Methods of Monitoring Fatigue Damage Under Variable Amplitude Loading in CFRP Composites

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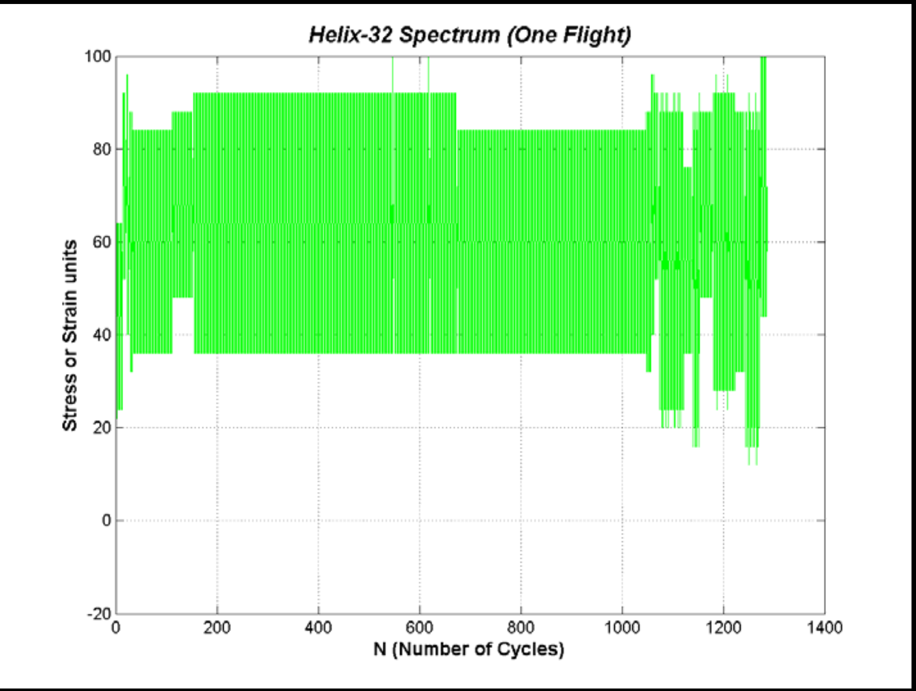
Objectives

- Overview of fatigue life prediction under random loading.
- Overview of non-destructive evaluation & testing (NDE/NDT) of fatigue damage in CFRP composites.
- Identification of a suitable damage monitoring technique for random fatigue loading conditions.

Current Life Prediction Methods

A Given Spectrum of Loading



Analysis

- Load Idealisation (e.g. Rainflow analysis)
- Data Manipulation (e.g. Goodman's Analysis)
- Damage Summation (e.g. Palmgren-Miner's)
- Failure Criterion

Output

Number of Cycles to Failure

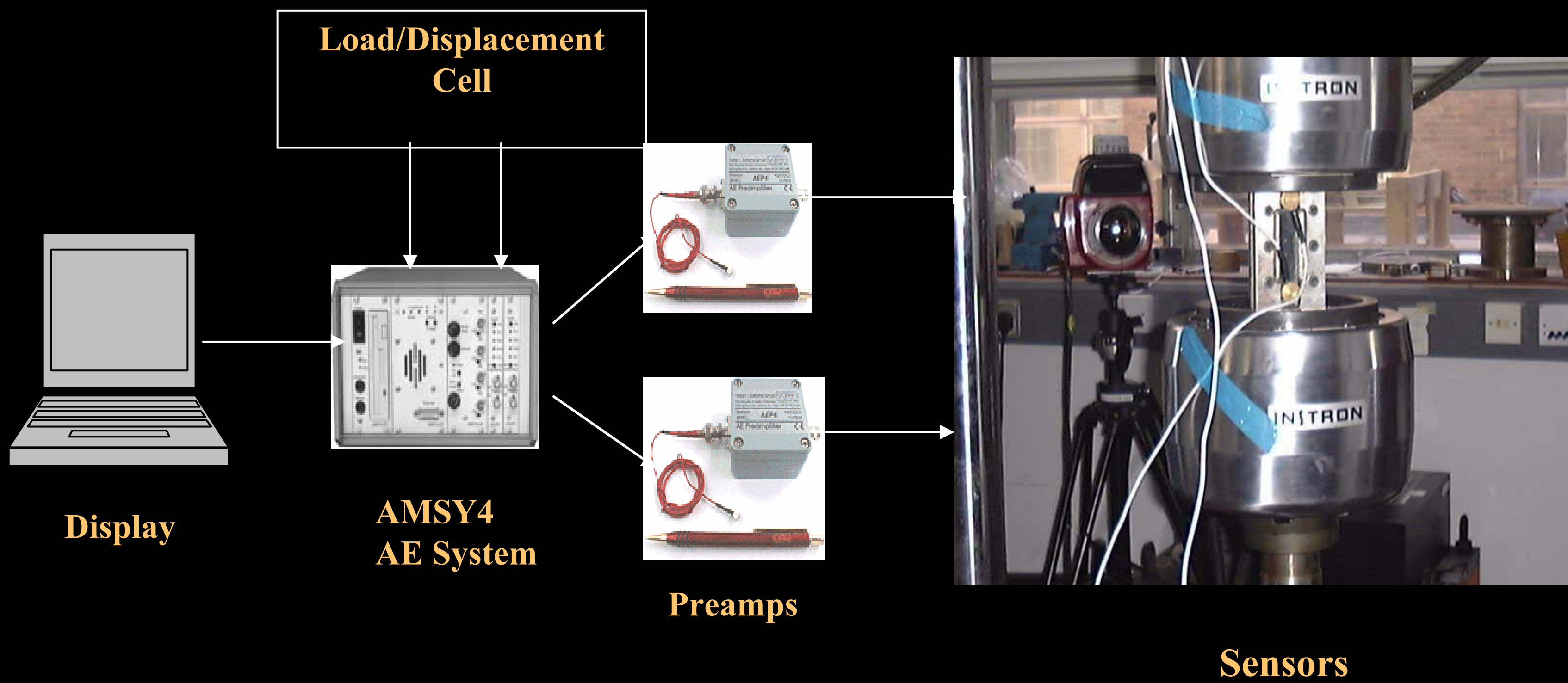
Inconsistency in Current Methods

1. Incompatibility of metal-based fatigue life prediction methods.
2. Inhomogeneity of composites leading to diverse damage mechanism.
3. inadequacy of the common stiffness/strength degradation monitoring.
4. Fatigue tests are being undertaken at high (unrepresentable) strain levels.
5. Inconclusive failure criterions.
6. Impact and static notch performance driven (damage tolerance philosophy).

What Needs to be Done?

Identify an appropriate damage monitoring method that can identify & characterise each damage event in order to understand the damage accumulation process.

Acoustic Emission Monitoring (1)



"Fatigue test set-up with AE as a damage monitoring NDT method"

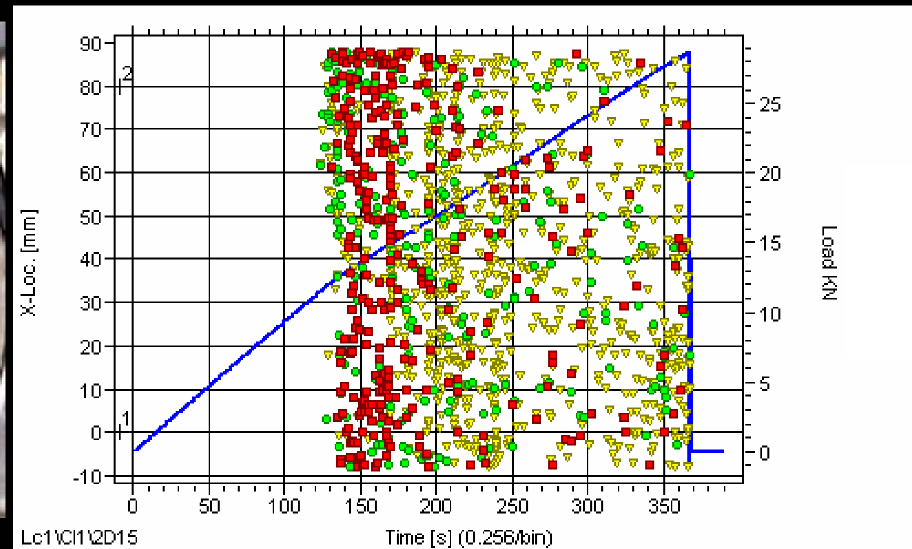
Acoustic Emission Monitoring (2)

913 CHTA - 5 - 34

$(-45_2/+45_2/90_4/0)_s$

Plain

280x30x2.42 mm

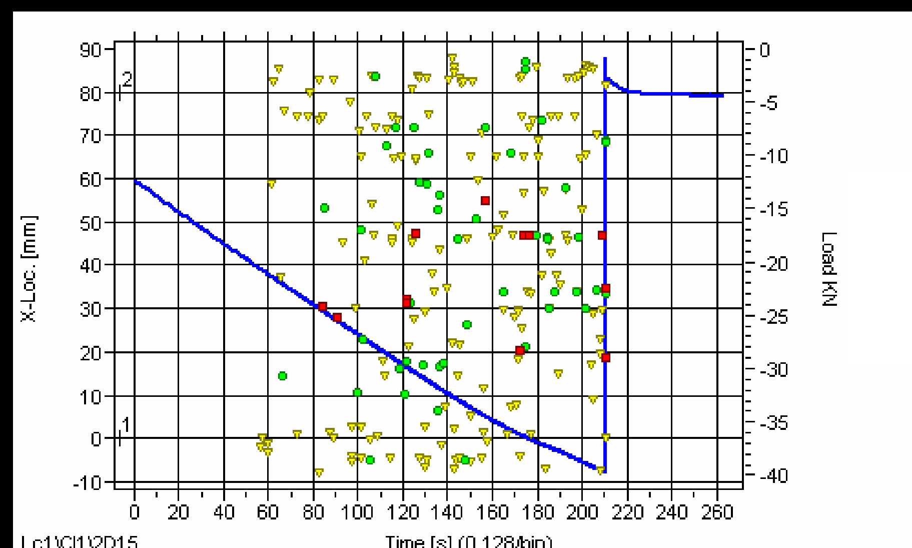


913 CHTA - 5 - 34

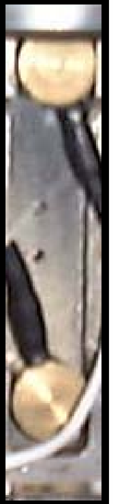
$(+45_2/-45_2/0_4/90)_s$

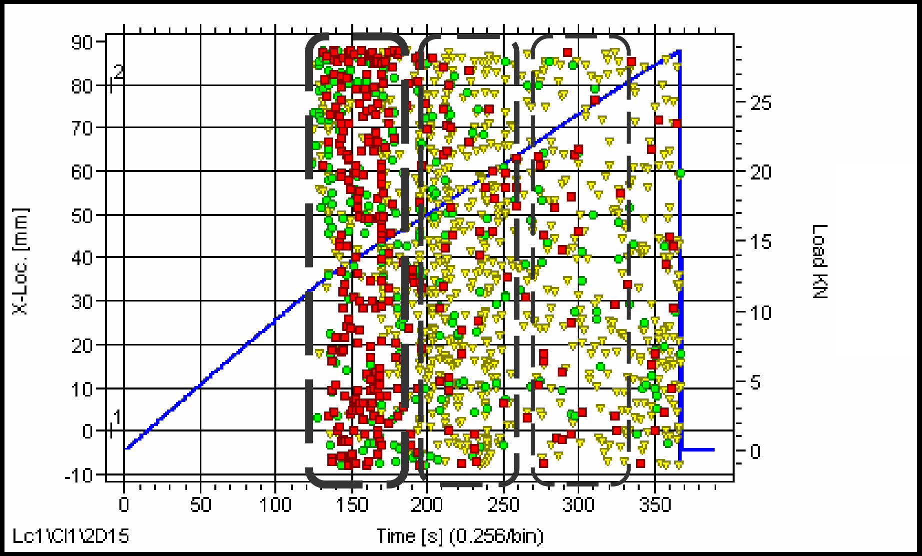
2x Φ2.5 pinholes

280x30x2.42 mm



Acoustic Emission Monitoring (2)



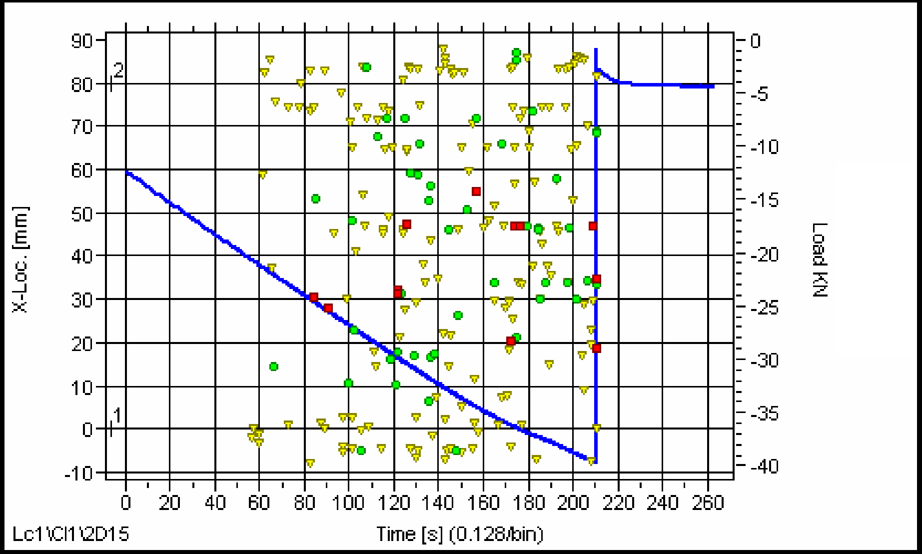


913 CHTA - 5 - 34

$(-45_2/+45_2/90_4/0)_s$

Plain

280x30x2.42



913 CHTA - 5 - 34

$(+45_2/-45_2/0_4/90)_s$

2x Φ2.5 pinholes

280x30x2.42

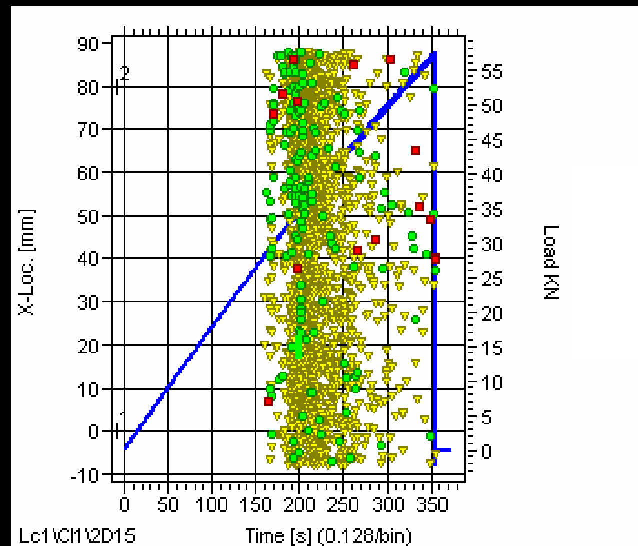
Acoustic Emission Monitoring (3)

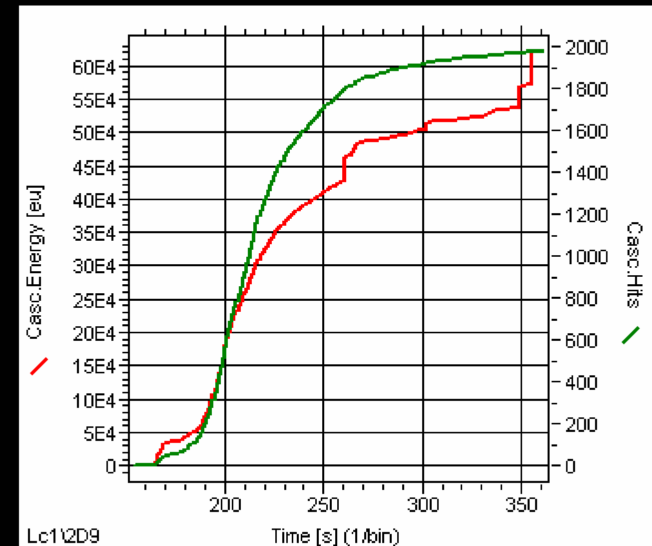
913 CHTA - 5 - 34

$(+45_2/-45_2/0_4/90)_s$

2x Φ2.5 pinholes

280x30x2.42 mm





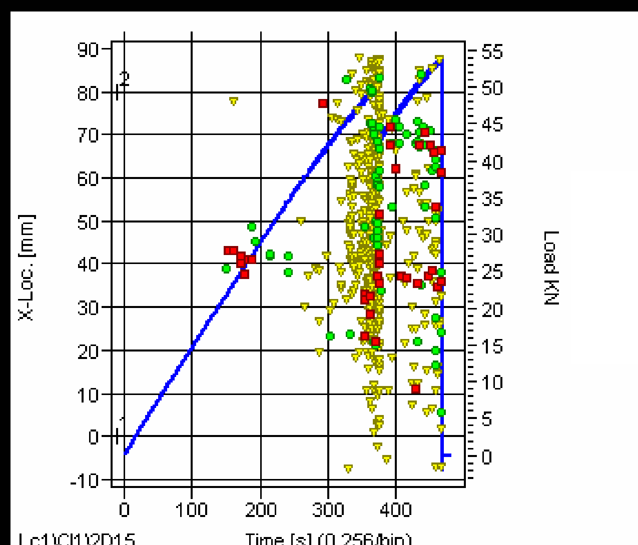
Various forms of damage for various lay-ups

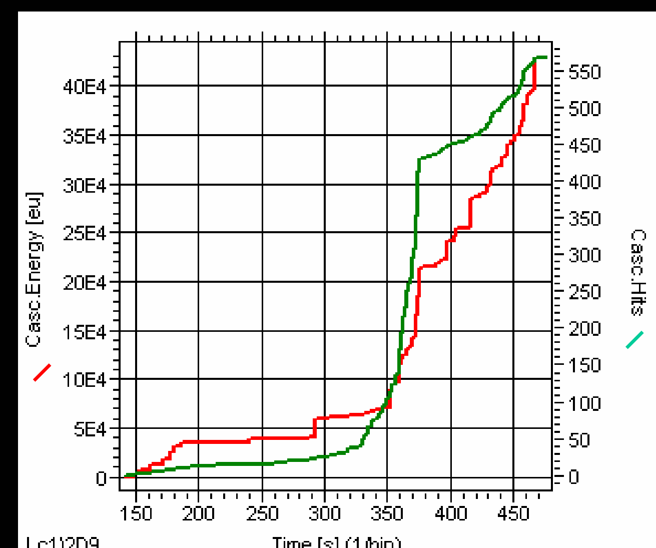
MAT806E & MAT802E RTM6 resin - 55

$(+45/0_4/-45)$

Ply drop-off

280x30x1.98 mm



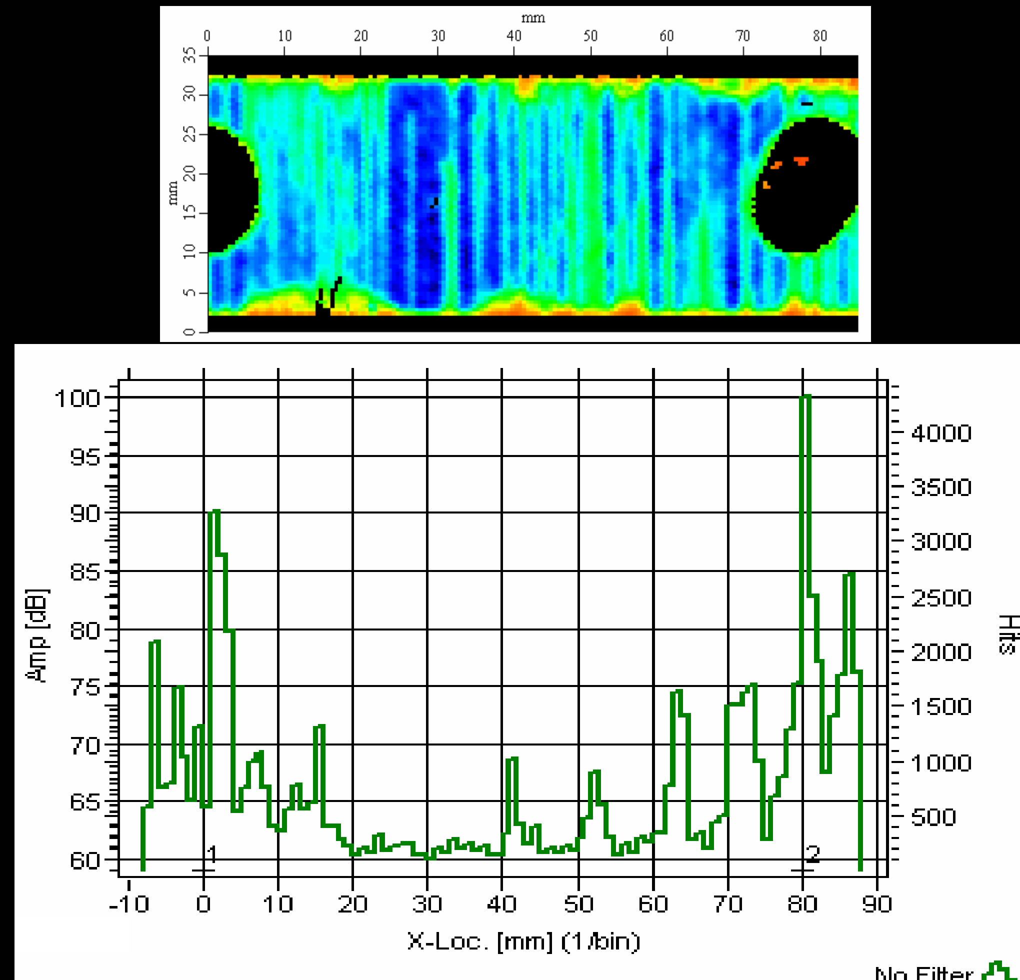


Correlation With C-scanning (1)

Specimen AWHLC8 was subjected to constant amplitude tensile fatigue loading at 37% UTS & R=0.1

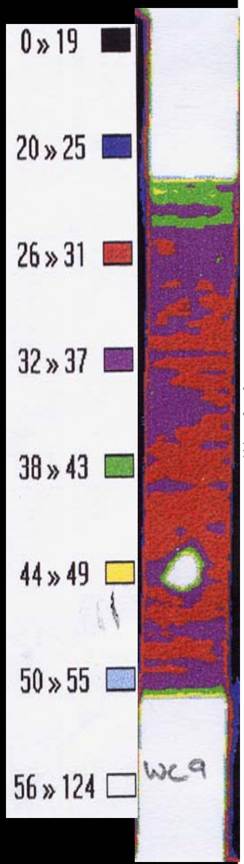
- Blue colour in C-scan picture indicates undamaged area while green colour shows damaged areas mainly along the 90 layers.

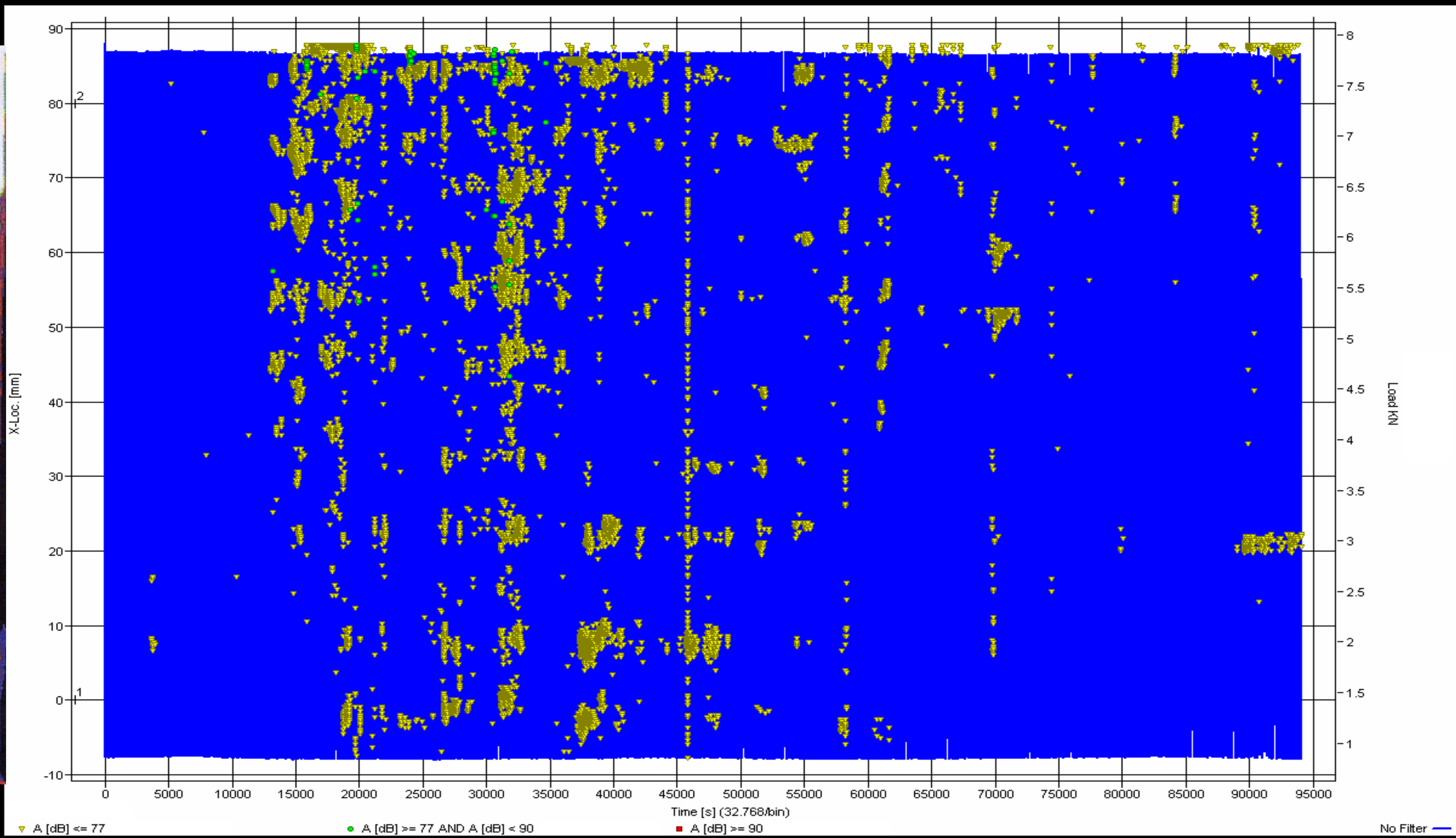
- Both graphs show a consistent pattern of damaged/undamaged zones.



“Comparison between C-scan and AE data”

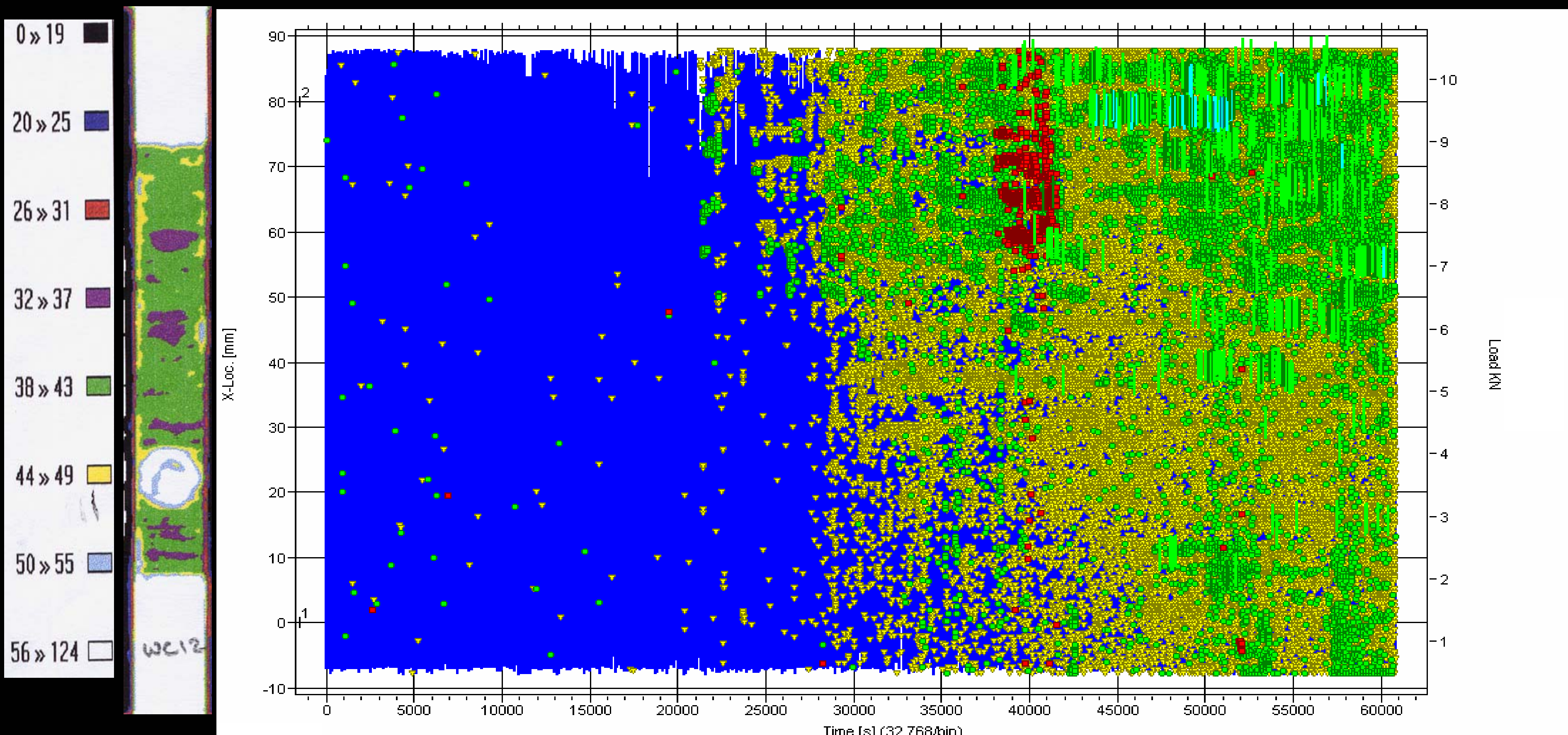
Correlation With C-scanning (2)





"Specimen AWHLC9 was subjected to constant amplitude fatigue test at 28% UTS for just over 370000 cycles"

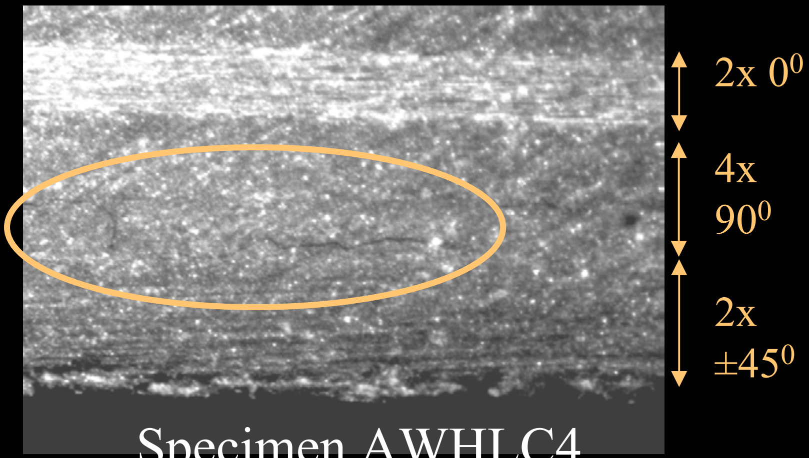
Correlation With C-scanning (3)



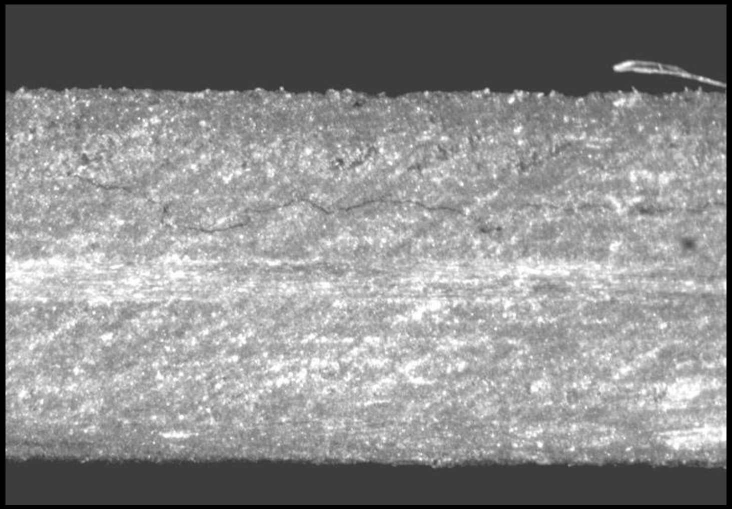
"Specimen AWHLC12 was subjected to Hi-mix two block fatigue loading at high block stress of 37.5% UTS for just over 300 000 cycles"

Correlation with Microscopic Pictures

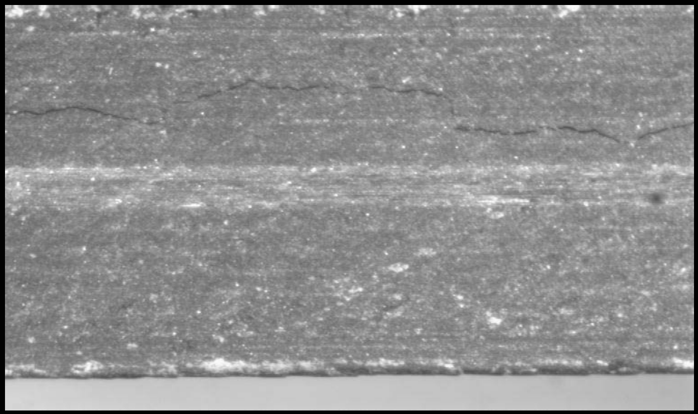
Cracks are mainly found along the 90^0 layers in the form of matrix damage leading to delamination and crack bridging across the 90^0 layers.



Specimen AWHLC4



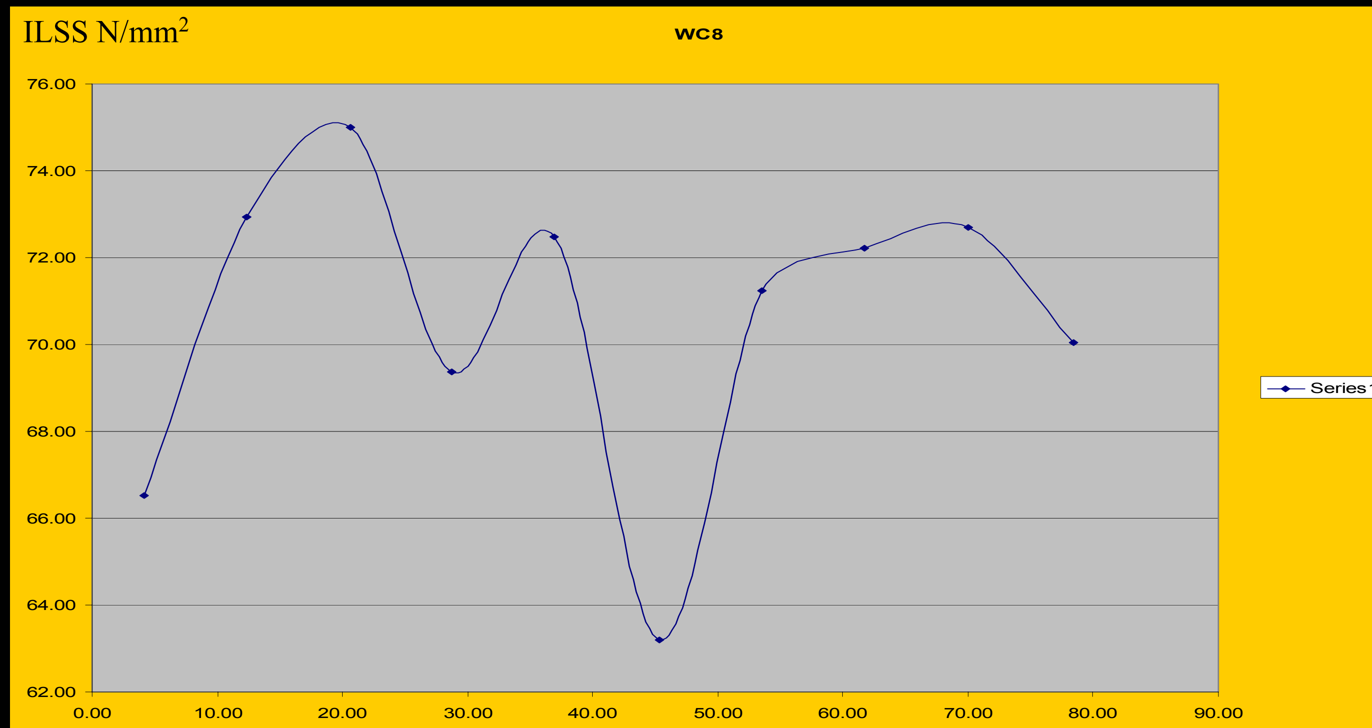
Specimen AWHLB12



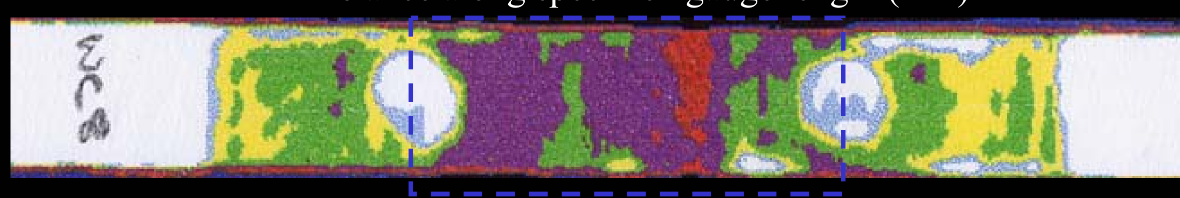
Specimen AWHLB6

Correlation with Short Beam Shear Tests

Variation in ILSS along the specimen indicating weakened zones on the specimen that could have been the result of fatigue damage.



Distance along specimen gauge length (mm)



Stiffness Degradation Monitoring

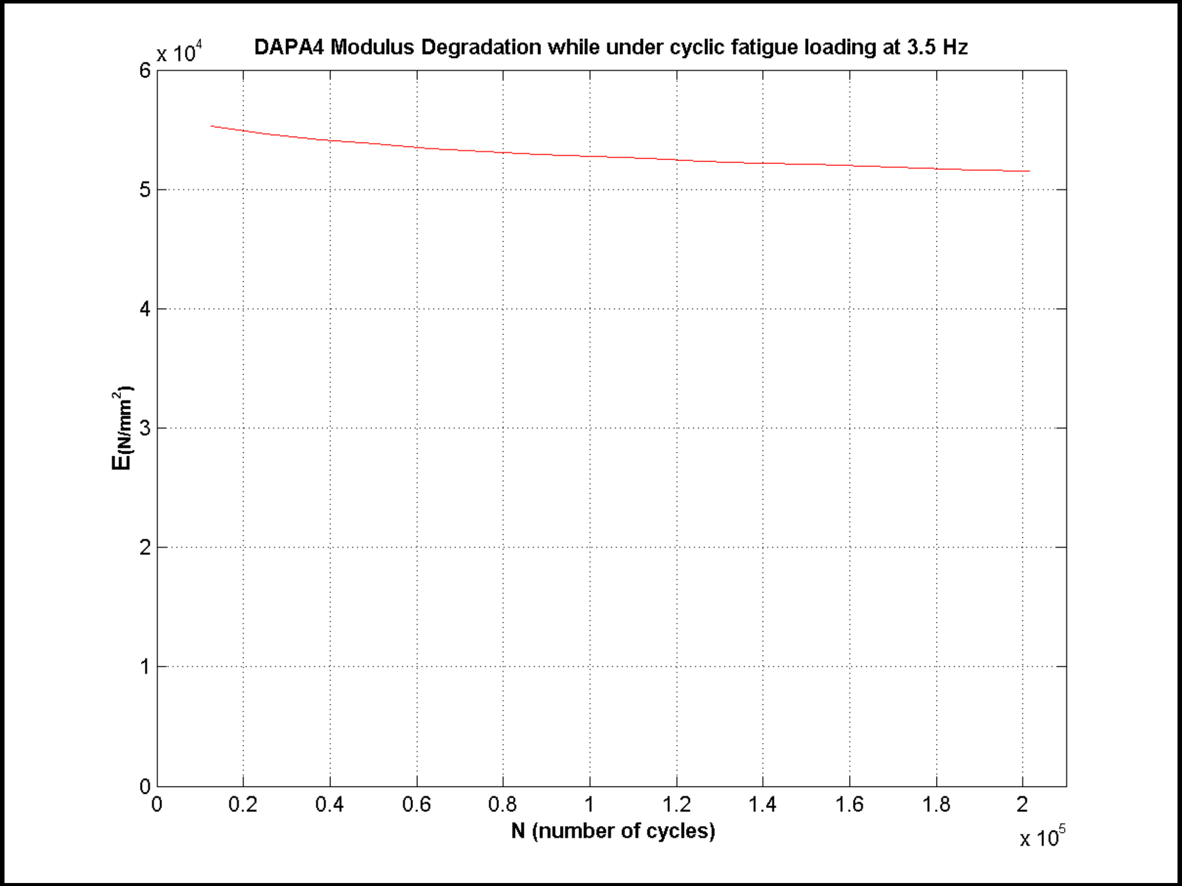
MAT806E & MAT802E RTM6 resin - 55

(+45/0$_4$/-45)

2x Φ2 pinholes

280x30x2.0 mm

- Data used for this method can only be recorded at intervals.
- Difficult to determine changes in damage state.



Modulus Degradation in tension sense of woven material specimen (+45,0$_4$,-45) subjected to2-block loading T-T C-C

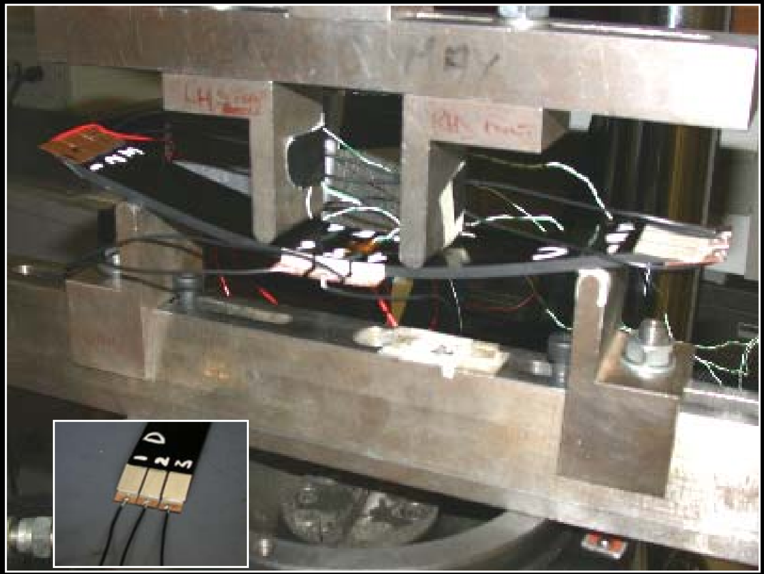
Potential Difference Monitoring

913 CHTA - 5 - 34

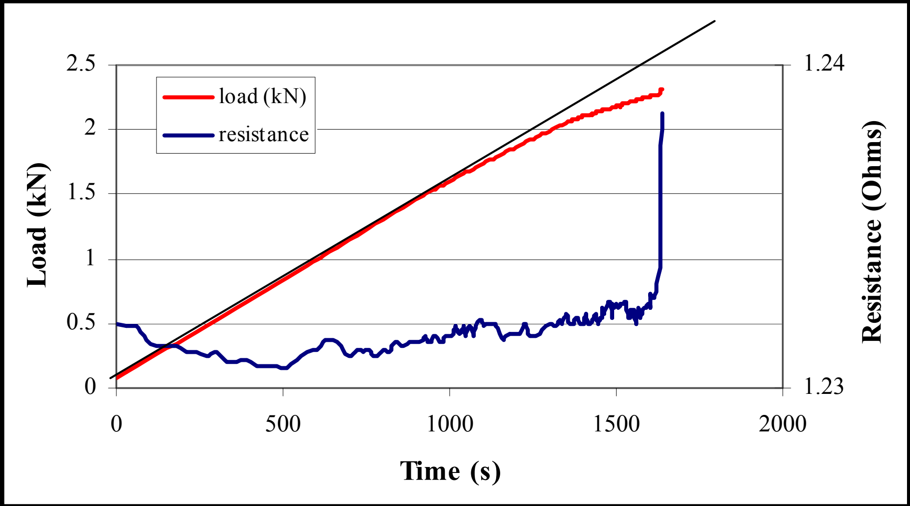
$(-45_2/+45_2/90_4/0)_s$

Plain

280x30x2.42 mm



- Method requires further data gathering and processing development.
- Not suitable for fatigue life prediction analysis.



Thermal Monitoring using DeltaTherm

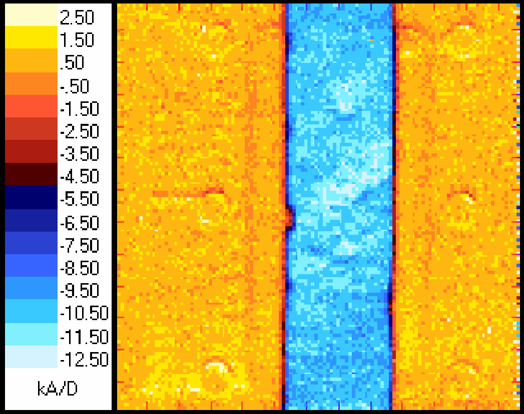
AWHLC12: 913 CHTA - 5 - 34

$(-45_2/+45_2/90_4/0)_s$

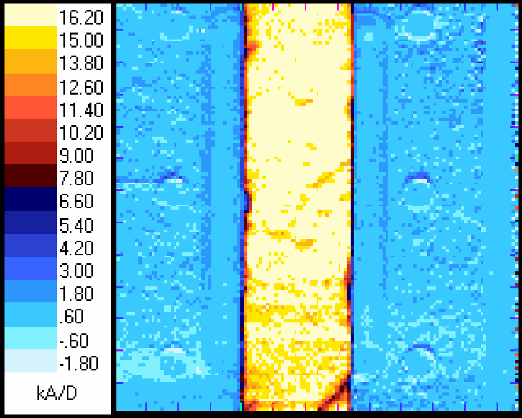
Plain

280x30x2.42 mm

Start of Test



At onset of damage as indicated by AE



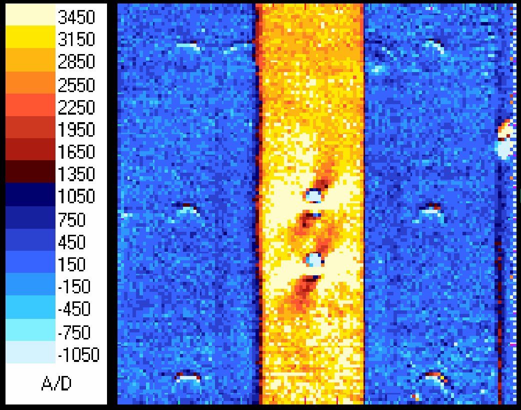
AWHLC19: 913 CHTA - 5 - 34

$(+45_2/-45_2/0_4/90)_s$

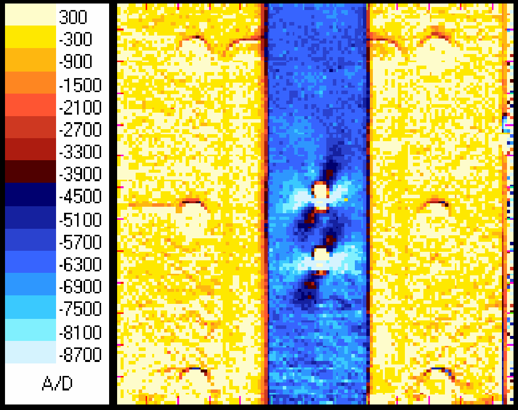
2x Φ2.5 pinholes

280x30x2.42 mm

2000 cycles



843000 cycles



- Method is suitable as a quick indication of specimen state.

Thermal Monitoring using Standard Thermal Camera

913 CHTA - 5 - 34

$(-45_2/+45_2/90_4/0)_s$

Plain

280x30x2.42 mm

- Method unable to reveal existing damage.
- Can only be used at intervals.

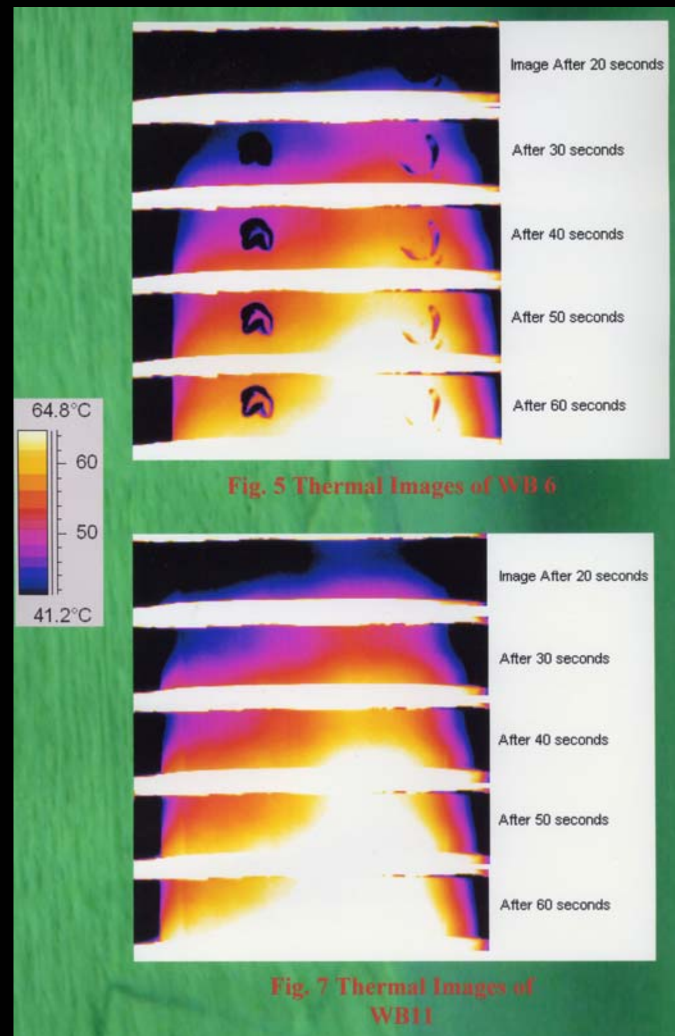
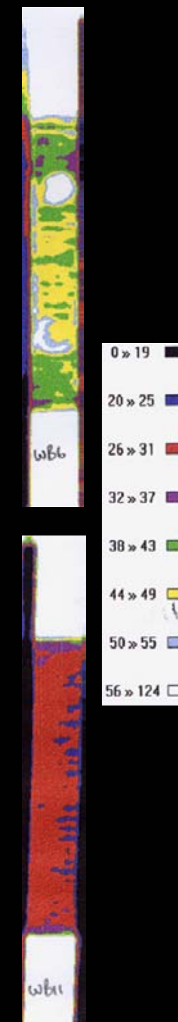
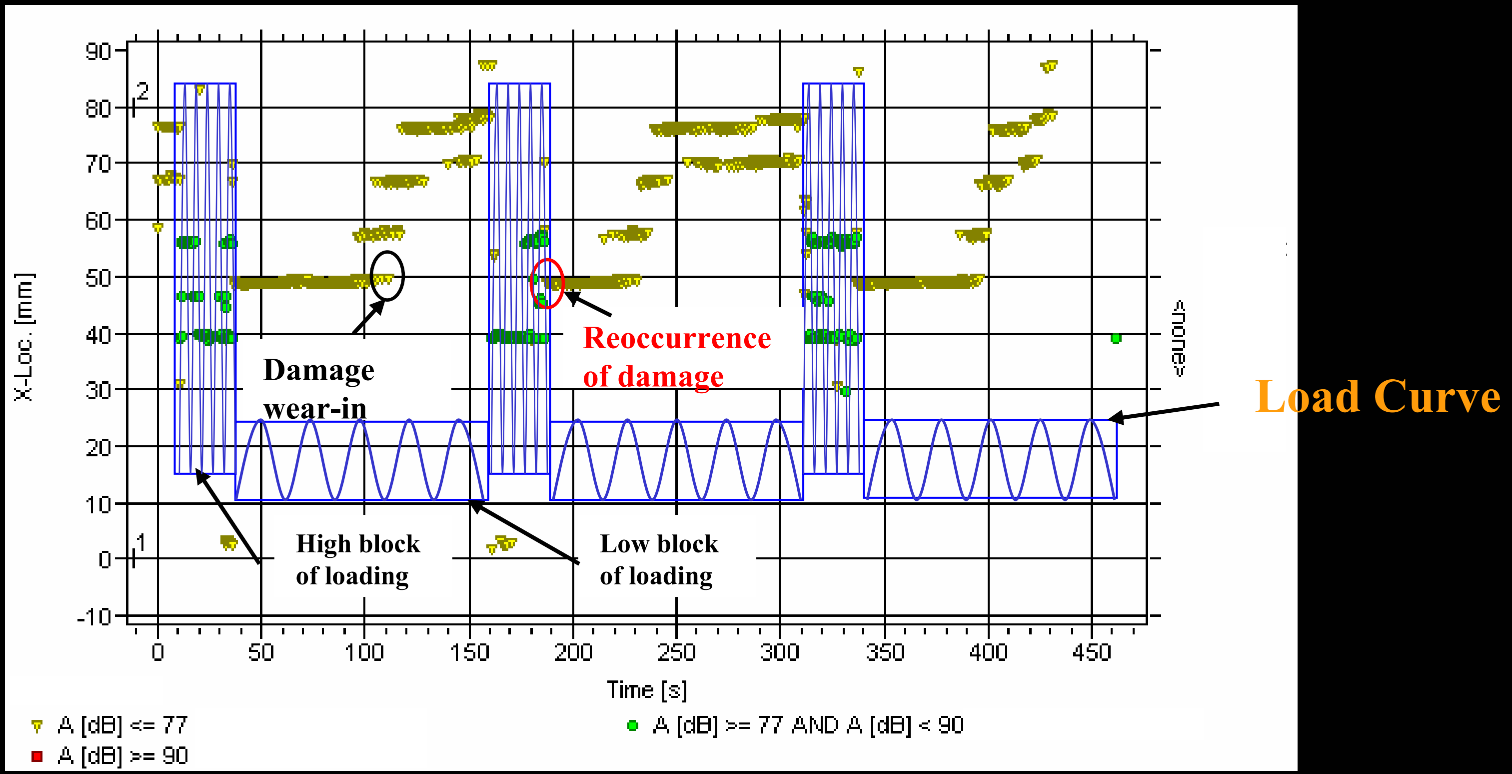


Fig. 5 Thermal Images of WB 6

Fig. 7 Thermal Images of WB11



AE capability in cycle by cycle monitoring

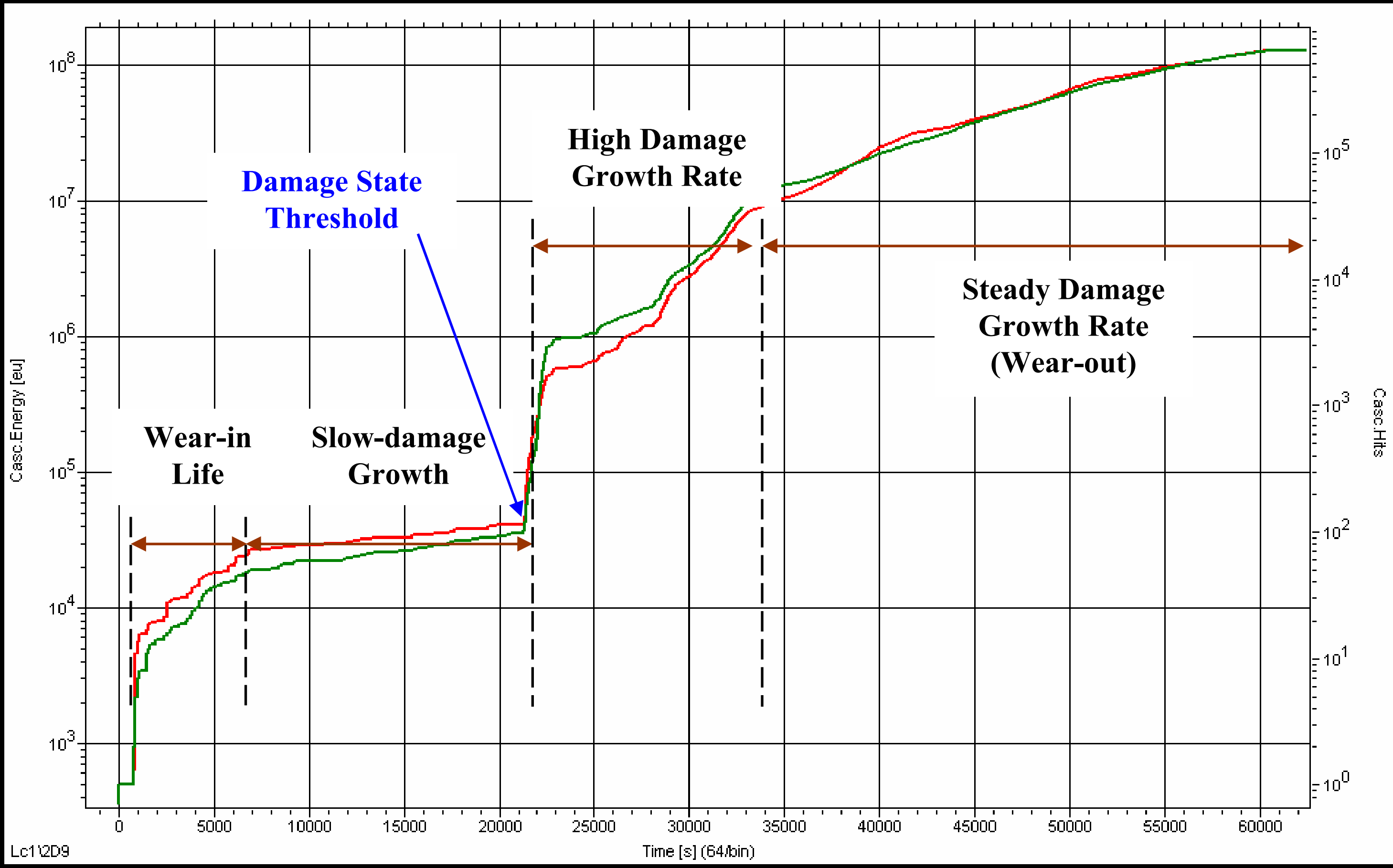


"Specimen AWHLB8; damage is found to be influenced by previous loading conditions, invalidating the use of Palmgren-Miner's rule"

Damage Accumulation as revealed by AE

Four Stages:

1. Wear-in
2. Slow damage growth rate
3. High damage growth rate
4. Steady damage growth rate



"Damage accumulation as indicated by cumulative AE energy (red) and number of AE hits (green)"

Conclusion

Acoustic emission technique is found to be a better technique because of the following benefits:

- Actual damage event identification.
- Discrimination of damage modes.
- Location of damage.
- Detection of meaningful failure states.
- Testing at realistic stress levels.
- Multiple gauge length zoning in specimens.
- Application on real components.

Acknowledgment

- **Dowty aerospace propellers (smiths).**
- **Agusta-Westland helicopters.**
- **U.K. Engineering and physical sciences research council (EPSRC).**
- **Vallen-Systeme GmbH.**