

# Cyclic fatigue behavior of woven hemp/epoxy composite: Damage analysis

**Davi S. de Vasconcellos**, F. Touchard, L. Chocinski-Arnault

[davi.vasconcellos@ensma.fr](mailto:davi.vasconcellos@ensma.fr)

# OVERVIEW

- Material and testing methods
- Results and discussion
  - Fatigue behavior
  - Damage analysis
    - Damage evolution
    - Acoustic Emission
    - CT scan and thermal field
- Conclusions and Further Work

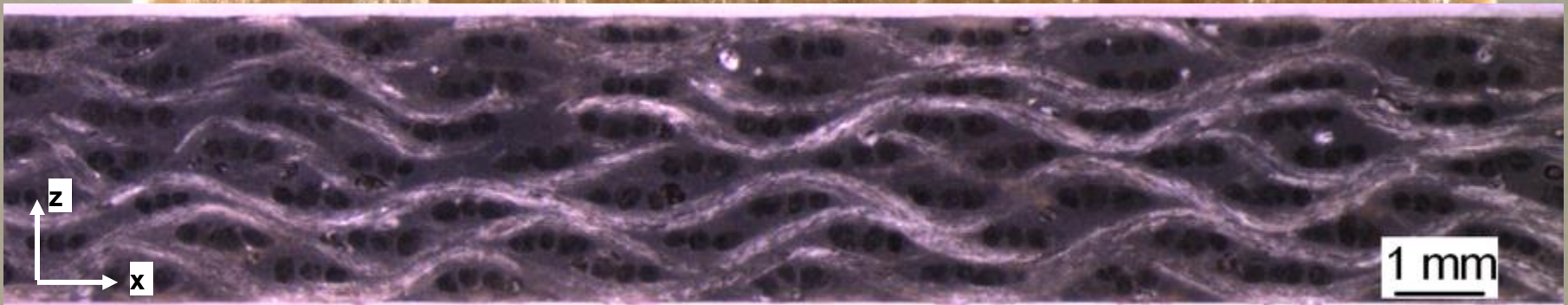
# Tested material

Composite:

- 7 layers of **plain weave fabric hemp**
- **epoxy** resin

fiber volume fraction =  **$38 \pm 5\%$**

Fabric weight =  $267 \text{ g/m}^2$   
Density =  $1.2 \text{ g/cm}^3$   
 $T_g = 100^\circ \text{ C}$



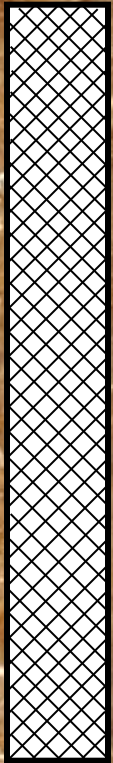
ECCM 15 - Cyclic fatigue behavior of woven hemp/epoxy composite: Damage analysis

# Tested specimens

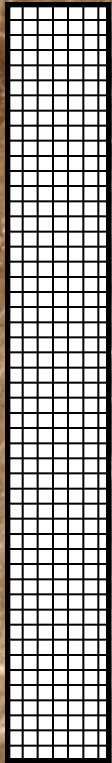


Two orientations related to the tensile axis:  $[0^\circ/90^\circ]_7$  and  $[\pm 45^\circ]_7$

Dimensions:  $150 \times 20 \times 3 \text{ mm}^3$



$[\pm 45^\circ]_7$



$[0^\circ/90^\circ]_7$

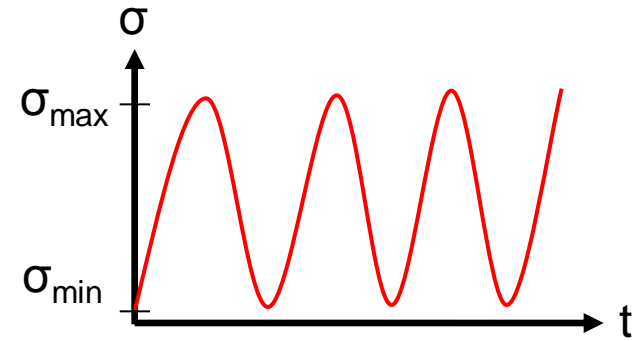
1 mm

# Testing methods

## Cyclic Fatigue

Frequency = 1 Hz

$R (\sigma_{\min}/\sigma_{\max}) = 0.01$

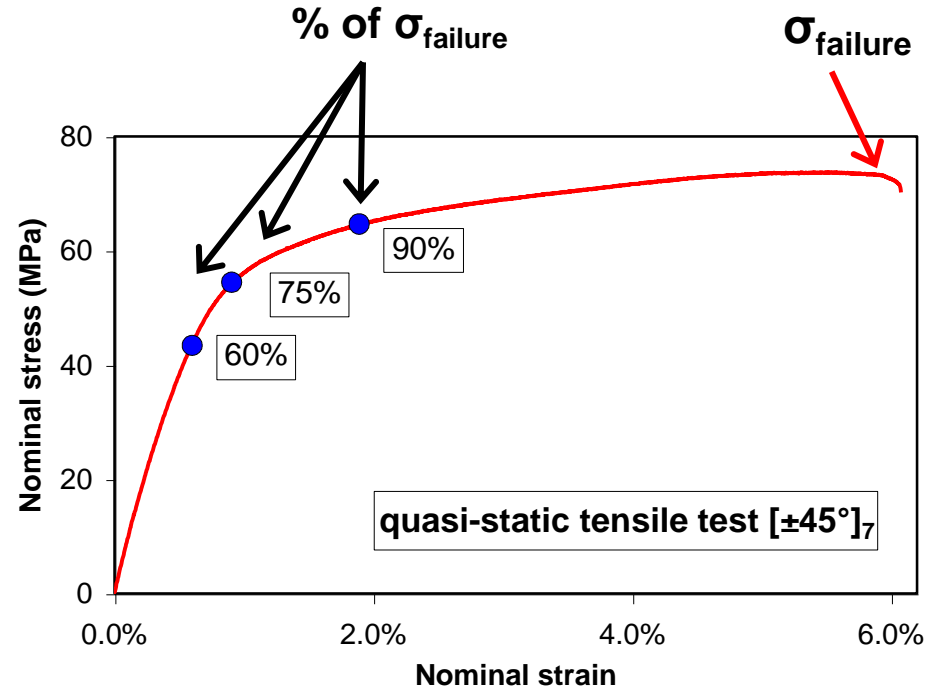
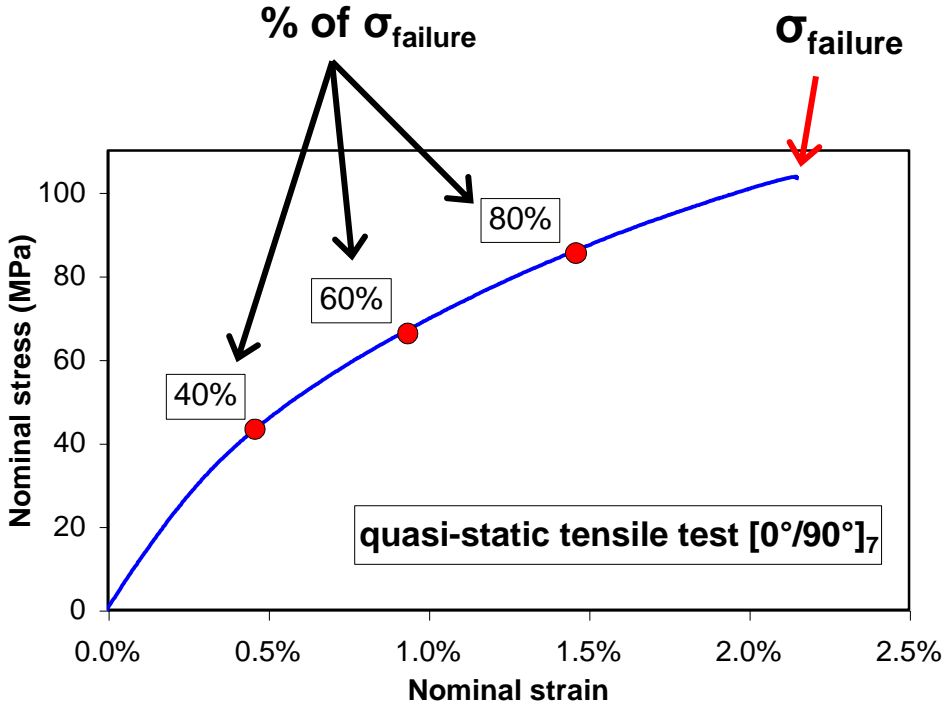
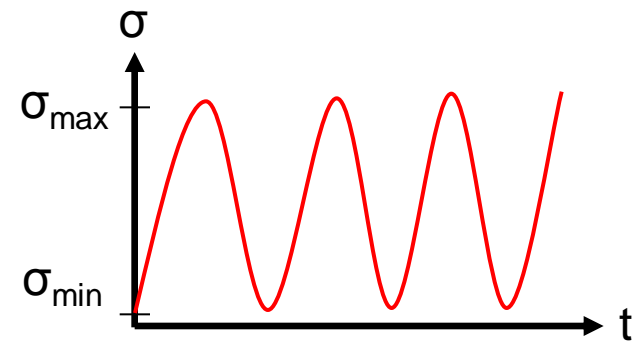


# Testing methods

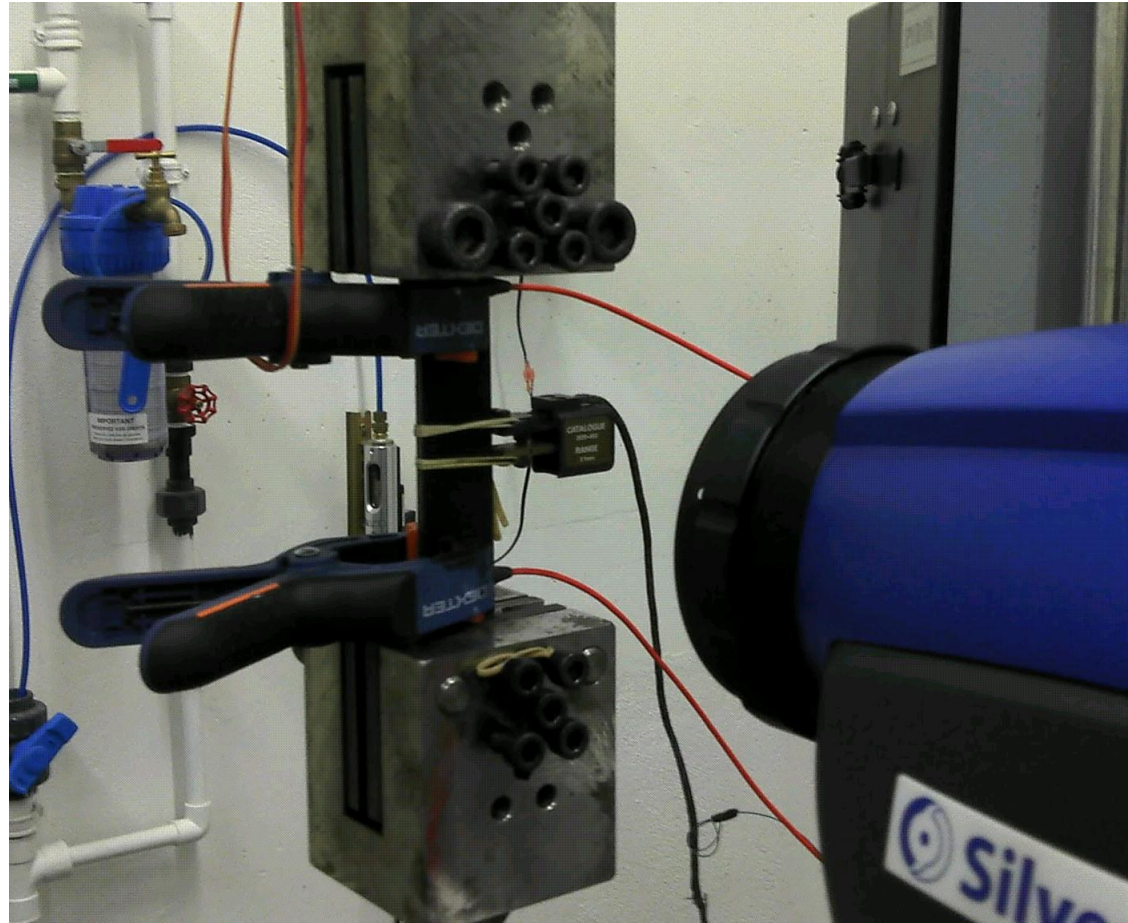
## Cyclic Fatigue

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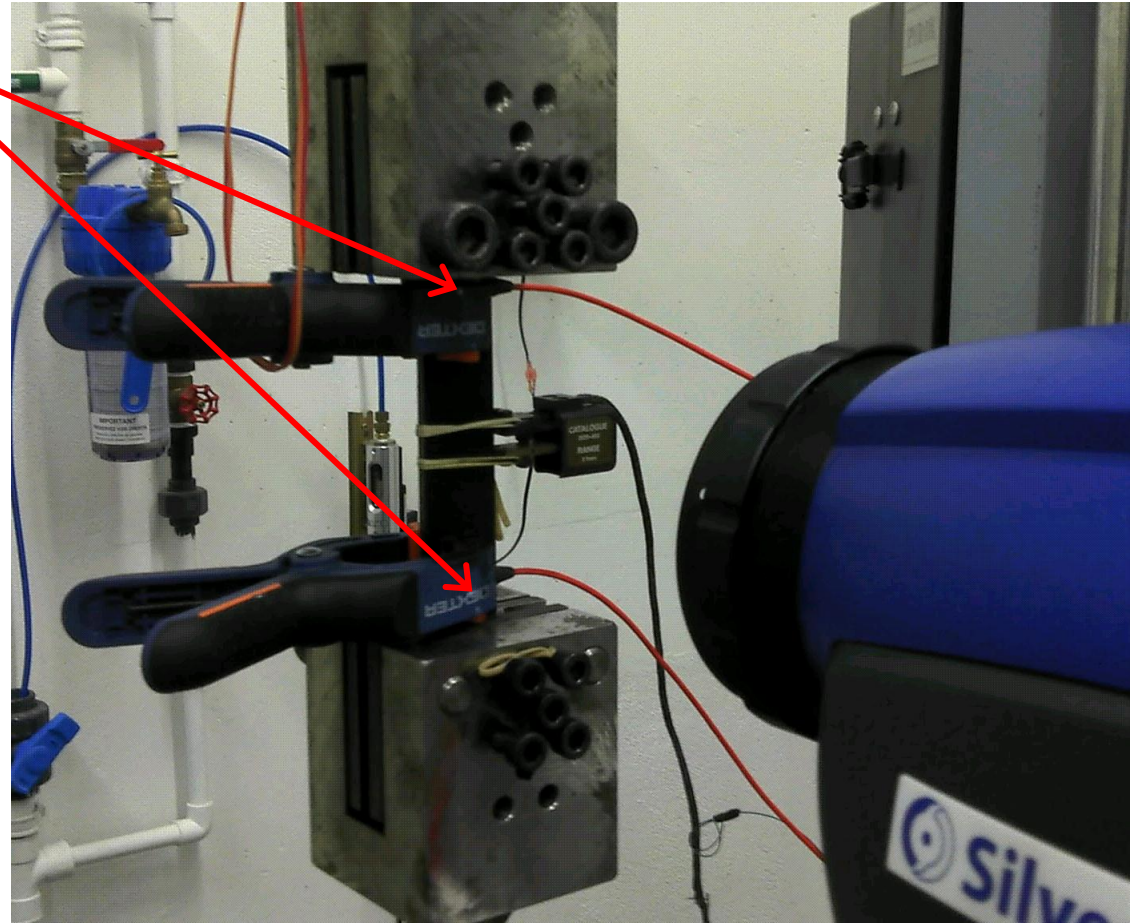
# Testing measurements



# Testing measurements

## 1) Acoustic Emission (AE)

- Physical Acoustics SA
- 80 mm distance between sensors





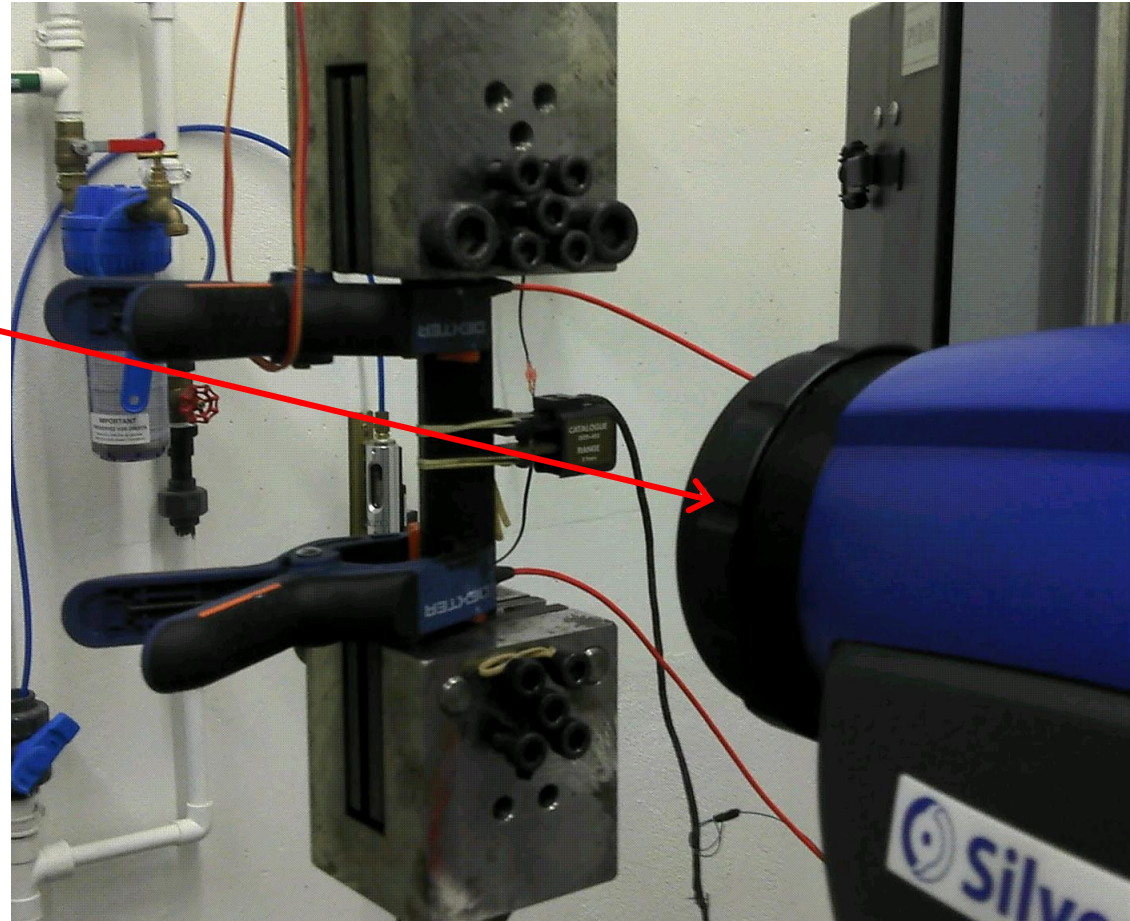
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## 1) Acoustic Emission (AE)

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## 2) Thermal field

- Infrared camera



# Testing measurements

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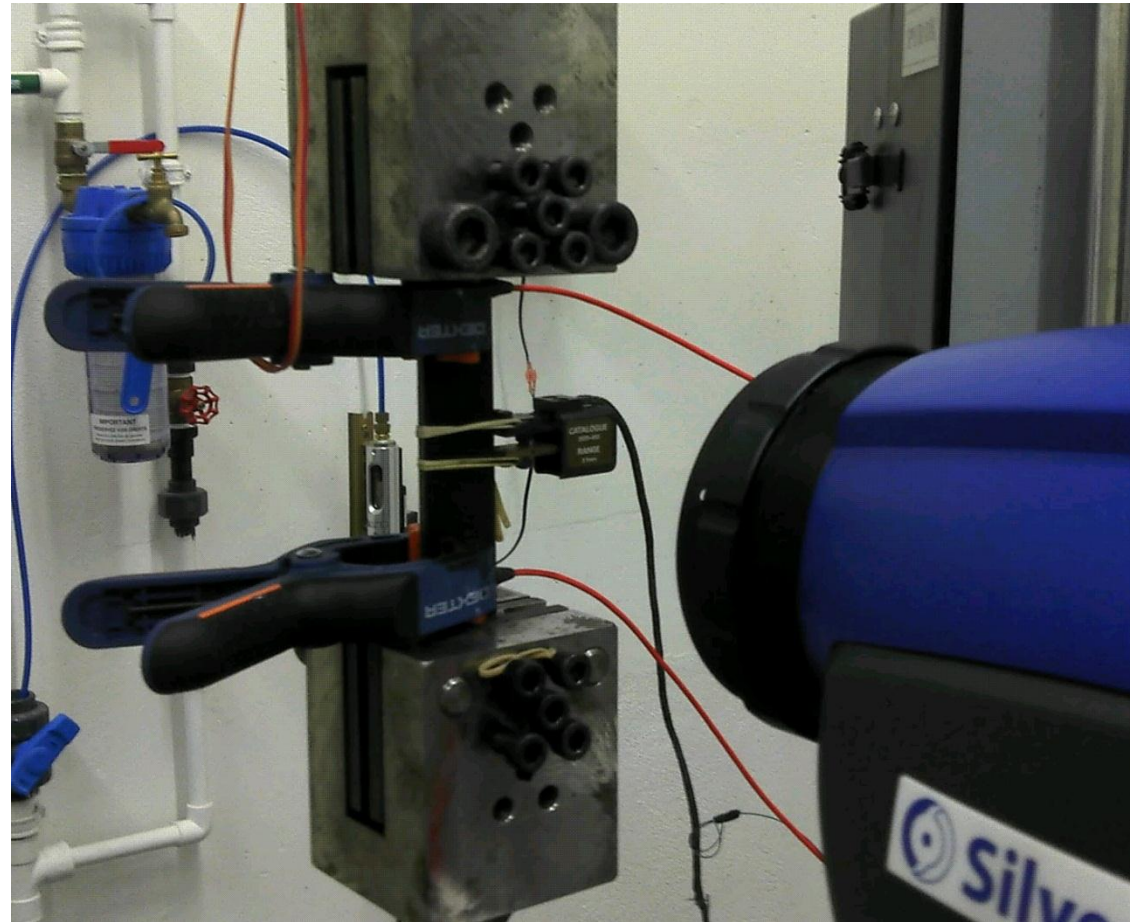
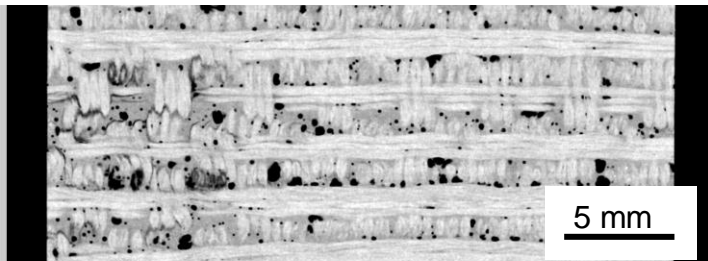
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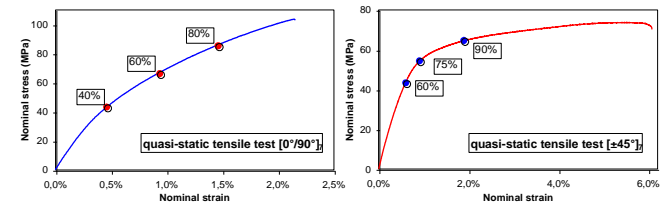
## 3) X-ray 3D CT-scan

- Jean Lamour Institute at Ecole des Mines de Nancy, France.
- **20x20 mm<sup>2</sup> zone near the failure.**
- resolution of 14.8  $\mu\text{m}/\text{pixel}$

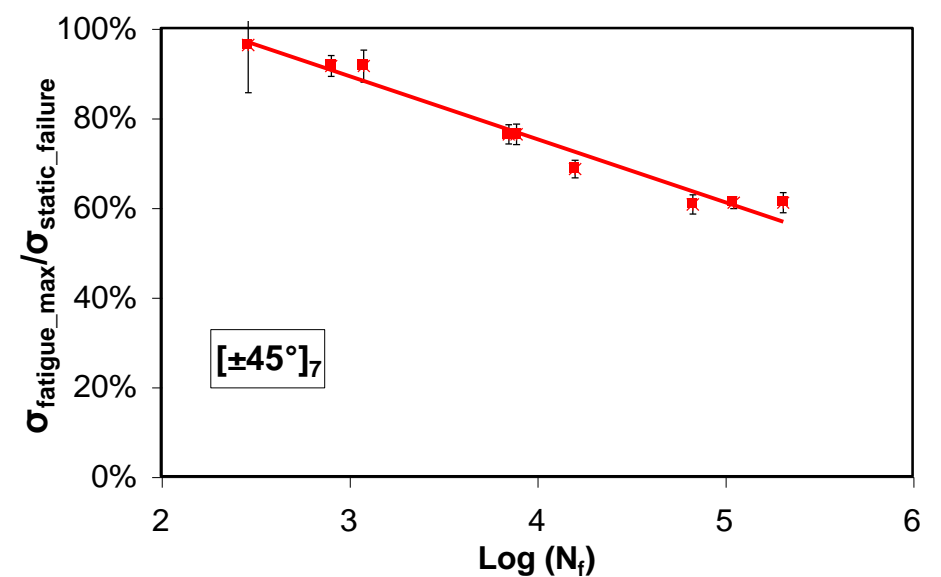
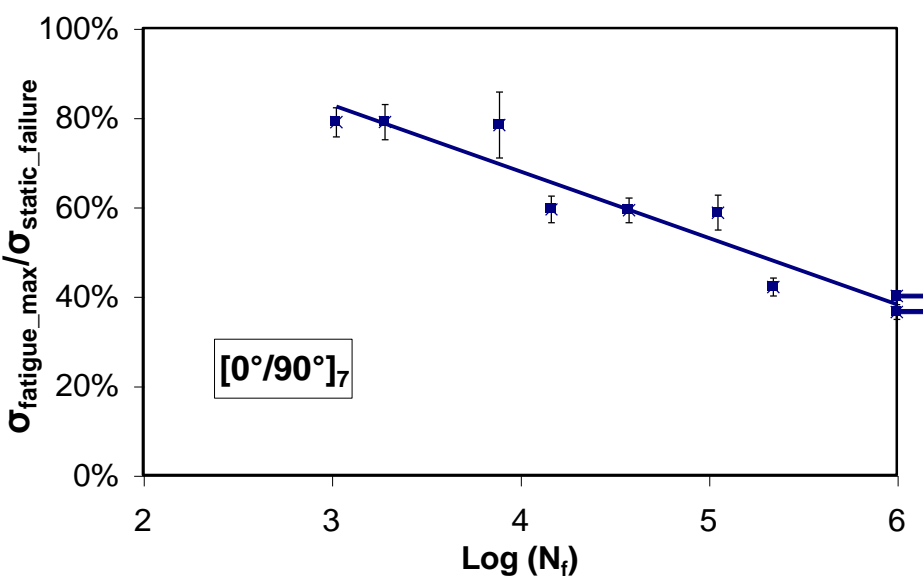


# Results – Fatigue behavior

## S-N Curves

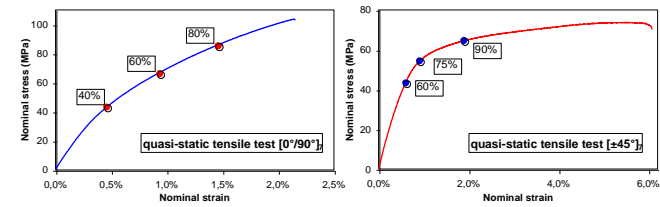


\* Sigma ratio is used to take into account tensile strength variations between different composite plates

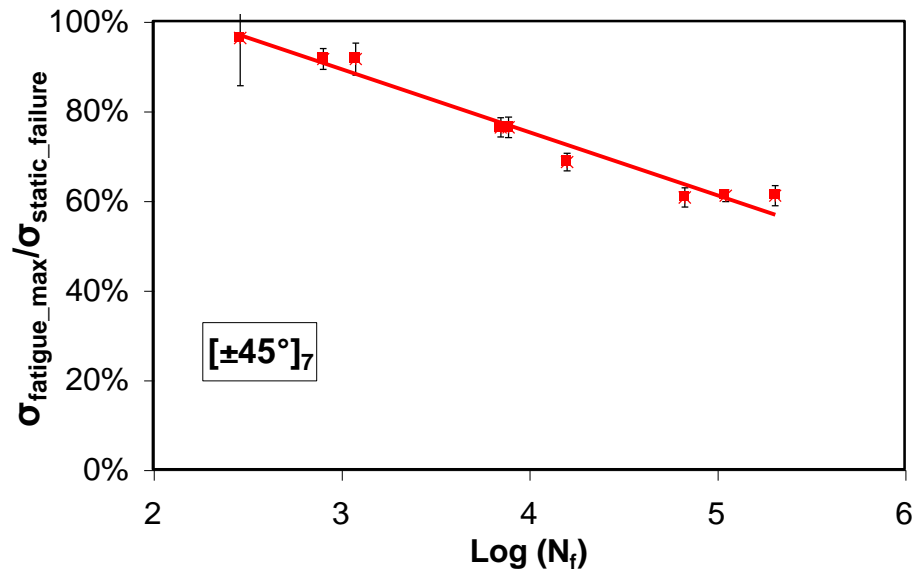
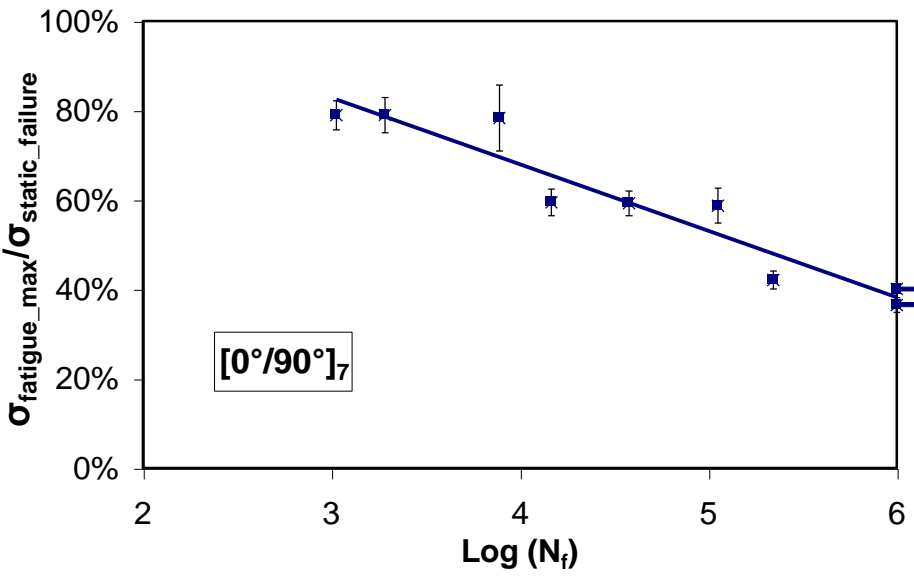


# Results – Fatigue behavior

## S-N Curves



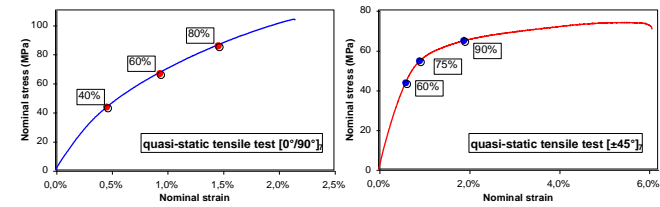
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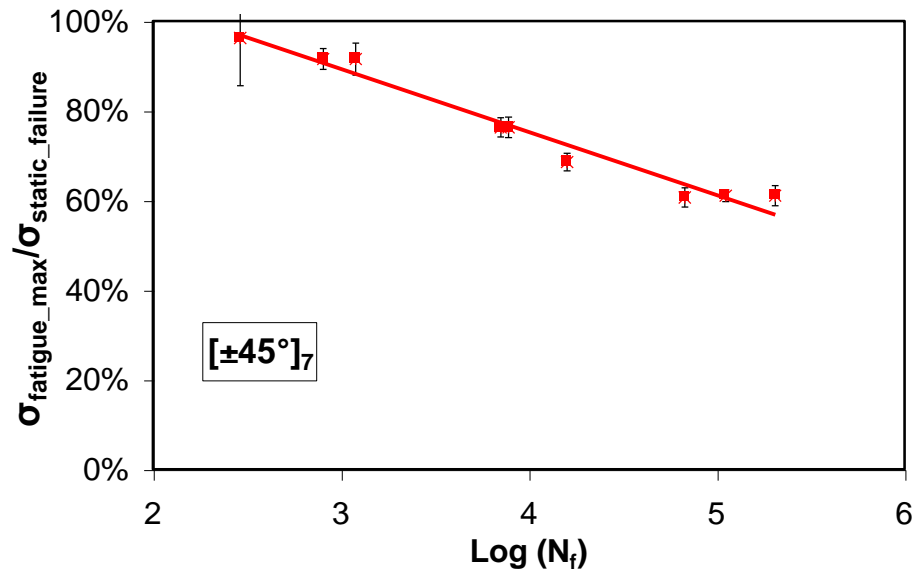
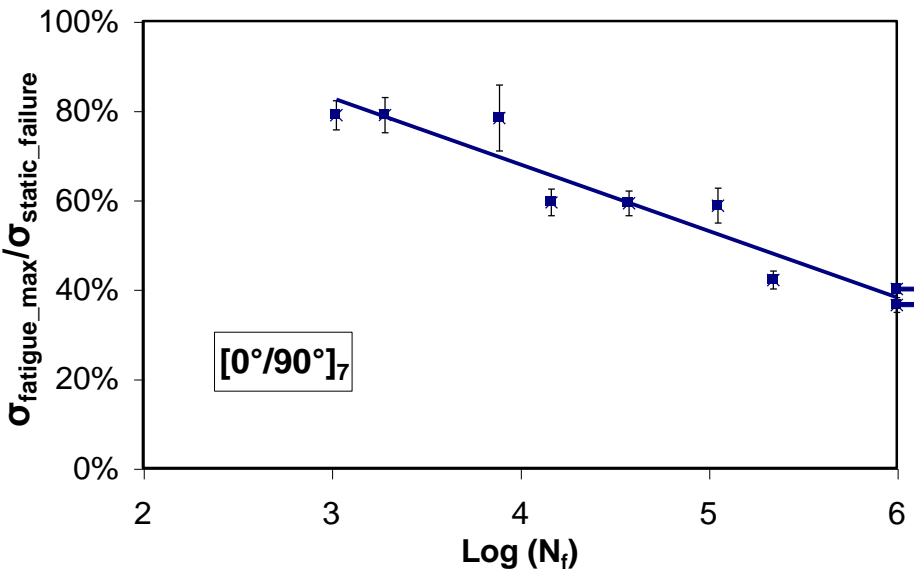
➔ Higher dispersion for  $[0^\circ/90^\circ]_7$  ➔ Yarns (natural aspect) on tensile direction

# Results – Fatigue behavior

## S-N Curves



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➔ Higher dispersion for [0°/90°]<sub>7</sub> ➔ Yarns (natural aspect) on tensile direction

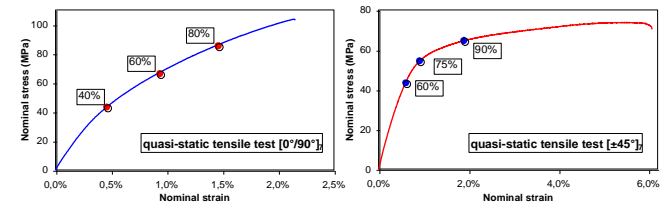
➔ Adapted Wöhler model in accordance with experimental points:

$$\text{Log}(N_f) = A - B \frac{\sigma_{\text{fatigue\_max}}}{\sigma_{\text{static\_failure}}}$$



# Results – Damage analysis

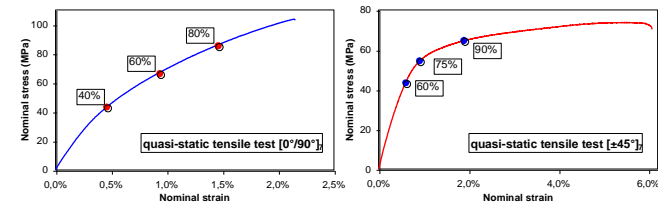
## Damage evolution



Three parameters:

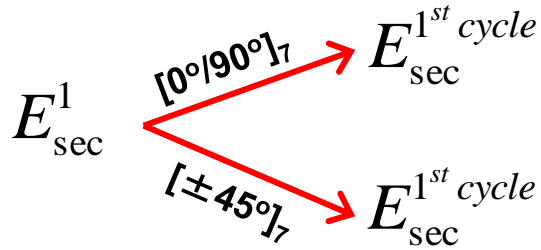
# Results – Damage analysis

## Damage evolution



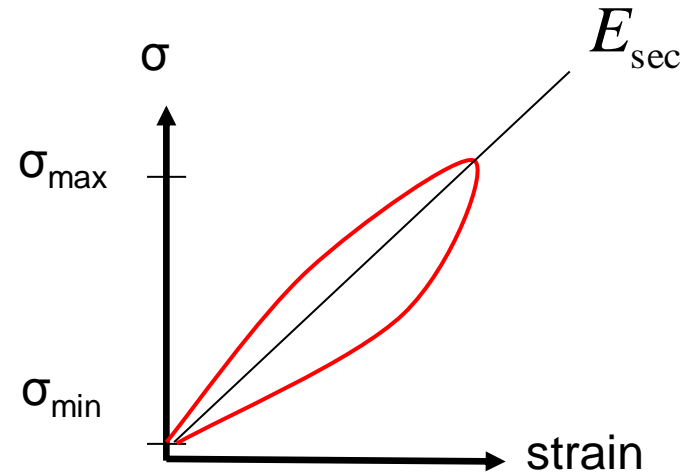
Three parameters:

1)  $E_{\text{sec}} / E_{\text{sec}}^1$



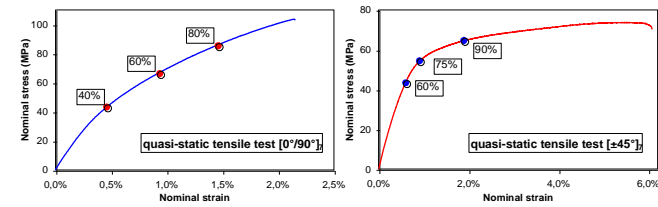
for  $\sigma_{\text{max}} = 40\% \sigma_{\text{static\_failure}}$

for  $\sigma_{\text{max}} = 60\% \sigma_{\text{static\_failure}}$



# Results – Damage analysis

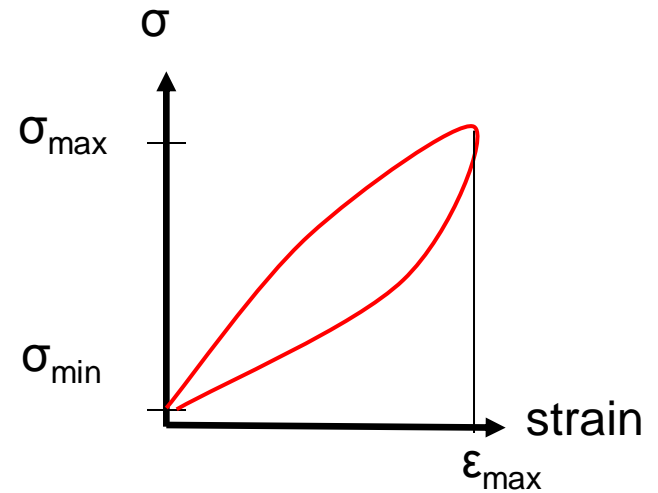
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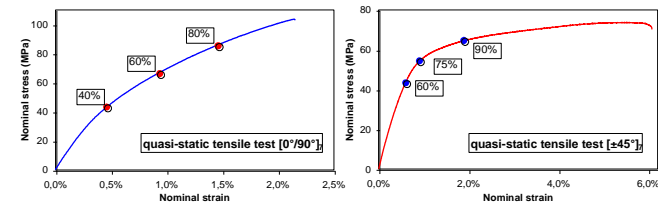
2)  $\epsilon_{\text{max}}$





# Results – Damage analysis

## Damage evolution

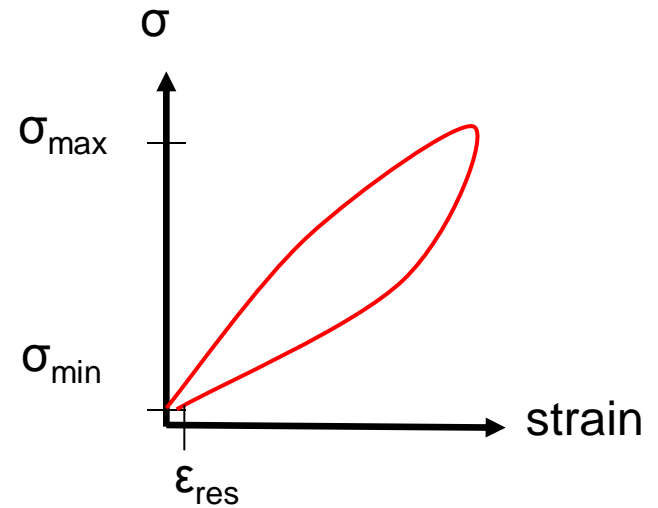


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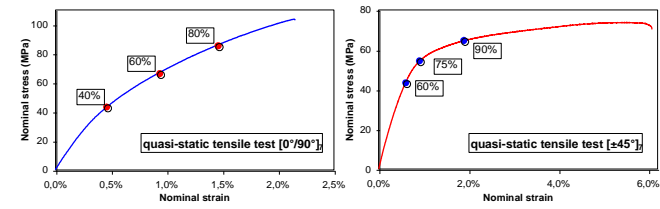
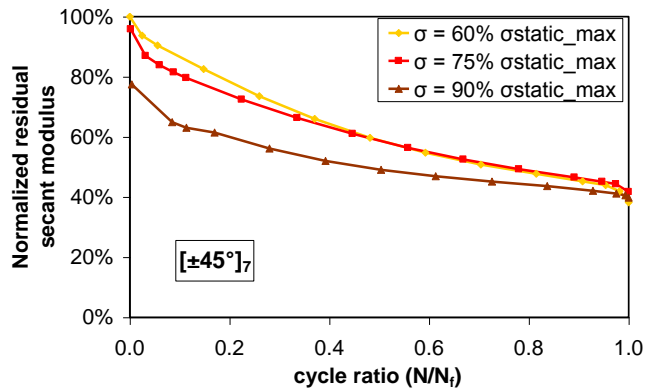
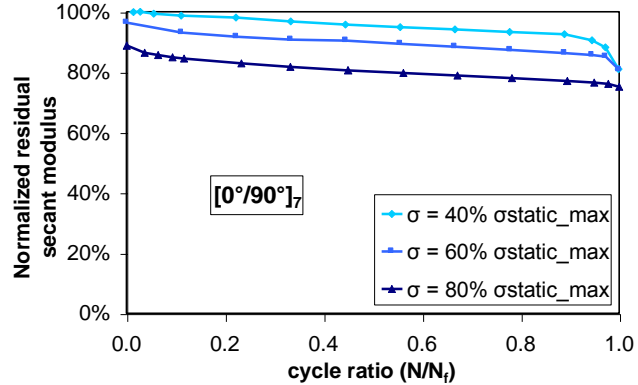
3)  $\epsilon_{\text{res}}$



# Results – Damage analysis

## Damage evolution

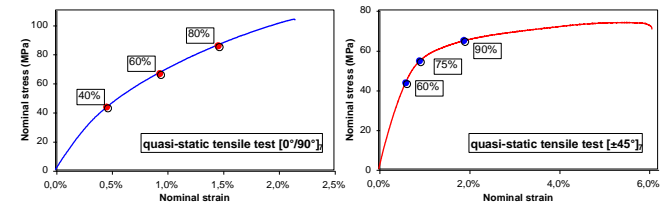
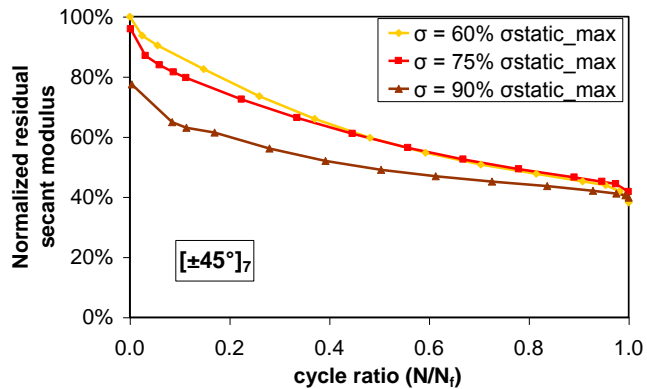
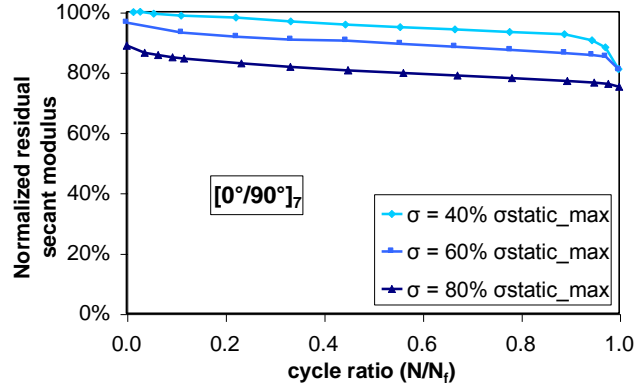
$$E_{\text{sec}} / E_{\text{sec}}^1$$



# Results – Damage analysis

## Damage evolution

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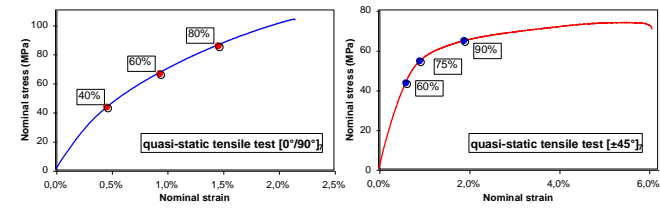


Influence of higher stress levels

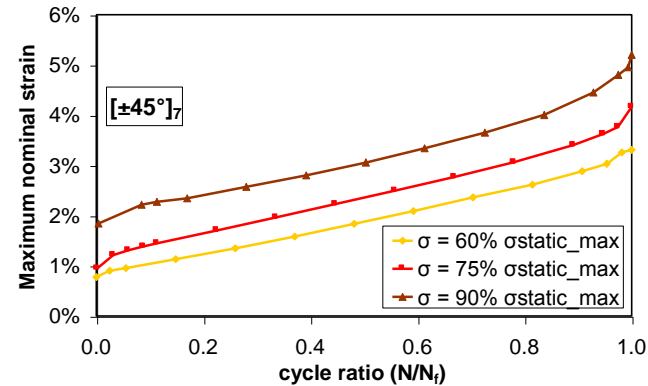
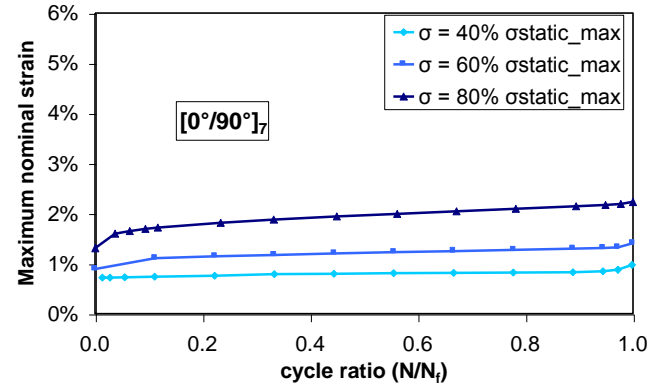
More influenced by the number of fatigue cycles

# Results – Damage analysis

## Damage evolution



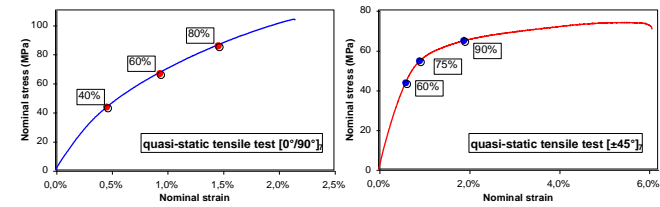
$\epsilon_{\max}$



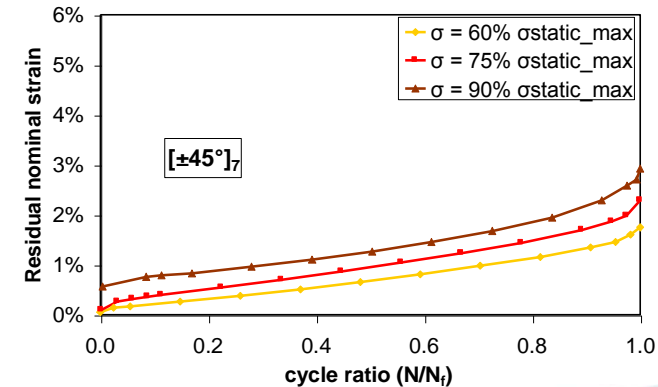
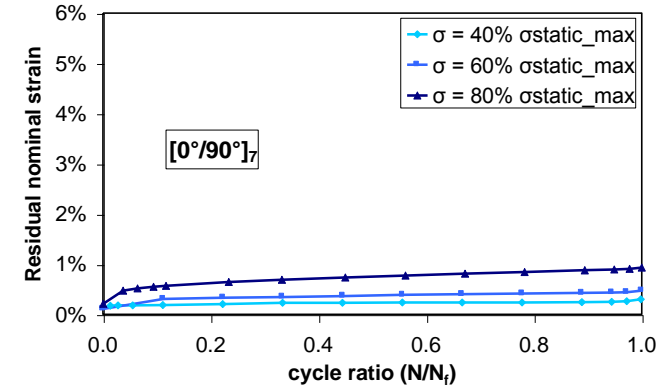
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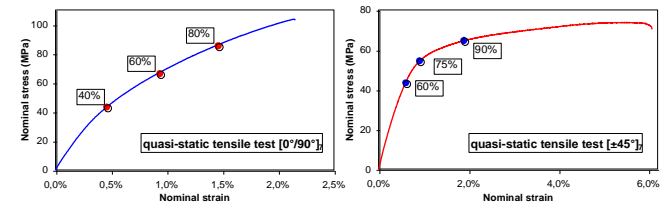
$\epsilon_{res}$



More influenced by  
the number of fatigue  
cycles

# Results – Damage analysis

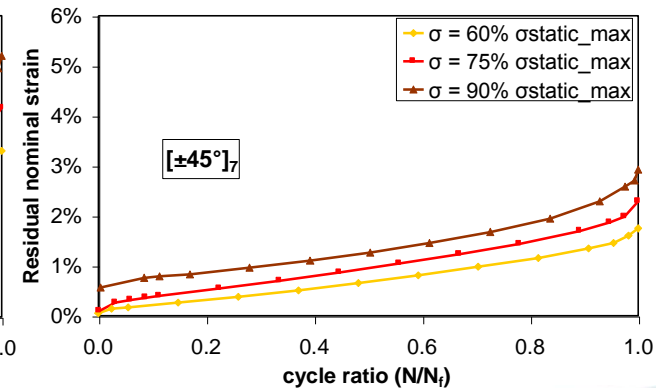
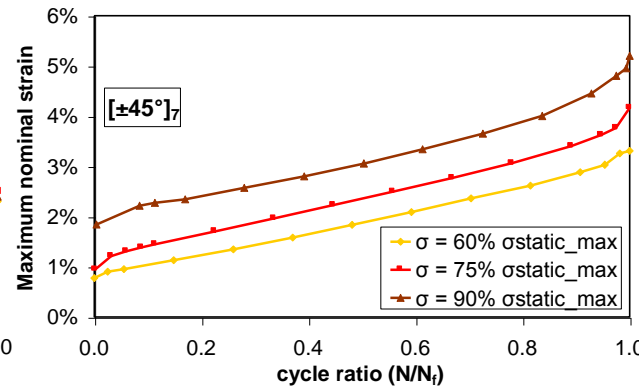
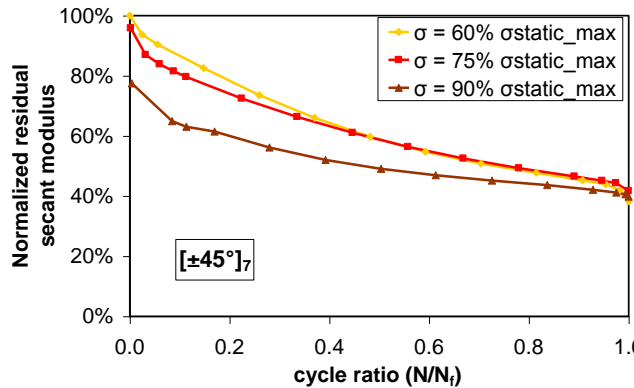
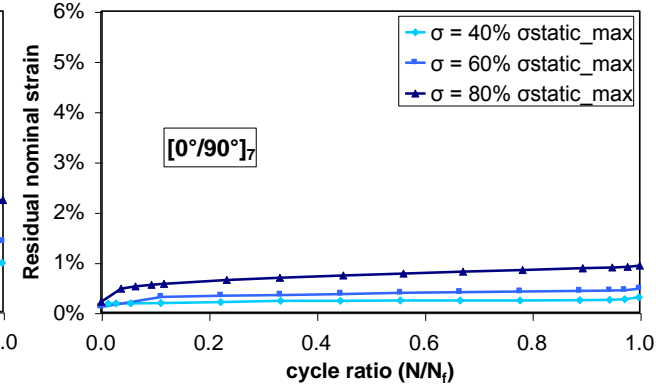
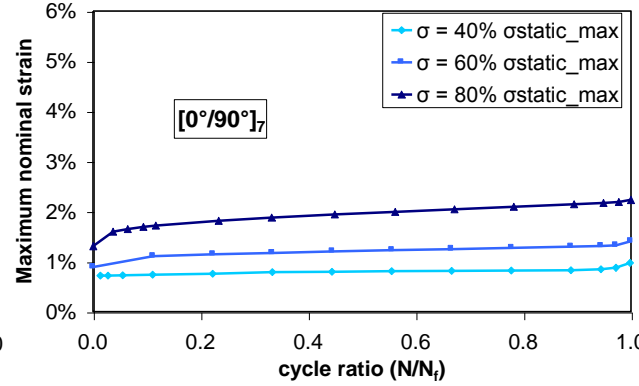
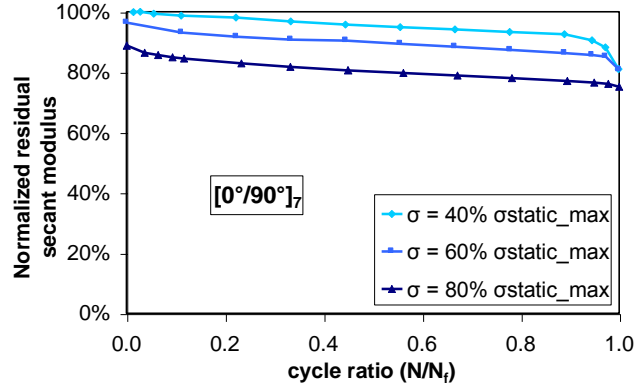
## Damage evolution



$$E_{sec} / E_{sec}^1$$

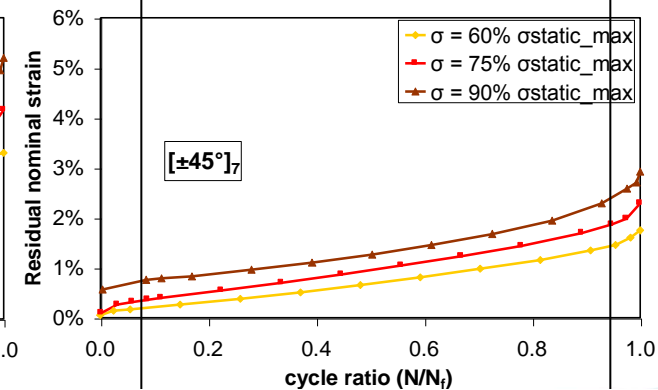
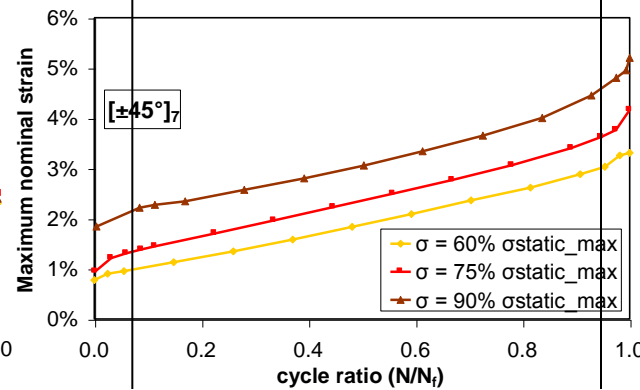
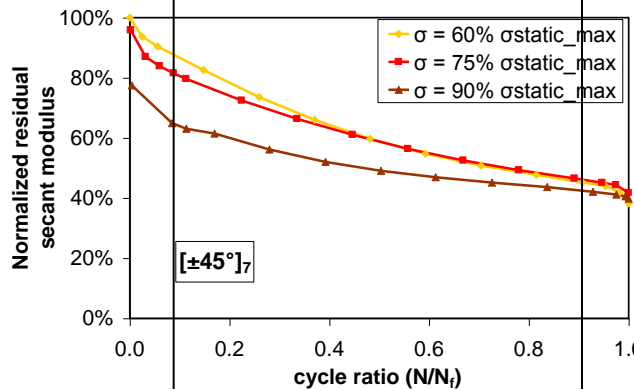
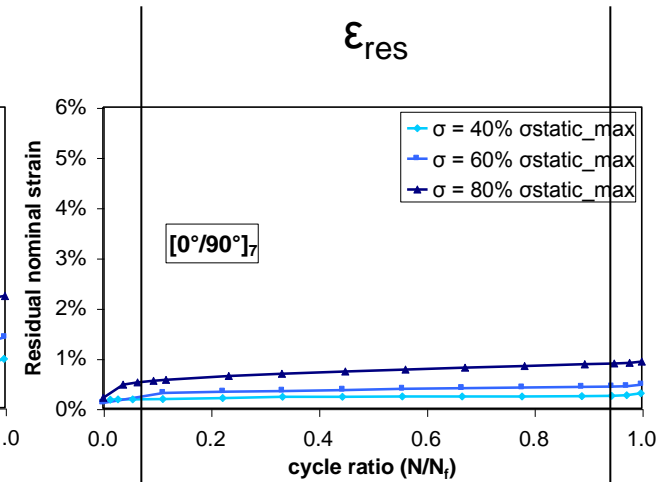
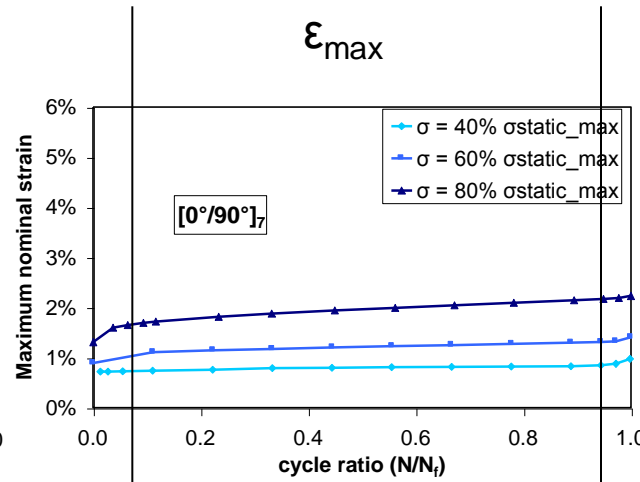
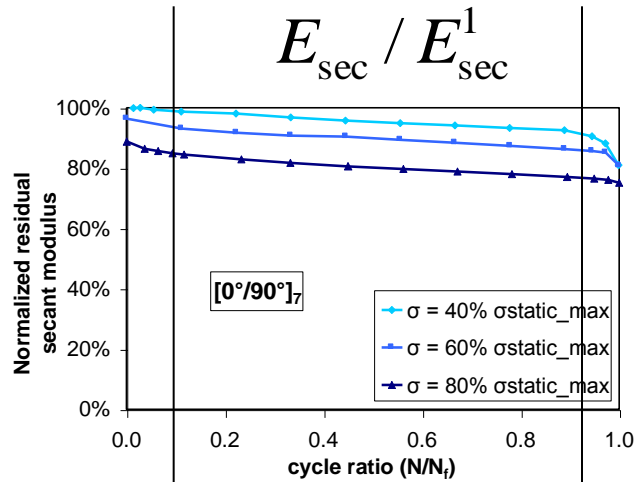
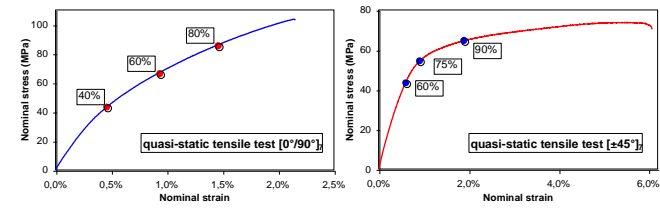
$$\epsilon_{max}$$

$$\epsilon_{res}$$



# Results – Damage analysis

## Damage evolution

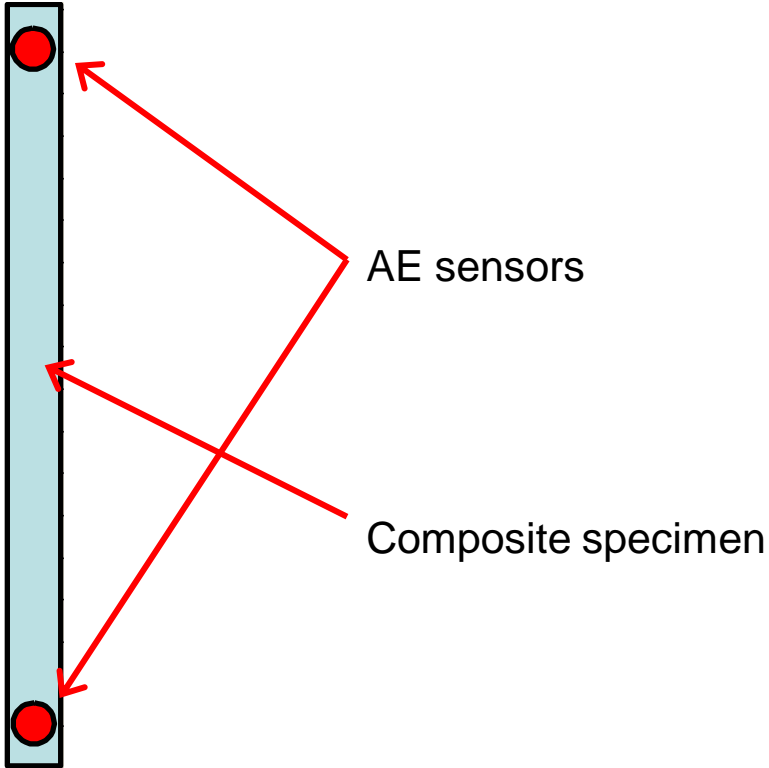
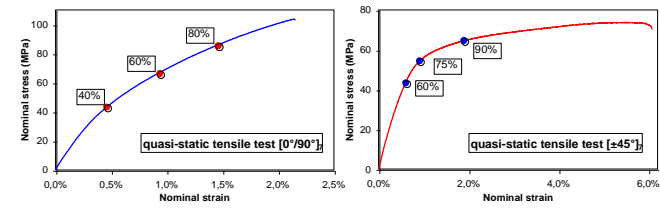


➔ Three marked phases



# Results – Damage analysis

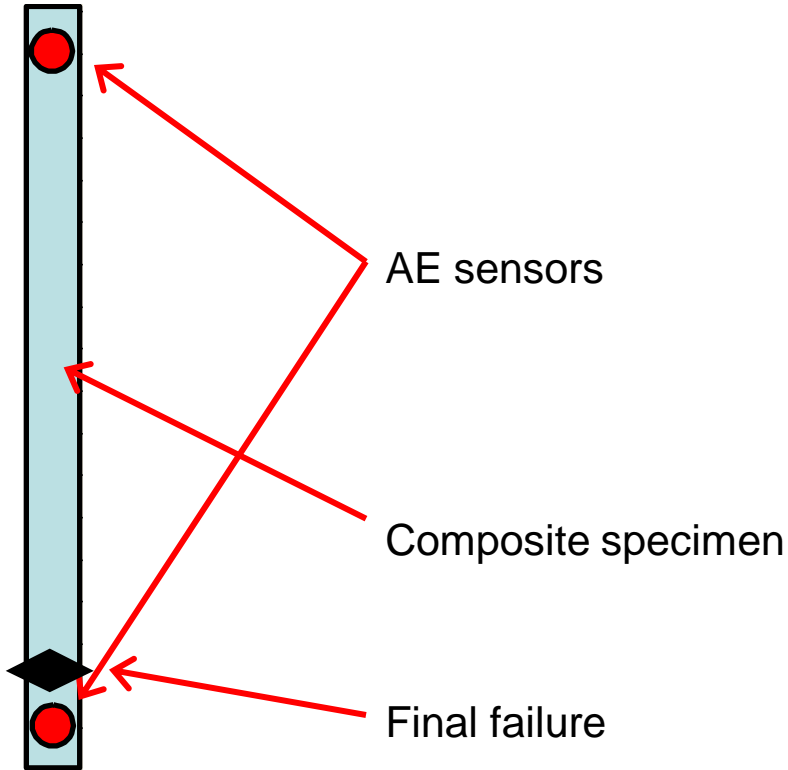
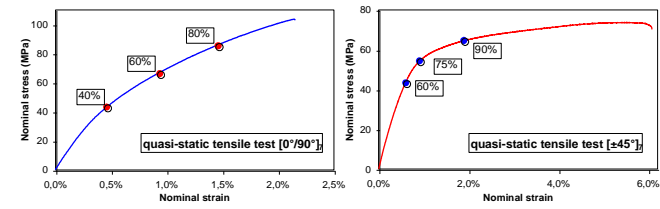
## Acoustic Emission





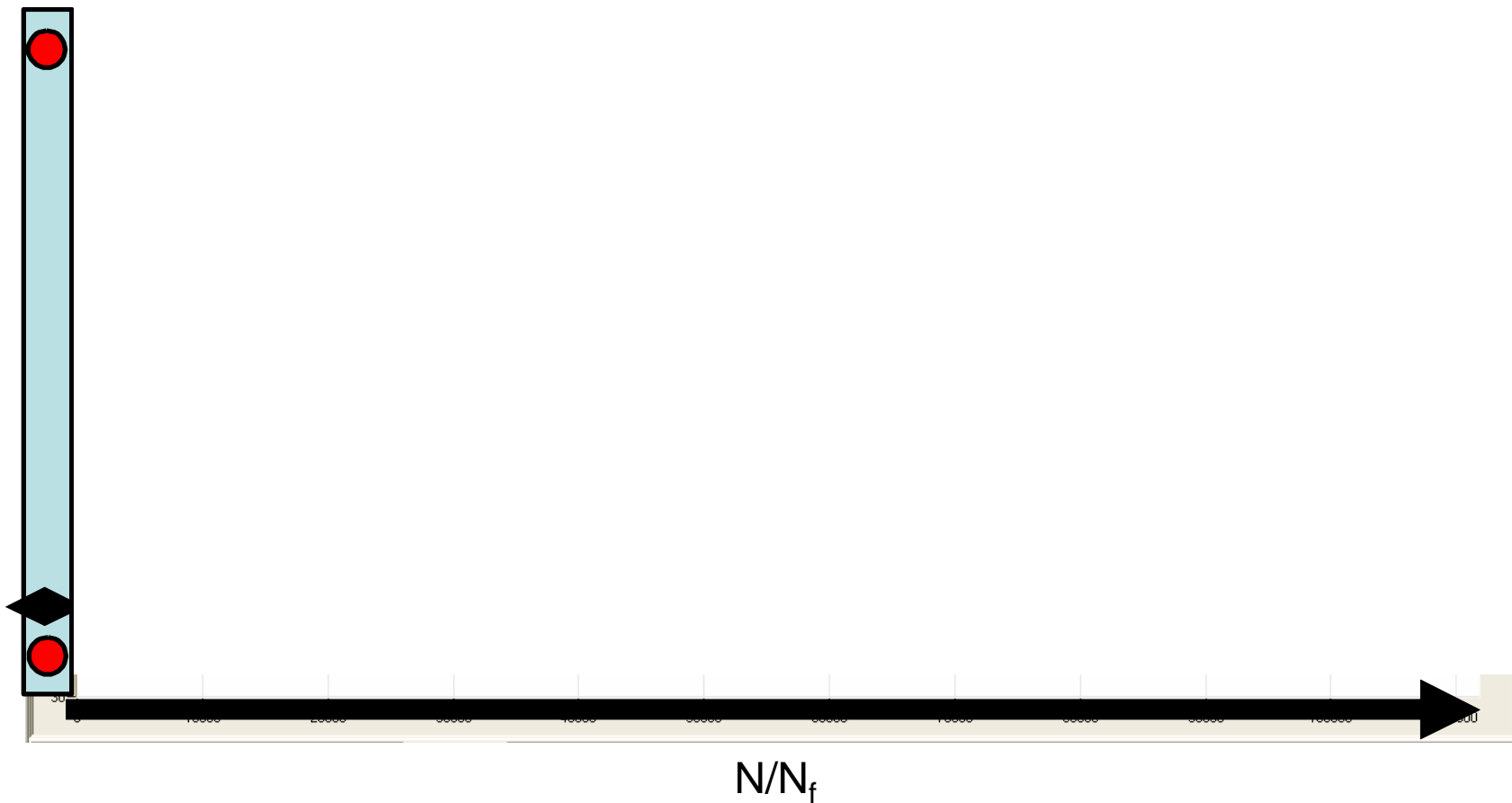
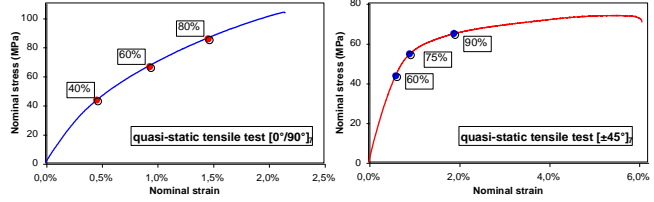
# Results – Damage analysis

## Acoustic Emission



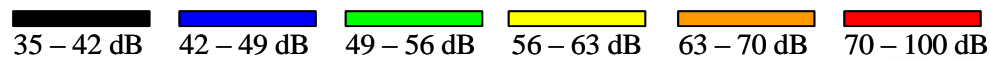
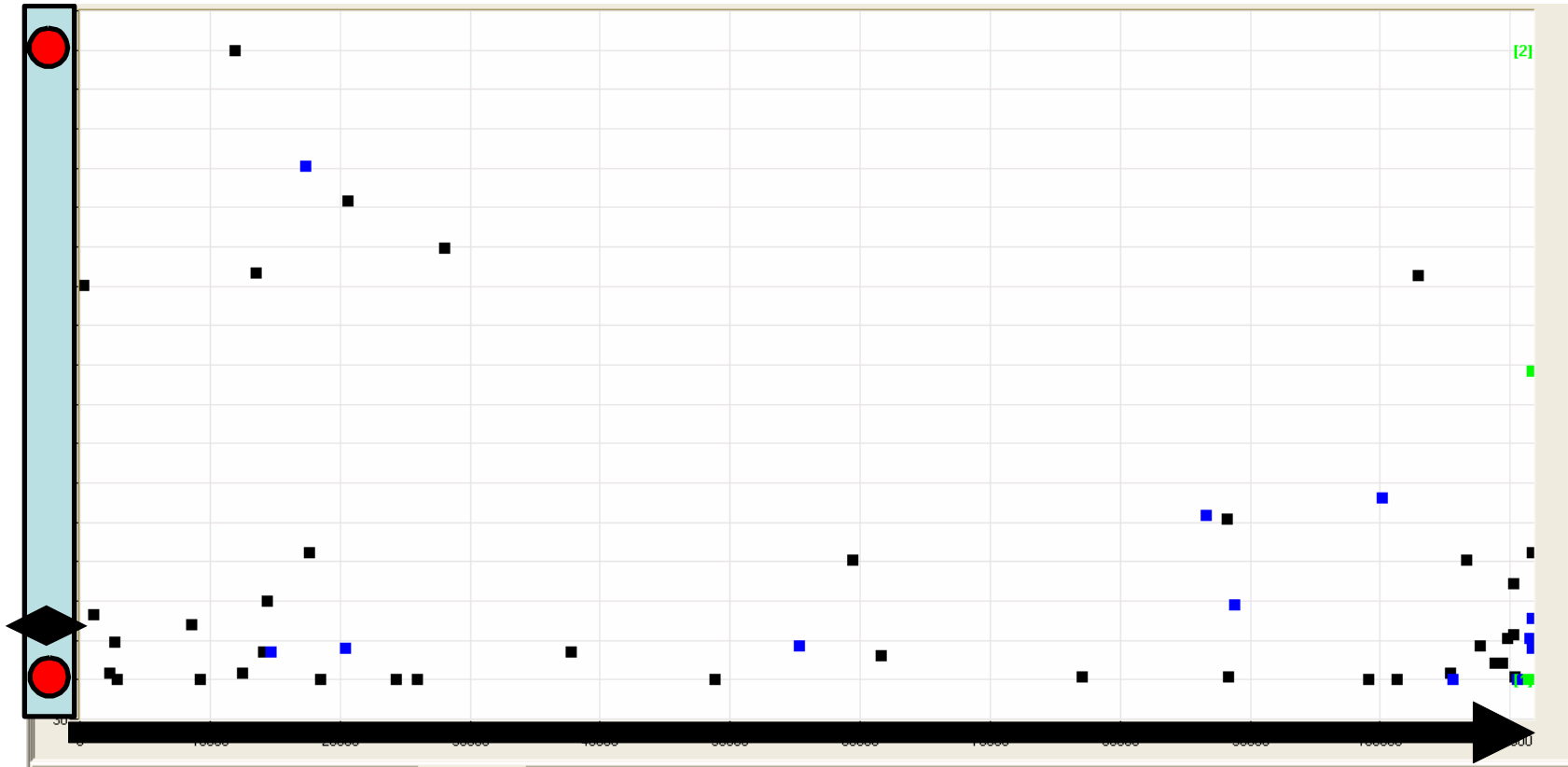
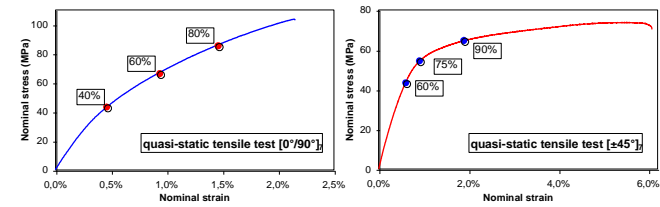
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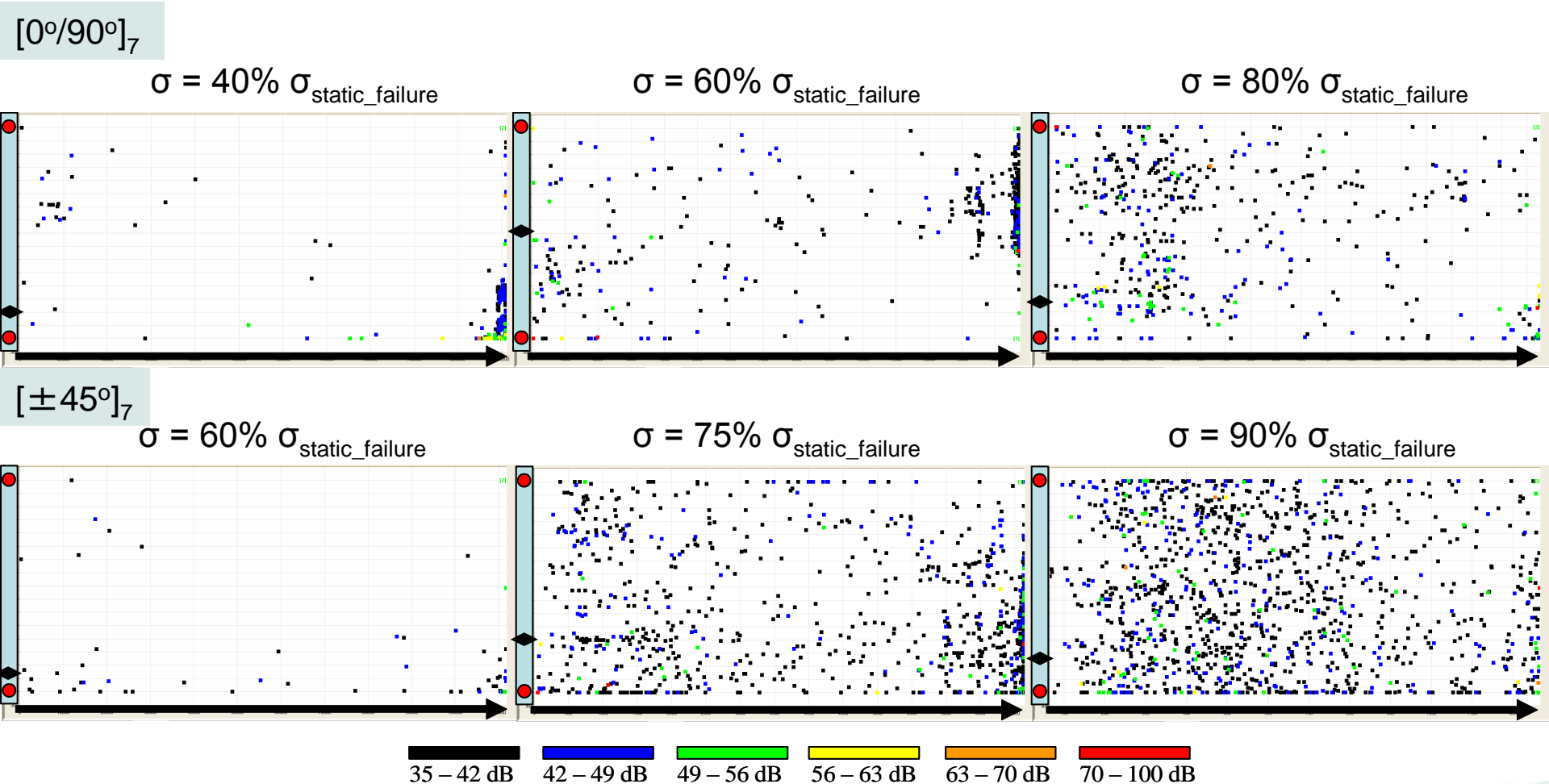
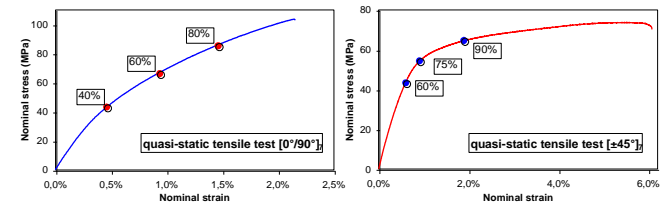
# Results – Damage analysis

## Acoustic Emission



# Results – Damage analysis

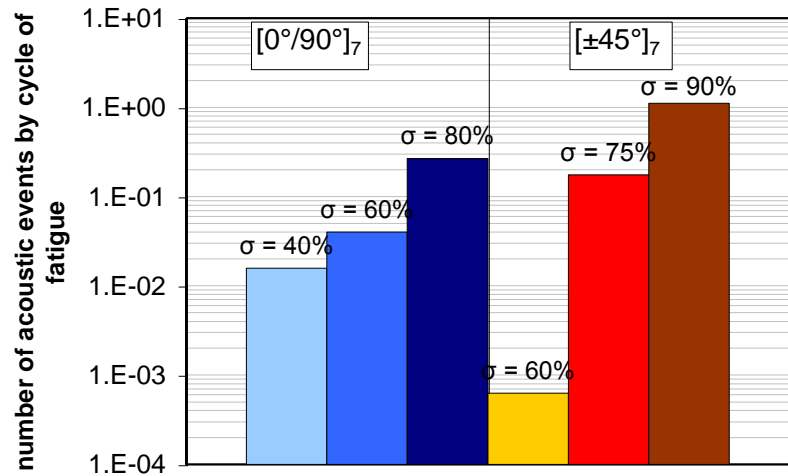
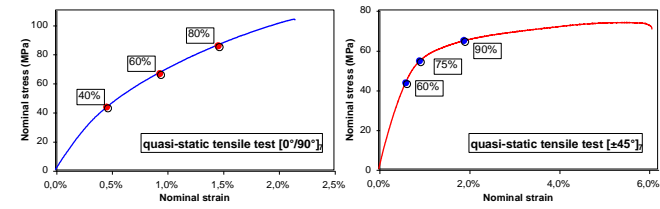
## Acoustic Emission



- AE events distributed all along the specimen and throughout the fatigue lifetime
- tendency to localize at failure zone

# Results – Damage analysis

## Acoustic Emission

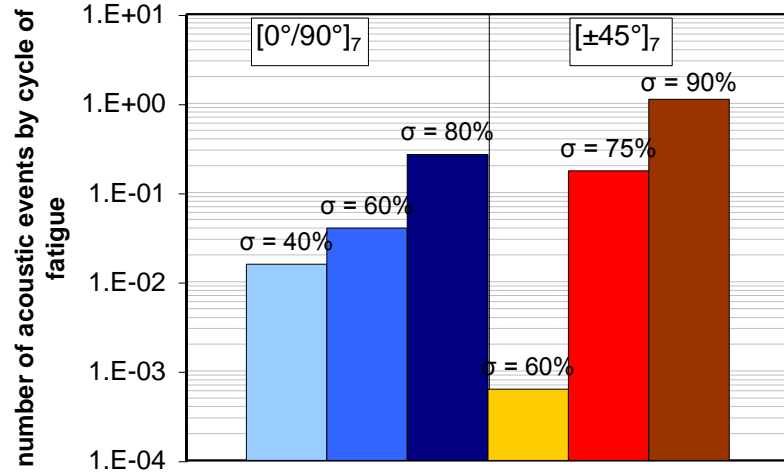
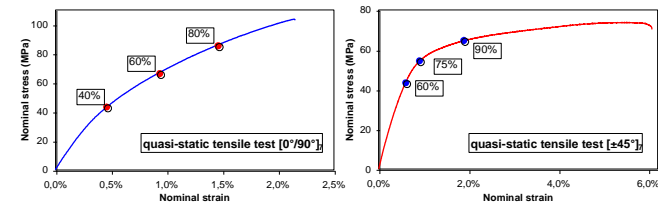


Graph represents: 
$$\frac{\text{AE events total number}}{\text{total fatigue cycles}}$$

- ➔ Influence of fatigue stress levels
- ➔ Significant difference for the lowest stress level in [±45°]<sub>7</sub>

# Results – Damage analysis

## Acoustic Emission



Graph represents:

$$\frac{\text{AE events total number}}{\text{total fatigue cycles}}$$

→ Influence of fatigue stress levels

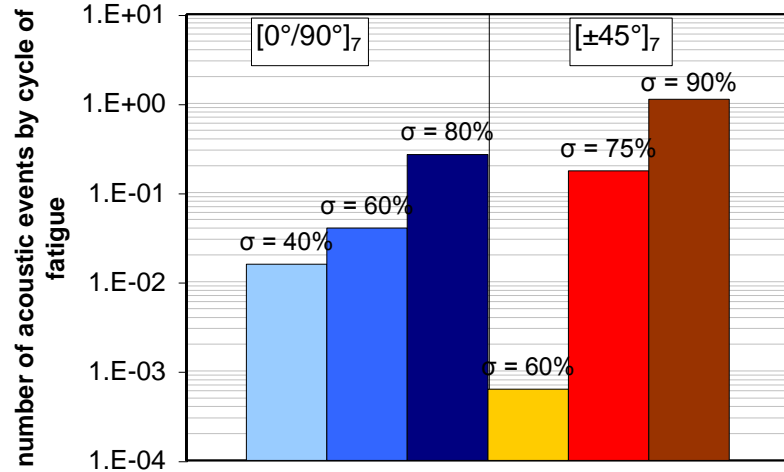
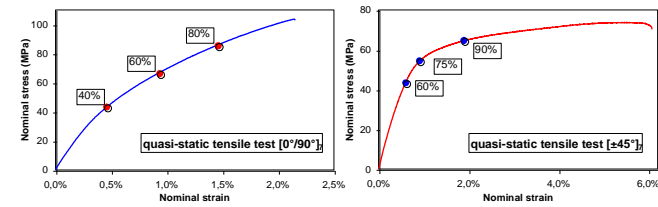
→ Significant difference for the lowest stress level in  $[\pm 45^\circ]_7$

→ Predominance of low amplitudes (35 to 45 dB) for all stress levels

Specimen	$\frac{\sigma_{\text{fatigue\_max}}}{\sigma_{\text{static\_failure}}}$	Mean amplitude [dB]	Standard deviation [dB]
$[0^\circ/90^\circ]_7$	40 %	43	3
	60 %	40	6
	80 %	41	6
$[\pm 45^\circ]_7$	60 %	40	5
	75 %	40	5
	90 %	40	5

# Results – Damage analysis

## Acoustic Emission



Graph represents: 
$$\frac{\text{AE events total number}}{\text{total fatigue cycles}}$$

- ➔ Influence of fatigue stress levels
- ➔ Significant difference for the lowest stress level in  $[\pm 45^\circ]_7$

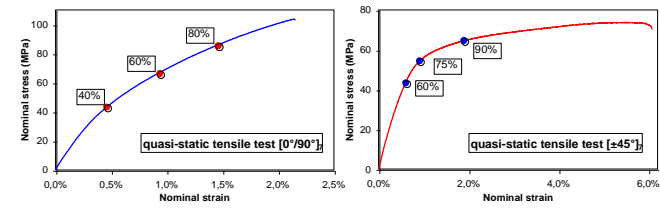
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Matrix cracks?

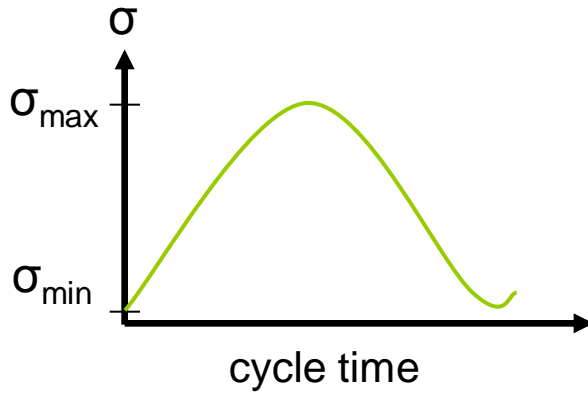
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# Results – Damage analysis

## Acoustic Emission



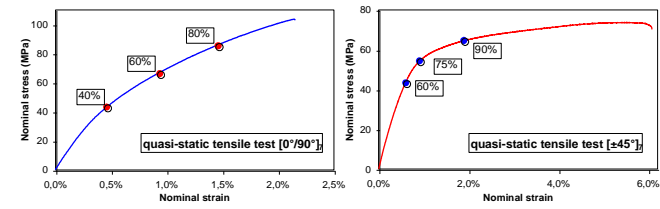
Each cycle:



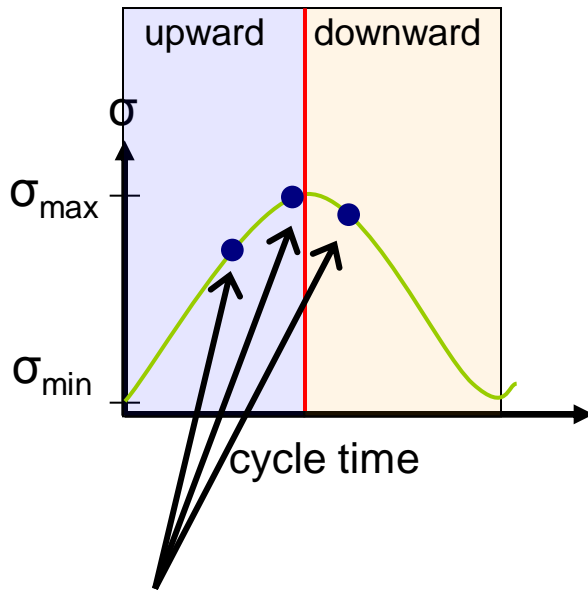


# Results – Damage analysis

## Acoustic Emission



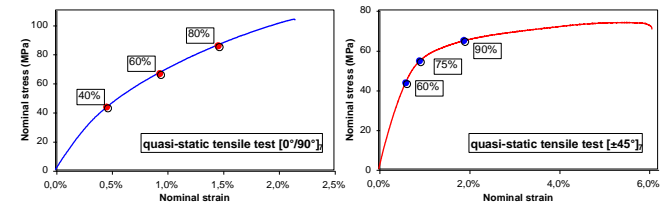
Each cycle:



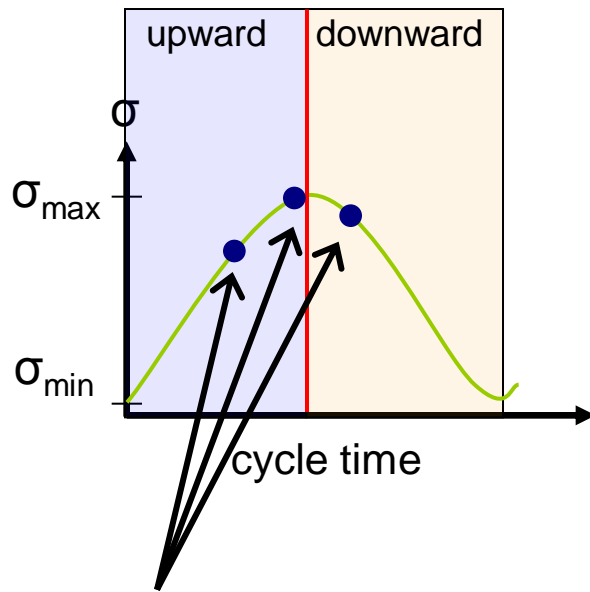
AE events

# Results – Damage analysis

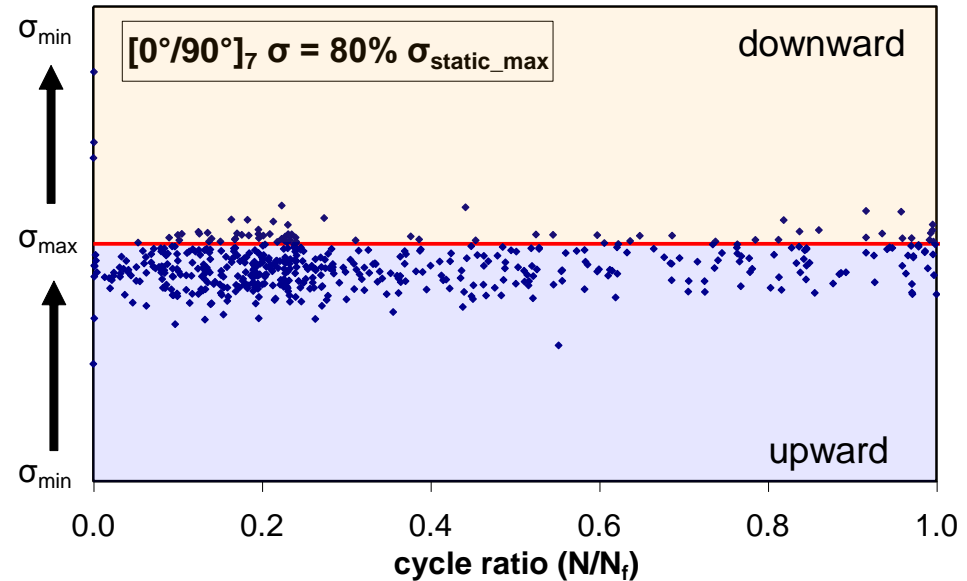
## Acoustic Emission



Each cycle:



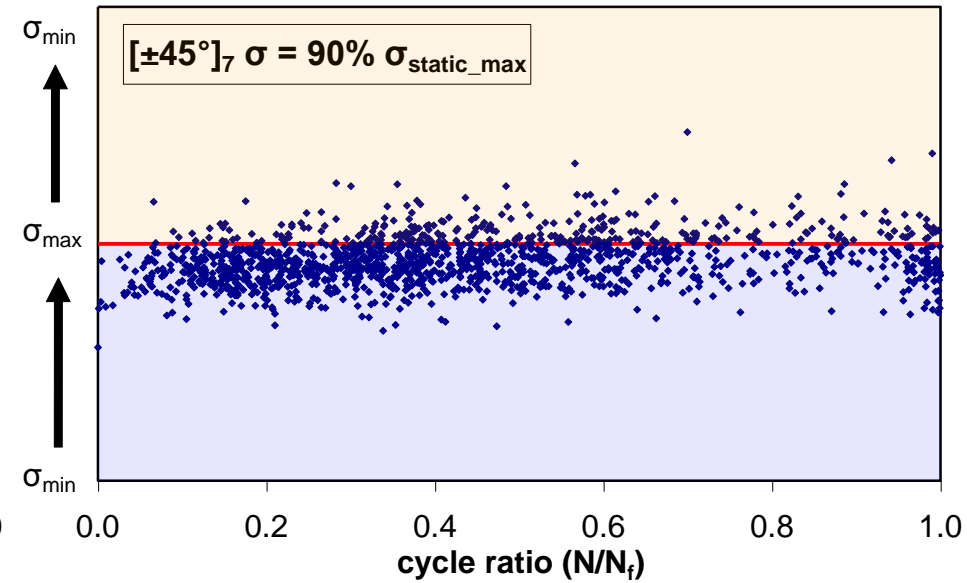
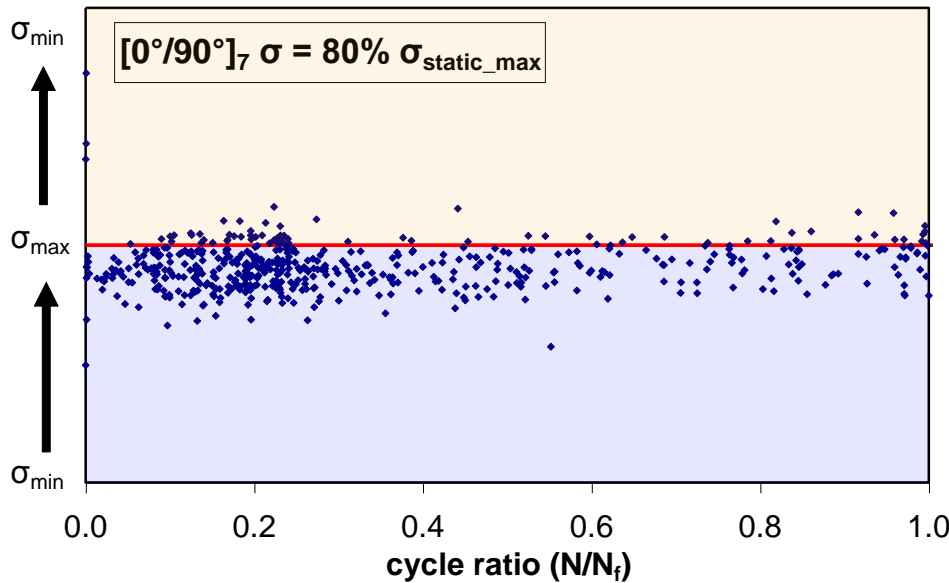
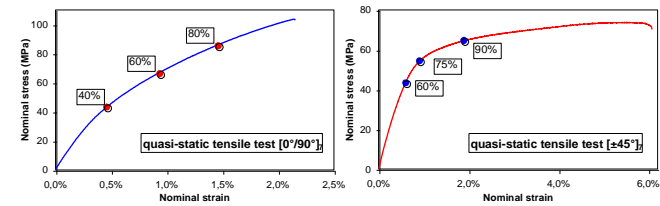
During fatigue lifetime:



AE events

# Results – Damage analysis

## Acoustic Emission

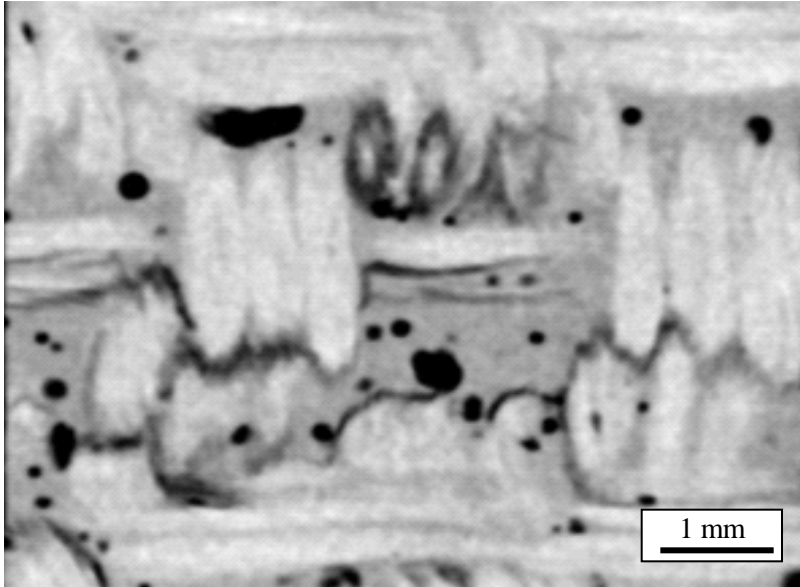


- Concentrated around maximum stress value
- Mostly in the upward region
- No acoustic event near minimum stresses

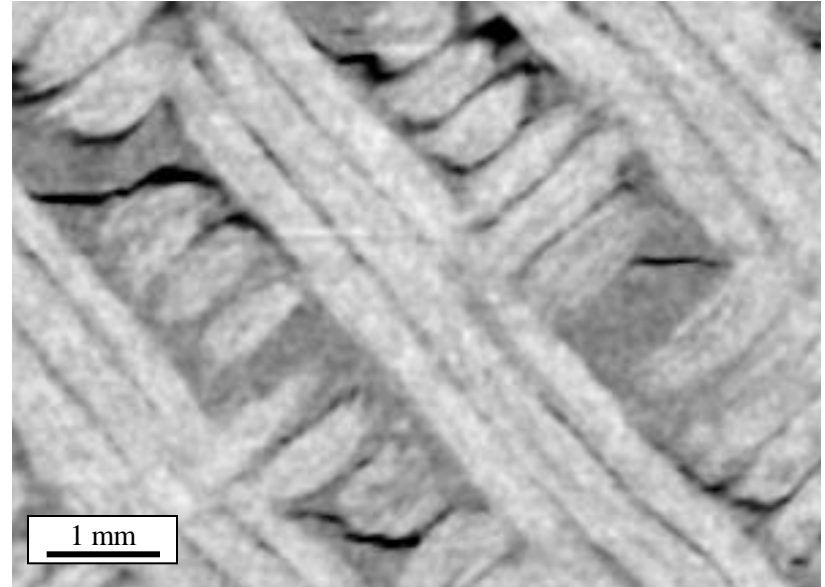
# Results – Damage analysis

## Microtomography and thermal field

$[0^\circ/90^\circ]_7$



$[\pm 45^\circ]_7$



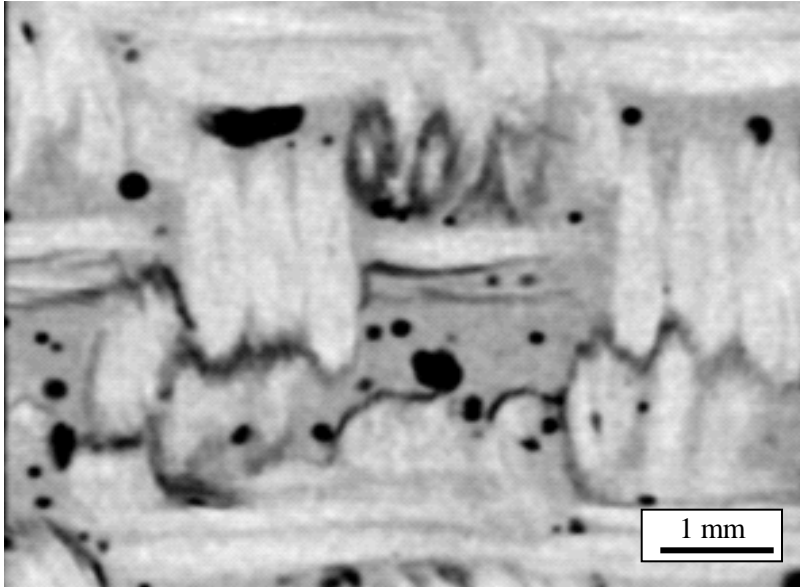
→ Matrix cracks mainly at the **interface**

- tend to be perpendicular to tensile axis (x)
- tend to follow interface

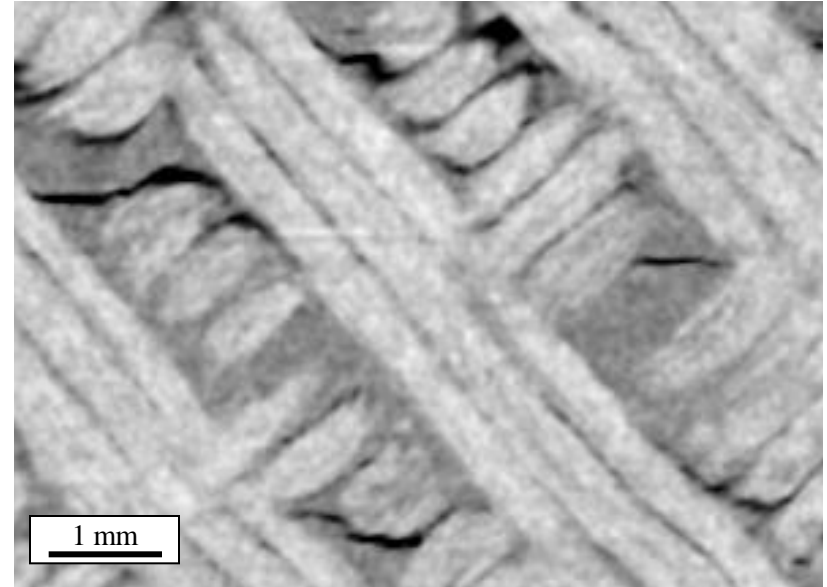
# Results – Damage analysis

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$[0^\circ/90^\circ]_7$



$[\pm 45^\circ]_7$



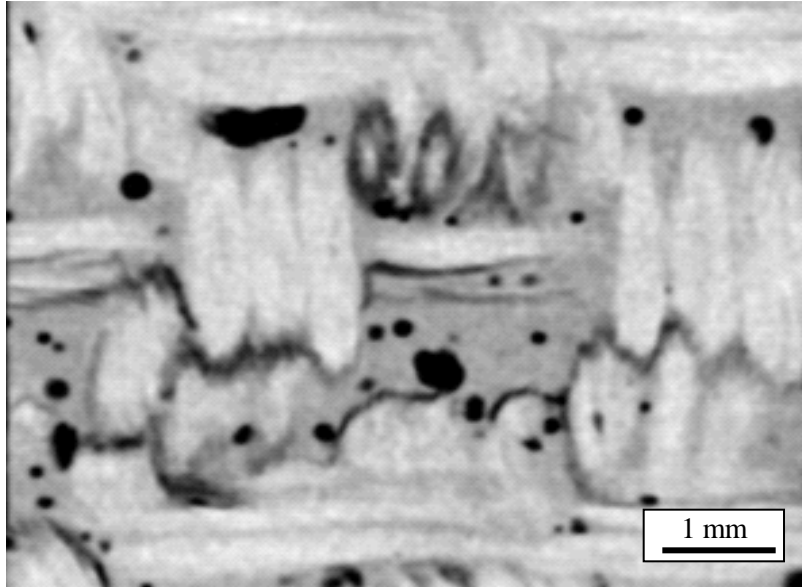
→ Matrix cracks mainly at the **interface**

→ confirms AE results (low amplitude ⇔ matrix cracks)

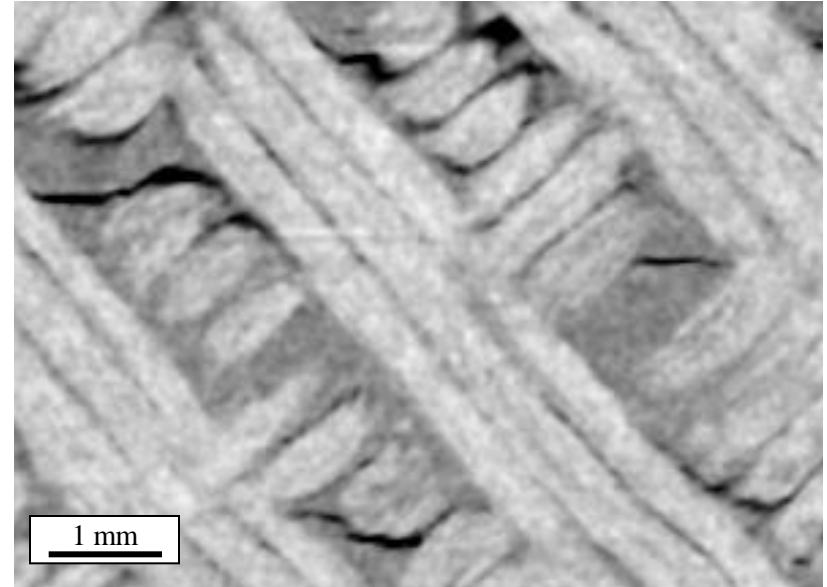
# Results – Damage analysis

## Microtomography and thermal field

$[0^\circ/90^\circ]_7$

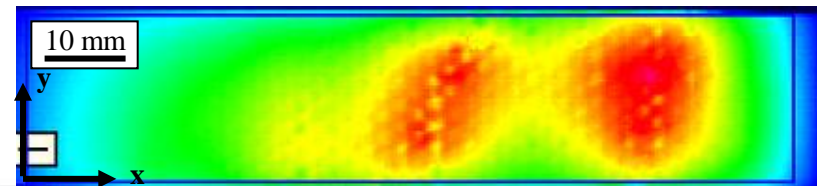


$[\pm 45^\circ]_7$



- Matrix cracks mainly at the **interface**
- confirms AE results (low amplitude  $\leftrightarrow$  matrix cracks)
- Friction of crack surface can increase material temperature and could explain heat concentration

Thermal field:



# Conclusions

Determination of the **cyclic fatigue behavior** of a **woven fabric hemp/epoxy composite** for two types of laminates:  $[0^\circ/90^\circ]_7$  and  $[\pm 45^\circ]_7$

- Significant dispersion due to the **natural aspect** of **hemp yarns**
- Significant loss of the secant modulus during **fatigue life**
- Acoustic events are **distributed** throughout the **specimen gauge** and the **fatigue life**
- There is a predominance of **low amplitude events** (35 to 45 dB)
- Those events probably correspond to **matrix cracks** development, mainly at the **interface**, as observed by CT-scan
- Internal frictions of crack surfaces are probably the cause of heat concentration observed by infrared camera.

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## Further Work:

- S-N-P curves
- Further interface studies
- AE analysis



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# Cyclic fatigue behavior of woven hemp/epoxy composite: Damage analysis

**Davi S. de Vasconcellos**, F. Touchard, L. Chocinski-Arnault

[davi.vasconcellos@ensma.fr](mailto:davi.vasconcellos@ensma.fr)