CompTest 2004

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Progressive Damage Characterization of Stitched, Bi-axial, Multi-ply Carbon Fabrics Composites

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Outlines

- Brief Material Description
- Aims
- Experimental Set-up
- Results
- Conclusions and Future Works

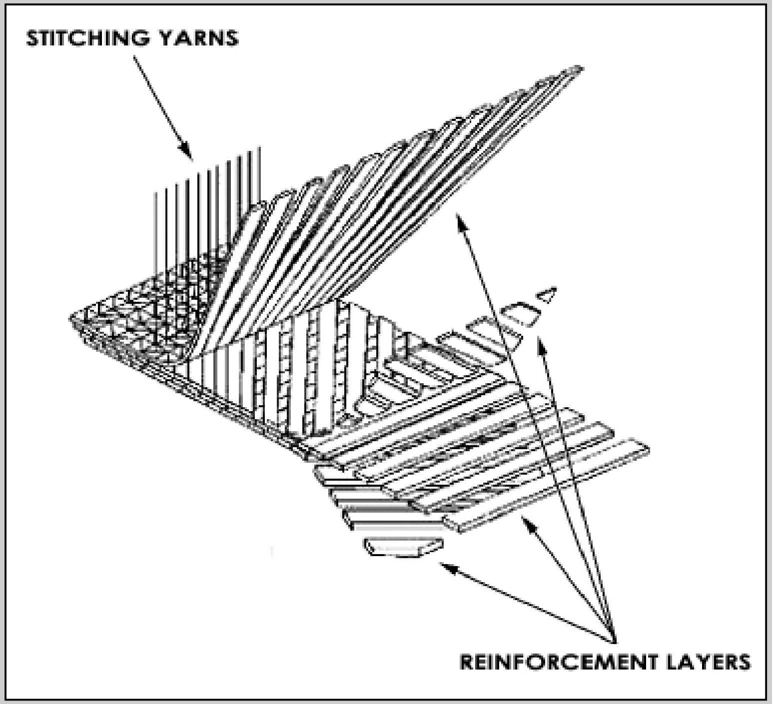
Multi-axial Multi-ply Carbon Fabrics (MMCFs)

also known as

Non-Crimp Fabrics (NCF)

- **Production:**
  Tows are spread in plies with any chosen orientation and then they are stitched together

- **Advantages:**
  - Unidirectional-straight reinforcement leads to better mechanical properties (No-crimp);
  - Reinforcement orientability;
  - Good drapeability and permeability;
  - Manufacturing time reduction.



Material (II)

Bi-axial (0/90°) Multi-ply Fabric

Reinforcement:

Producer:	Seartex *Gmbh*
Architecture:	Bi-axial 0°/90° , 24K, T600
Ply Areal Density:	150±5% g/m^2
Stitching Yarn:	Polyester(PES)
Stitching Pattern:	Tricot-Warp
Areal Density:	6±5% g/m^2
Fabric Areal Density:	325g/m^2 (*exp.*)

Resin system:

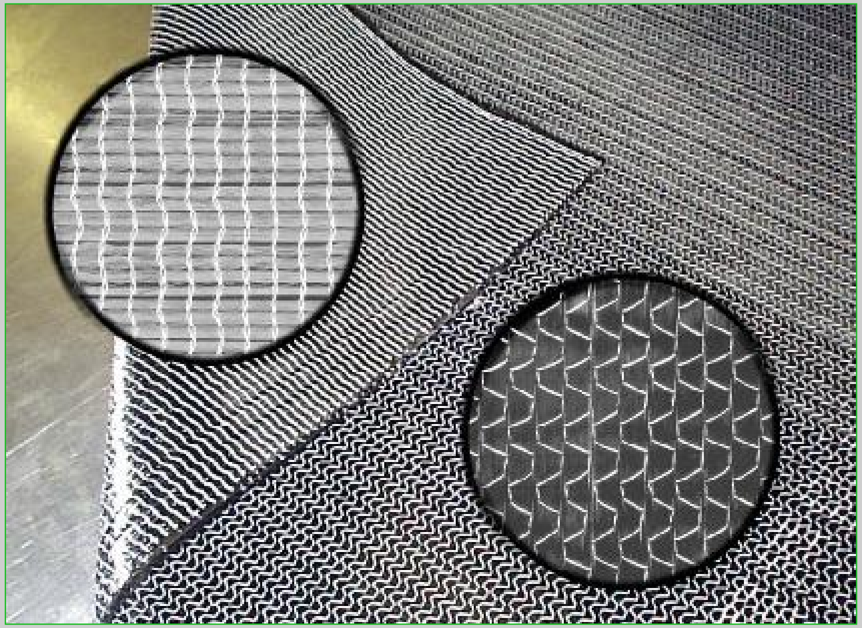
Producer:	Shell ®
Resin:	Epikote® 828 LV
Hardener:	Epikure® DX 6514
Mixing Ratio:	Resin/Hardener = 100/17

Lay-up:

8 fabrics (16 plies) symmetrical lay-up

$[\ (0/90)\ /\ (90/0)\ /\ (0/90)\ /\ (90/0)\ ]_S$

Final Thickness:	~ 3.5 mm
Volume fraction:	V_f ~ 40%

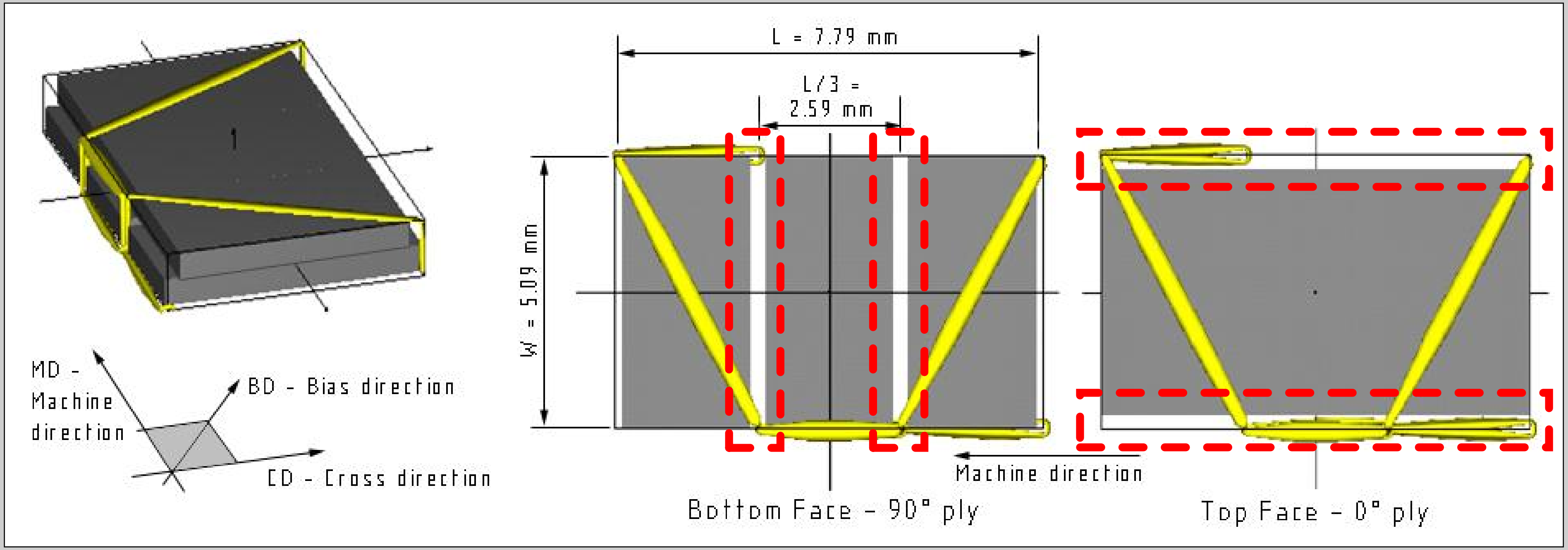


RTM Process' Parameters

Mold Vacuum	0,4 ÷ 0,6 bar
Injection Pressure	2 ÷ 4 bar
Injection Temperature	40° C
Injection Time	20 ÷ 25'
First Cure	70°C / 60'
Final Cure	160°C / 60'

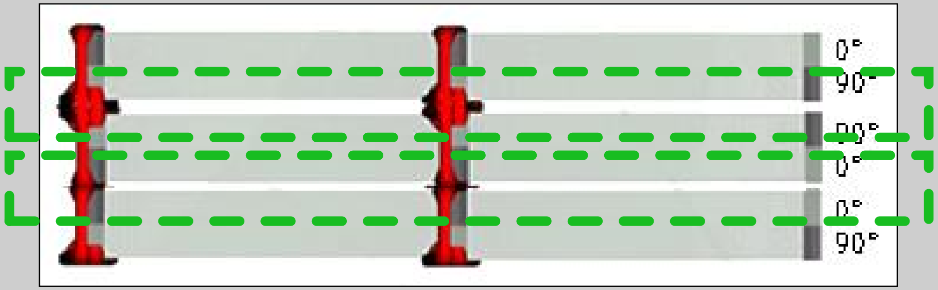
Unit Cell

From WISETEX modelling



Stitching induced Fabric defects:

- INTRA-layer CHANNELS
  - MD Channels @ 0.56 mm
  - CD Channels @ 0.28 mm
- INTER-layer GAPS
  - 0/0° Gaps @ 60 mm
  - 90/90° Gaps @ 80 mm



Main Goal

DAMAGE CHARACTERIZATION under Quasi-static loads

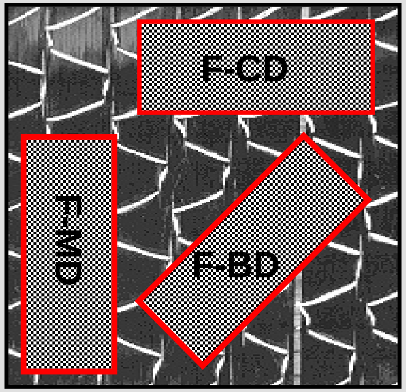
Intermediate steps:

- Damage evolution monitoring during quasi-static tensile tests along characteristic material directions;
- AE parameters analysis in relation to applied strain;
- Direct Damage Observation by the mean of NDT;
- Evaluation of the stitching role on damaging process

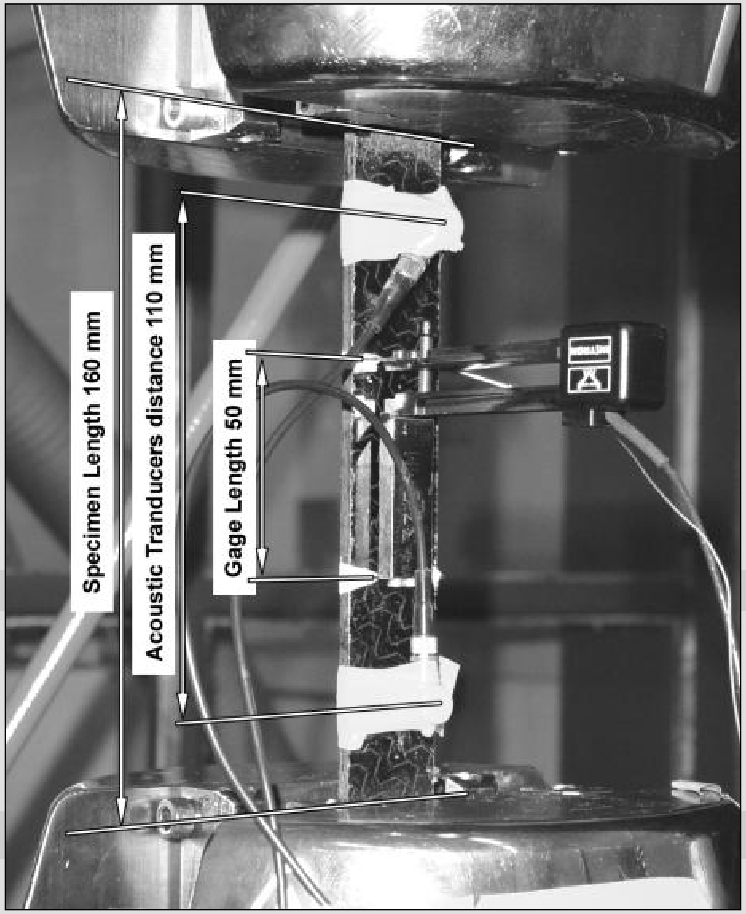
Experimental Set-Up (I)

Damage evolution monitoring

Tensile tests according with ISO 527-4



- è 3 test direction: *Machine*, *Cross* and *Bias* directions;
- è 100 kN INSTRON 4505;
- è 50mm gage length axial extensometer
- è Imposed displacement:
  - *1 mm/min along MD and CD*
  - *3 mm/min along BD*



Acoustic Emission Records

- è 2 broadband transducer
- è Digital wave equipment

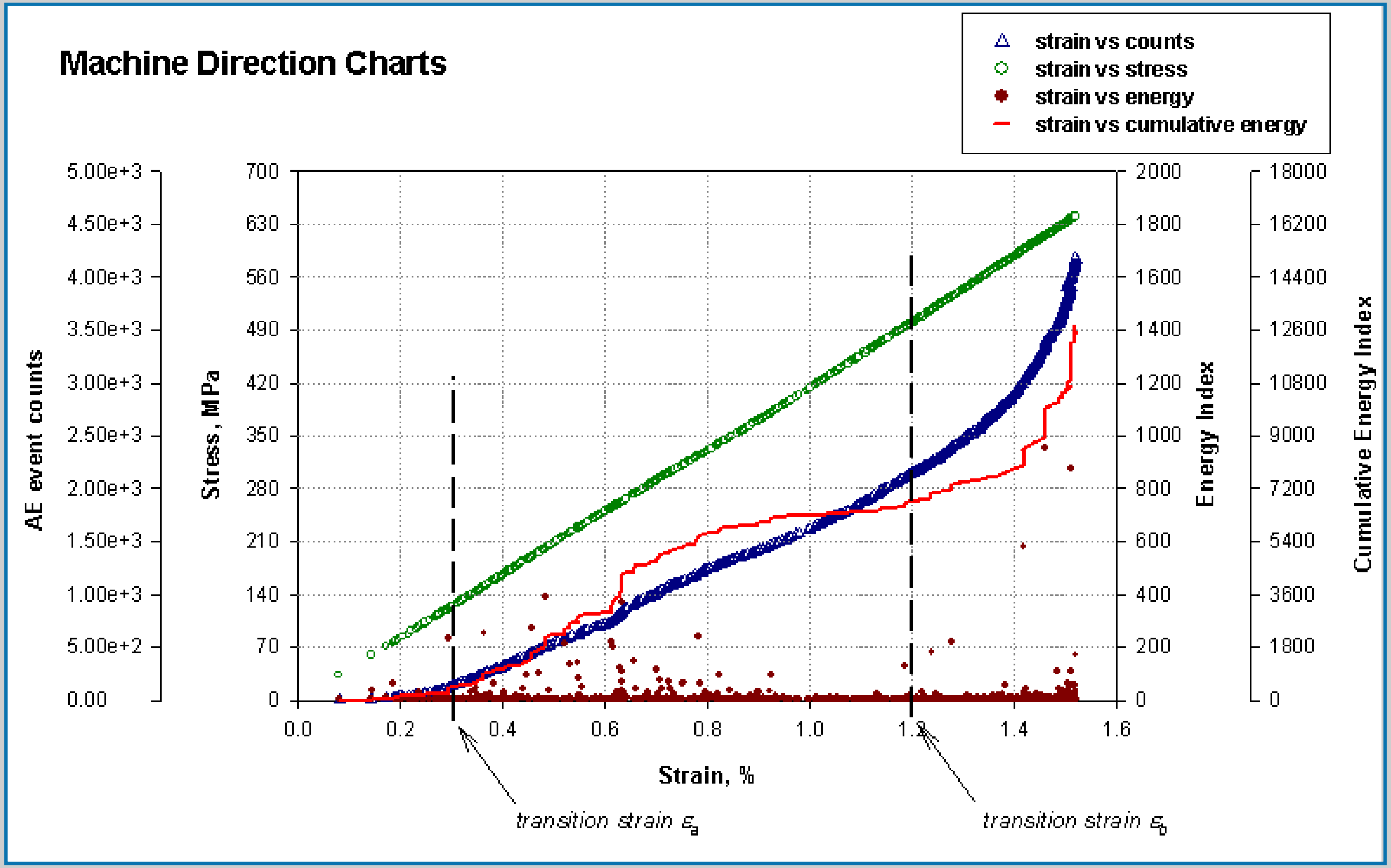
Electrical Resistance Technique

Results

Results

Damage evolution monitoring

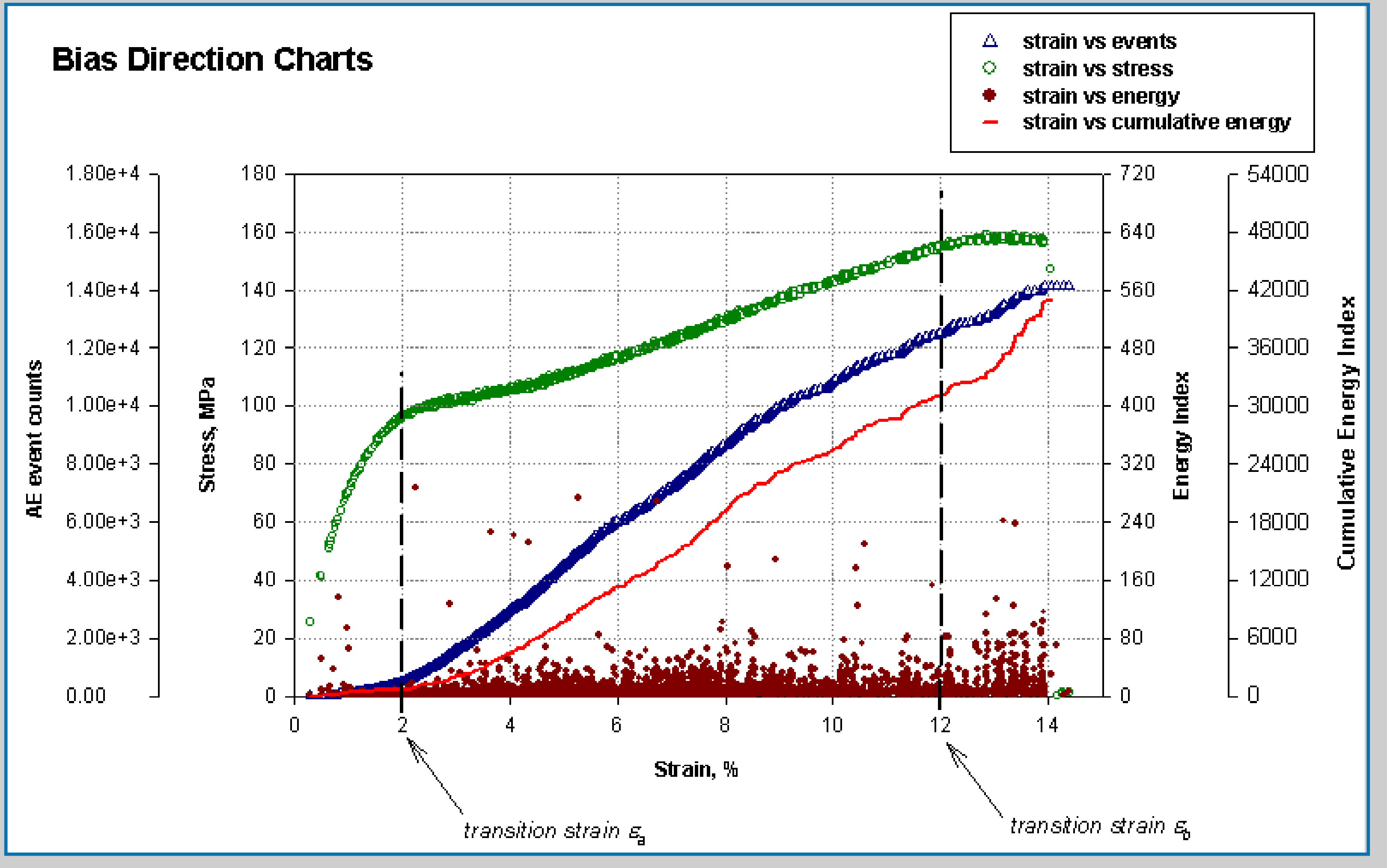
Stress and AE parameters vs strain



Results

Damage evolution monitoring - AE

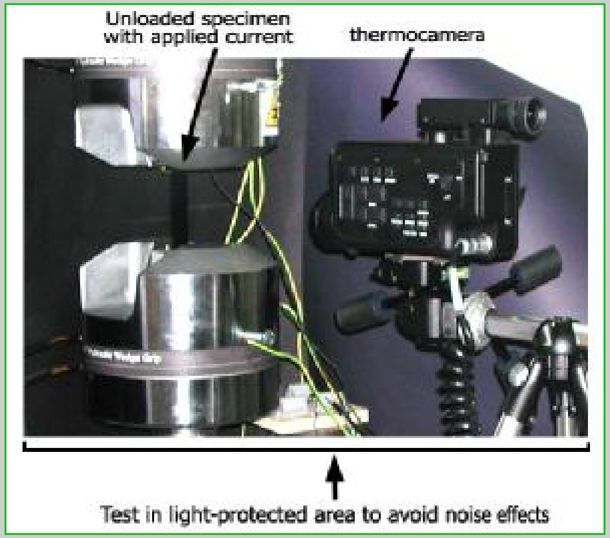
Stress and AE parameters vs strain

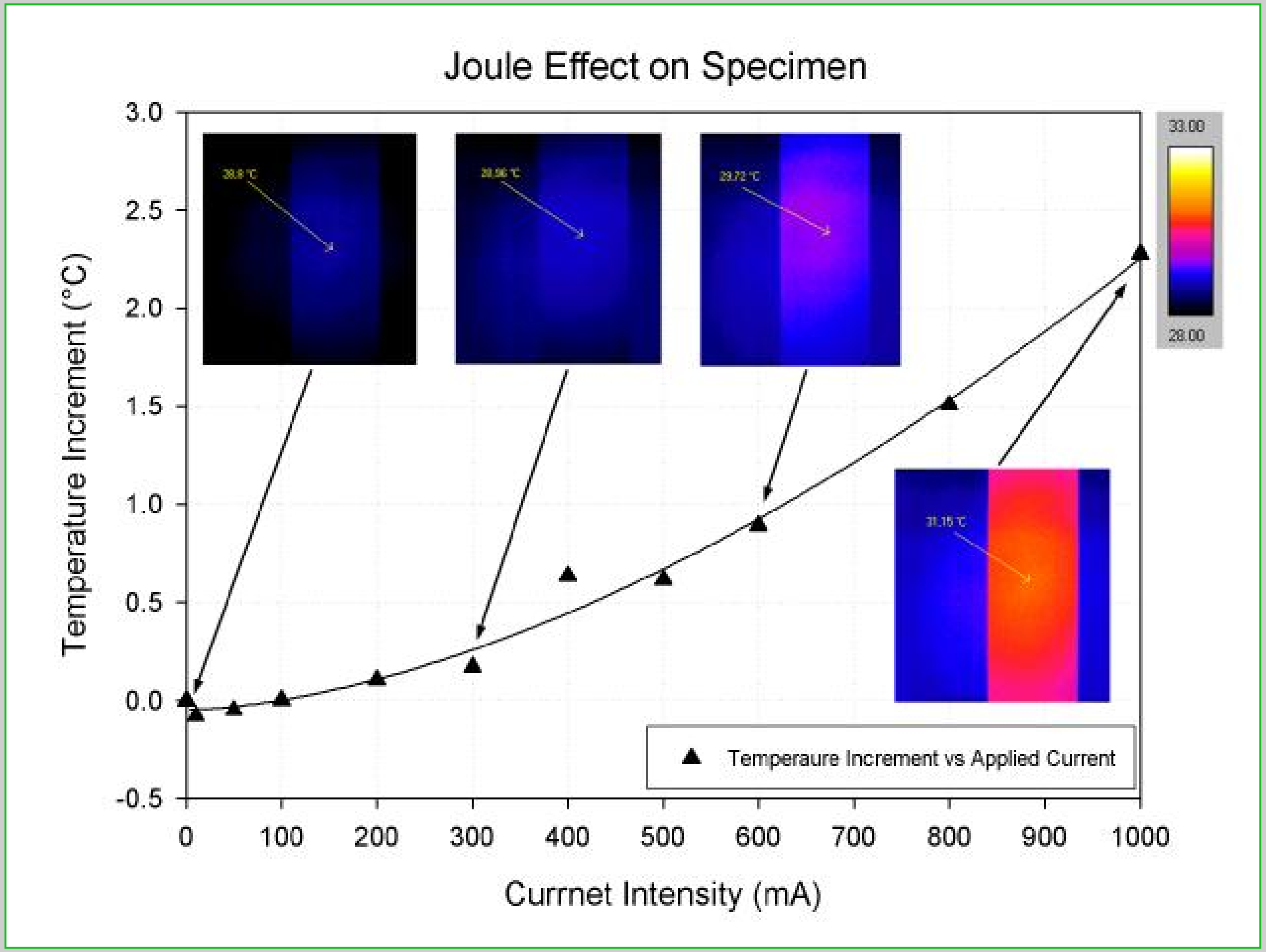


Results

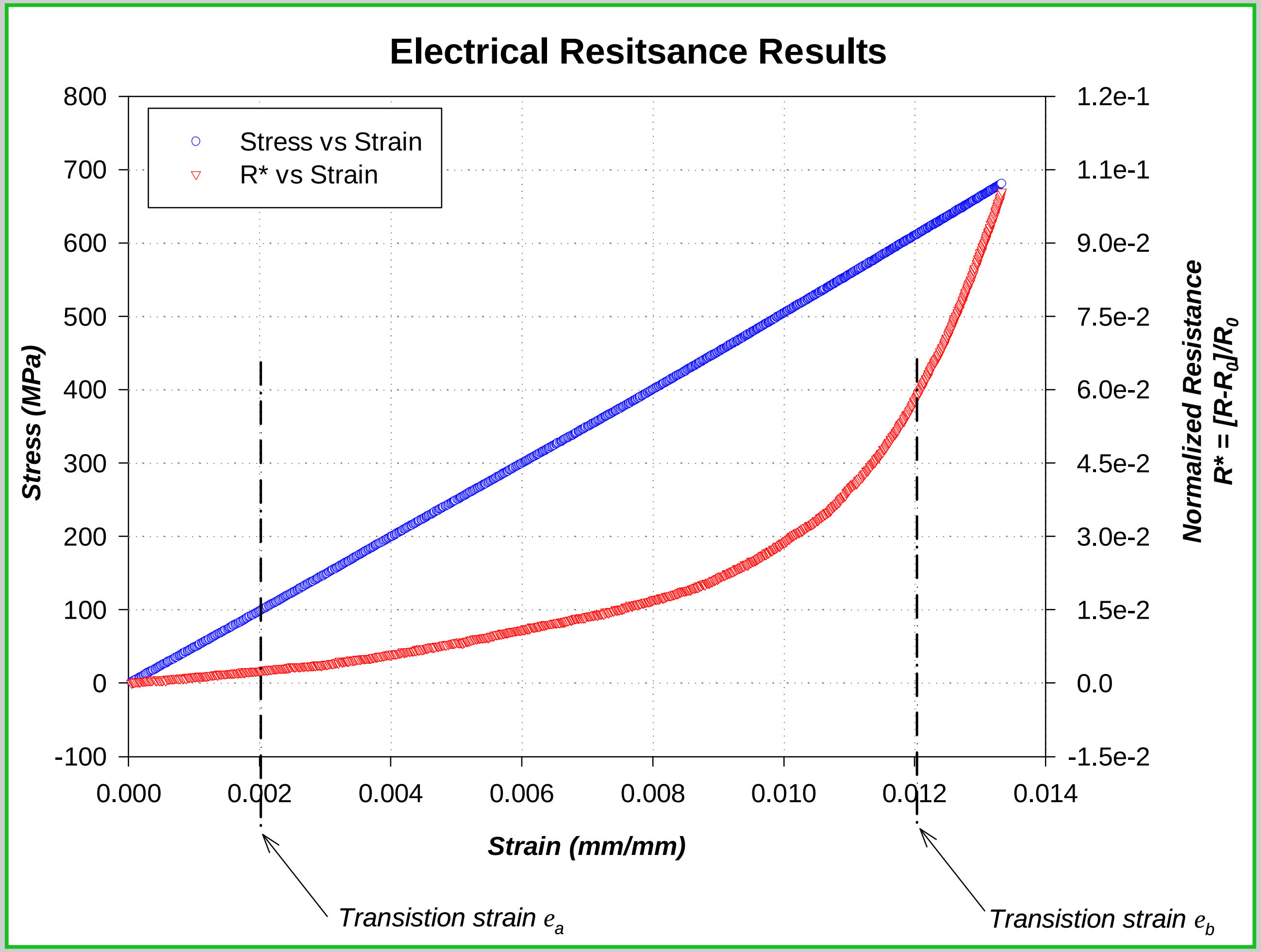
Damage evolution monitoring - ER

Joule Effects evaluation





ER results



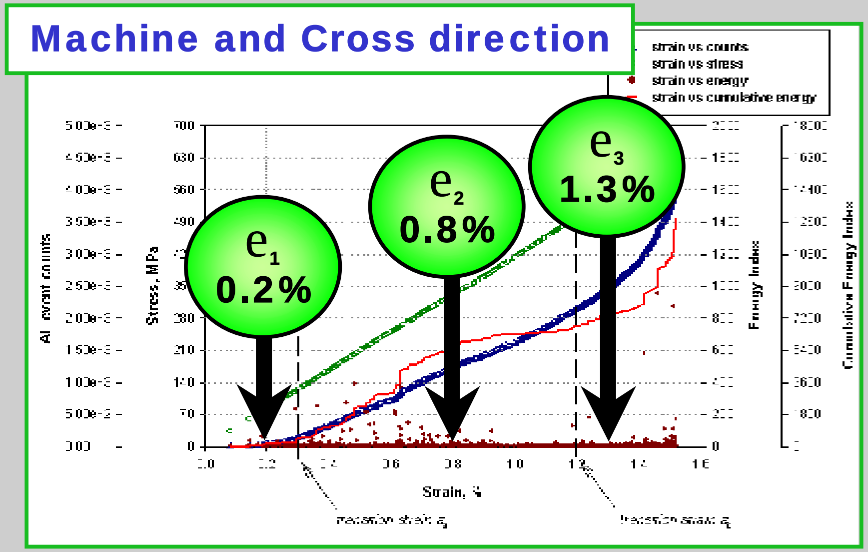
Electrical Resitsance Results
Stress vs Strain
R* vs Strain
Stress (MPa)
Normalized Resistance
R* = [R-R0]/R0
Strain (mm/mm)
800
700
600
500
400
300
200
100
0
-100
1.2e-1
1.1e-1
9.0e-2
7.5e-2
6.0e-2
4.5e-2
3.0e-2
1.5e-2
0.0
-1.5e-2
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
Transistion strain ea
Transistion strain eb

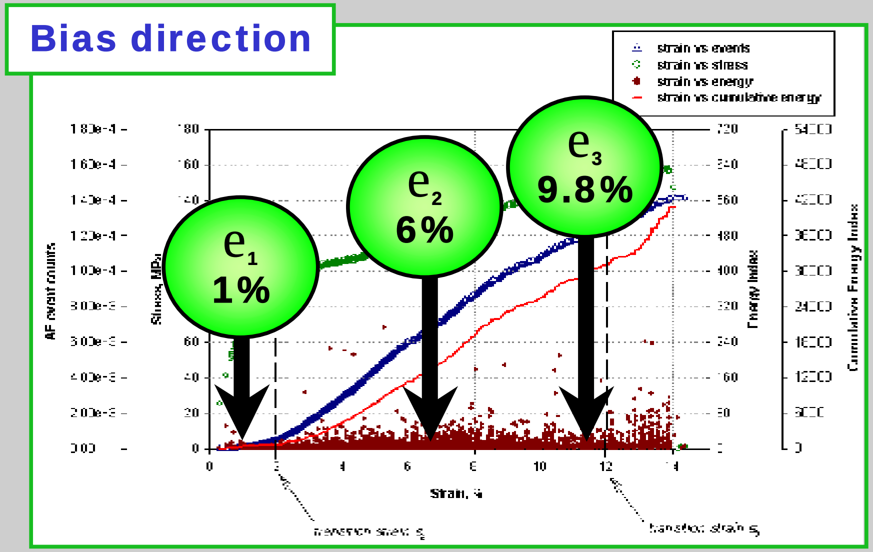
Experimental Set-Up (II)

Damage Observation by NDT

- **To identify damage at different levels of evolution**

  è 3 different strain levels has been chosen





- **Tensile tests were stopped at strain ε_1, ε_2, ε_3**

  è Damage inspection by NDT

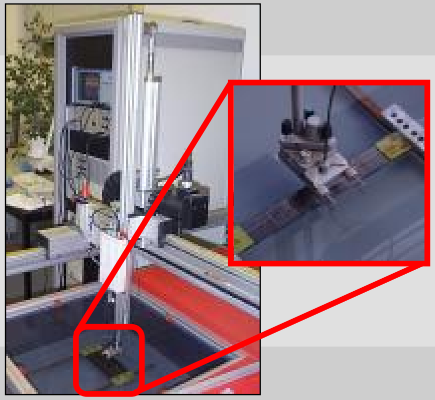
Experimental Set-Up (III)

Damage Observation by NDT

Ultrasonic C-Scan

<u>*HFUS 2000 Ultrasonic system*</u>

Transducer	5 MHz, pulse-echo type
Resolution	375 mm (max)
Oscilloscope	digital, 175 MHz



X- Ray Radiography

<u>*Philips HOMX 161 - AEA Tomohawk software*</u>

CCD	1024 x 1024, 12 bit
Shutter speed	25 frame/s

<u>*X-Ray Source Parameters*</u>

Voltage	80 – 100 KV
Current	0.3 A
Iris opening	80 %

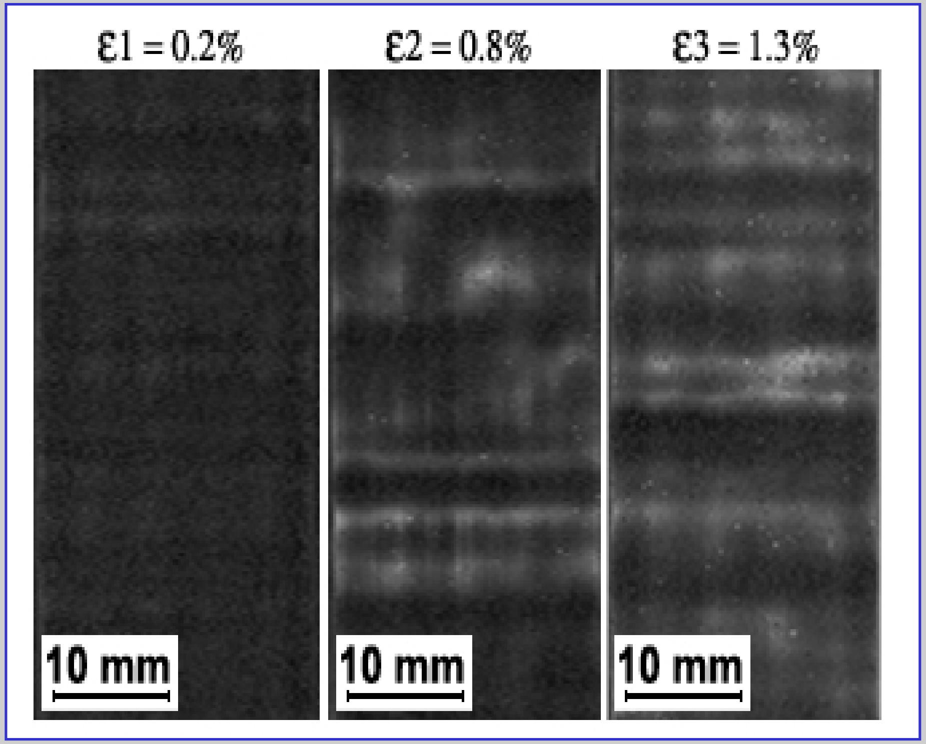
<u>Contrast Media</u> Di-iodomethane, 24 hours bath

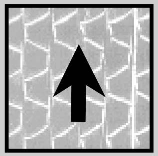
Results

Damage Observation by NDT

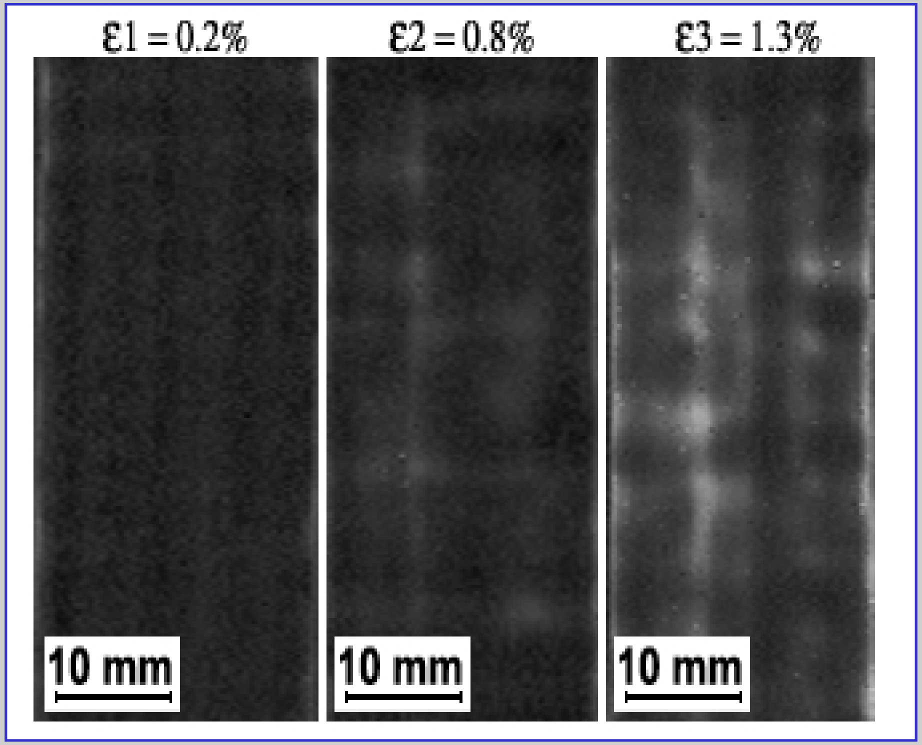
C-Scan Images

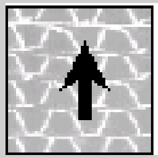
MACHINE Direction





CROSS Direction

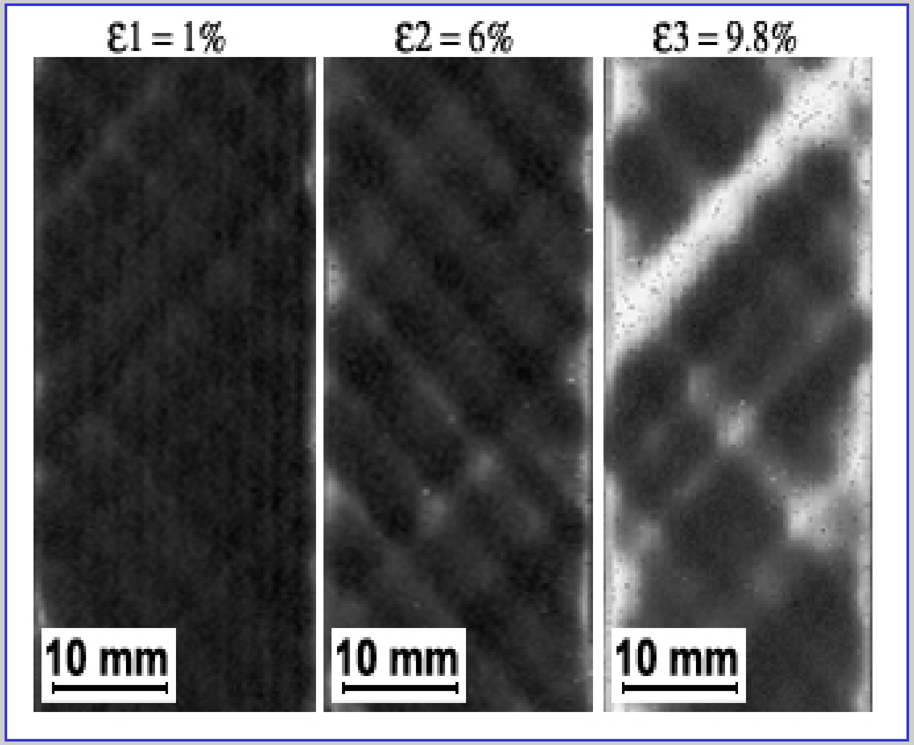


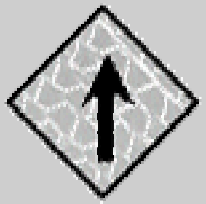


Damage Observation by NDT

C-Scan Images

BIAS Direction

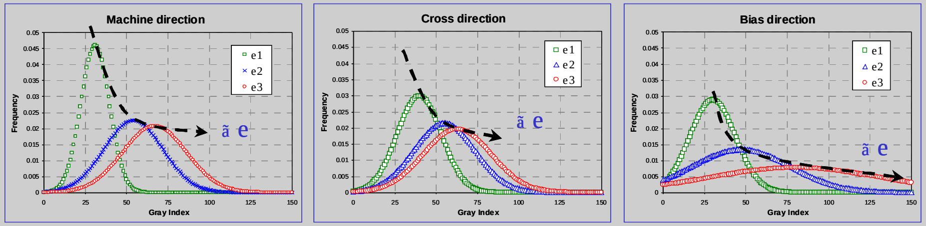




Results

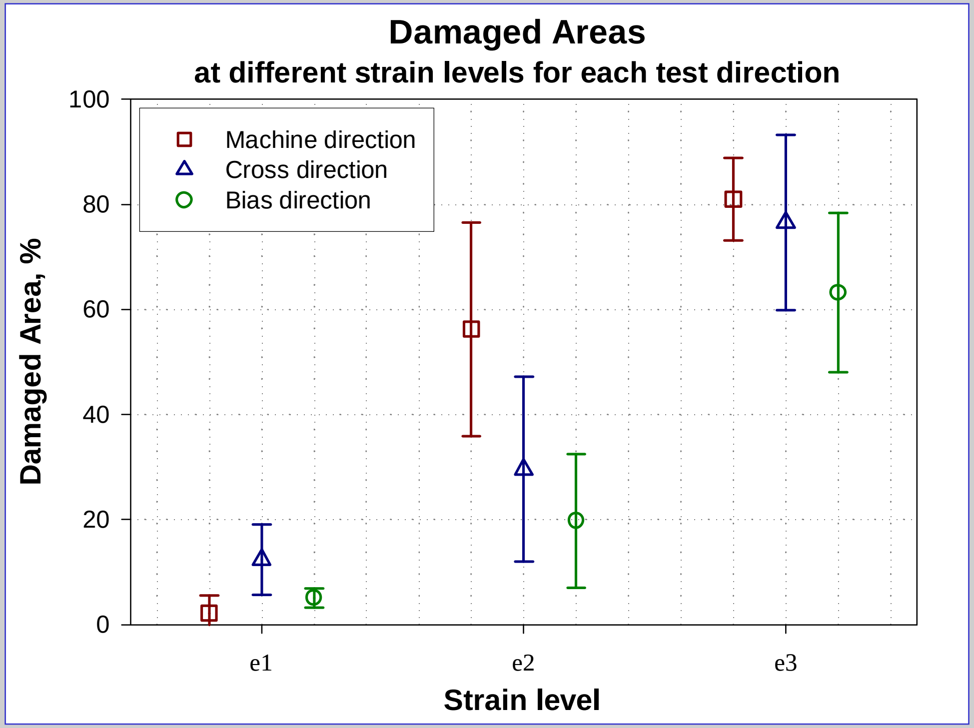
Damage Observation by NDT

Greyscale Histograms



Damaged Area

	MD and CD	BD
ε_1	0.2 %	1%
ε_2	0.8 %	6 %
ε_3	1.3 %	9.8%

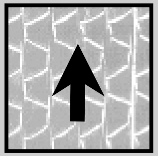


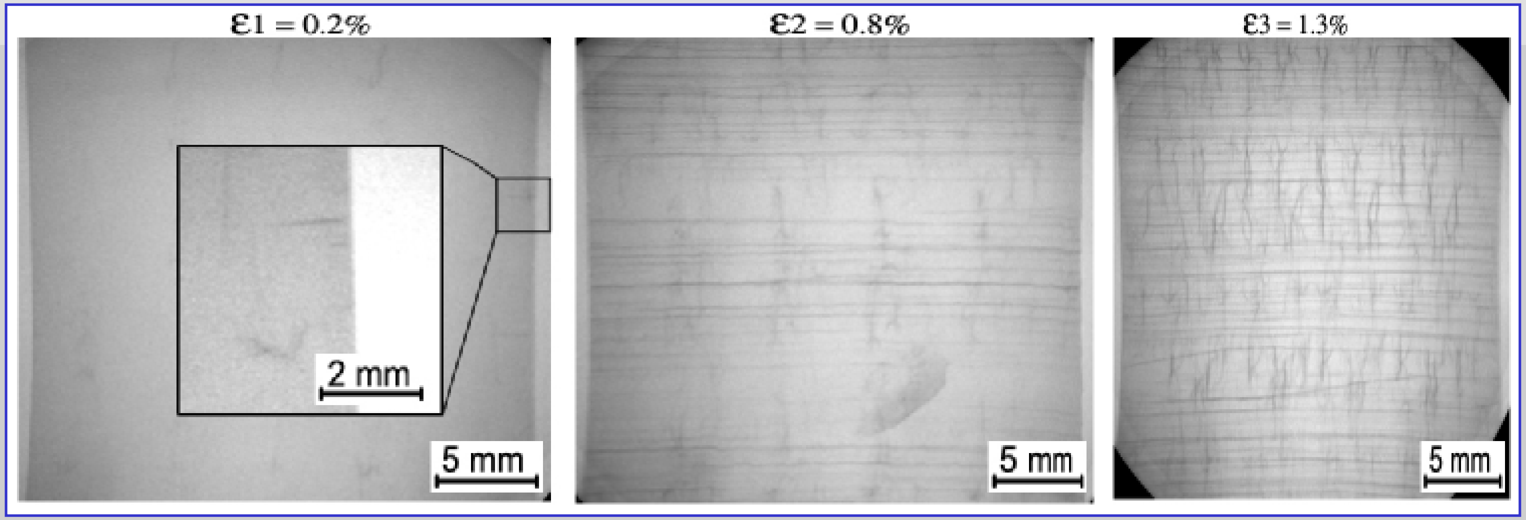
Results

Damage Observation by NDT

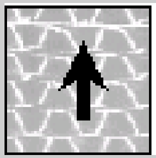
X-Ray

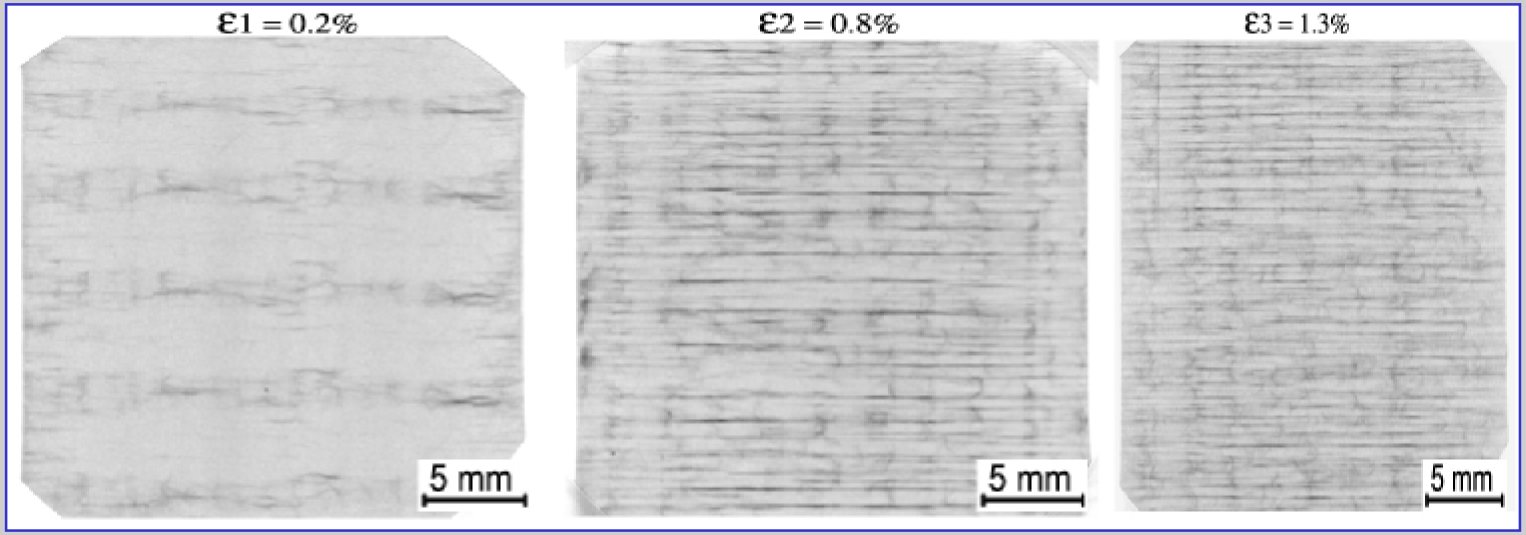
MACHINE Direction





CROSS Direction



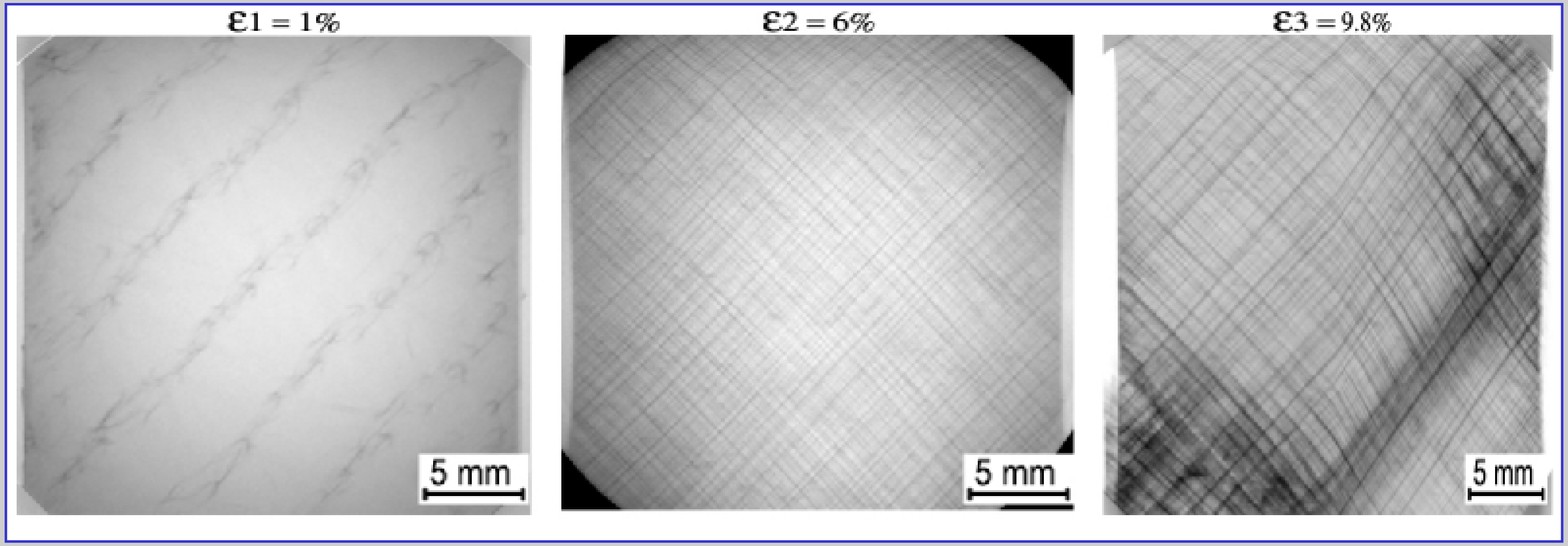


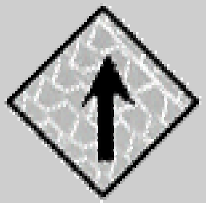
Results

Damage Observation by NDT

X-Ray

BIAS Direction

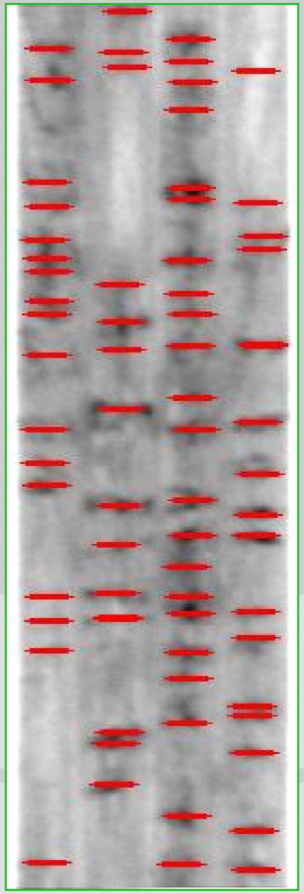


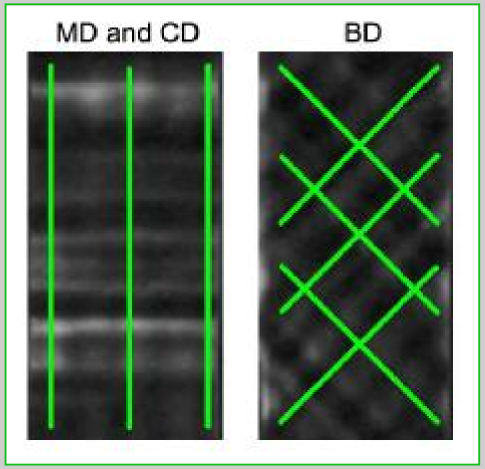


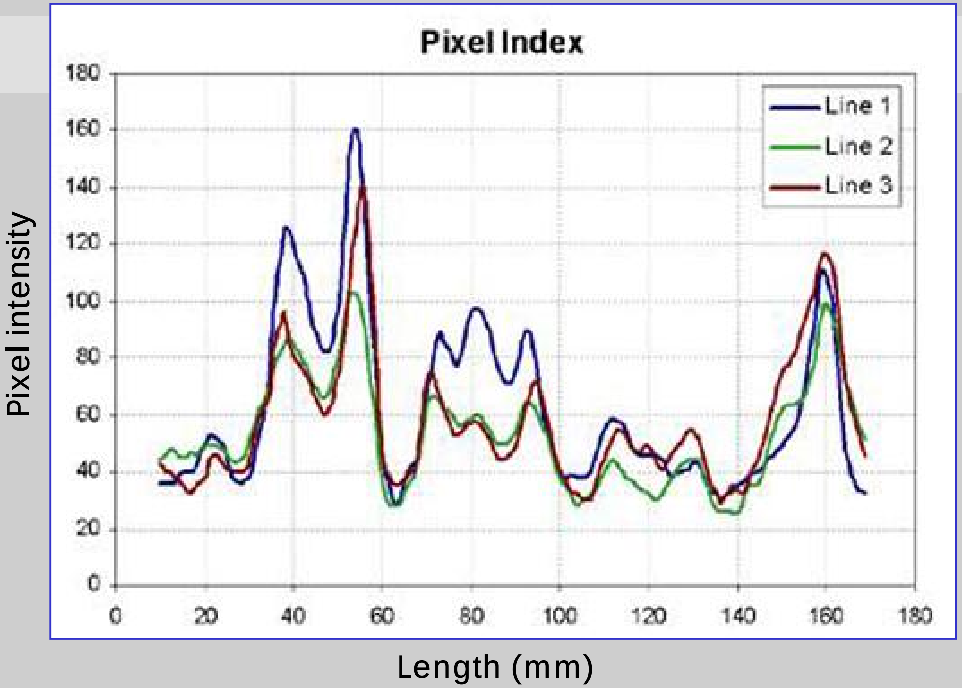
Results

Damage geometrical aspects

Damage Pattern measurements







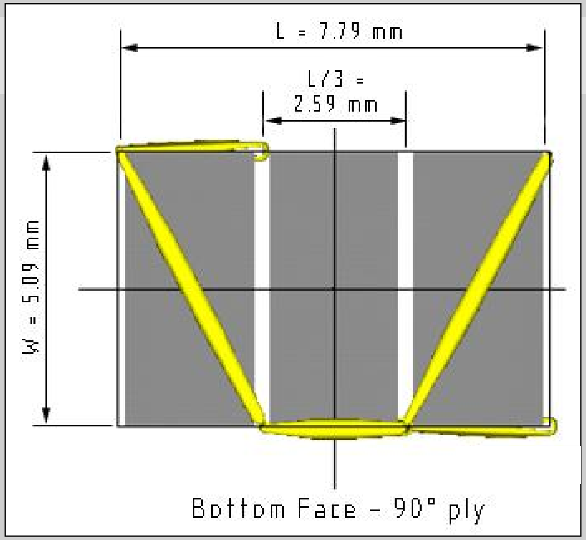
- **Side radiographies indicates that damage seems distributed repetitively into single fabrics which are are randomly stacked;**
- **Pixel's intensity is plotted along section;**
- **Signals are processed with FFT to have main characteristics distances between damages;**

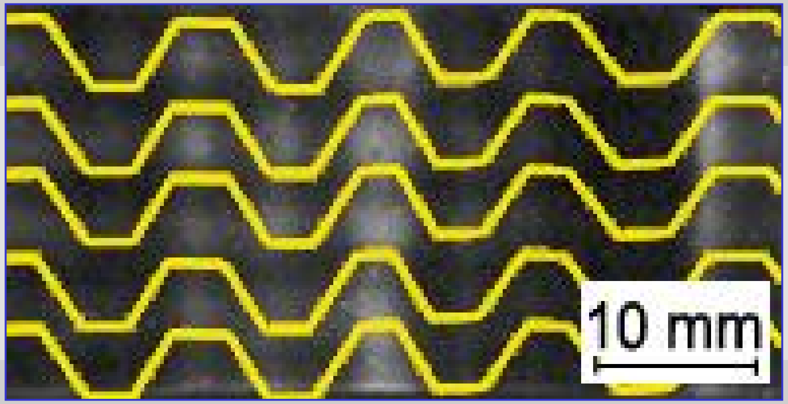
Results

Damage geometrical aspects

Damage Pattern measurements

	1st period L1	2nd period L2	3rd period L3	4th period L4
MD	2.63 mm	3.44 mm	4.97 mm	7.47 mm
CD	5.6 mm	n.p.	n.p.	n.p.
BD (+45°)	2.3 ÷ 2.77 mm	3.46 ÷ 4.61 mm	5.54 mm	6.93 mm
BD (-45°)	5.54 mm	n.p.	n.p.	n.p.





- **Characteristic distances are close to unit cell characteristic dimensions;**
- **Stitching pattern superposed with ultrasonic images coincide well with damage pattern.**

DAMAGE INITIATE and DEVELOPS FROM STITCHING INDUCED DEFECTS

Conclusions

- Damage has been initially monitored in its evolution by AE recordings and Characteristic regions has been appreciated;
- Different damage mechanism grow at different strain levels;
- Typical damage modes has been observed by non-destructive X-Ray and Ultrasonic techniques;
- Along MD and CD:
  - After initial micro-cracks, damage develops steadily, interesting mainly the matrix, until high strains are reached;
  - At high strains, when matrix cracking mechanism saturate, damage interests longitudinal fibers and grows unsteady till final collapse.
- Along BD:
  - Because of matrix dominated characteristic, stiffness decrease quickly has matrix damage starts to grow;
  - At high strains, some matrix cracks merge together into edge-to-edge flaws that grow leading to final separation of specimen.
- Damage grows following a typical pattern which characteristic lengths are very close to stitching pattern geometry;
- Stitching induced defects are damage nucleation regions.

Future Work

- **Damage monitoring by refined DC technique;**
- **Damage mode direct identification by optical microscopy;**
- **FE Numerical simulation of damage development.**

Thank you for attention.

Any questions ?