FATIGUE OF POLYMER COMPOSITES WHAT IS GOOD PRACTICE?

Joint Webinar from The National Physical Laboratory and Instron

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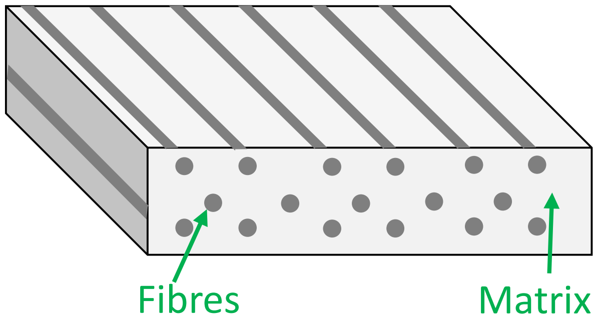
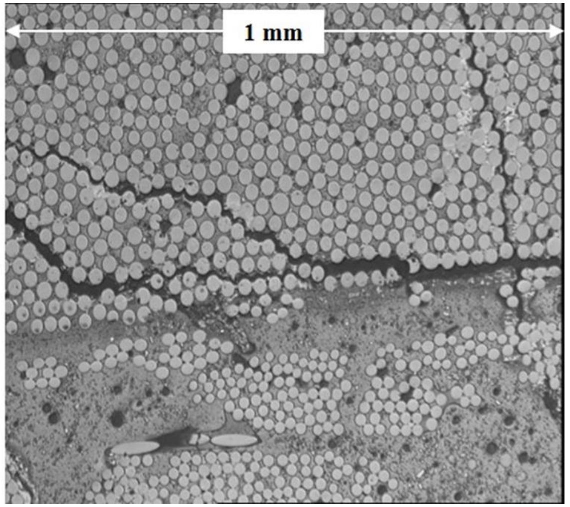
Polymer Matrix Composites

- A material which is made up of two or more distinct macroscopic, and not microscopic, materials
- Polymer composites are plastics within which there are embedded fibres or particles
- The plastic is known as the **matrix**, and the fibres or particles, dispersed within it, are known as the **reinforcement**

Close up of a composite





Why be interested in composites fatigue?

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Large scale commercial use and still growing

Aerospace

- Majority structural material for most new aircraft designs
- High temperature fibre composites already being incorporated into turbines

Automotive structures

- High-end passenger vehicles for many years
- Slower background growth in other cars and commercials
- Becoming an integral part of electric vehicle designs

Power and civil engineering

- Wind turbines – huge installed base – pioneered design utilising composites fatigue

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Common approaches to fatigue testing and what it entails

GENERAL PRINCIPLES

Validating design and materials assurance

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Ensuring fitness-for-purpose

Preventing failure

Criticality

Environment & location

Loading conditions

Structural performance

Design features

Inspection

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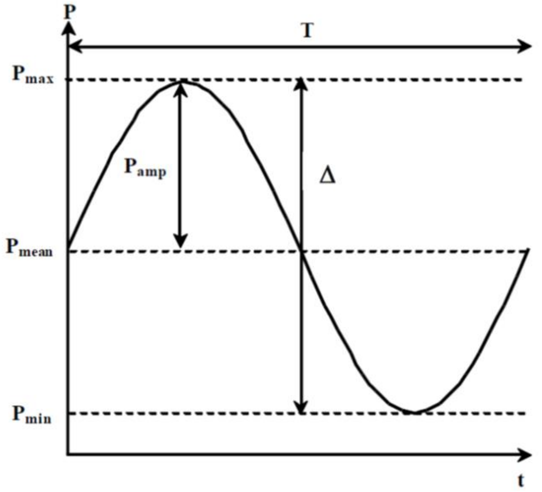
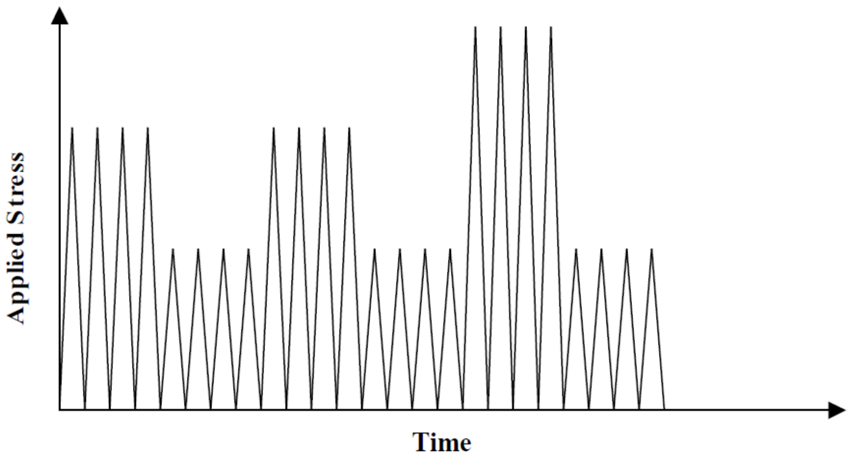
Cyclic fatigue

- Constant amplitude & frequency
- Variable amplitude & frequency spectral loading

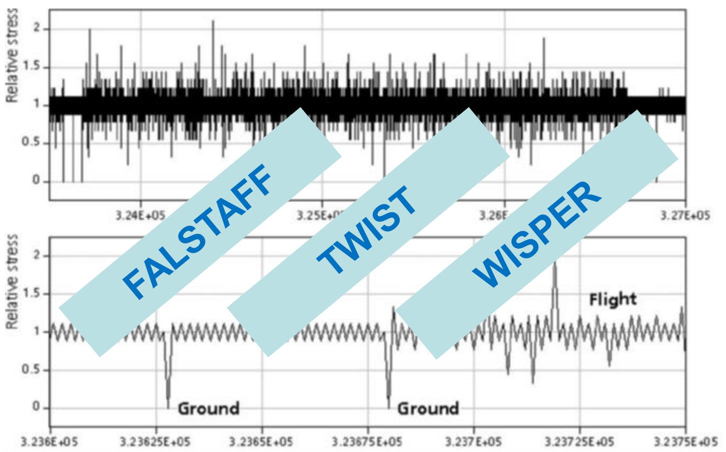
Sinusoidal waveform (1 cycle)



Blocking of constant amplitude cyclic stresses



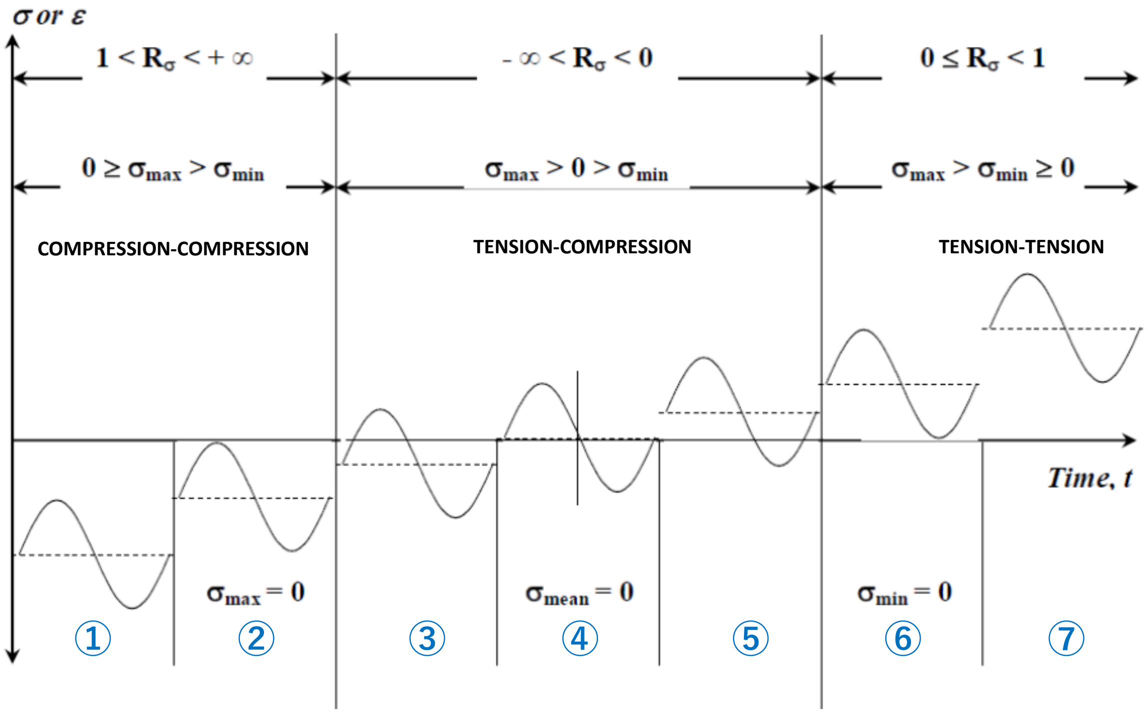
Spectral load profiles



Increasing fidelity & complexity

Fatigue regimes

- Selection of most appropriate fatigue regime
- Not just sinusoidal – triangular, square etc.



① Compression-compression cycle
② Zero-compression alternating cycle
③ Compression-dominated alternating cycle
④ Fully reversed or fully alternating cycle
⑤ Tension-dominated alternating cycle
⑥ Zero-tension cycle
⑦ Tension-tension cycle

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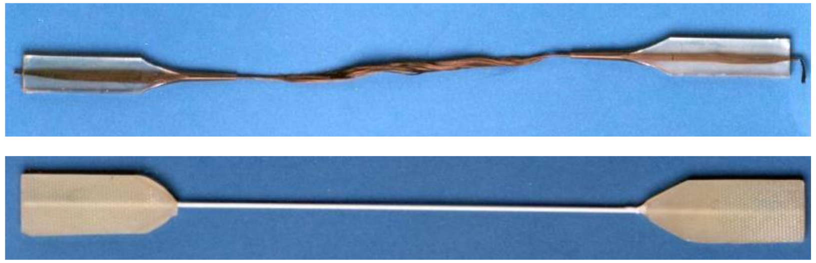
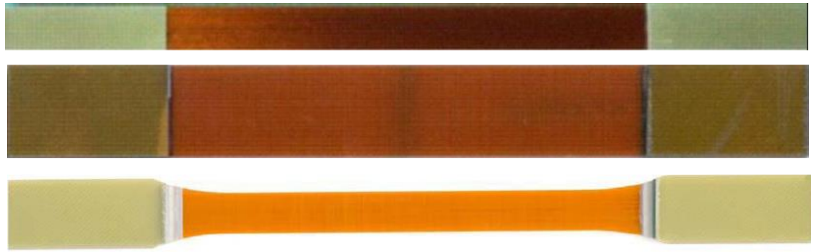
Selection of test method….a lot of them!

- Large number of international standards for quasi-static characterisation
- ISO 13003 Fibre-reinforced plastics - Determination of fatigue properties under cyclic loading conditions

Fibre bundles and composite rods (tension)



In-plane tension

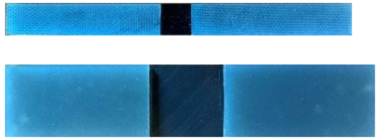


UD - long

UD - trans

MD

In-plane compression



UD - long

MD

Loading could be end, shear, combined

Effect of stress concentrations

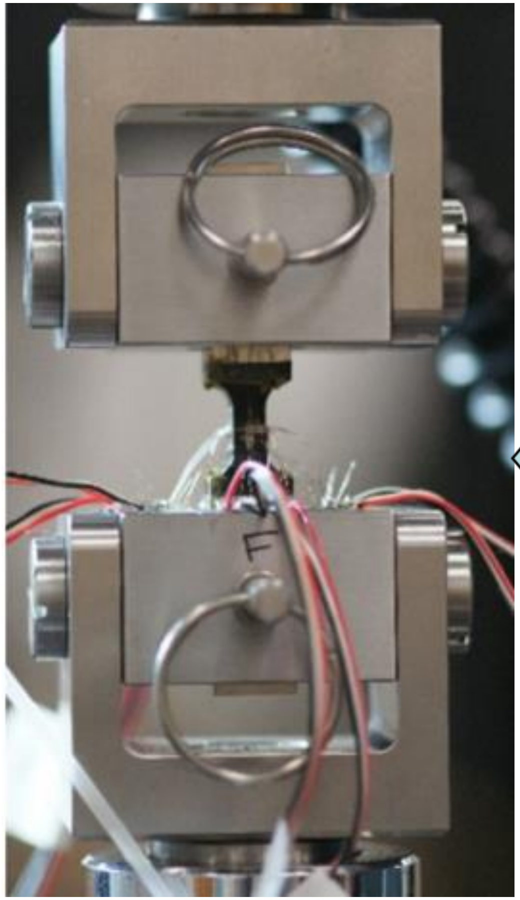
Open-hole-tension (tension-tension)

Open-hole-compression (compression-compression, tension-compression)

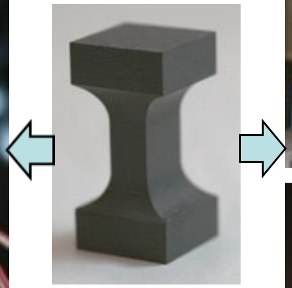
++ flexure, shear etc

Selection of test method: through-thickness

T-T Tension

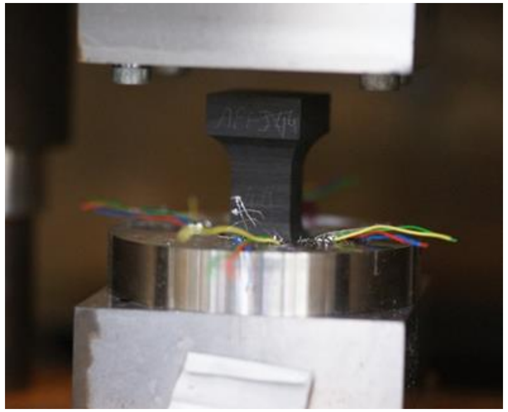


Type III coupon



ISO CD 20975-1

T-T Compression



T-T Shear

V-notched beam shear (ASTM D5379)

Specimens

Preparation and test conditions

- Specimen preparation, geometry, loading arrangement & environmental conditions should be the same as those used for monotonic tests
- Applied conditions should be recorded throughout

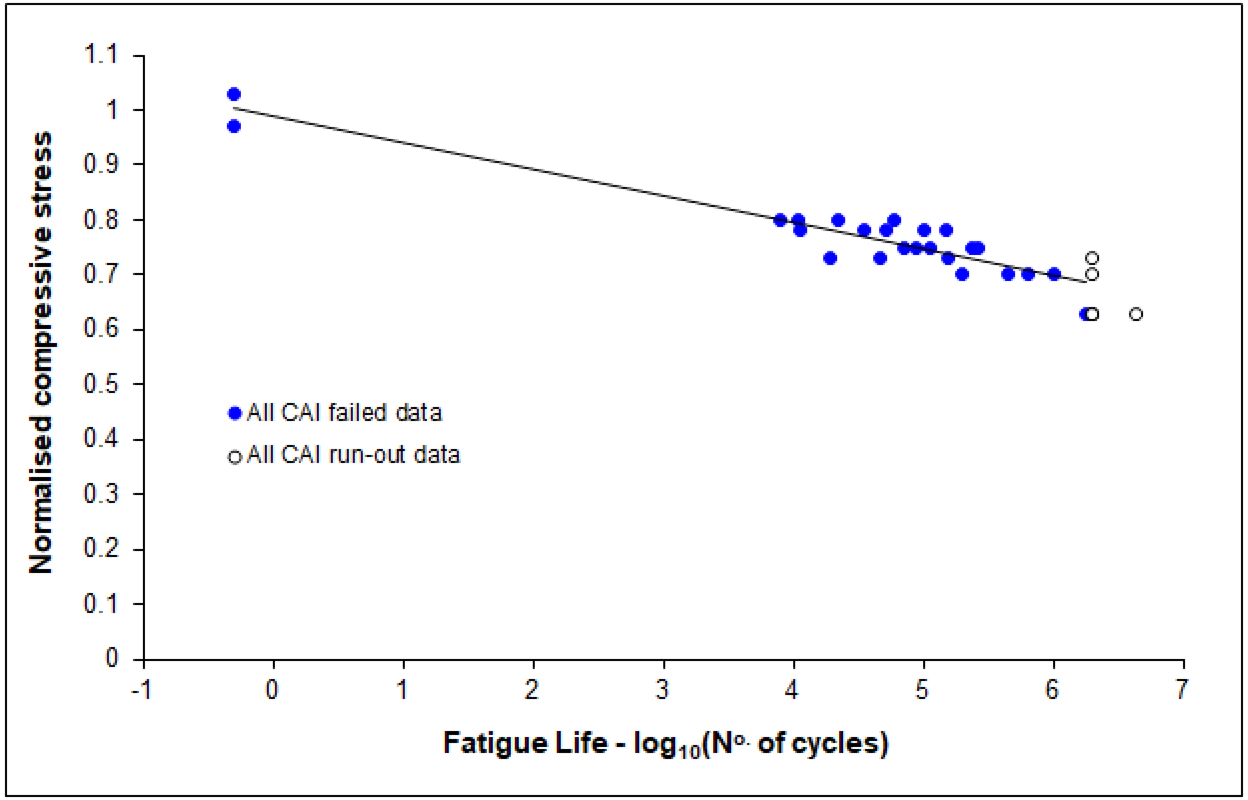
Dimensions

Percentage error			
Dimensional	Linear	Square	Cubed error
± 1	± 1	± 2	± 3
± 5	± 15	± 10	± 16
± 10	± 10	± 21	± 33

Specimens

Number

- 5 specimens at 5 stress levels
- Typically 80, 70, 55, 40 & 25% of ultimate
- For greater precision numbers of specimens should be increased (ISO 2602)



Determination of ultimate properties

- Stiffness and strength of polymer composites can be rate dependent
- Ultimate properties should be measured at a loading rate equivalent to fatigue testing conditions (i.e. test frequency)
- Fatigue test rate: that resulting in failure in a time equivalent to 0.5 x the cycle time

  i.e. test duration (s) = 0,5 $\times$ frequency (Hz)
- Ultimate properties determined from tests on at least 5 specimens

Data - presentation

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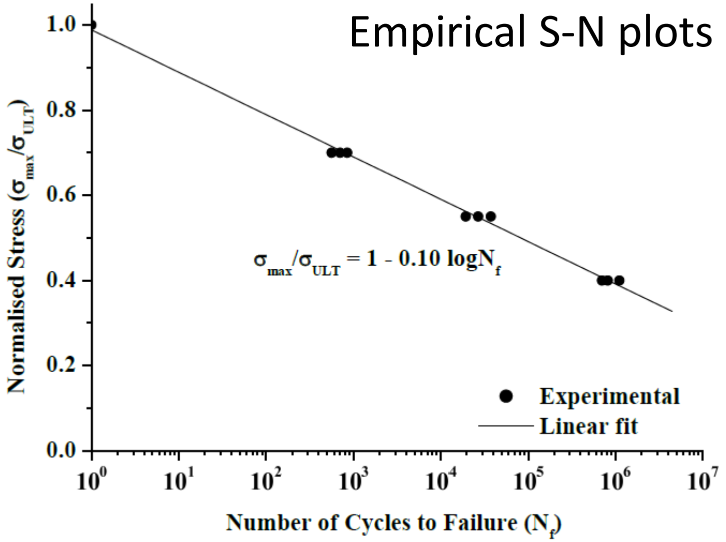
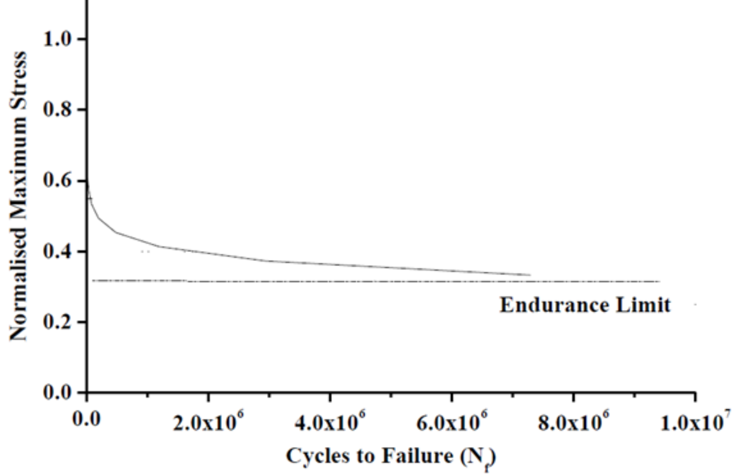
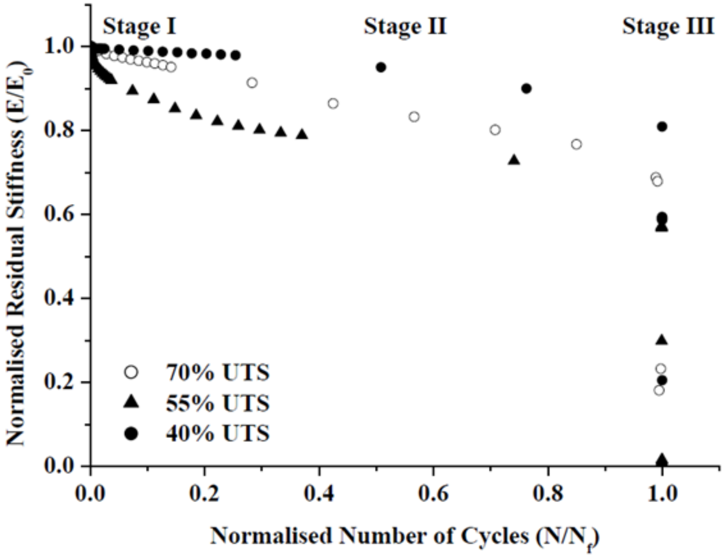
Empirical S-N plots

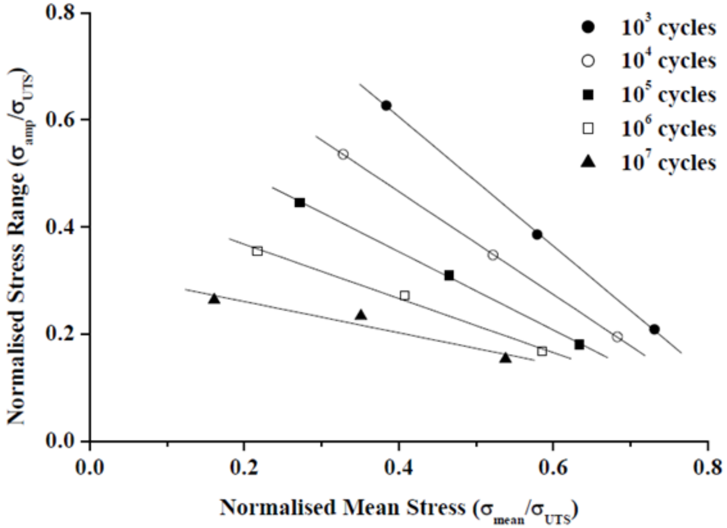


S-N plot: endurance limit





Constant-life (Goodman-Haigh)plot



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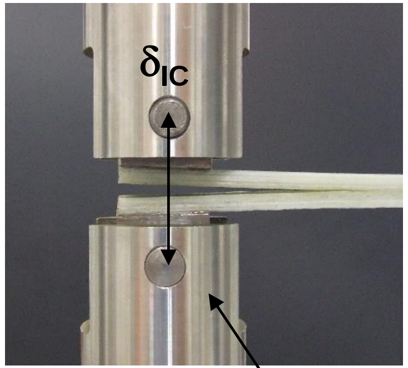
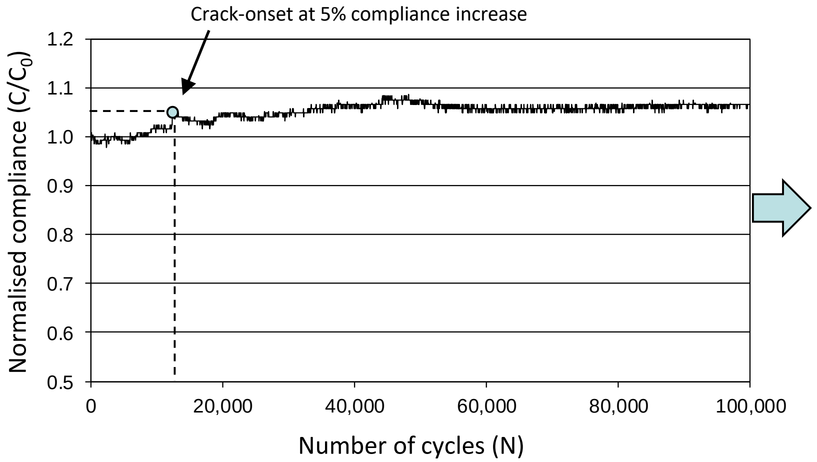
Fracture toughness

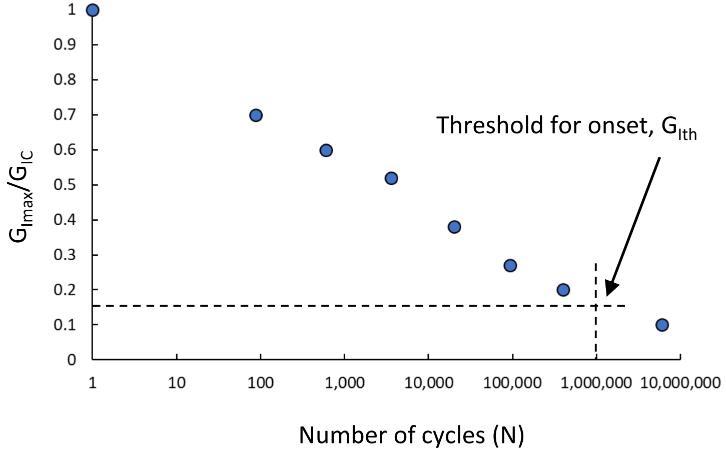
E.g. mode I (opening)



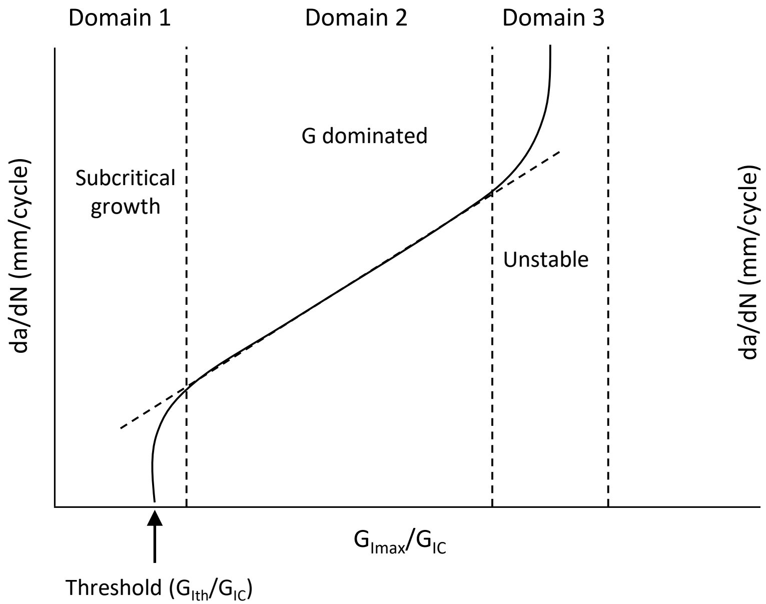
$$\delta_{Imax} = \sqrt{\frac{G_{Imax}}{G_{IC}}}\,\delta_{IC}$$

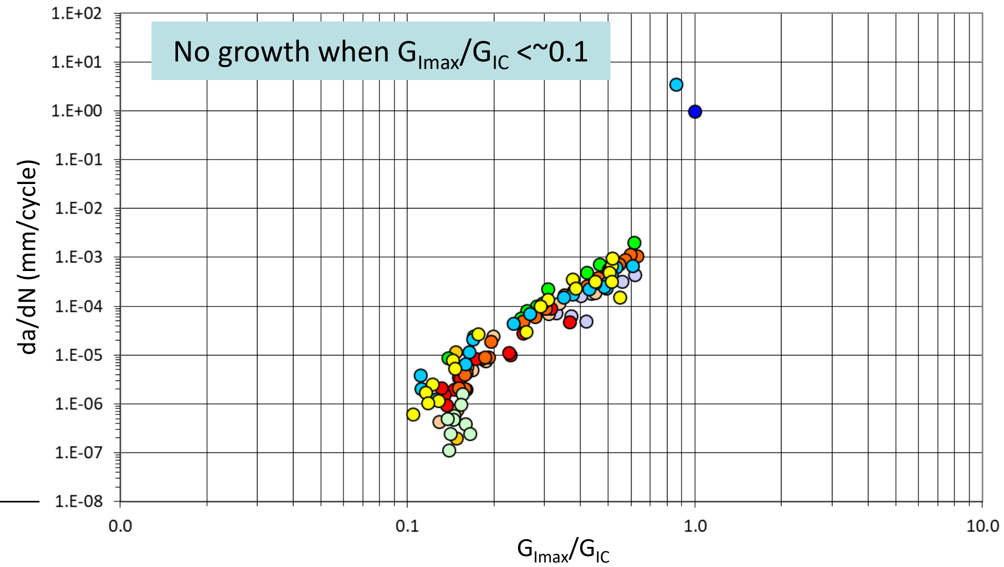
Onset





Growth





Experimental work and necessary equipment

PRACTICALITIES OF TESTING

Fatigue testing equipment

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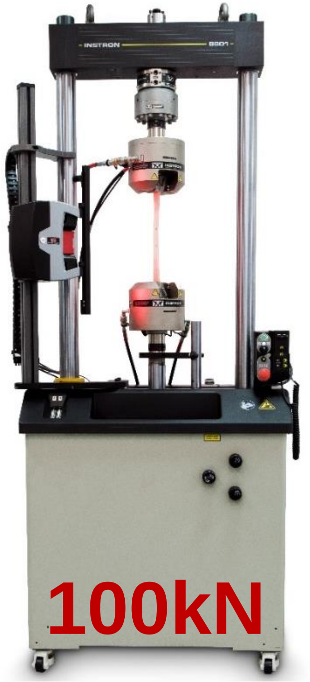
- Commonly servohydraulic due to force capacity



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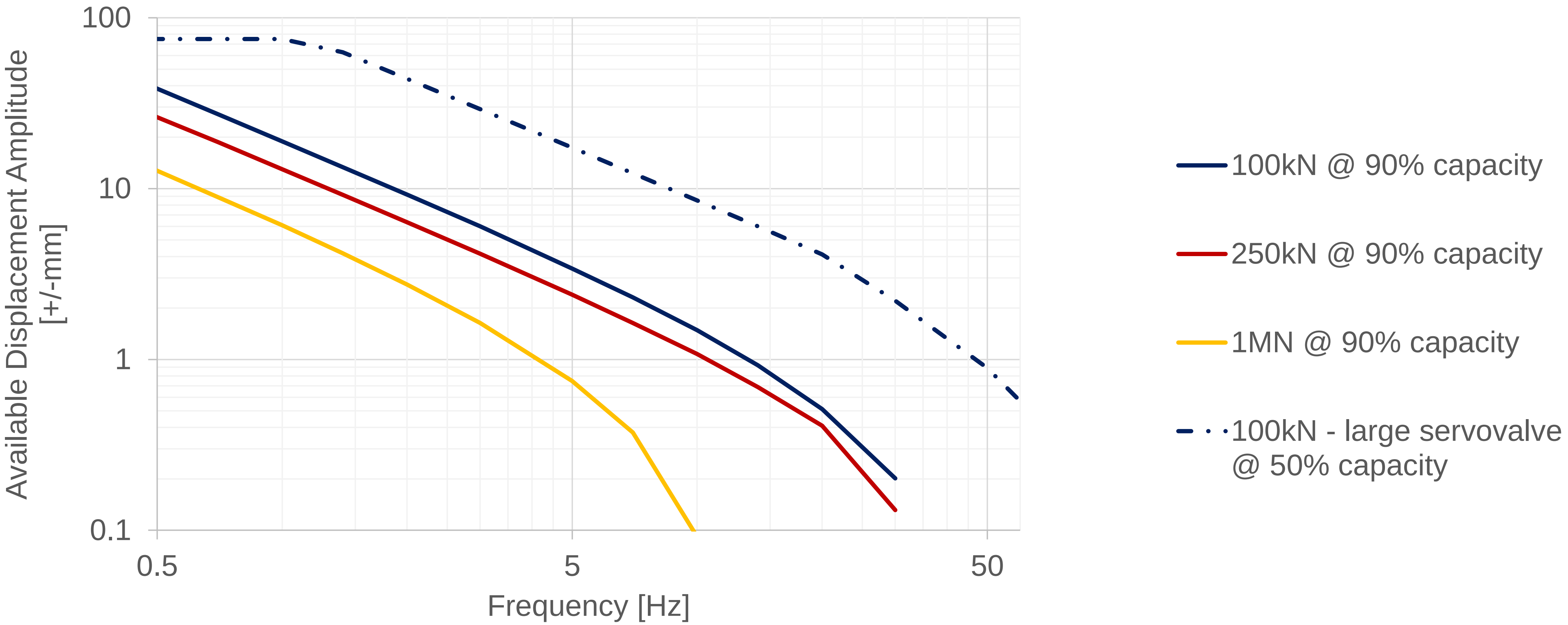
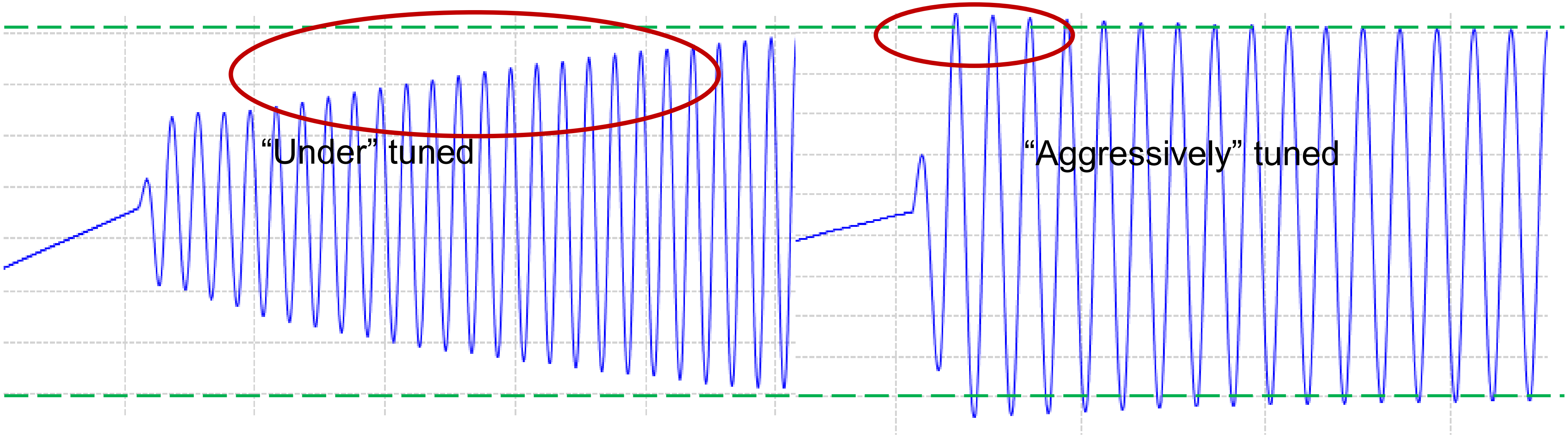
Performance and control

Available displacement and force varies with test machine… a lot!



Control - Tuning

- **Tuning** dynamic systems is **important** yet often neglected!
- Ensures the machine behaves stably and command is met immediately

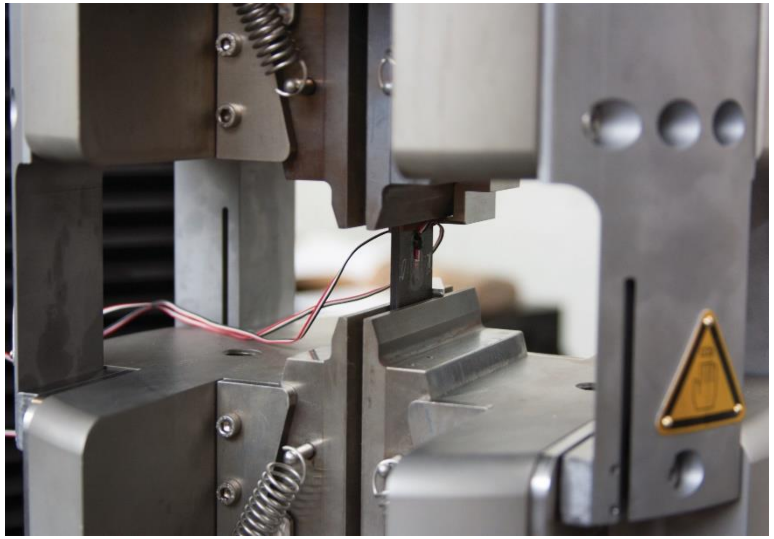


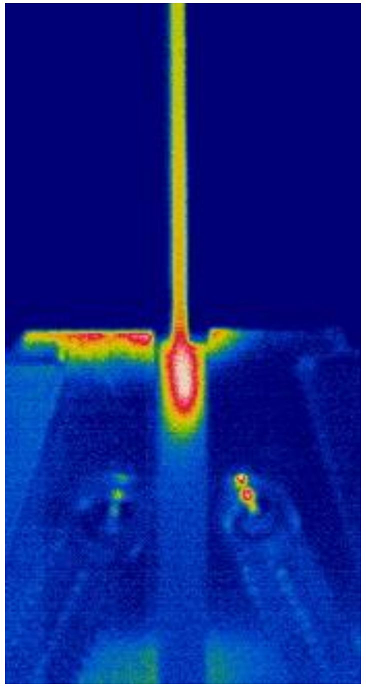
Taking care of your equipment

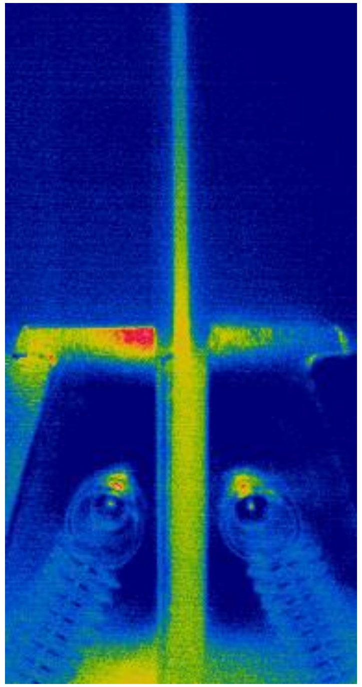
- Composite failures create fragments
- **Highly abrasive**
  - Can easily get into hydraulic seals and cause wear
- **Carbon fibres conductive**
  - Easily aspirated and can damage control electronics / computers without cooling intake filters
- **Keep your lab clean for the operators too!**

Gripping specimens

- Secure and repeatable
  - Hydraulic, wedge-action (or pneumatic)
  - Standard jaw faces fine for most specimens with end-tabs
  - Smoother jaw faces with hard-coatings for tab-less gripping







Specimen and machine alignment

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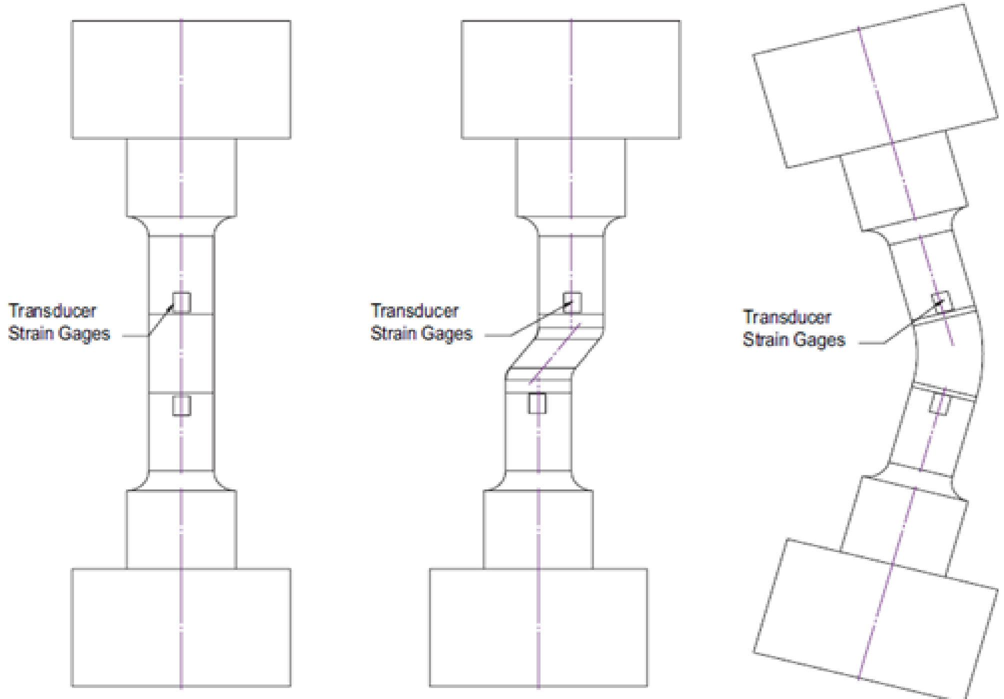
- Important to align the system so no extraneous applied stress
  - Relatively easy with appropriate fixtures
  - Verified using a calibrated strain-gauged specimen
    - Standards ASTM E1012, ISO 23788
    - **Nadcap accreditation requirement**



(A) Properly Aligned Alignment Transducer

(B) Concentric Misalignment of Alignment Transducer Creates an "S" Shape

(C) Angular Misalignment of Alignment Transducer Creates an "C" Shape

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Temperature control

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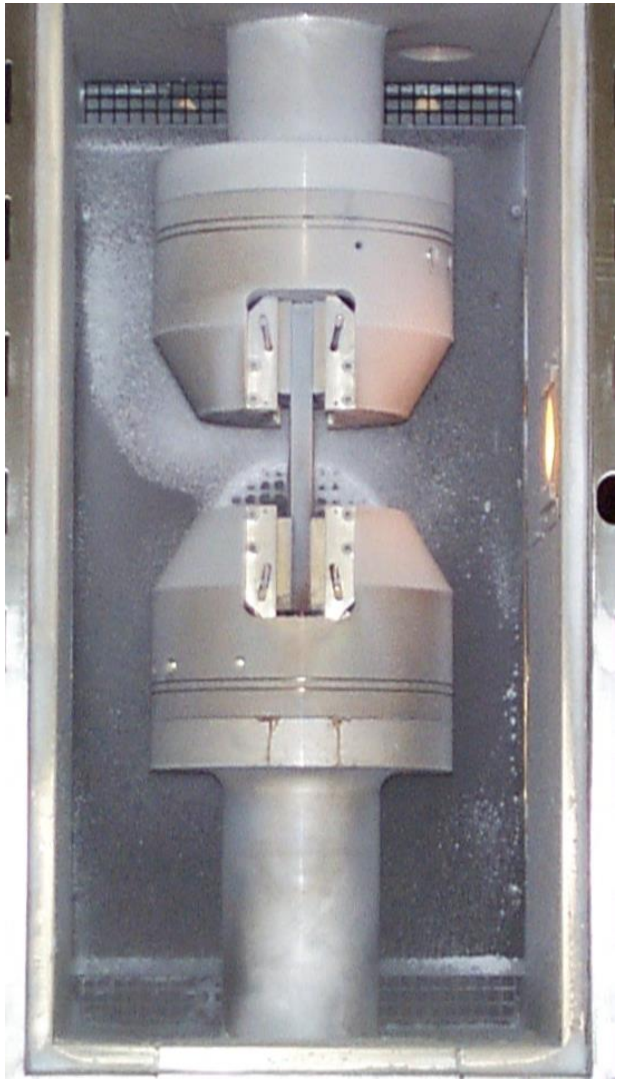
- Often important to address effects of different operating temperature
  - Composite properties vary significantly more within the operating window than metals – so does fatigue performance.
- Use of convective temperature chamber.
  - Must keep hydraulics out of high temperature

- **BUT temperature control is complicated by autogenic heating of the specimen!**



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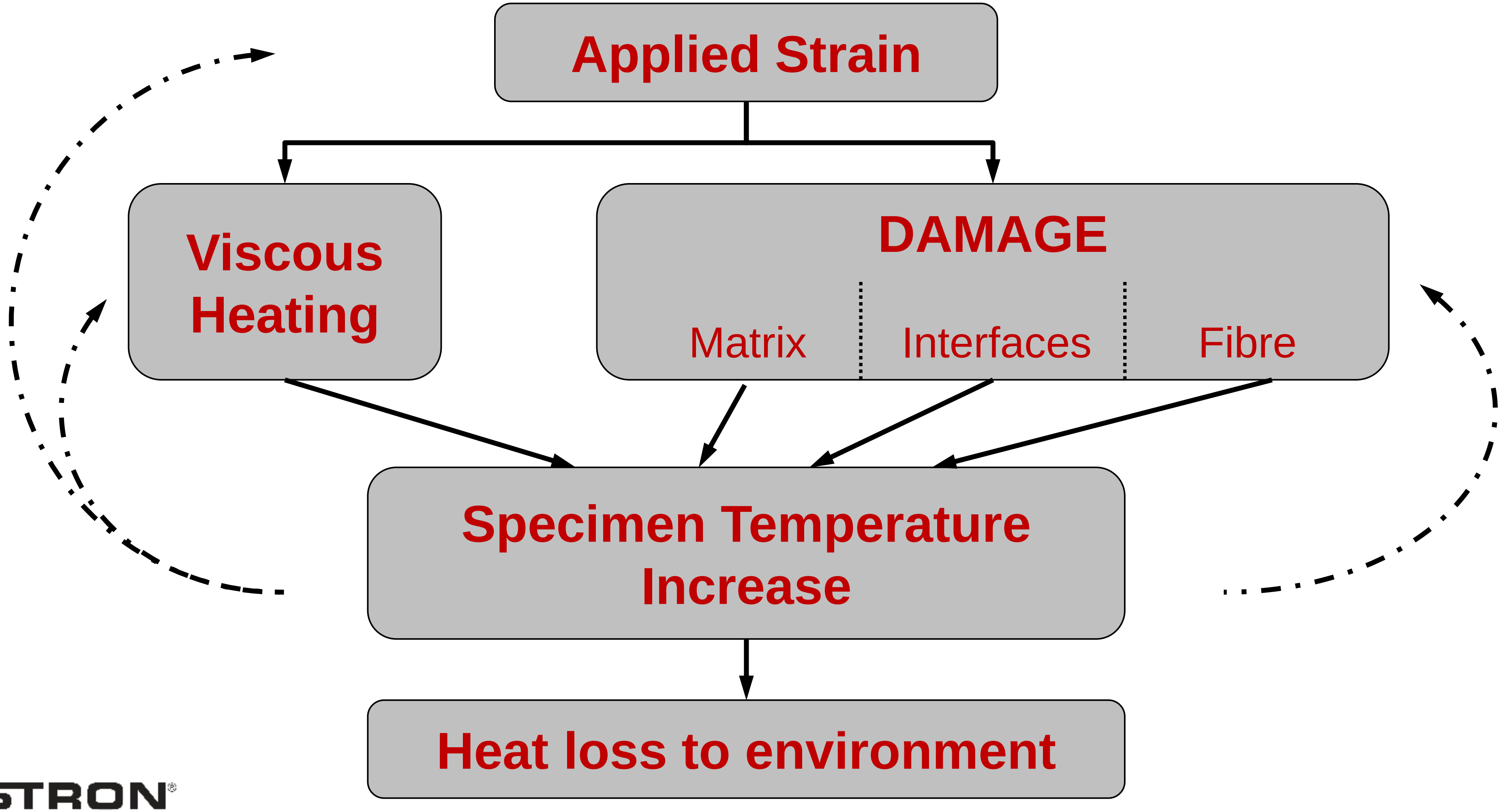
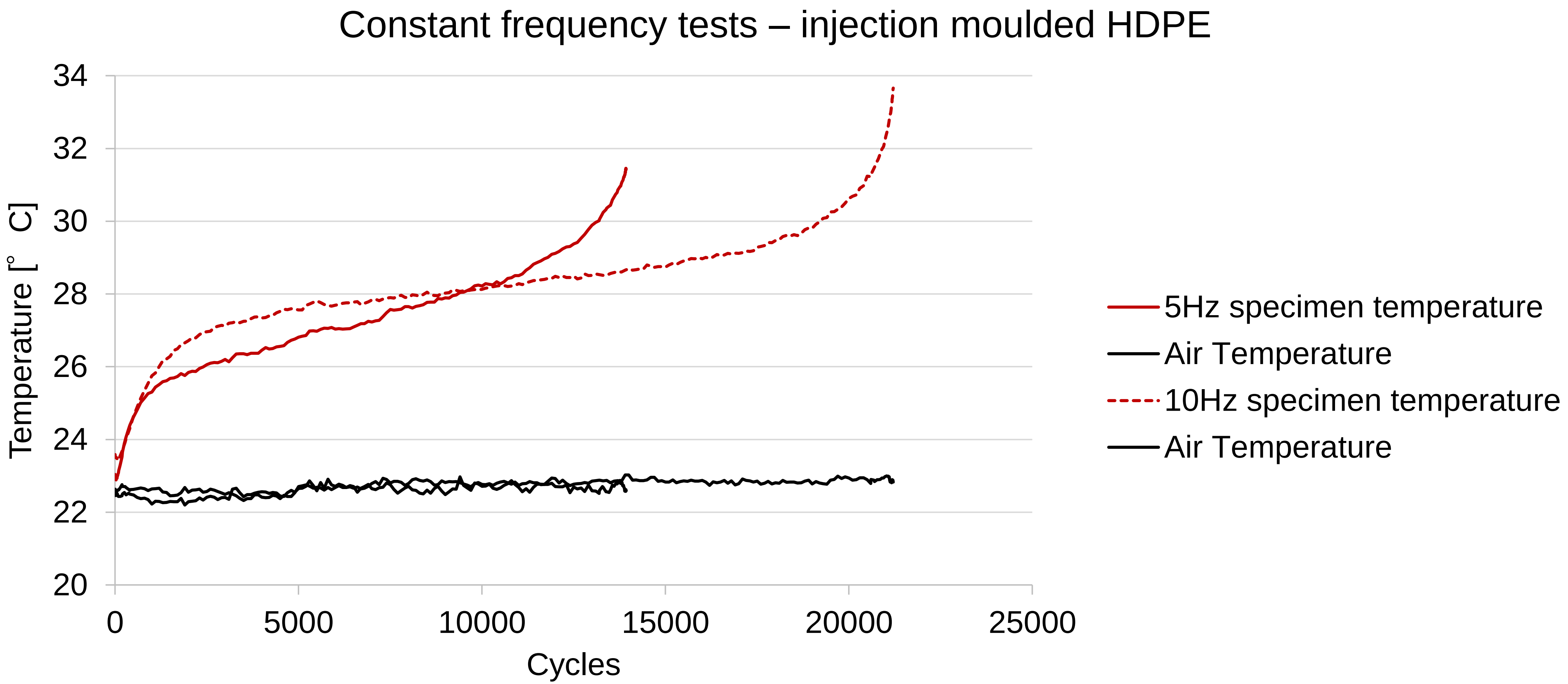
Autogenic heating (self-heating)

- Composite materials under cyclic load generate heat internally



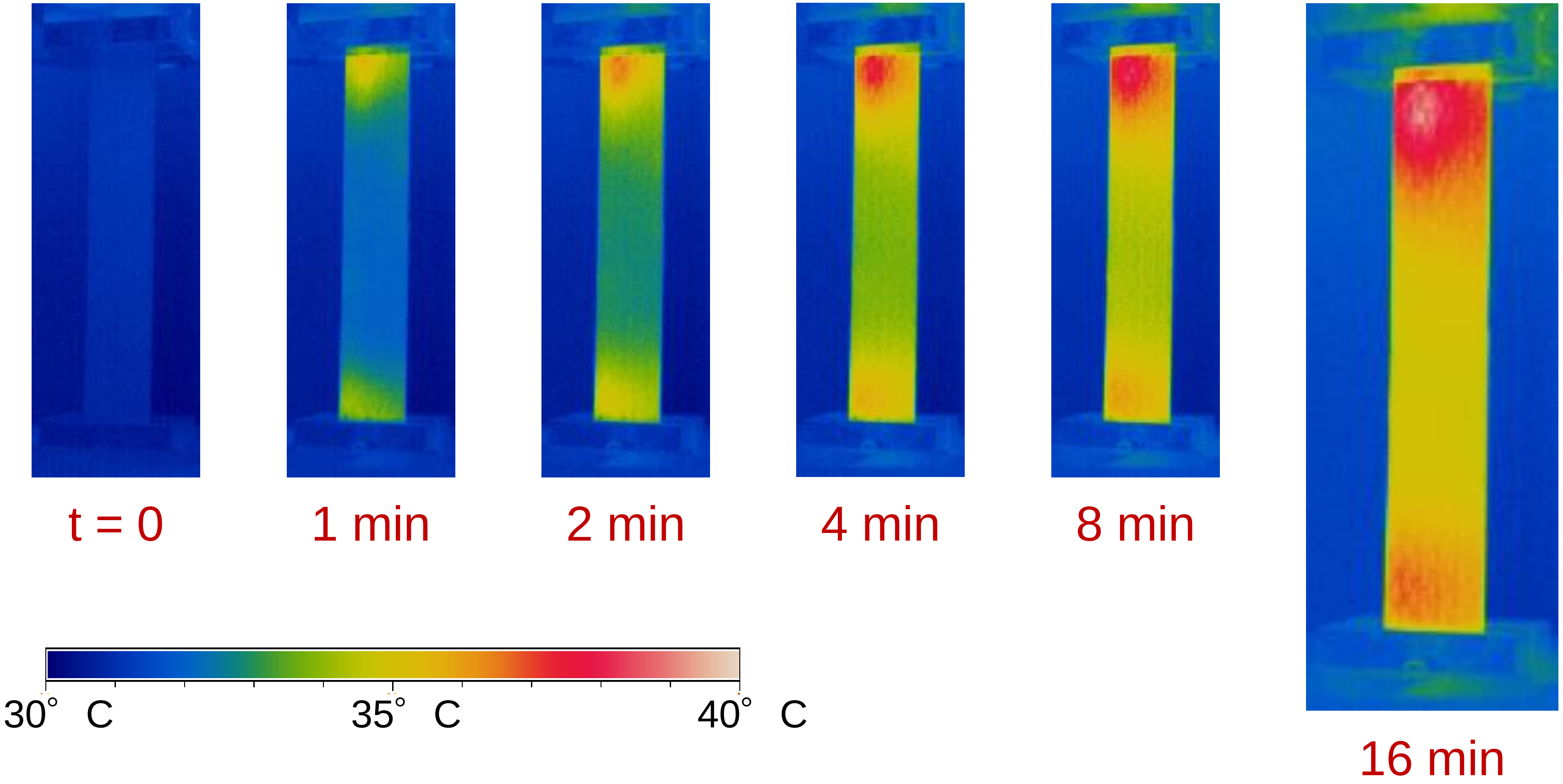
Fixed frequency heating illustration



Example of cyclic heating

Woven CFRE

- 80% UTS, R = 0.1, 5 Hz



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Controlling self-heating effects

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- 3 key approaches – **not mutually exclusive!**
  - Limited frequency & lab climate control
    - This is very limiting; typically <3Hz to achieve truly constant temperature
  - Temperature control chamber
    - Useful/popular since composite properties are often more temperature sensitive across their operating range than metals – but cannot do anything about autogenic heating
  - Adaptive frequency
    - Allowing some latitude on strain rate means that frequency can be adjusted during test to keep temperature stable

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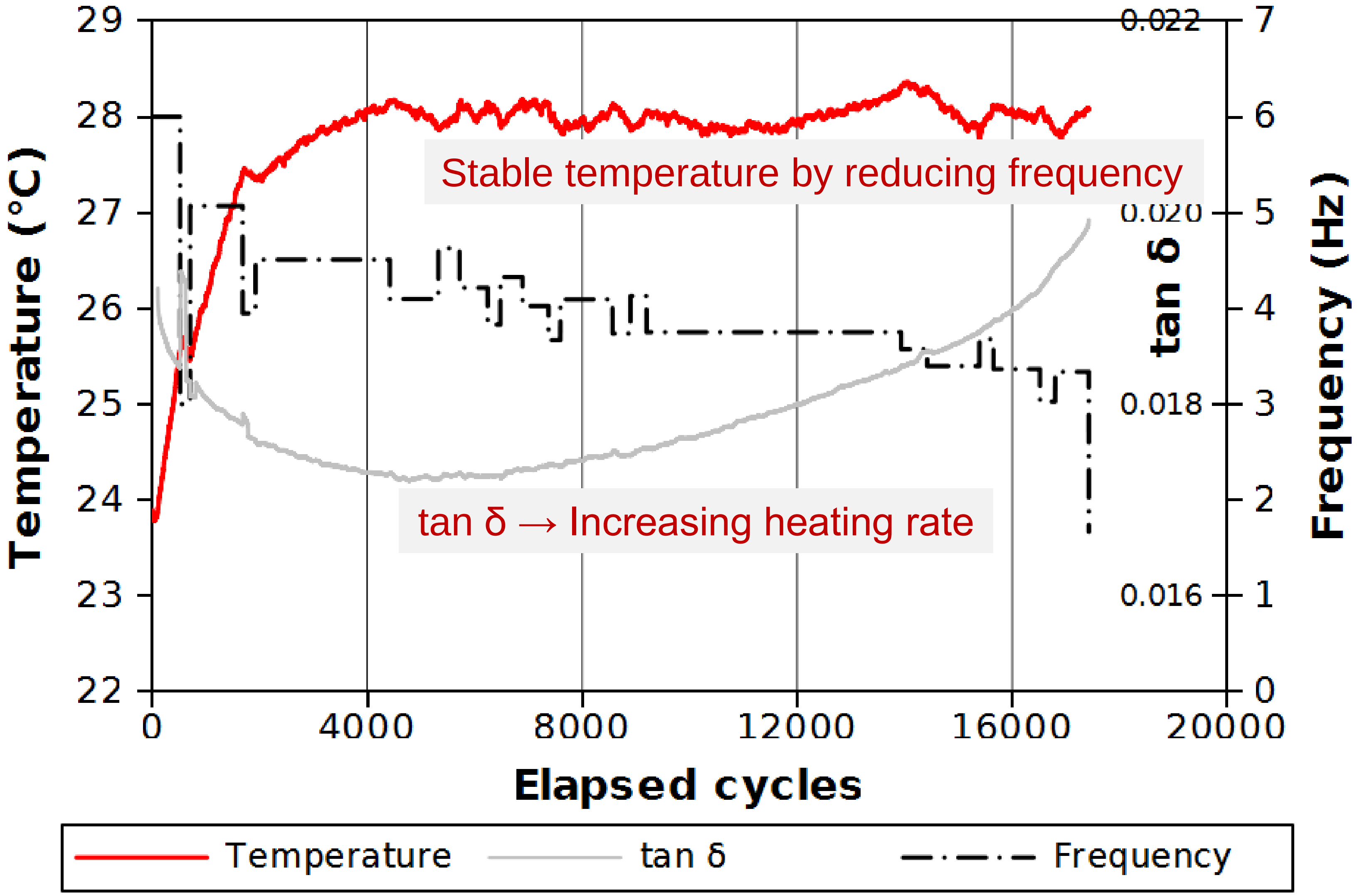
Preventing Over-Heating



* GFRE loaded to 60% UTS at R = 0.1, target temperature 28.0 ± 0.5 ° C

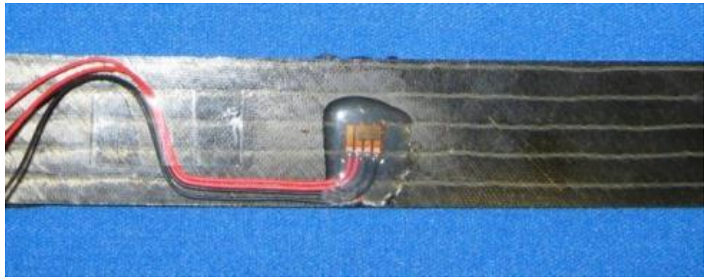
Measurements and transducers

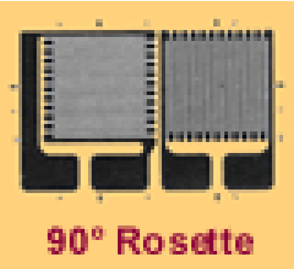
- Composites fatigue characterisations focus on stress (force) control
  - All loading scenarios are expected to be (linear) elastic

- Typically rely on loadcell and actuator position measurement
  - These are fundamental parts of all dynamic test machines

Strain measurement

- Less common, but useful research tool
  - Extensometer
  - Video / Laser / Image Correlation
  - Strain gauge





Derived measurements

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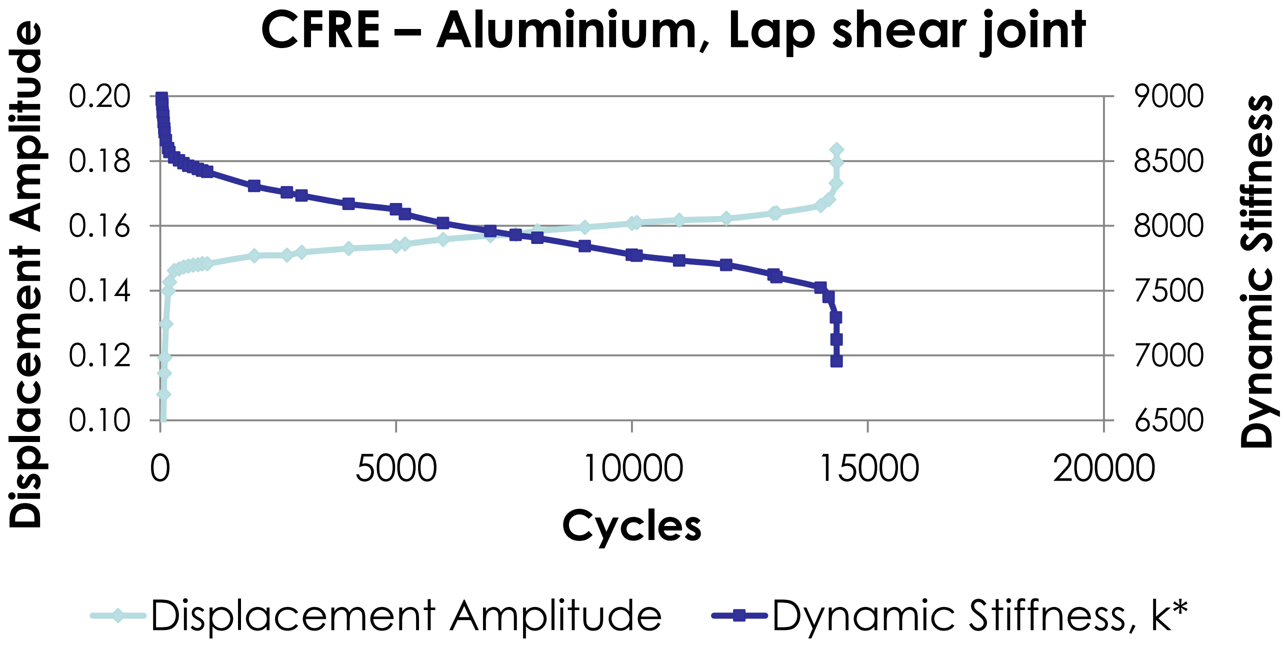
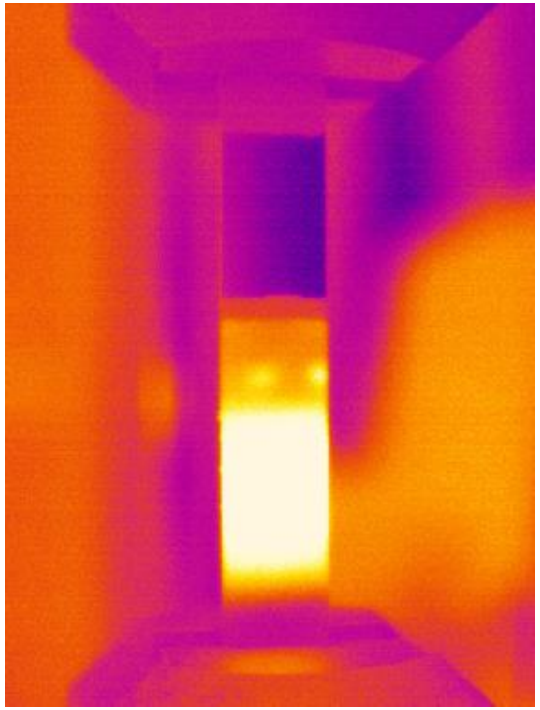
- Specimen stiffness or dynamic modulus
  - Clear measure of damage/degradation of specimen properties
  - Damping can also be derived



- Thermal emission
  - Best used as a full-field technique, providing additional qualitative insight



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Non-destructive techniques for detecting and monitoring fatigue damage

DAMAGE DETECTION

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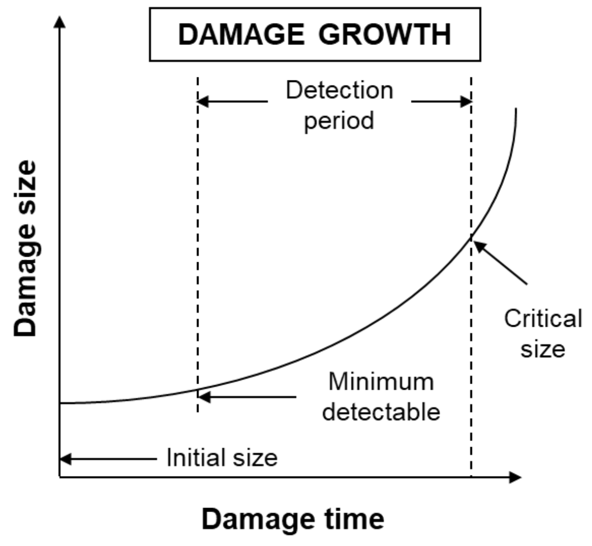
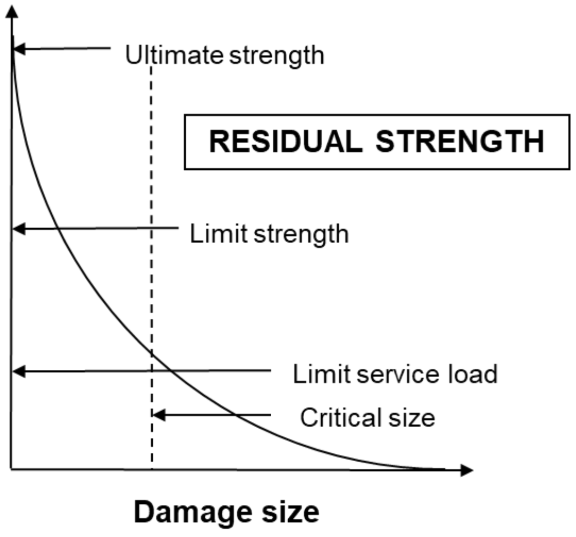
Keeping track of damage

- Correlate measured response to how the material is behaving
- Damage tolerant designs
- Characterises initiation thresholds & growth rates
- Enables scheduling of inspection and estimate of remaining life
- Relies on effective NDE

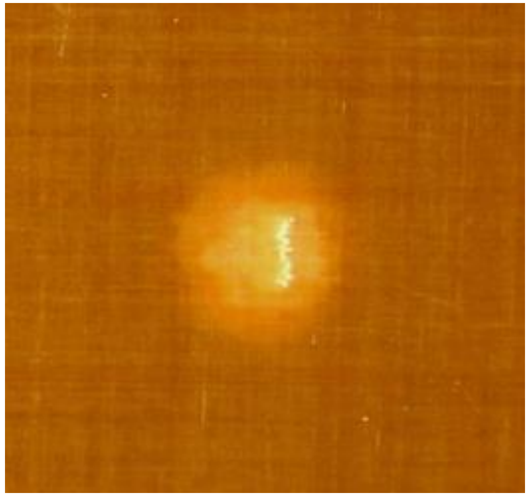




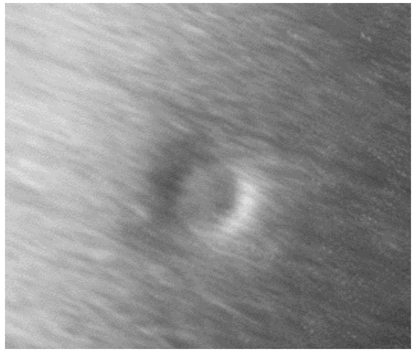
Visual inspection

- Inspection of material with the naked eye
- Accepted technique for quality control purposes
- Most commonly used technique for composites and other material systems
- Enhanced via use of cameras, lighting systems, endoscopes and automated defect recognition tools

Some application for translucent GFRP materials

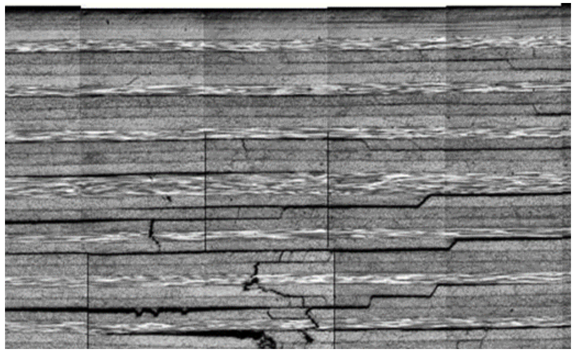


Less application for CFRP



0.3 mm deep dent is deemed barely visible!

But…



Thermography

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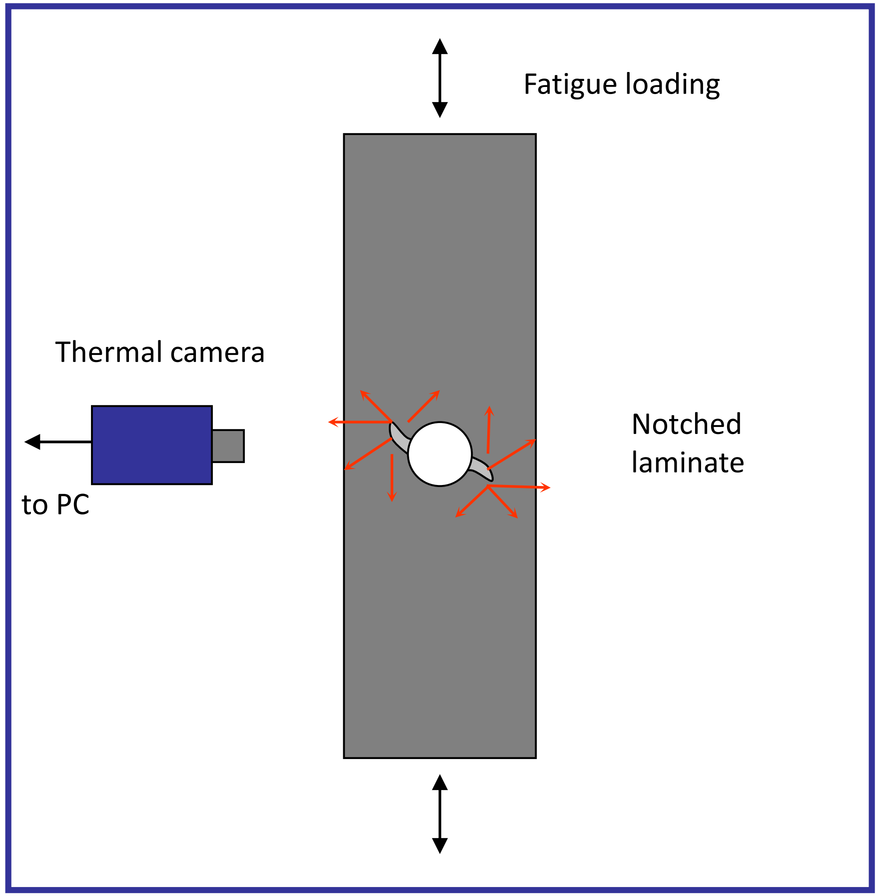
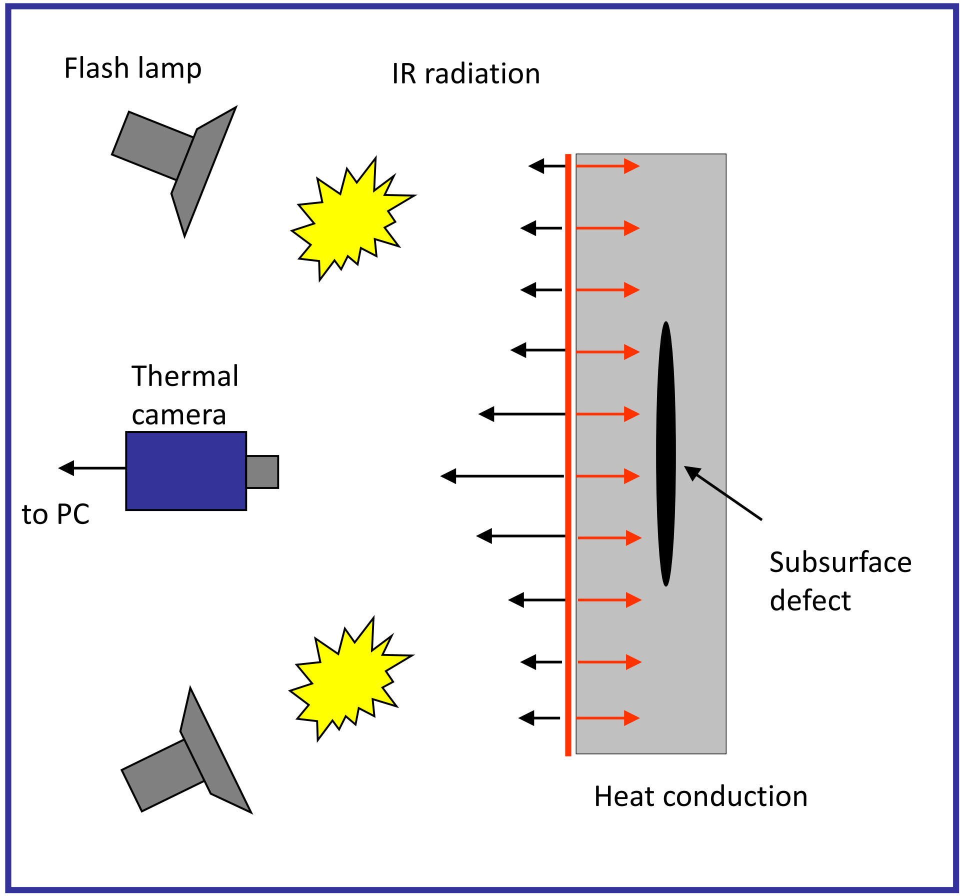
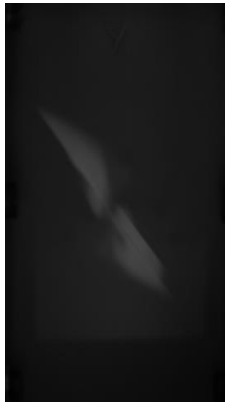
Passive



Transient or pulse



Fatigue of CAI specimens



50,000 cycles

2,000,000 cycles

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Acoustic emission

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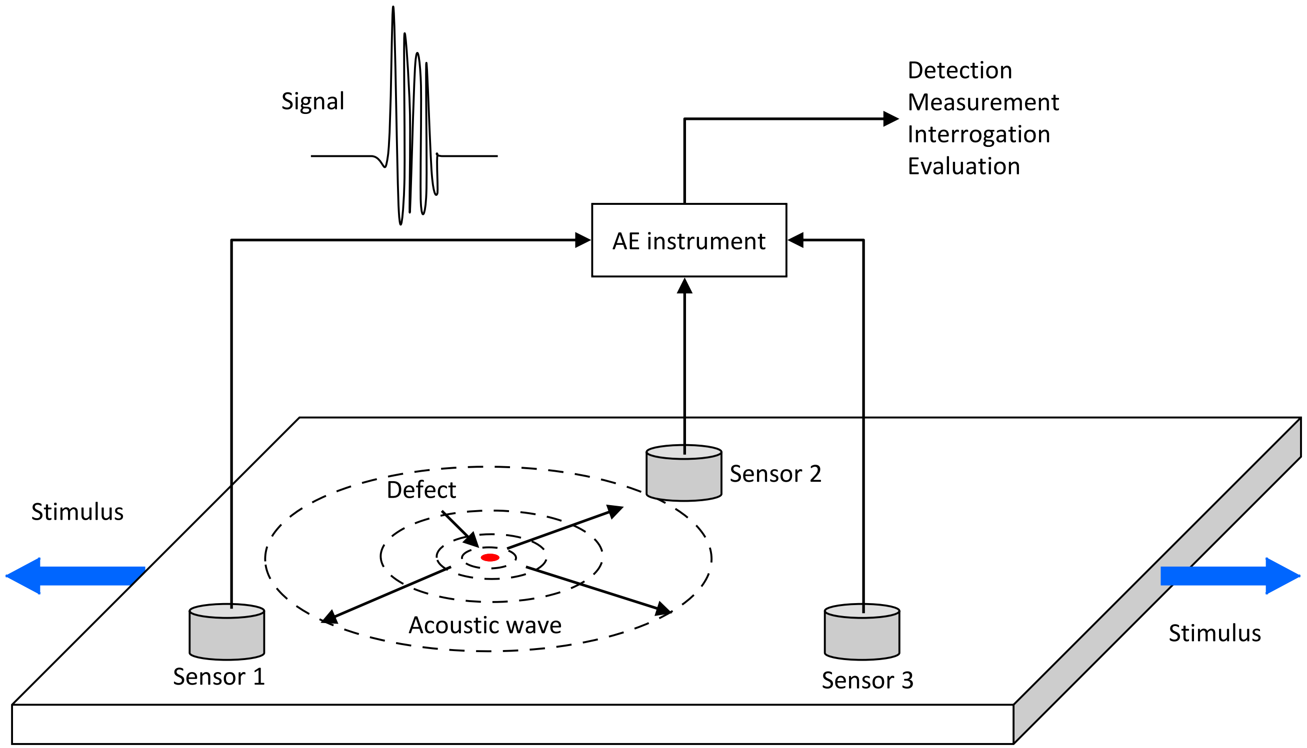
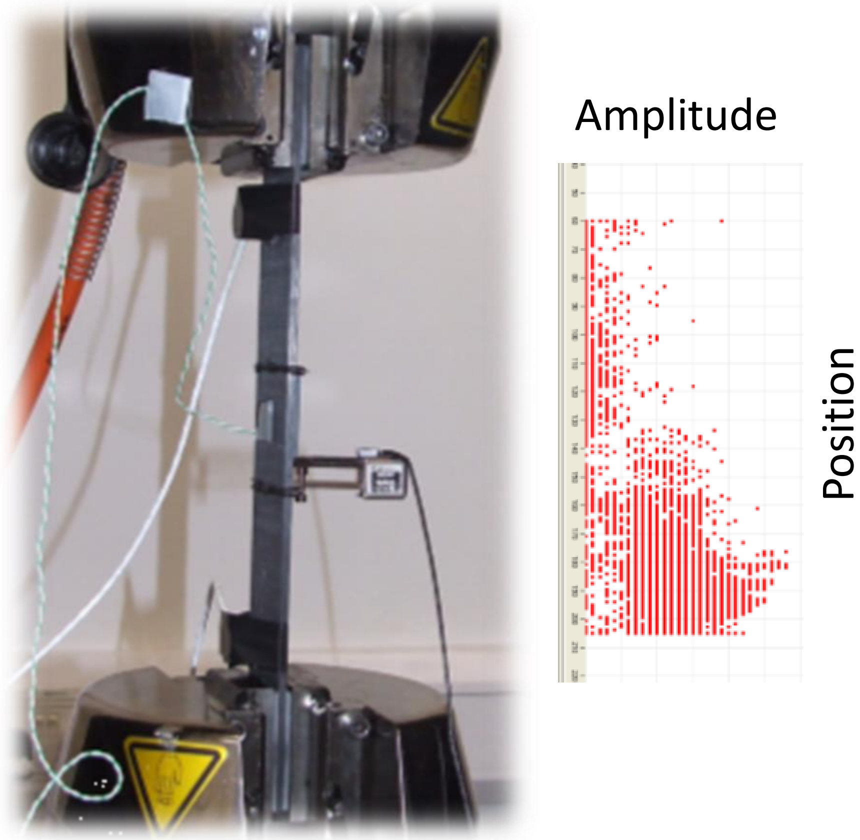
Principle





Linear location of damage using AE

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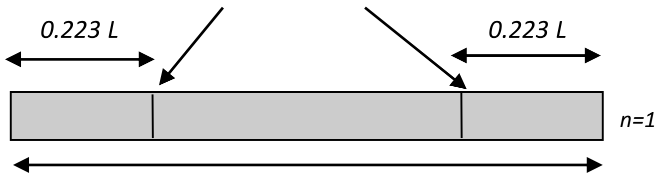
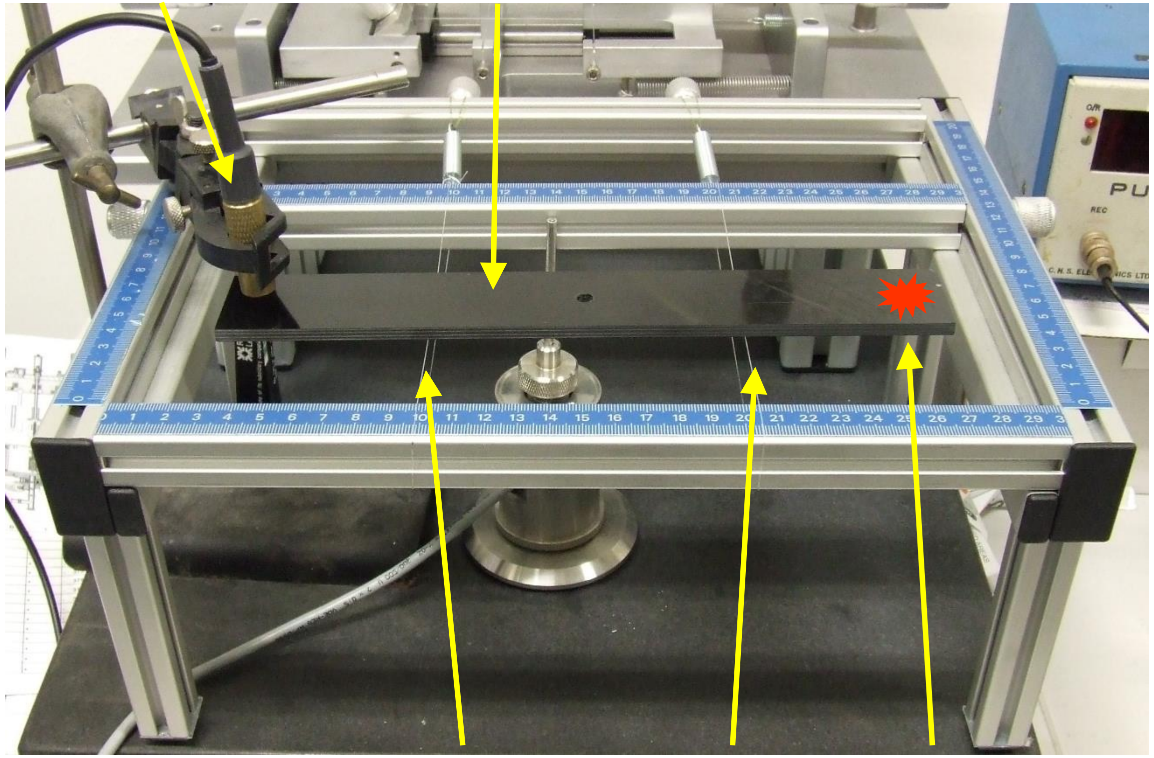
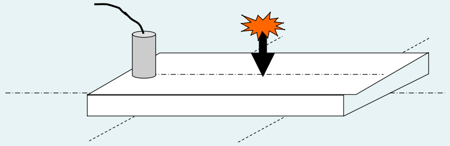
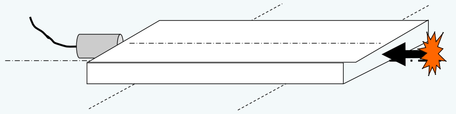
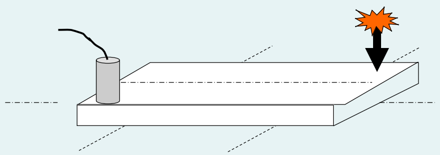
Impact excitation



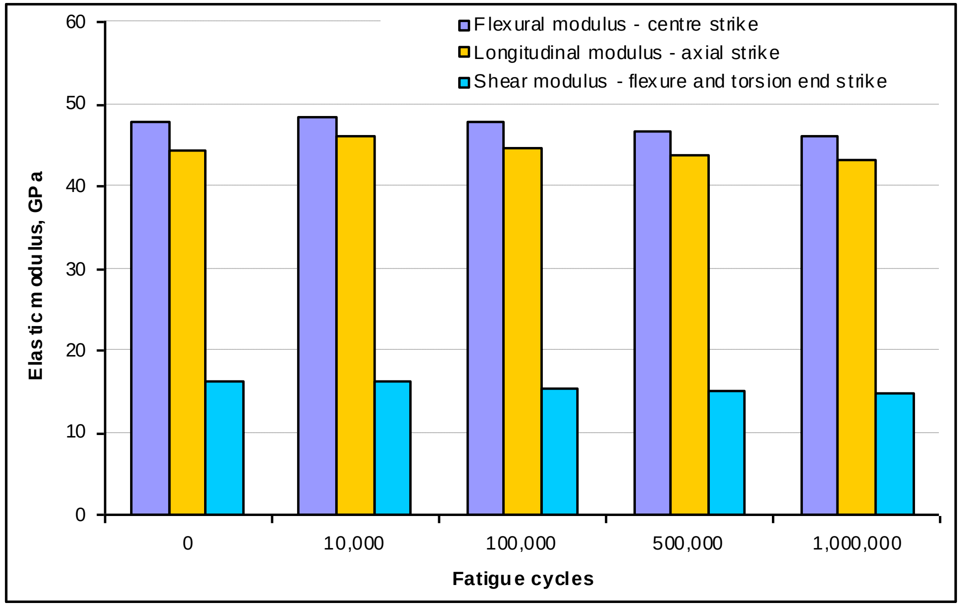


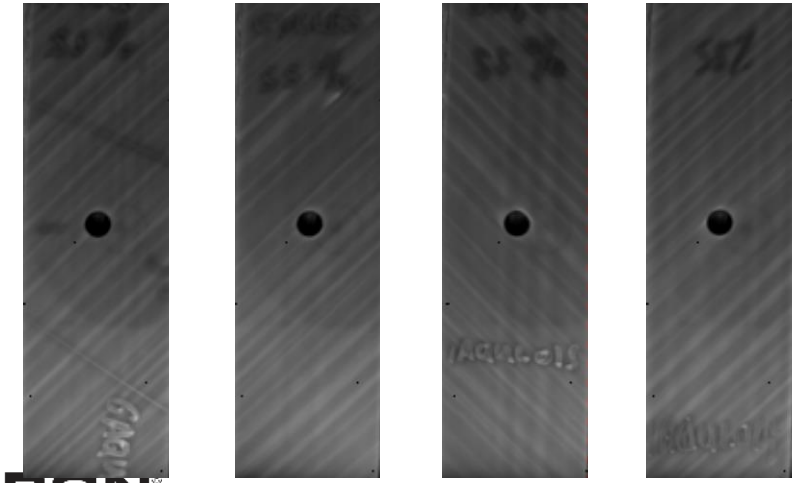
Impact mode	Impact and vibration detection locations	Modulus measured
Flexural - centre		Flexural , E_f
Longitudinal - end		Axial, E_{xx}
Flexural & torsion – end		Shear, G_{xy} Flexural, E_f

- ASTM E 1876 – Dynamic Young's Modulus, Shear Modulus and Poisson's Ratio by Impulse Excitation of Vibration

Impact excitation results - OHT

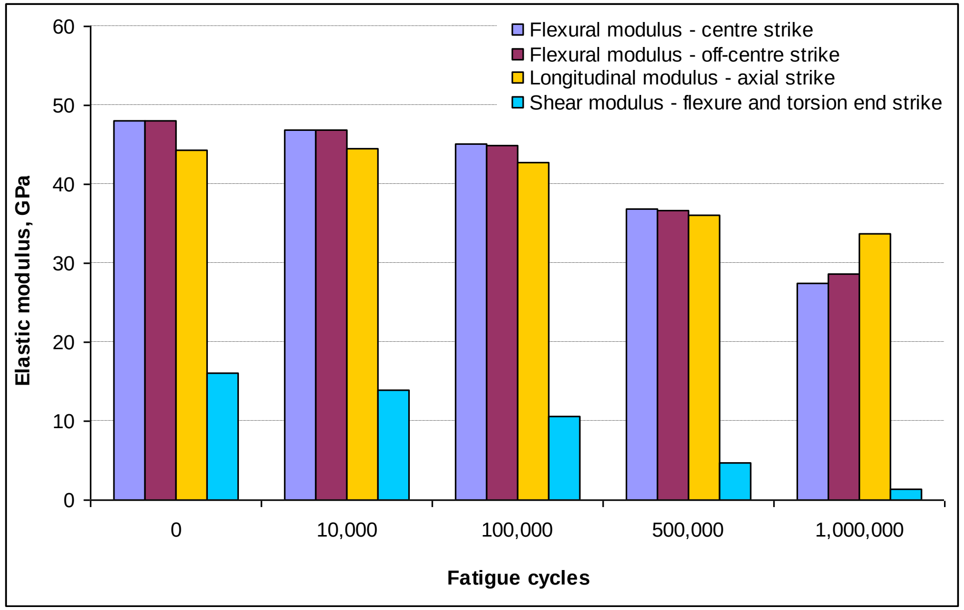
55 % OHT strength





10,000 100,000 500,000 1,000,000

80 % OHT strength



10,000 100,000 500,000 1,000,000

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CONCLUSIONS

Conclusions

NPL National Physical Laboratory

- Fatigue design of composites experimental and empirical analytical models
- More complicated than for other classes of material
- Correct selection of test method, coupon, experimental parameters etc
- Not a trivial undertaking but valuable

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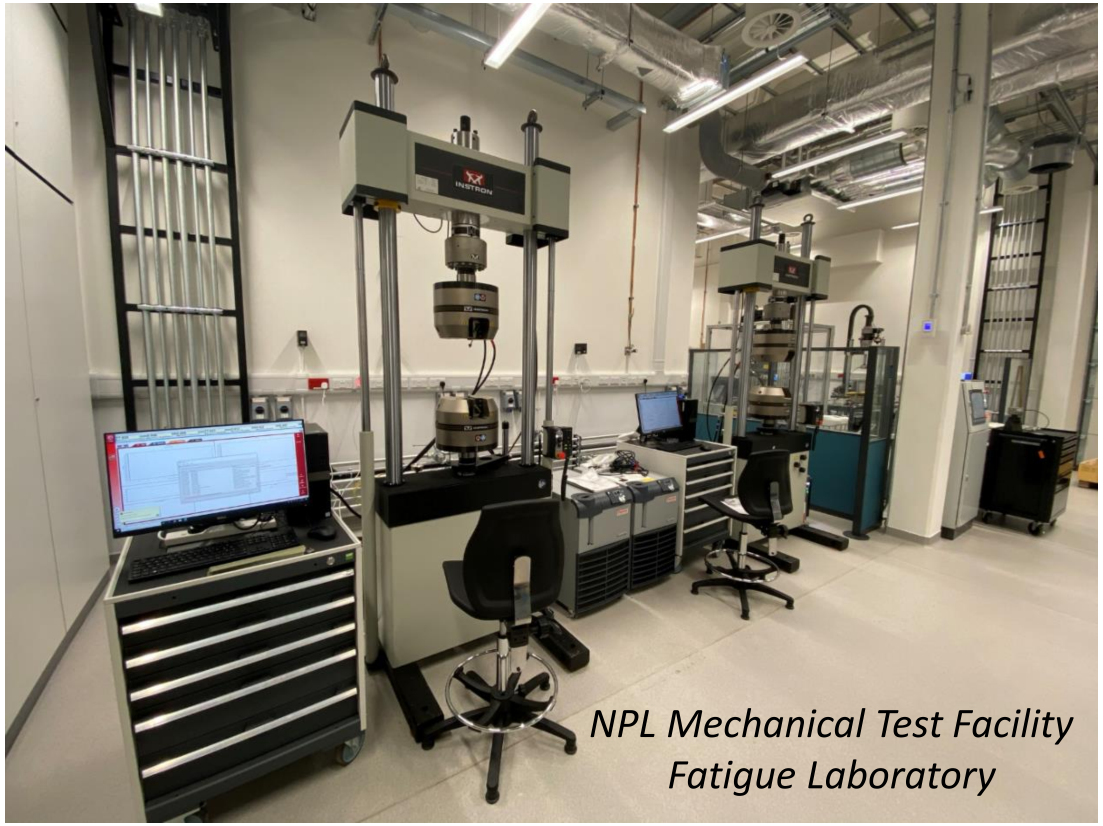
Are there any questions?

Q & A

Dates for your diary

- Webinar: Launch of NPL Mechanical Test Facility (16th February 2021)
- Webinar: "The use and advantages of small-scale testing based around the ETMT technology" (15:00 GMT, 16th March 2021)

- www.npl.co.uk/products-services/advanced-materials
- www.instron.co.uk



NPL Mechanical Test Facility
Fatigue Laboratory