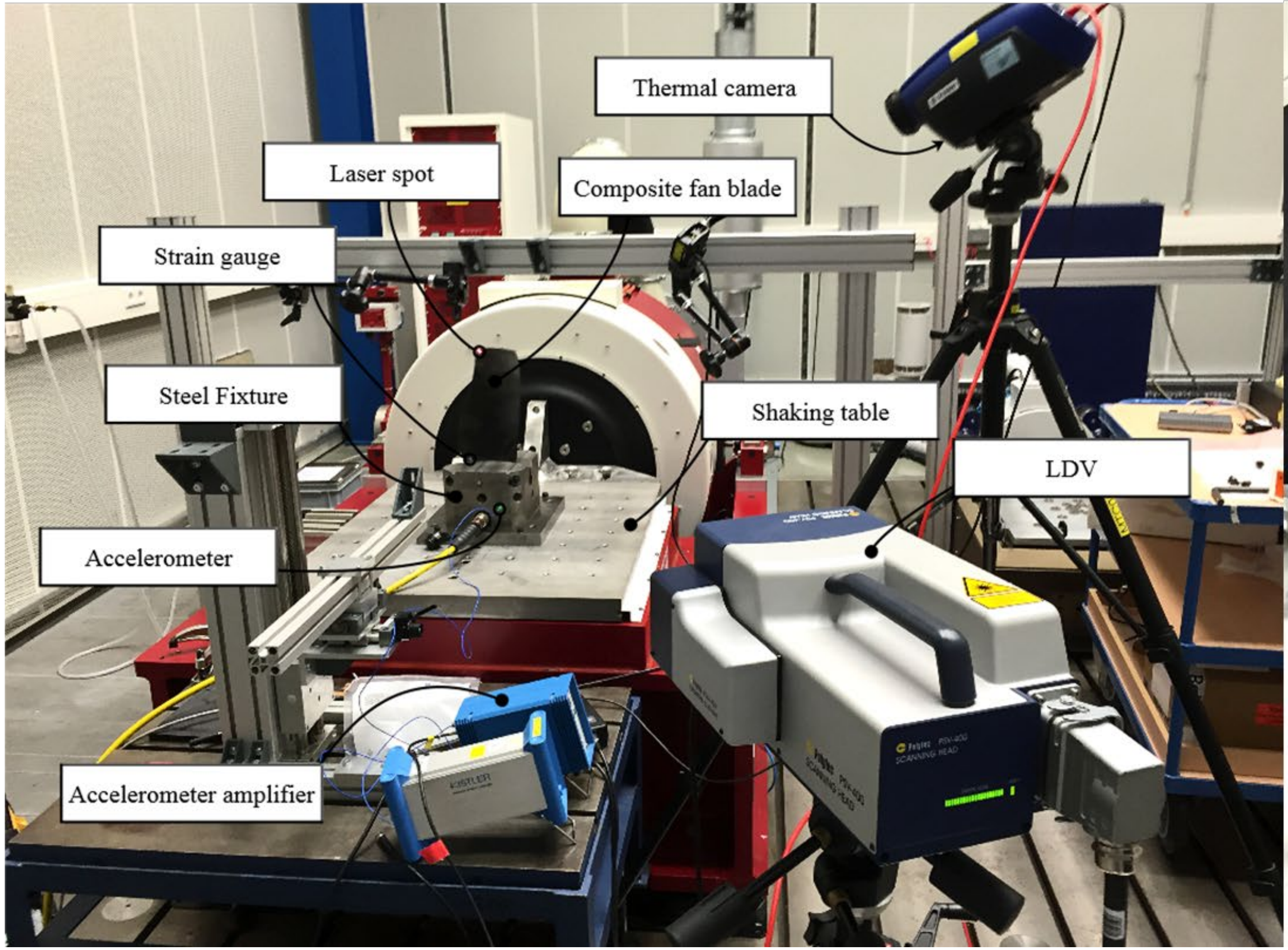


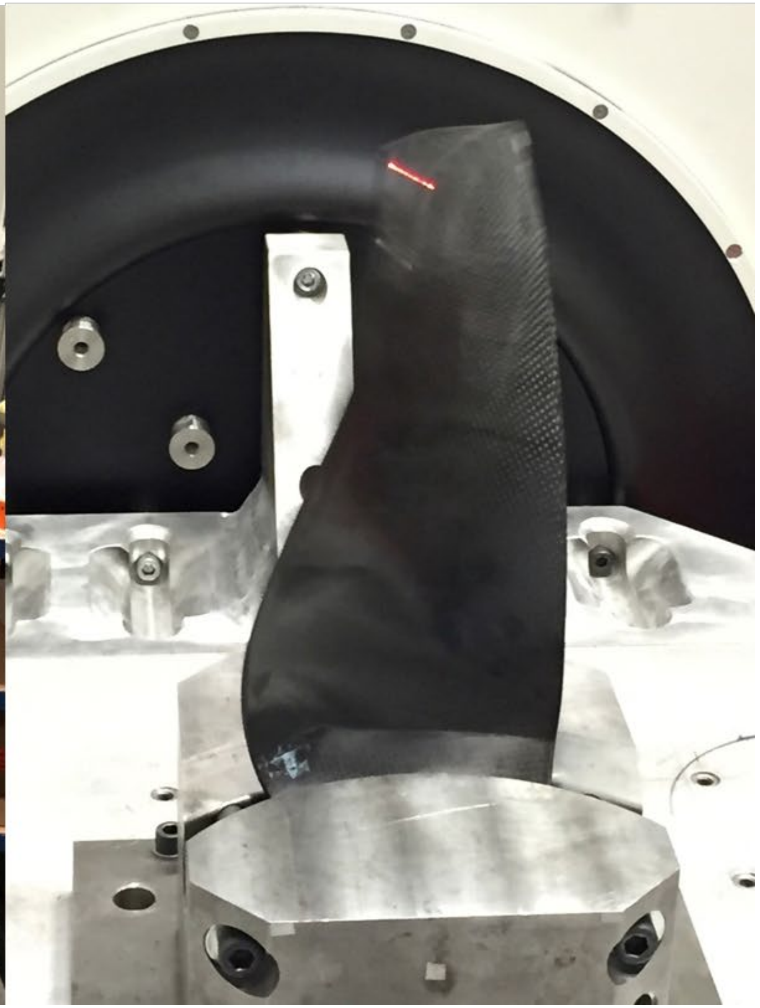
The Critical Event

- FEA allowed us to understand that the critical event appears when the delamination growth is driven by mode I.
- The mode mixity analysis G_{II}/G_T is performed alongside the calculation of phase change, where da/dN is calculated by a Paris relationship obtained from literature.

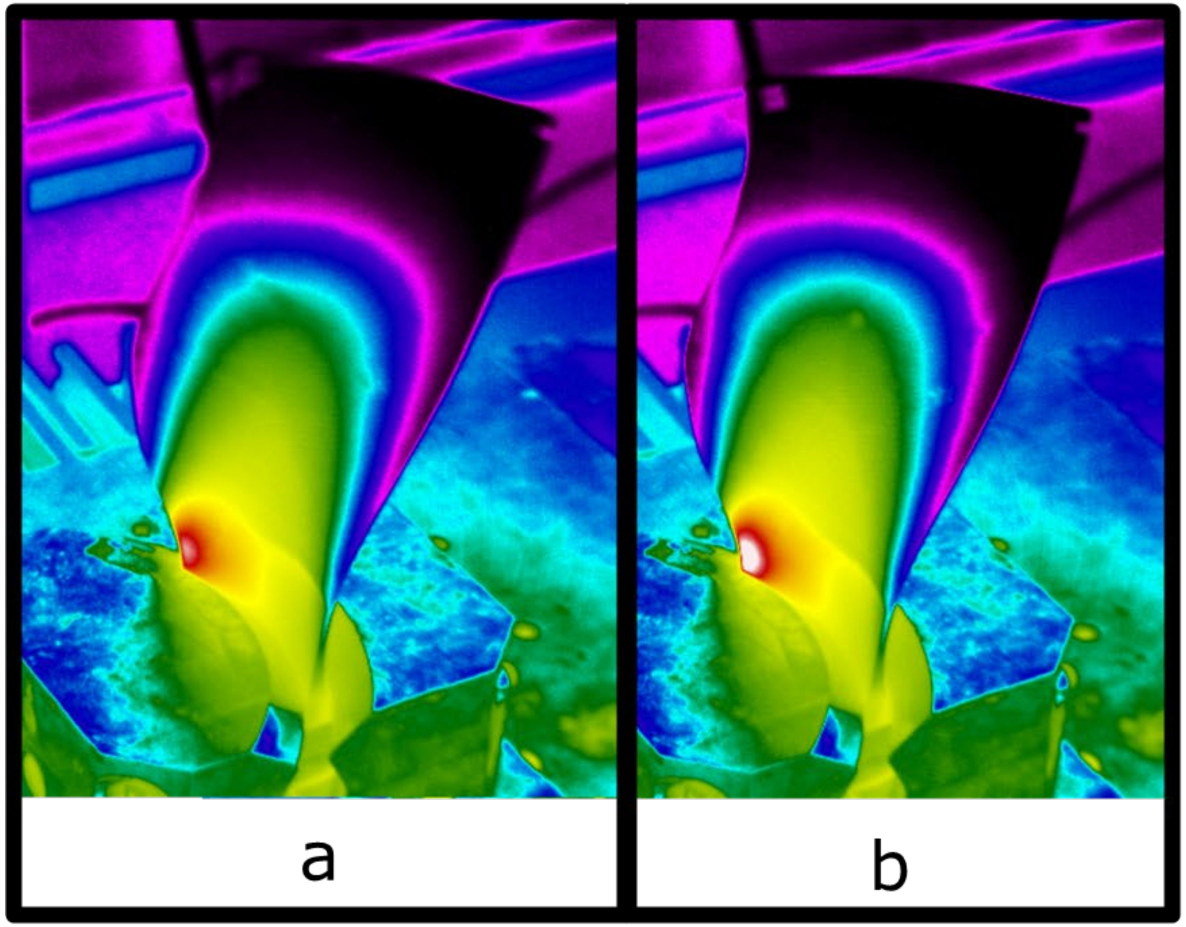


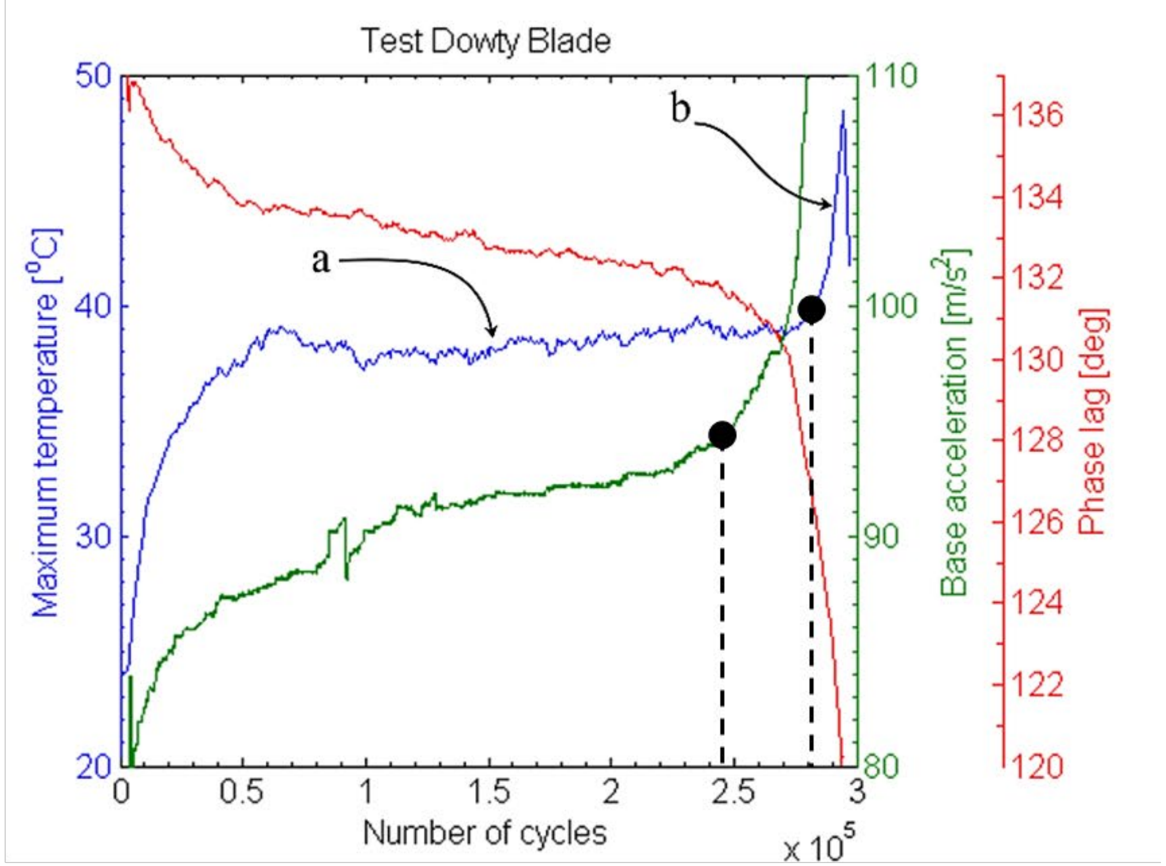
Verification of the failure criterion





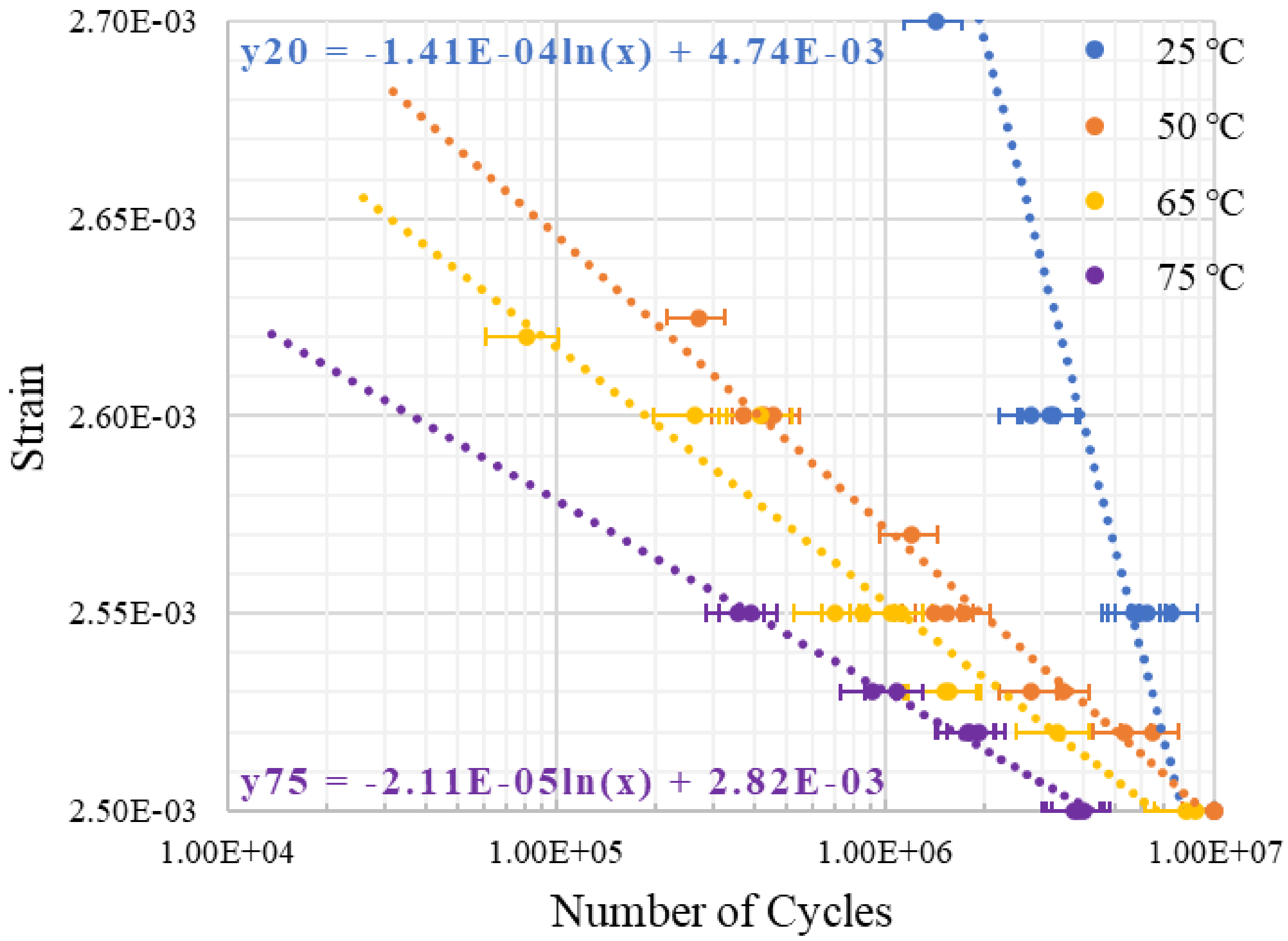
Verification of the failure criterion





S-N curve using the critical event as failure criterion

- The critical event underpins the moment when the delamination reaches a critical size leading to a temperature hot-spot.
- It can be used as failure criterion to build S-N curves yielded in matters of months rather than years.



FE modelling of Phase-Temperature relationship

It is a step-wise quasi-static forced vibration-based analysis coupled with heat transfer:

❑ DYNAMIC (2D)

1. Modal analysis → identification of the target mode
2. Forced vibration at the natural frequency → calculation of the strain severity & Deflection shape

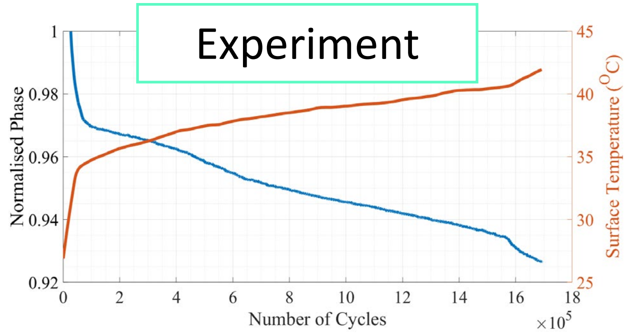
❑ STATIC (2D)

1. Deflection shape boundary conditions → equivalent dynamic stress state under static load
2. Virtual Crack Closure Technique calculation → G-I and G-II
3. Calculation of number of cycle to failure → open the next node along an identified crack path
4. Calculate the global strain energy → output work
5. Node open → generation of a new FE model → go back to point (2)

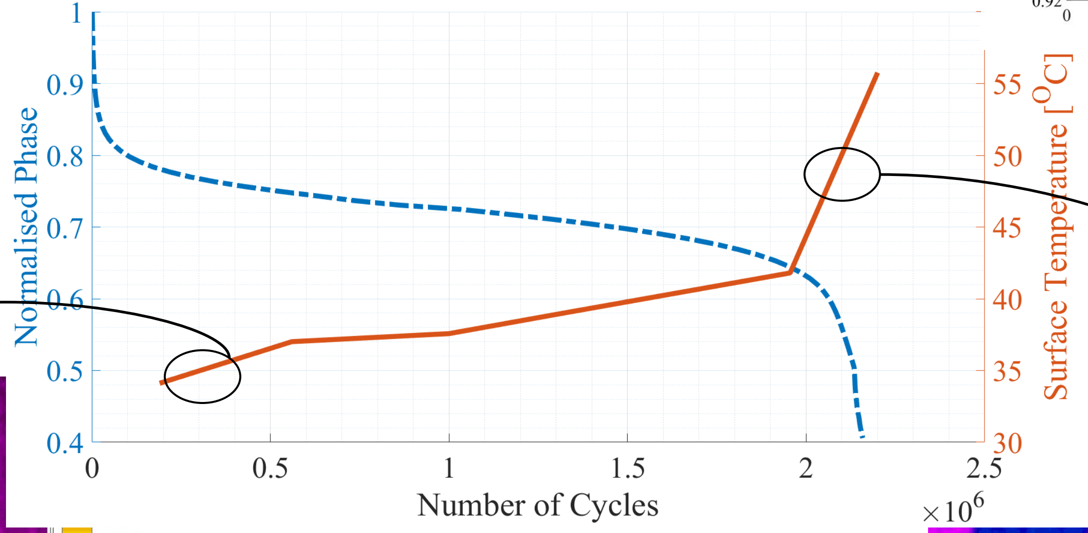
❑ HEAT TRANSFER (3D)

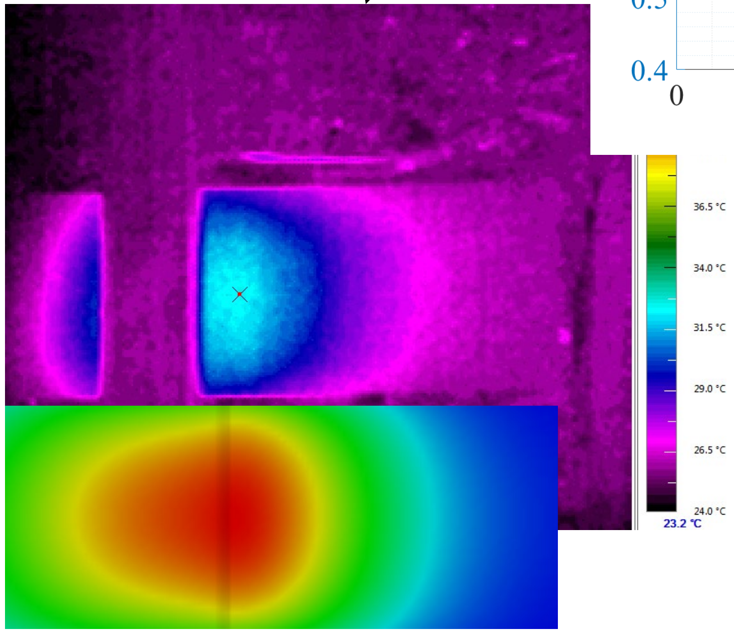
6. Calculate the heat given by work at point (4) → scale it by the number of cycles
7. Calculate the slippage → use friction coefficient to calculate friction work
8. Start from point (5)

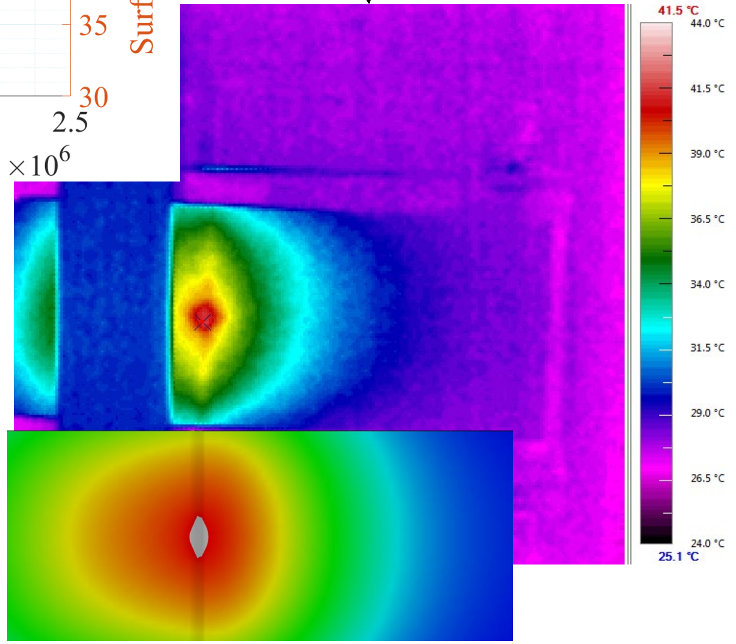
Modelling of phase and temperature curves



- It was possible to model by FEA using a blend of 2D for the phase curve and 3D for the heat-transfer analysis to derive the temperature curve



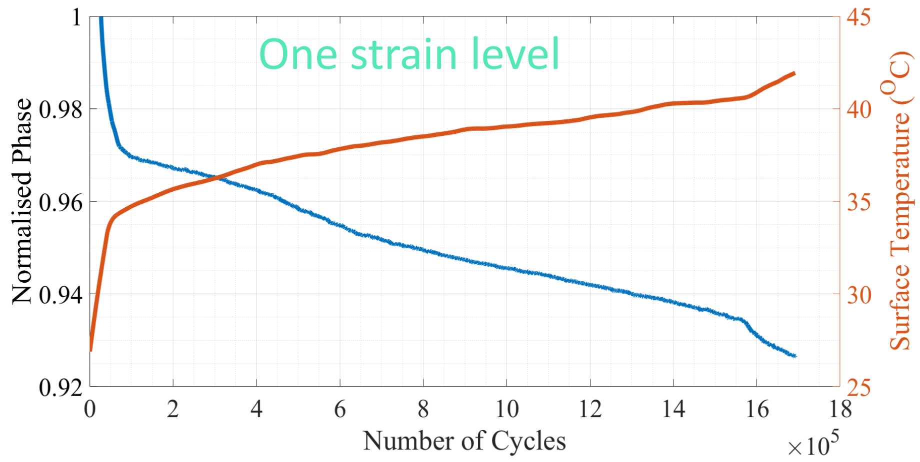


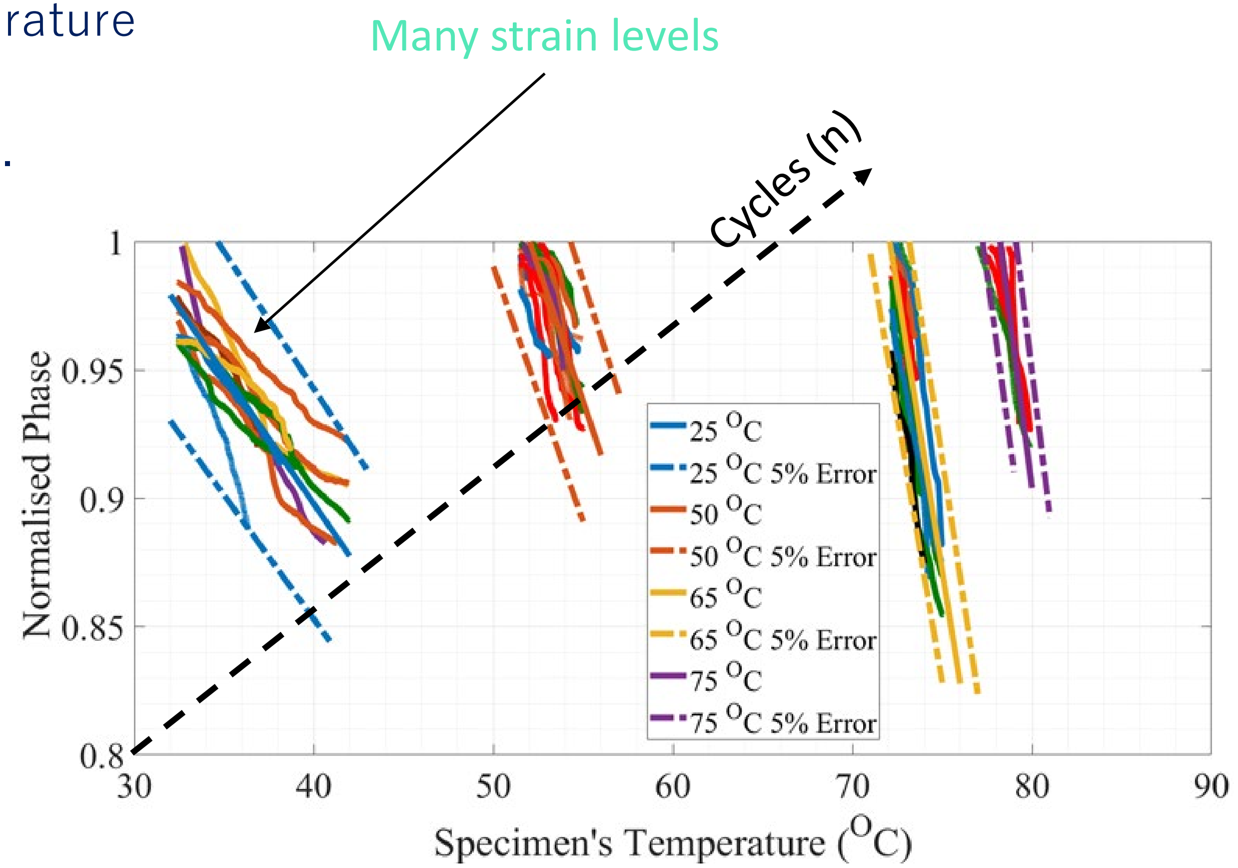


Phase-Temperature relationship

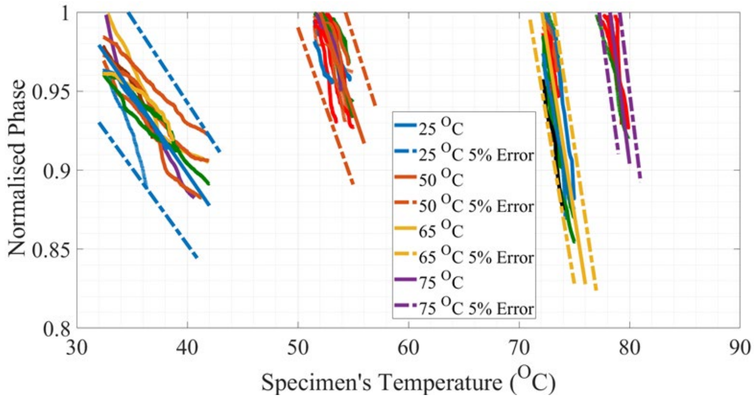
- The phase-temperature relationship bears a very important relationship.
- It indicates that the effect of environmental temperature is more detrimental than the strain severity.
- This is achieved without generating any S-N curve.

By plotting the phase (blue) against the temperature (red)

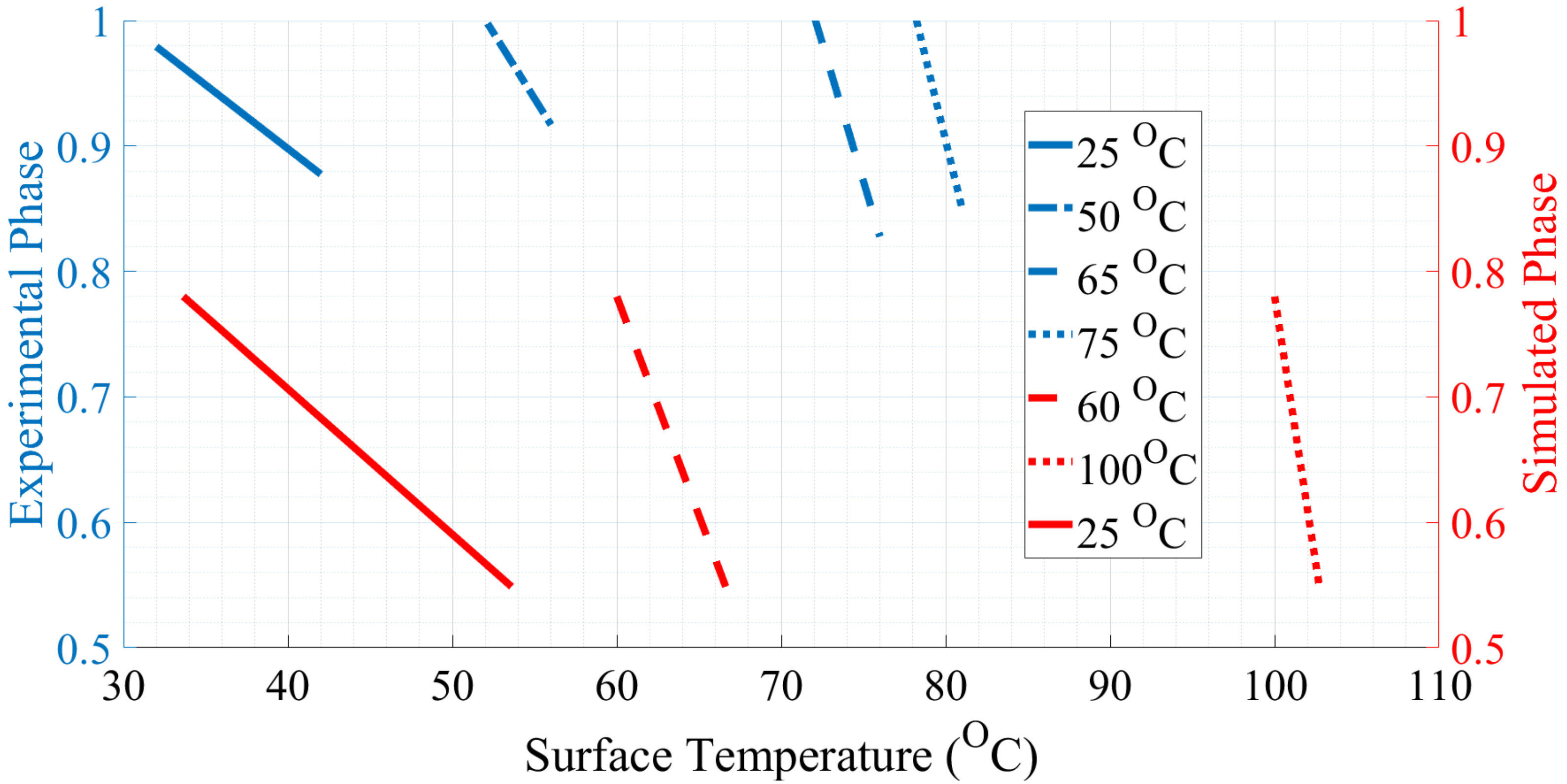




Phase-Temperature relationship model



- The phase-temperature relationship bears a very important relationship about time-temperature superposition.



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Material Characterisation Testing

Matias Lasen (UT)

Funded by
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Summary

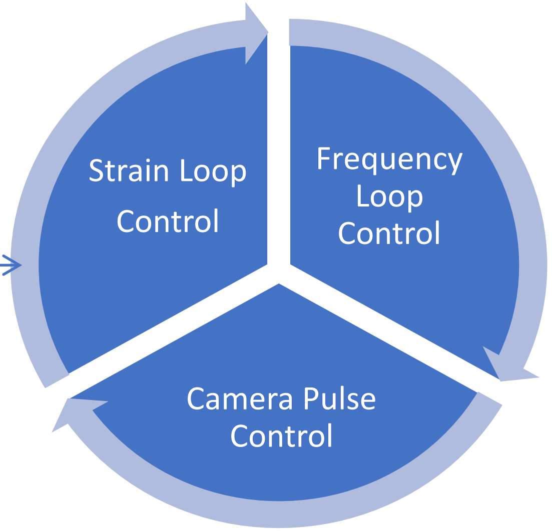
01 Experiments overview

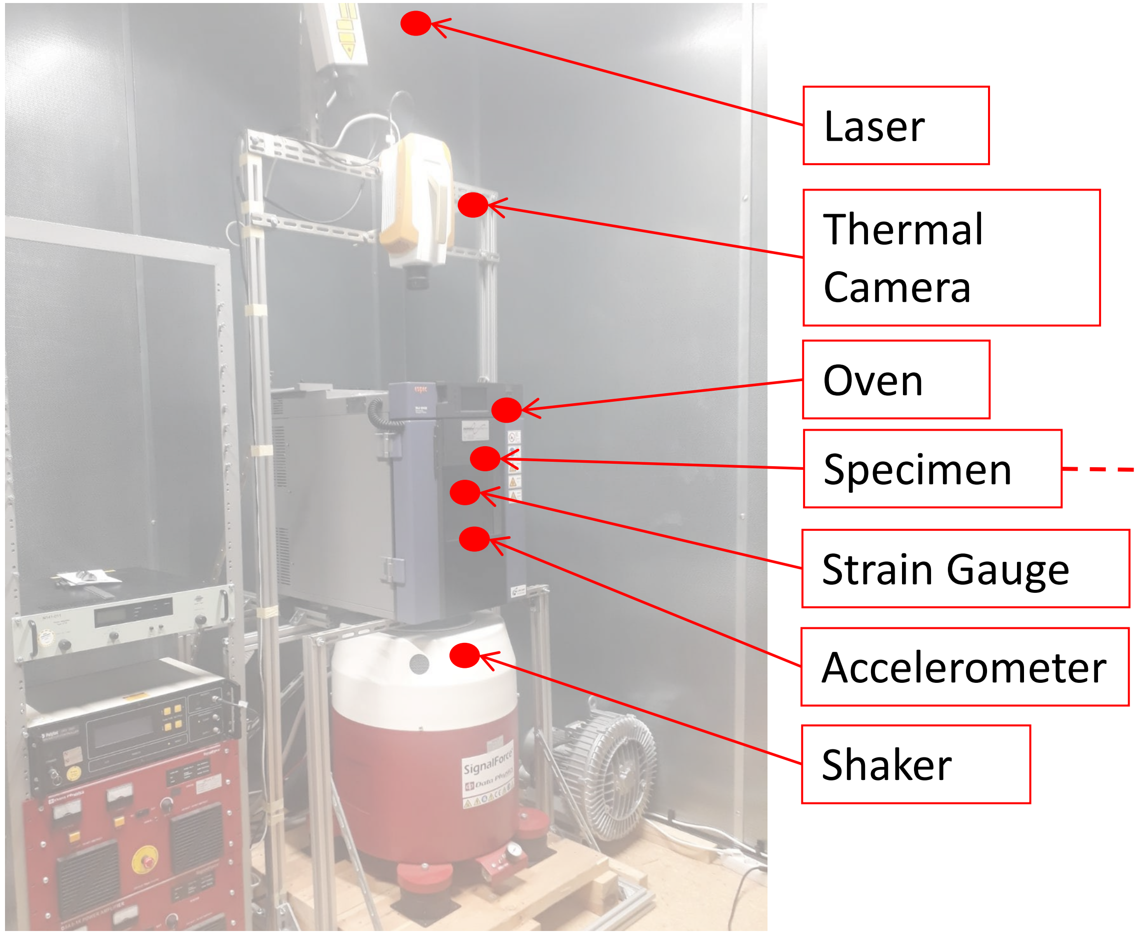
Experiments overview

1. Modal Analysis

2. Strain-Displacement Calibration

3. High Cycle Fatigue





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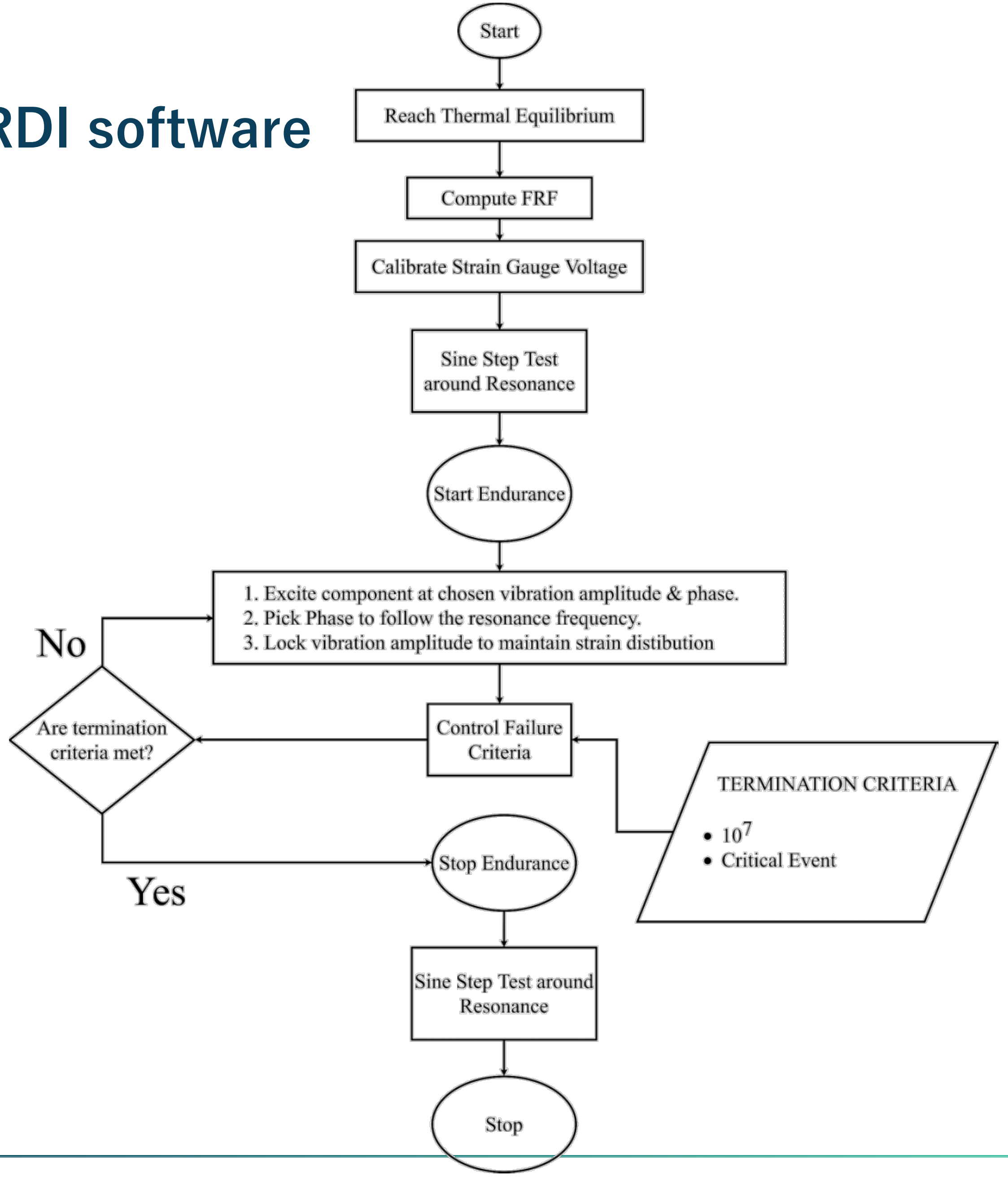
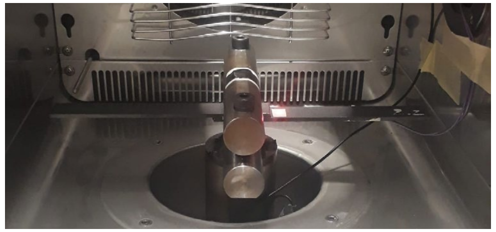
MONTEVERDI software



02 Experiments details

Modal Analysis

1. Modal Analysis



Why do we need Modal Analysis?

Because we need the resonant **Frequency** and resonant **Phase** to run HCF at resonance.

We want to run HCF at resonance: **less energy for excitation.**

We need the phase so that the **PID control uses it as a target parameter**.

(We repeat the Modal Analysis after HCF to observe the strength decay)

Implementation

Step sine.

Input parameters: Frequency band, freq steps, #cycles of excitation, shaker voltage (low).

Output Example

Frequency (Hz)	REAL	IMMAGINARY	REFERENCE
2.700E+2	-4.546E+0	-5.584E+1	6.269E+2
2.708E+2	-4.212E+0	-5.563E+1	6.252E+2
2.716E+2	-4.289E+0	-5.598E+1	6.233E+2
2.724E+2	-4.232E+0	-5.602E+1	6.214E+2
2.732E+2	-4.073E+0	-5.565E+1	6.197E+2
2.740E+2	-4.374E+0	-5.605E+1	6.175E+2
2.748E+2	-4.095E+0	-5.582E+1	6.157E+2
2.757E+2	-4.115E+0	-5.602E+1	6.137E+2

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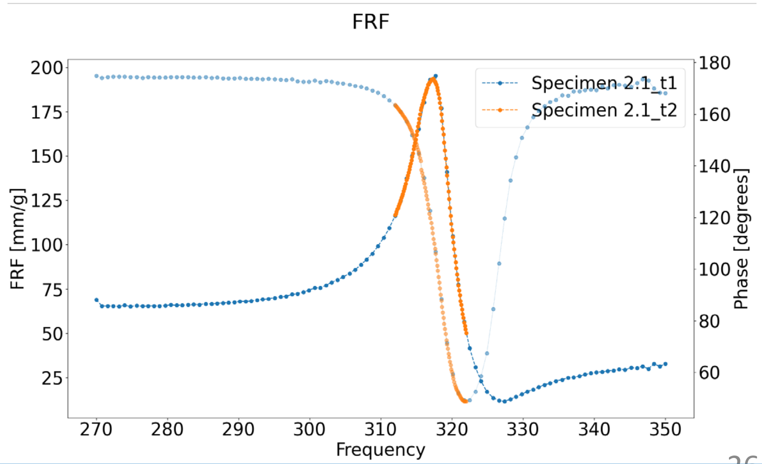

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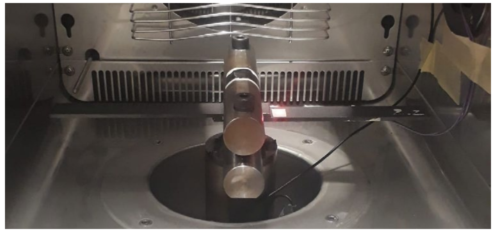
Strain - Displacement calibration

2. Strain-Displacement Calibration



Why do we need a SD calibration?
Because Strain Gauges and wires fatigue making measurements unreliable. Then, the use of LDV is convenient. And because we need a target displacement for PID during HCF.

Implementation
Excitation at constant frequency (Resonance from Modal Analysis), at different input voltages to the shaker (low). Repeat 4 times at each voltage to observe the scattering.
Input: Resonant frequency, #cycles at each freq/volt, volts.

Output Example

```
Displacement (m) Strain (-)  Shaker-Amplitude (V)
9.23398E-5  5.80347E-3  1.00000E-1
9.23624E-5  5.79897E-3  1.00000E-1
9.23853E-5  5.80185E-3  1.00000E-1
9.23330E-5  5.79576E-3  1.00000E-1
1.84906E-4  1.16154E-2  2.00000E-1
1.84941E-4  1.16198E-2  2.00000E-1
1.85023E-4  1.16232E-2  2.00000E-1
1.84991E-4  1.16268E-2  2.00000E-1
2.77779E-4  1.74366E-2  3.00000E-1
2.77890E-4  1.74571E-2  3.00000E-1
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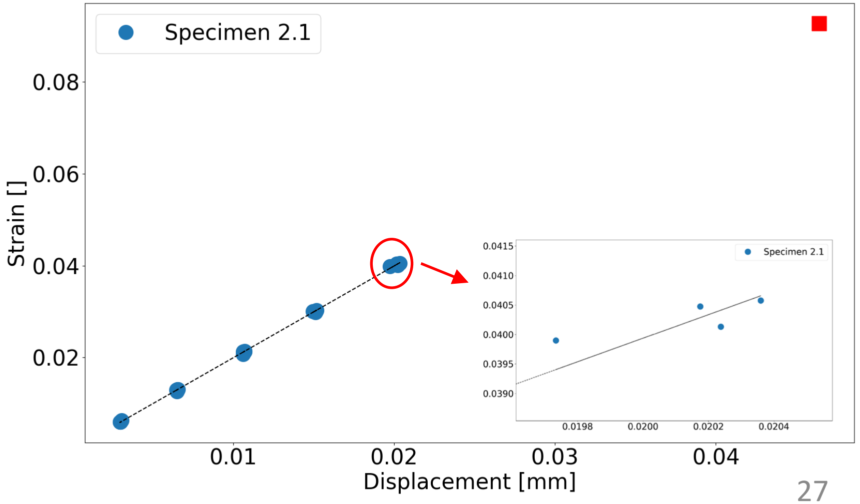

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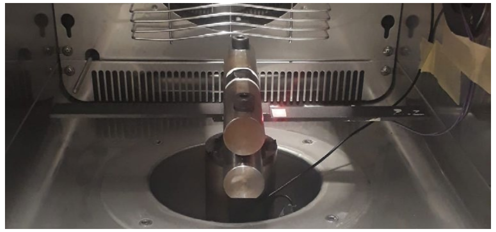
High Cycle Fatigue

3. High Cycle Fatigue



Why do we need a HCF test?
To understand the phase decay as a structural fatigue parameter.

Implementation
PID reaches target displacement. (from calibrated strain).
PID adjusts the excitation frequency (with a button) after a threshold of phase decay is reached, using the phase from Modal Analysis as control input.

Output Example

Cycles (n)	Phase (degree)	Frequency (Hz)	Amplitude (m)	Reference (g)
6.27385E+1	1.92601E+2	4.05480E+2	3.19772E-8	5.11378E-3
1.01110E+2	2.34258E+2	2.47999E+2	8.74193E-8	5.41938E-3
1.55434E+2	3.27524E+2	3.51091E+2	4.49507E-8	4.90535E-3
2.03921E+2	1.55413E+2	3.13378E+2	6.38281E-8	1.60780E-2
2.53739E+2	2.34042E+2	3.21973E+2	3.26599E-7	4.91977E-2
3.03607E+2	2.32058E+2	3.22297E+2	5.23439E-7	8.39597E-2
3.53451E+2	2.40643E+2	3.22143E+2	7.70052E-7	1.20537E-1

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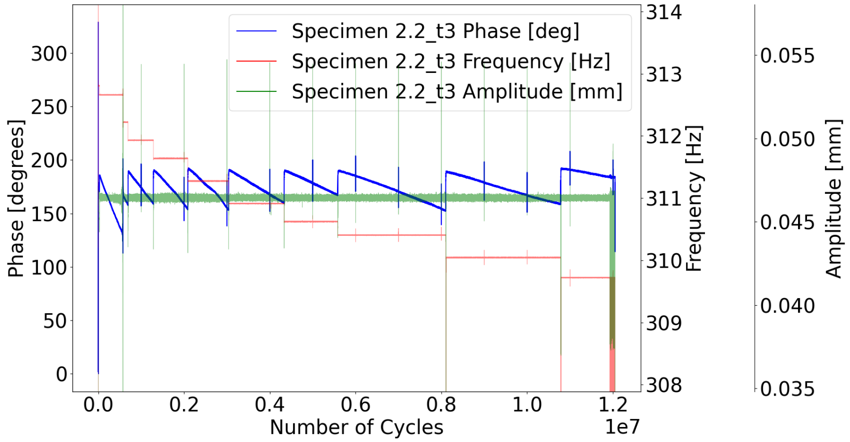


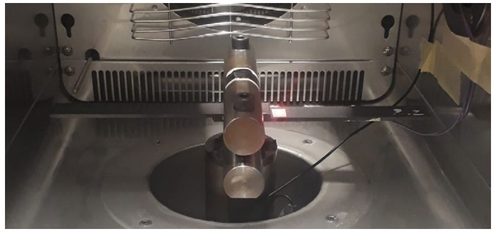
28

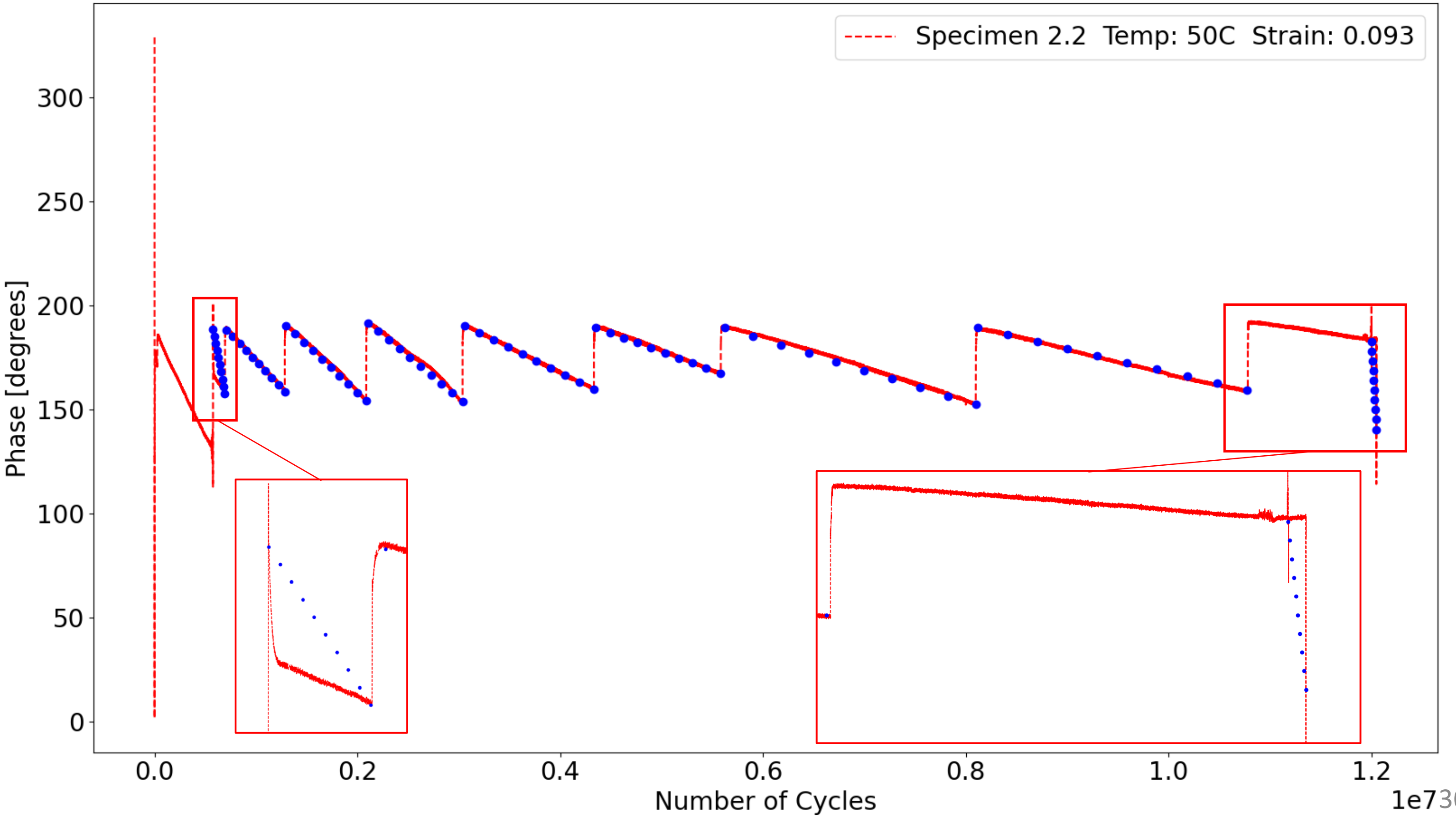
03

Results

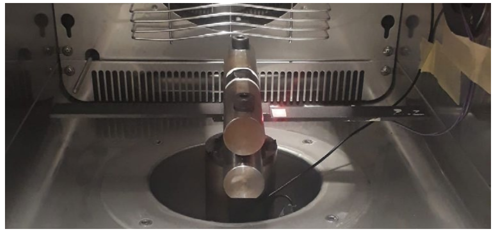
Post processing

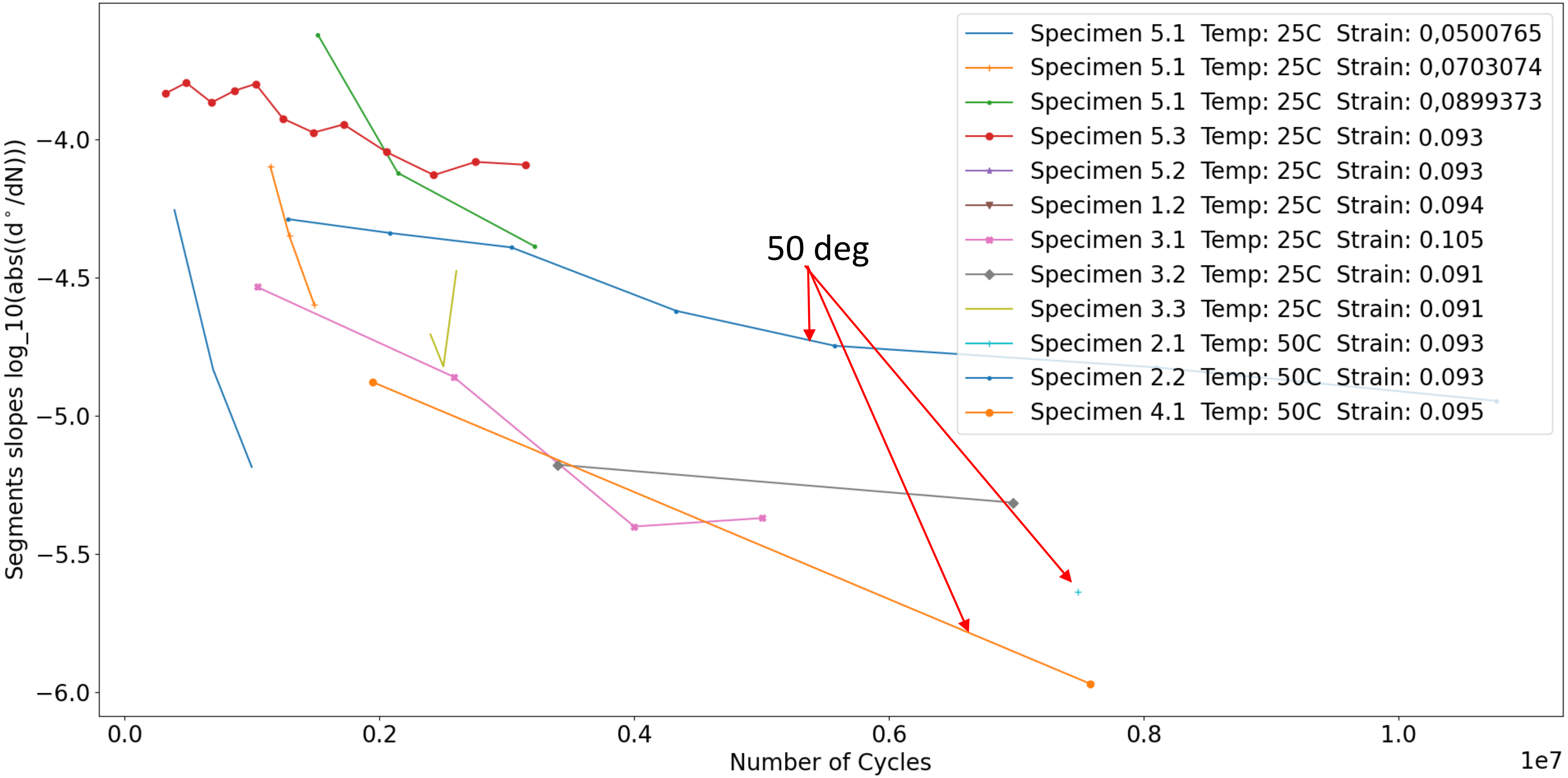
We use the segments of phase decays as signature and plot them against number of cycles





Results





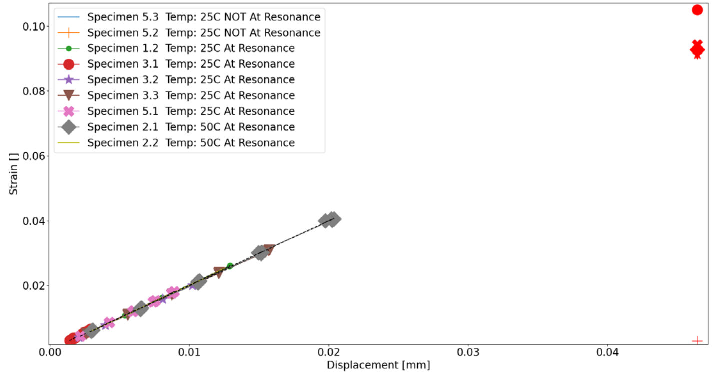
Specimen 5.1 Temp: 25C Strain: 0,0500765
Specimen 5.1 Temp: 25C Strain: 0,0703074
Specimen 5.1 Temp: 25C Strain: 0,0899373
Specimen 5.3 Temp: 25C Strain: 0.093
Specimen 5.2 Temp: 25C Strain: 0.093
Specimen 1.2 Temp: 25C Strain: 0.094
Specimen 3.1 Temp: 25C Strain: 0.105
Specimen 3.2 Temp: 25C Strain: 0.091
Specimen 3.3 Temp: 25C Strain: 0.091
Specimen 2.1 Temp: 50C Strain: 0.093
Specimen 2.2 Temp: 50C Strain: 0.093
Specimen 4.1 Temp: 50C Strain: 0.095
50 deg
Segments slopes log_10(abs((d°/dN)))
−4.0
−4.5
−5.0
−5.5
−6.0
0.0
0.2
0.4
0.6
0.8
1.0
1e7
Number of Cycles

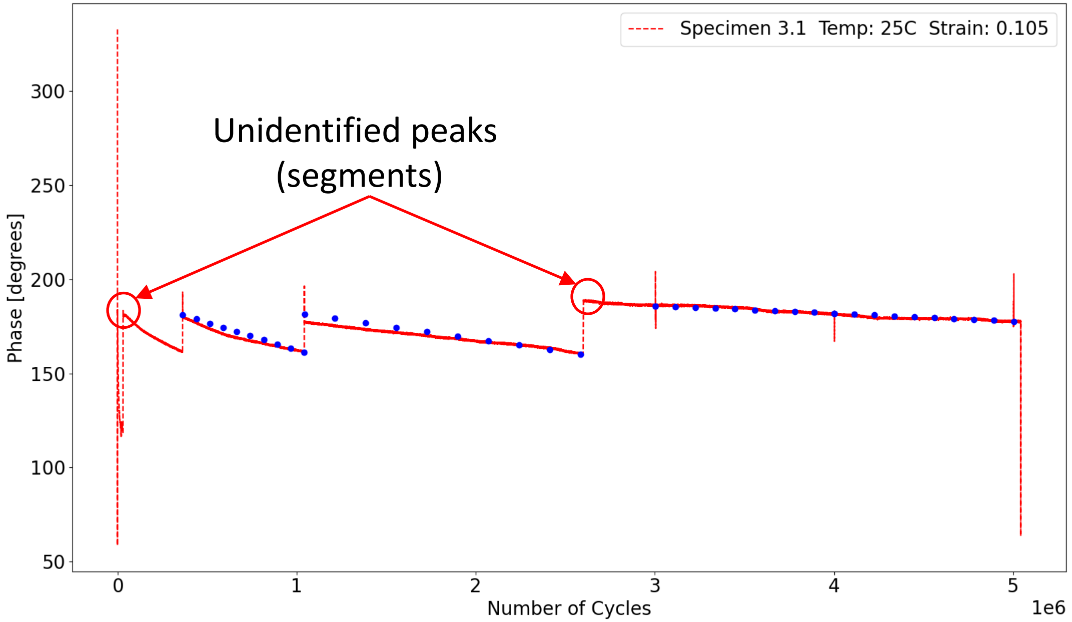
04 Methods improvements

Methods improvements

1. To use a subset of samples for material CHARACTERISATION ONLY. To avoid introducing damage into the components, and reduce specimen preparation (no gauges in every specimen needed)

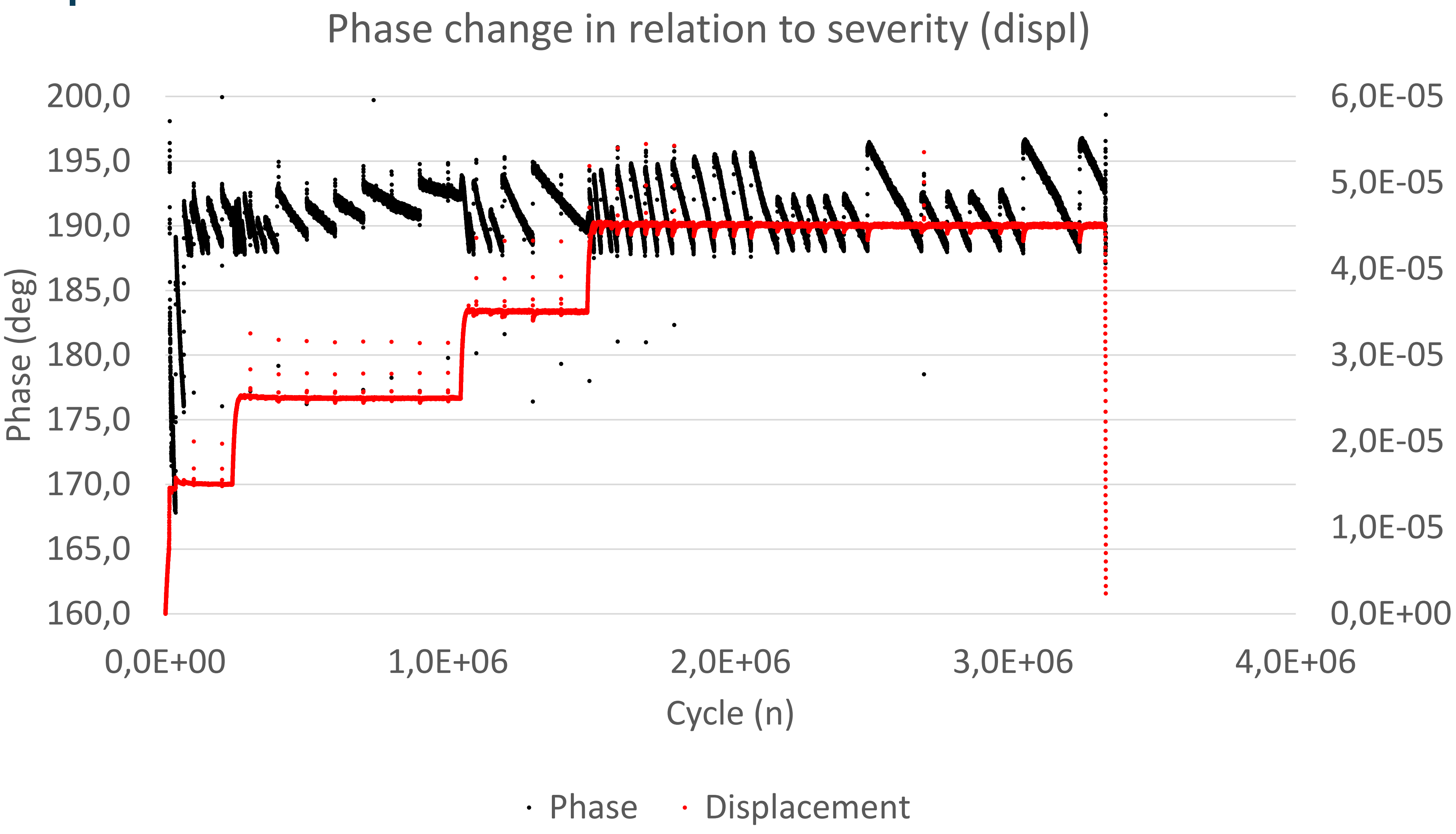
2. To implement into the control .VI a marker to easily detect peaks from frequency-PID adjustments. (Done)





Methods improvements

3. To implement an increasing step in severity per sample (rather than one severity per sample)



Thank you!

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standart

for Durability Modelling of Composites

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