Experimental methodology and finite element analysis for damage studies in textile composites

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Acknowledgements

The presentation reports collaborative research results of:

K.U. Leuven
Larissa Gorbatikh
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Thanh Truong Chi
Katleen Vallons
Bjorn Van den Broucke
Ignaas Verpoest
Matteo Vettori
Jian Xu

3Tex
Alexander Bogdanovich
Dmitry Mungalov

EADS Innovation Works
Peter Middendorf
Bjorn Van den Broucke

Uludag University
Mehmet Karahan

Osaka University
Tetsusei Kurashiki
Kenta Hamada
Satori Hirosawa
Hiroaki Nakai
Masaru Zako

The research in K.U. Leuven was funded by:

EU: TECABS; ITOOL; MOMENTUM; Marie Curie HPMT-CT-2000-00030
Flanders: STWW/000148; GBOU/020209
K.U. Leuven: GOA/98/05; OT/02/58

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2. Experimental: Road map for characterisation of damage in textile composites
3. Example: 2D and 3D woven glass/epoxy composites
4. Finite element analysis of damage: Predictions and numerical artifacts
5. Conclusions: Overview of damage studies with different textile architectures

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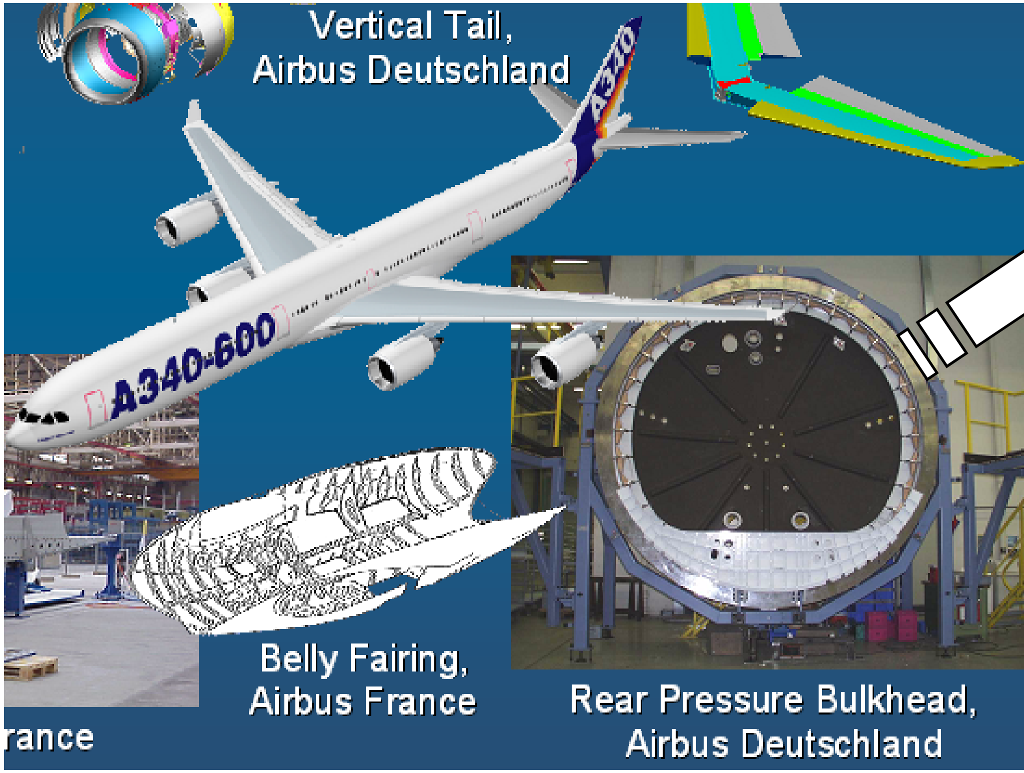
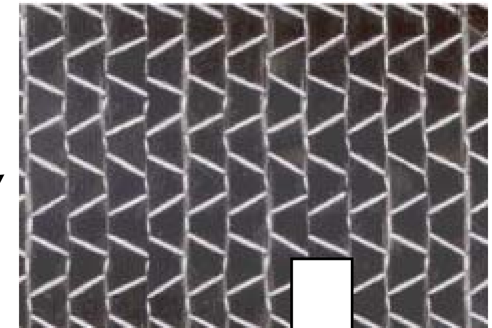
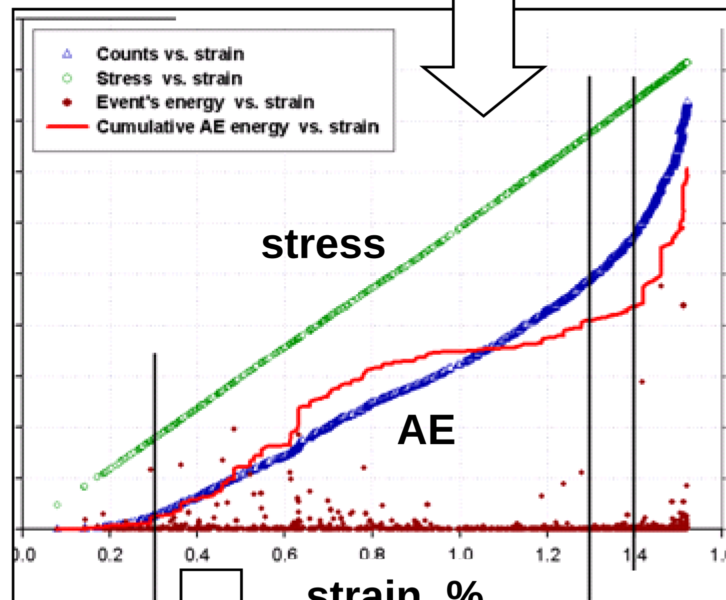
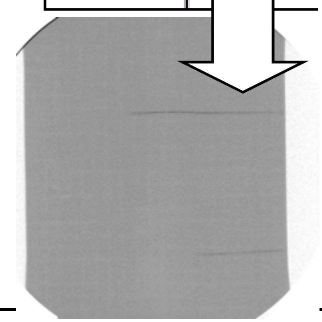
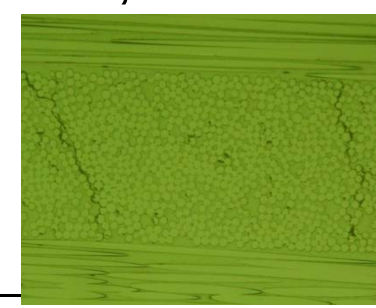
Design strain and damage initiation theshold











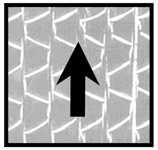
No stiffness reduction up to failure

Design strain: 0.3 ... 0.4%

Ultimate strain / Design strain = 4...5

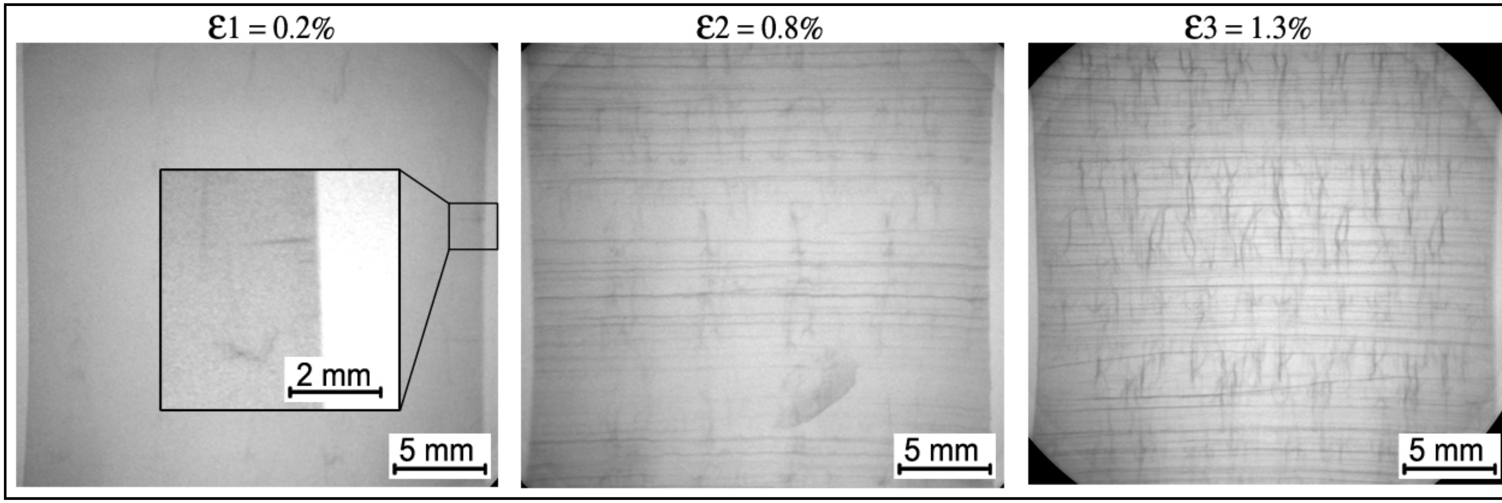
Corresponds to the damage initiation threshold

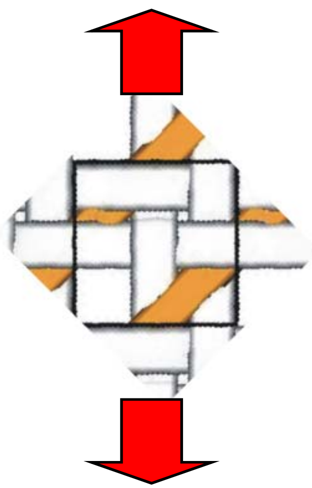
Progressive damage: Patterns



MD

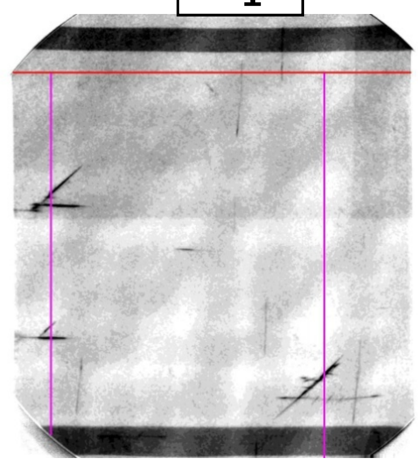
Carbon/
epoxy
NCF



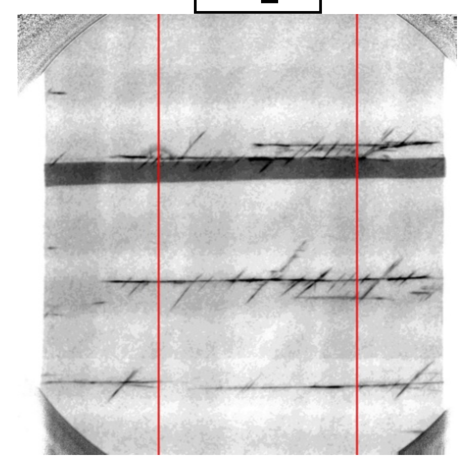


Carbon/ epoxy
3-axial braid

ε_1

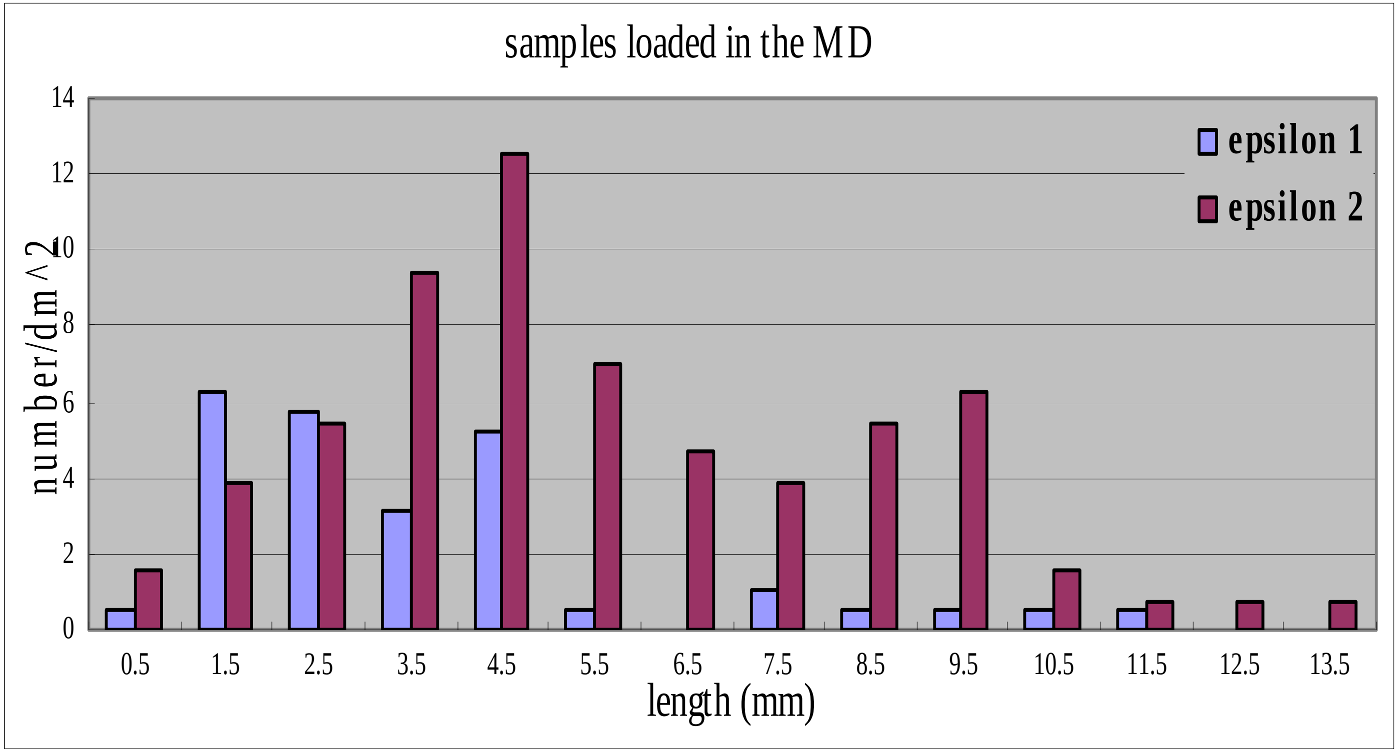


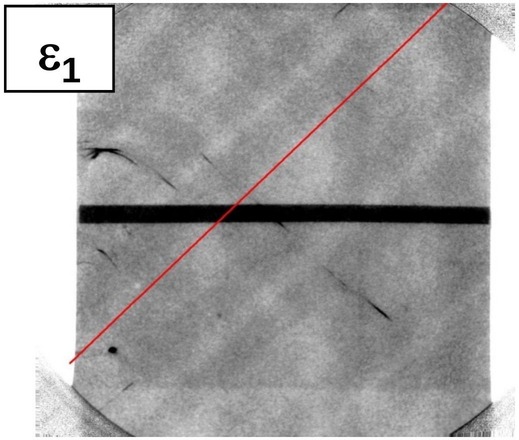
ε_2

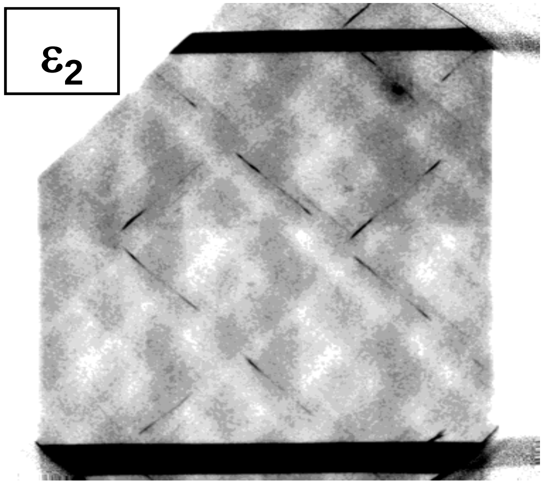


Progressive damage: Evolution of crack length distribution

Carbon/ epoxy
3-axial braid

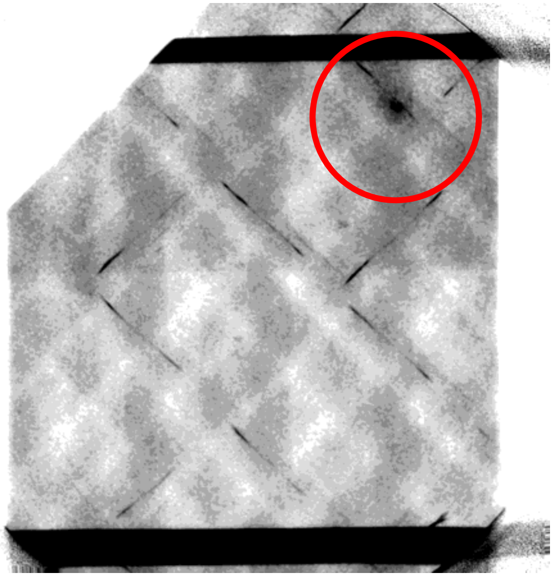


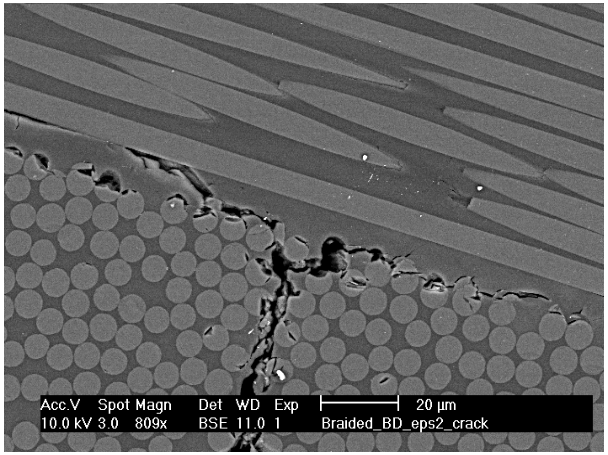


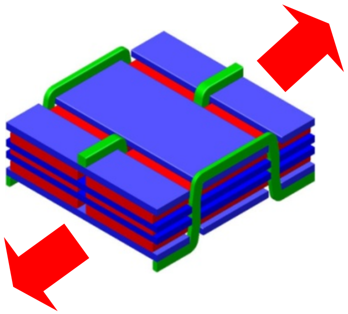


Transversal cracks and bundle-boundary cracks

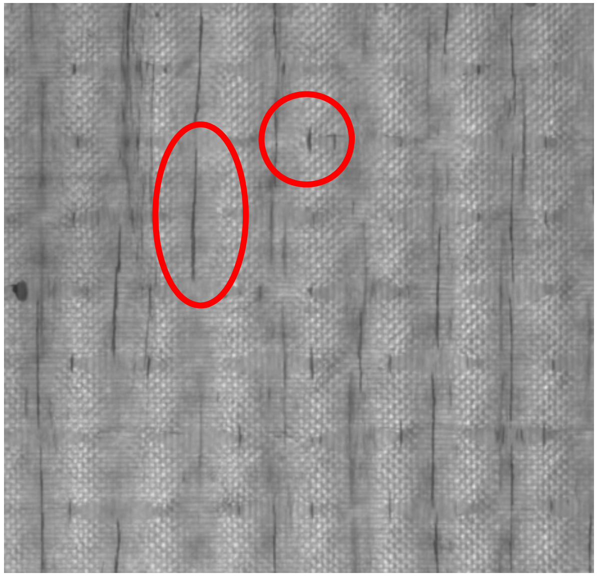
Carbon/ epoxy
3-axial braid

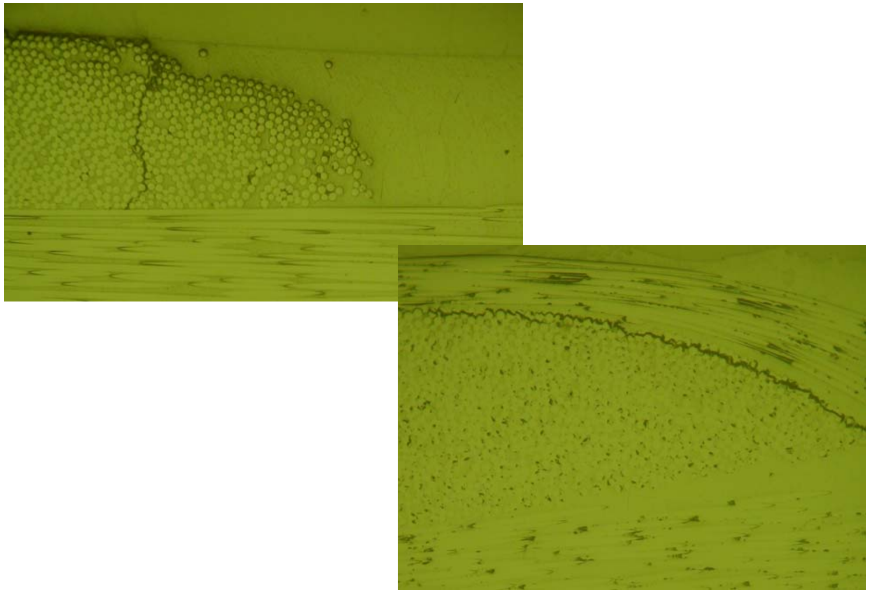




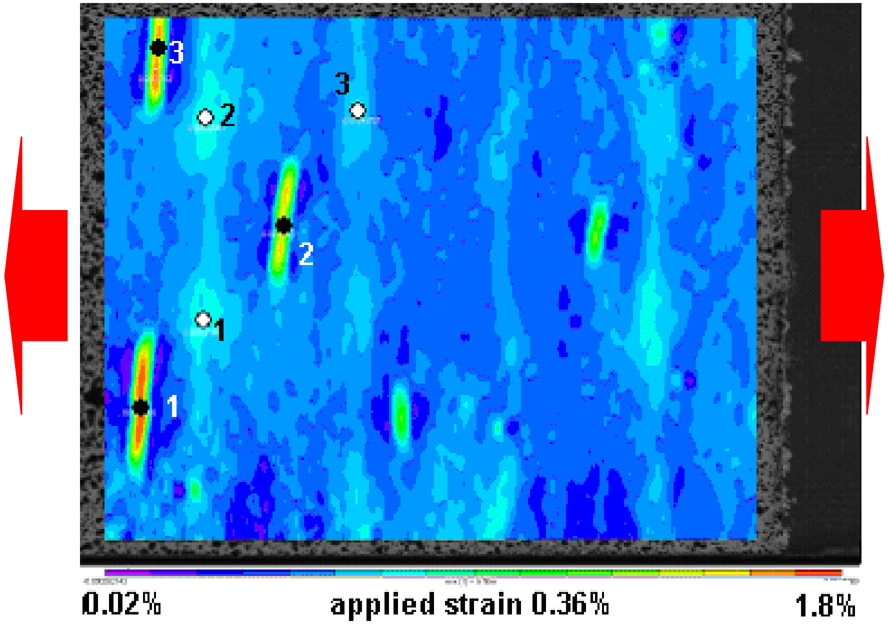


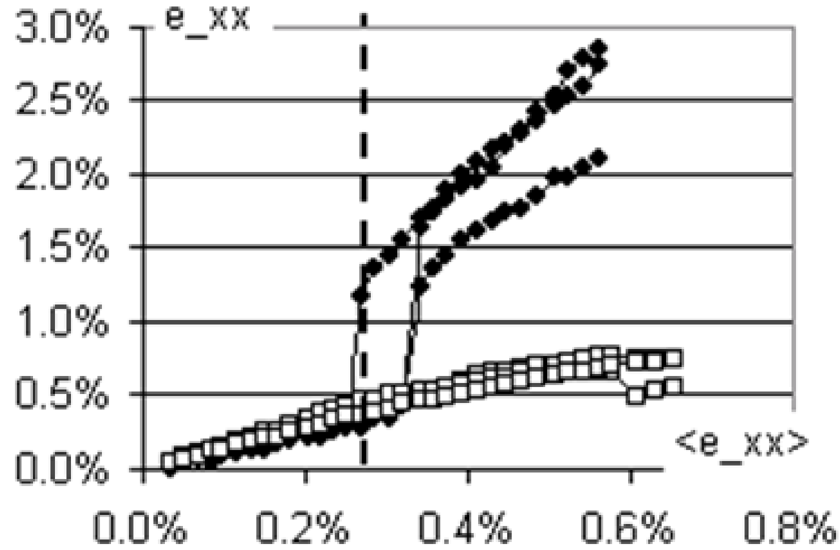
Glass-epoxy
3D woven



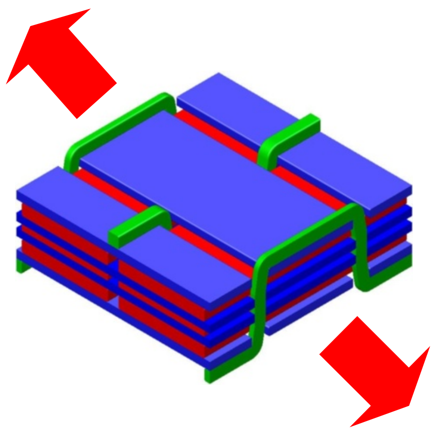


3D woven composite materials used in this study were provided by 3Tex Inc

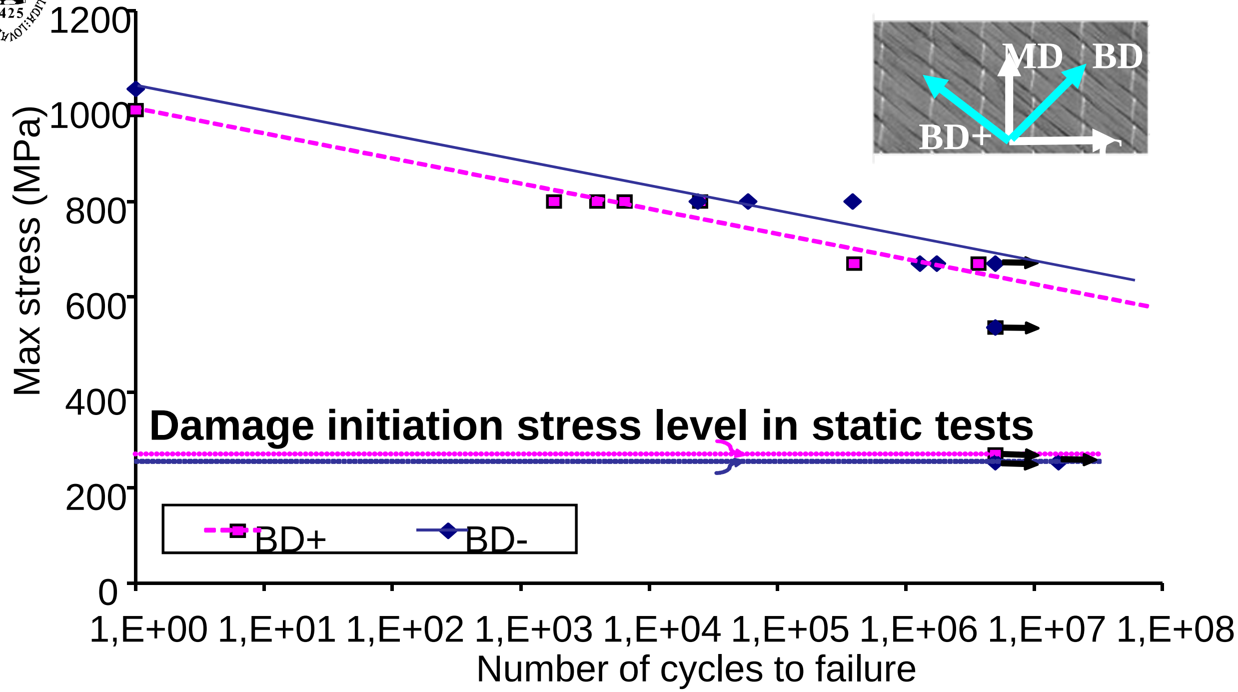




Glass-epoxy
3D woven

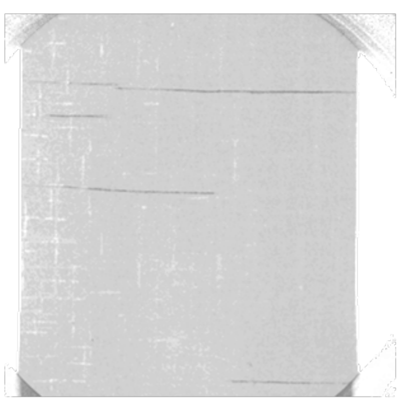


Quasi-static damage initiation threshold and tension-tension fatigue



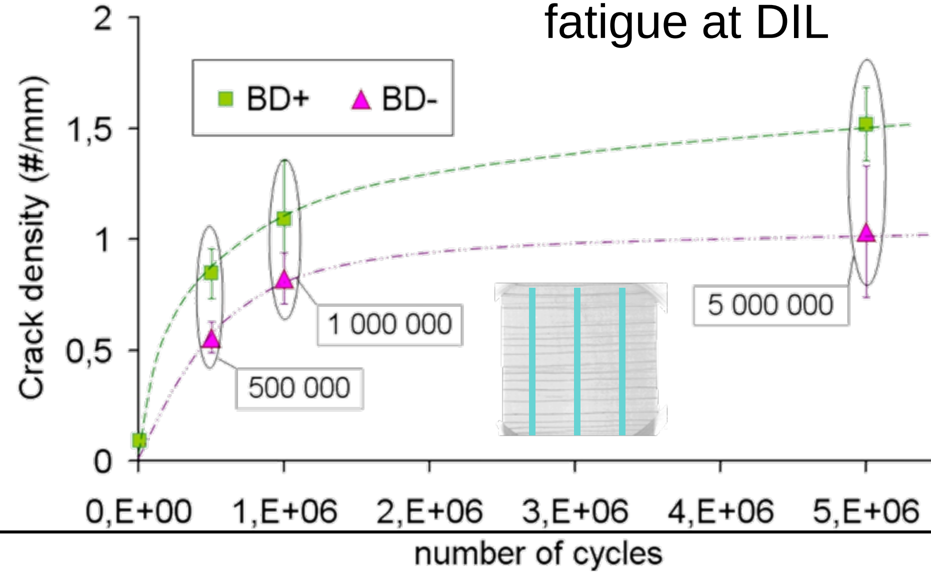
Carbon/epoxy NCF

fatigue at DIL



$5x10^3$ cycles

$5x10^5$ cycles



Tensile damage features in textile composites

- Damage induced by processing: Thermal and cure stresses
- Damage initiation (“first ply failure”, but localised)

  Transversal damage inside fibre bundles

  Boundaries of the bundles
- Damage propagation and associated reduction of the material stiffness

  Grow and stoppage of the cracks

  Multiplication of the cracks

  Correlations with the reinforcement structure

  Fibre fracture
- Correlations quasi-static – fatigue

"I have six honest serving men (they taught me all I knew). Their names are..."

...What is happening to the material stiffness as damage is progressing?

Non-linear tensile diagram

...Why has damage been initiated?

The cause of the first crack(s)

...When has damage been initiated?

Damage initiation threshold

...How does damage progress?

Propagation and multiplication of cracks and local debondings

...Where are the damage locations inside the reinforcement unit cell?

Inside the impregnated yarns? On their boundaries? In matrix pockets?

...Who (which damage modes) are in evidence?

Transversal? Shear? Debondings? Delaminations? Splitting?..

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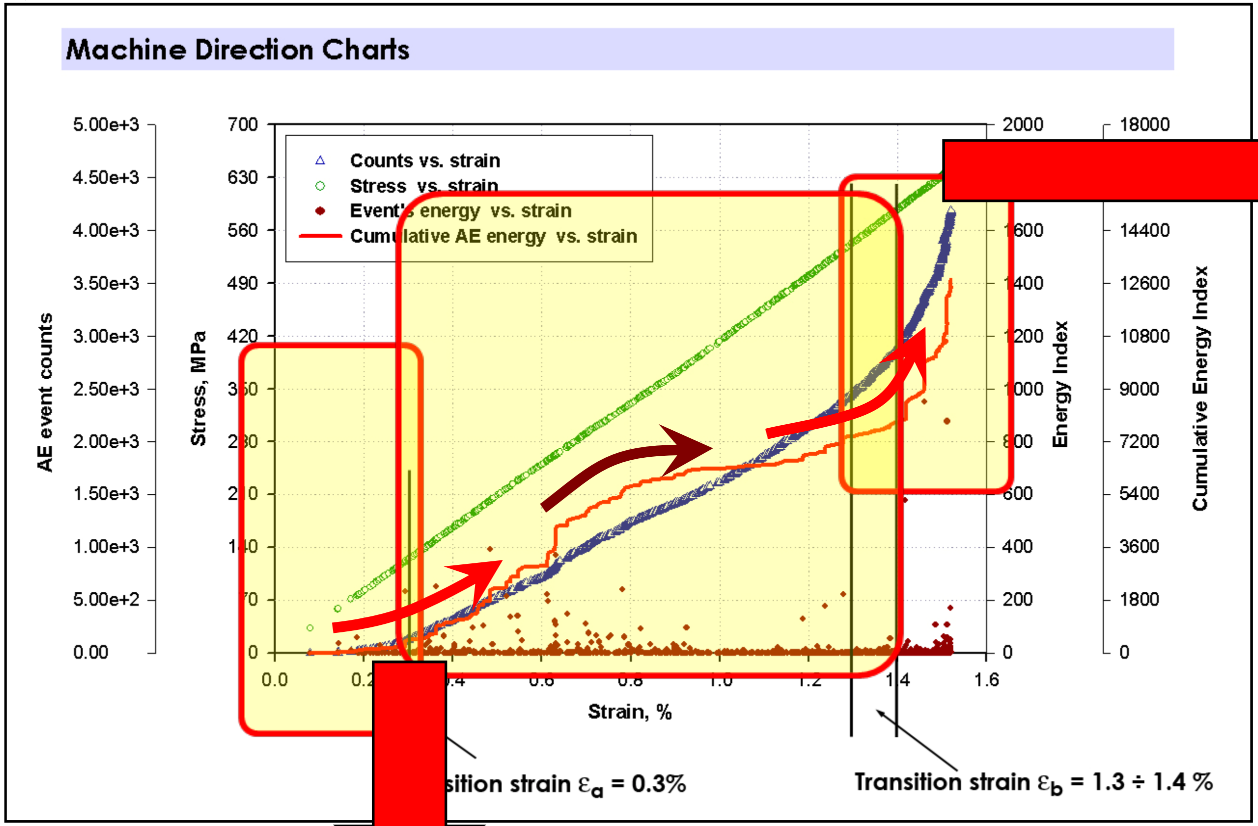
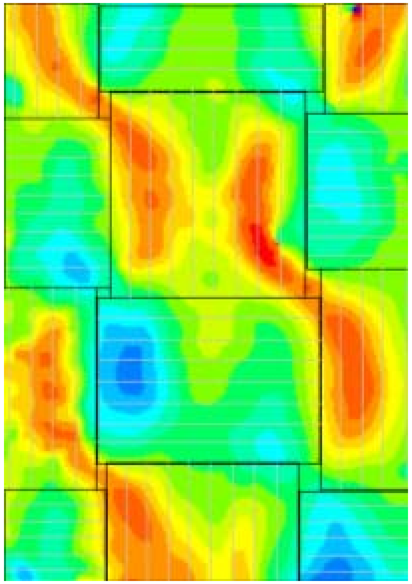
Tensile test with strain-mapping and AE



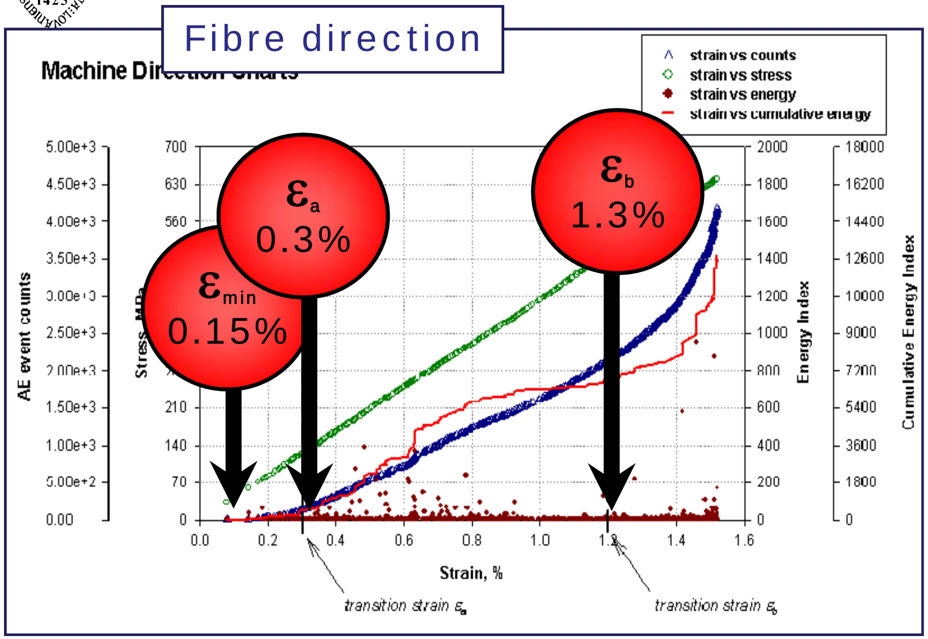
Tension diagram

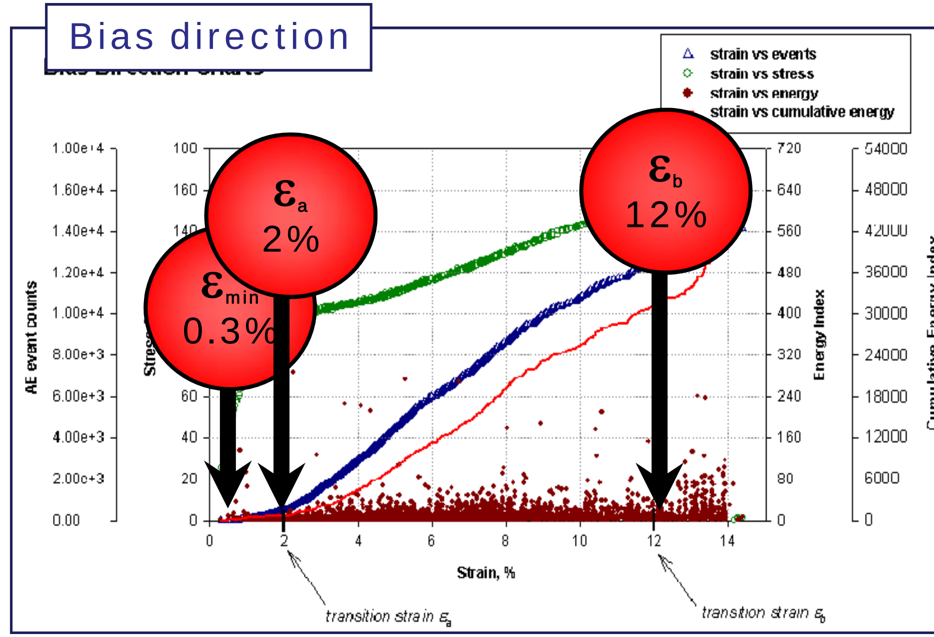
AE: Damage initiation threshold

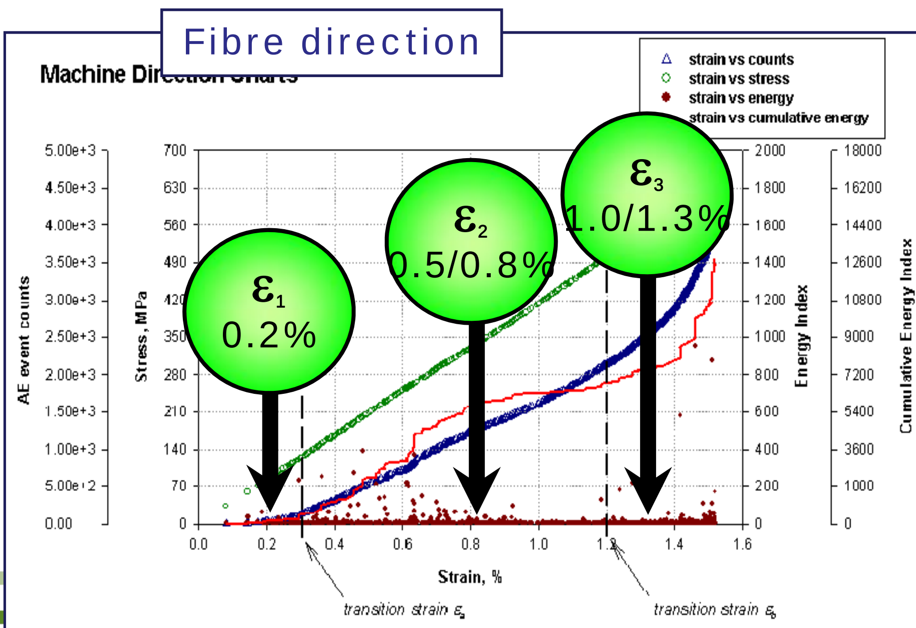
Strain maps

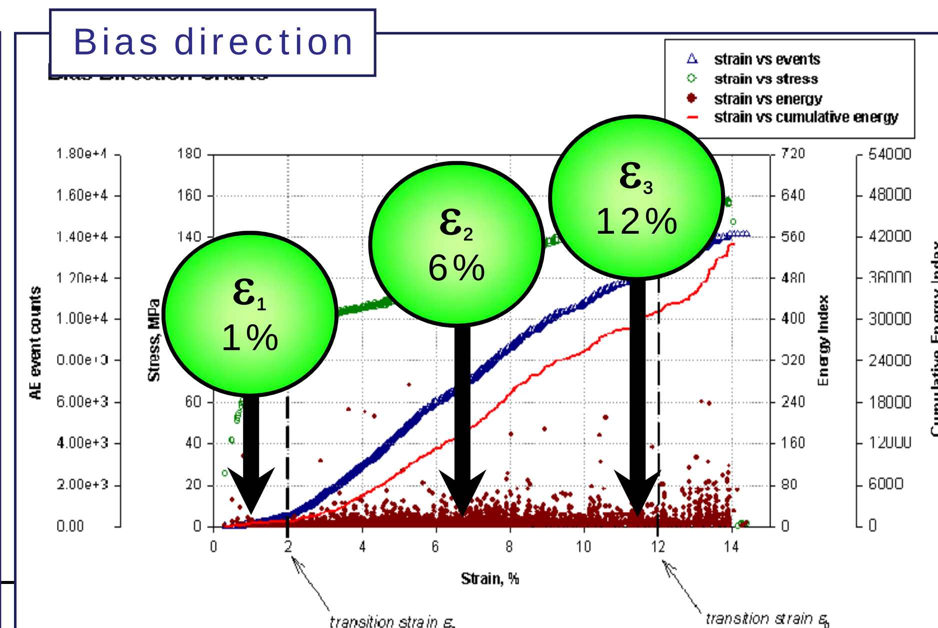


Damage initiation thresholds and characteristic strains for “post-mortem”



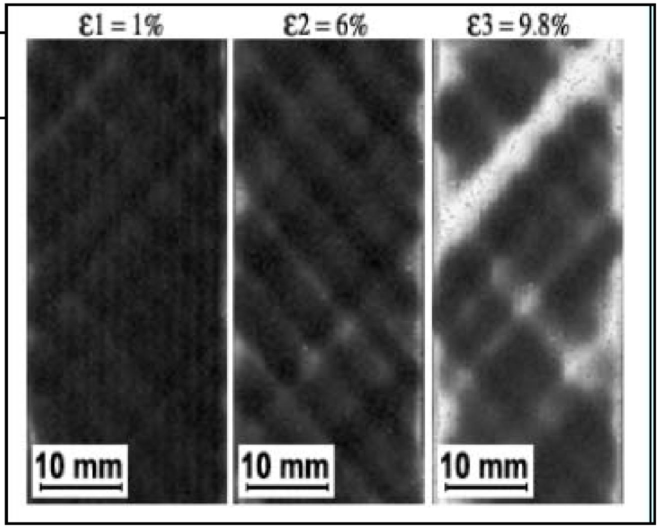






C-scan and X-ray of damaged samples

C-scan

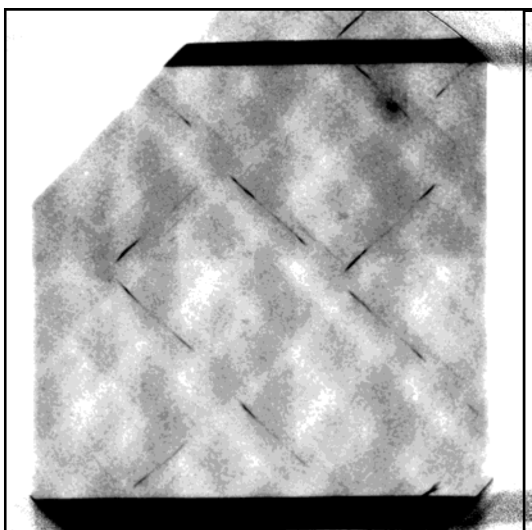


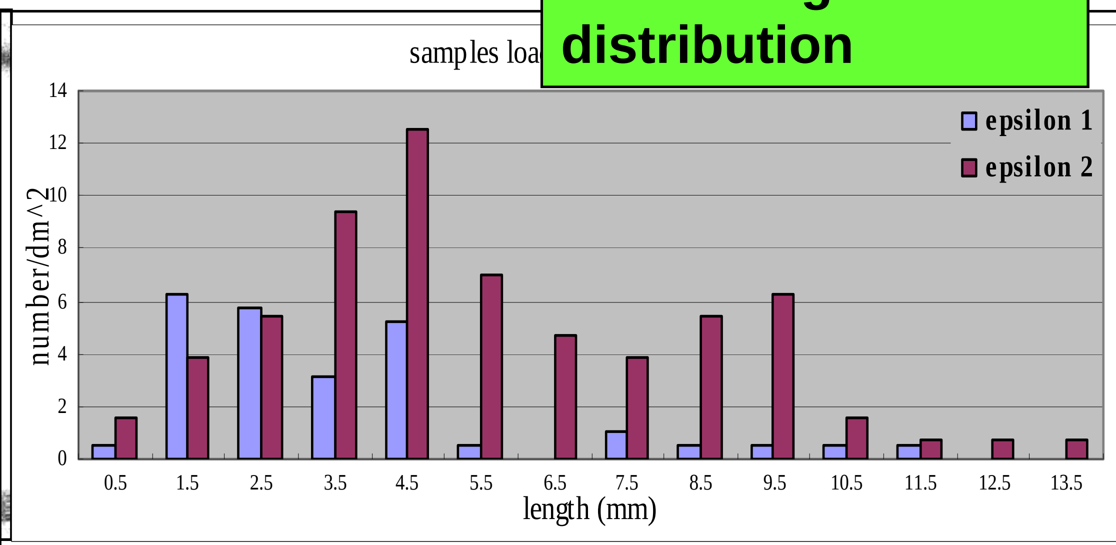
Dynamics of extent of damage

Damage periodicity

Cracks placement and orientation

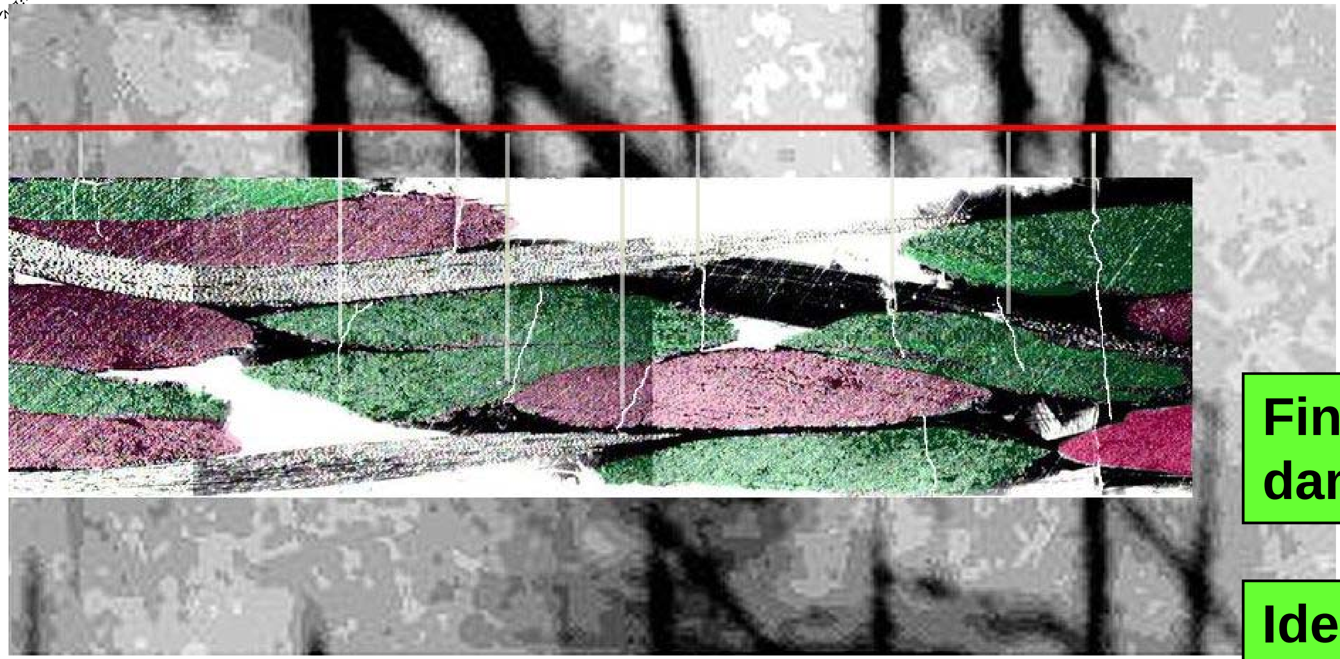
X-ray





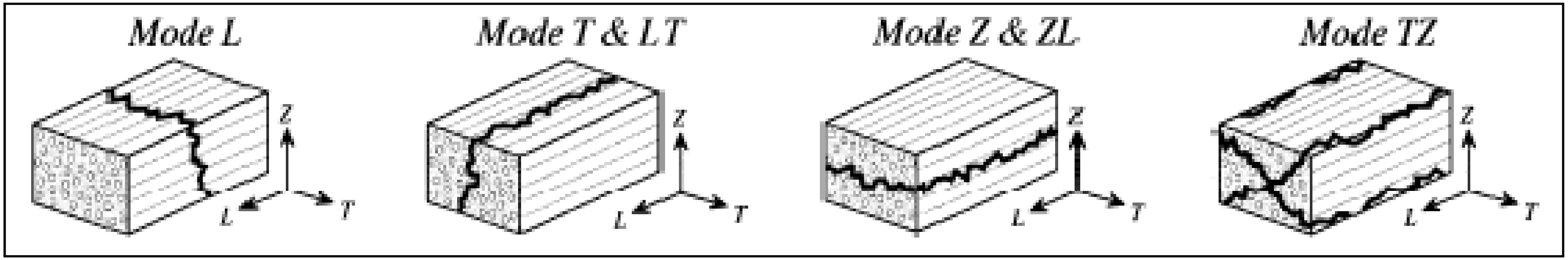
Crack length distribution

Optical microscopy

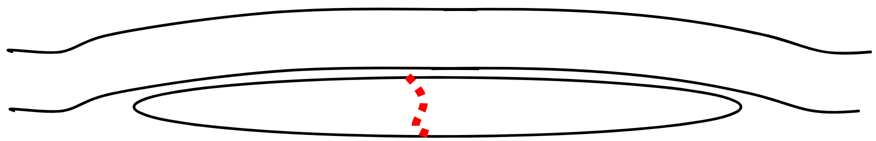


Fine structure of damage

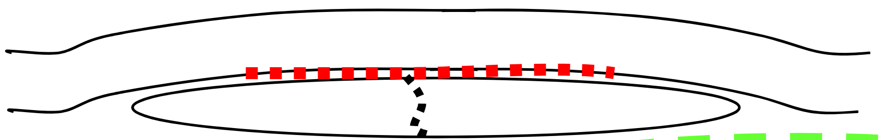
Identification of damage modes



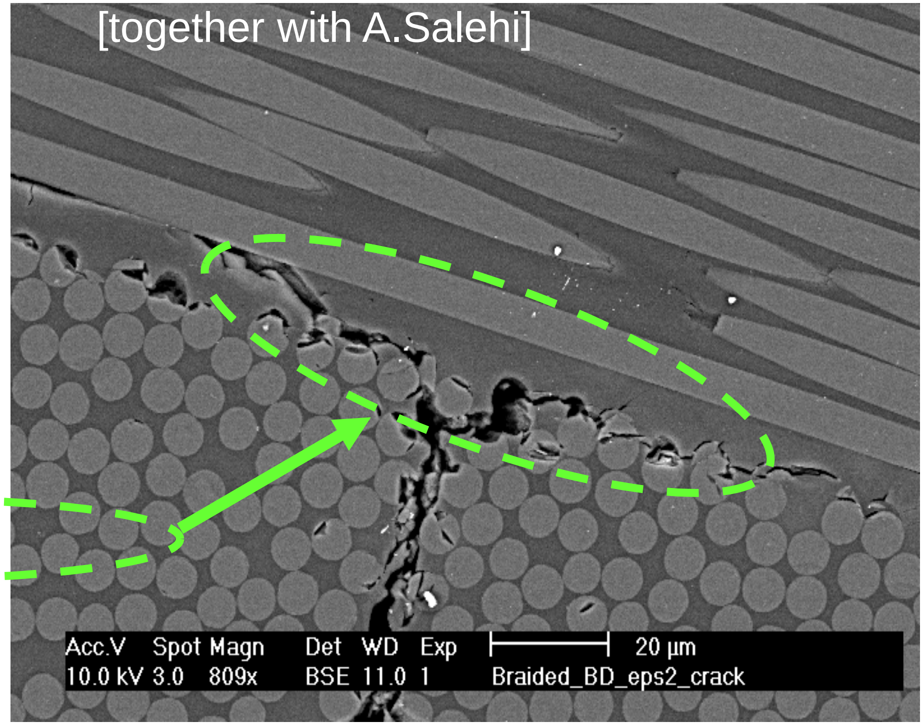
SEM



ε_1 - damage initiation: transverse cracks (inter-fibre failure)

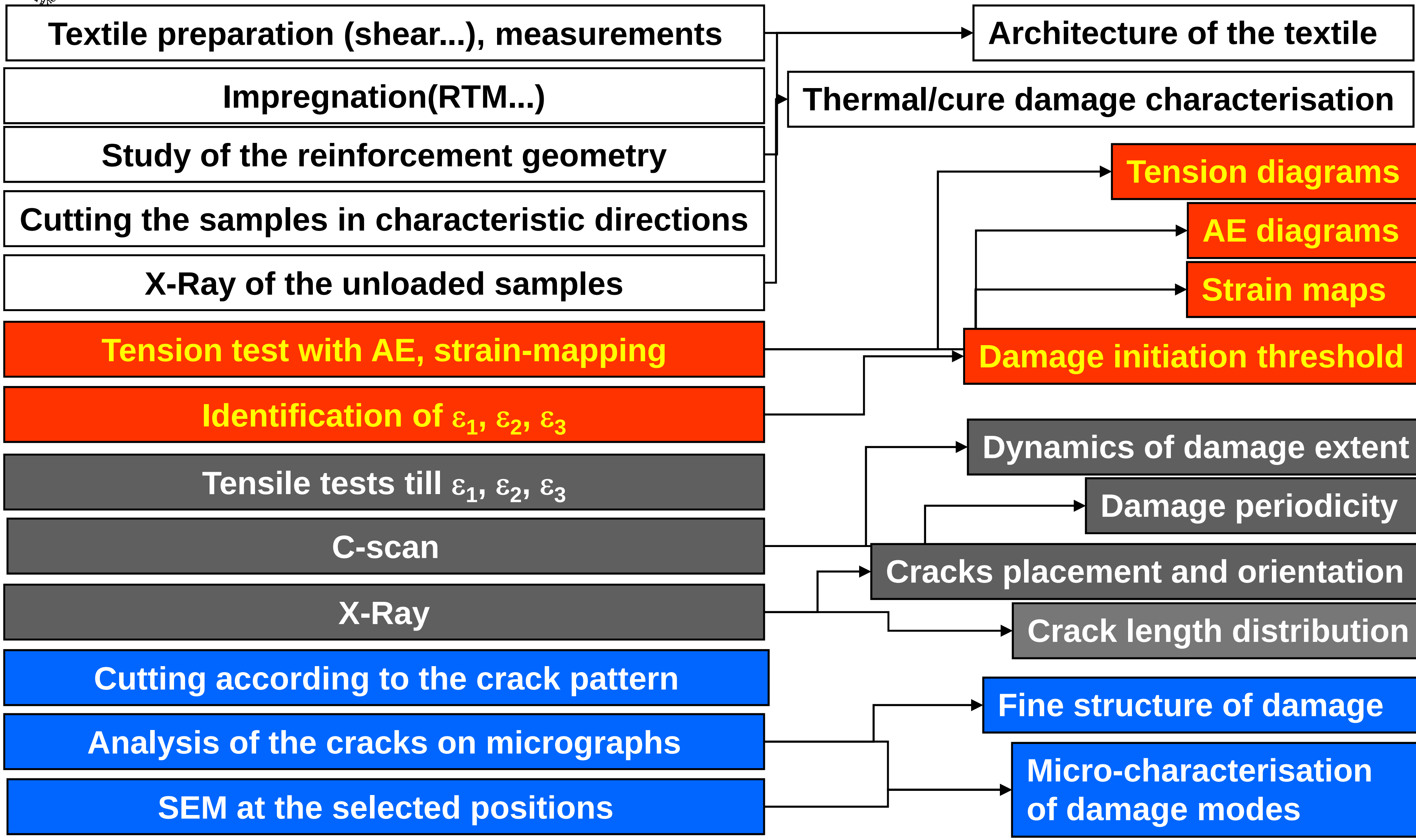


ε_2 - damage propagation: boundary crack



Micro-characterisation of damage modes

Experimental road map



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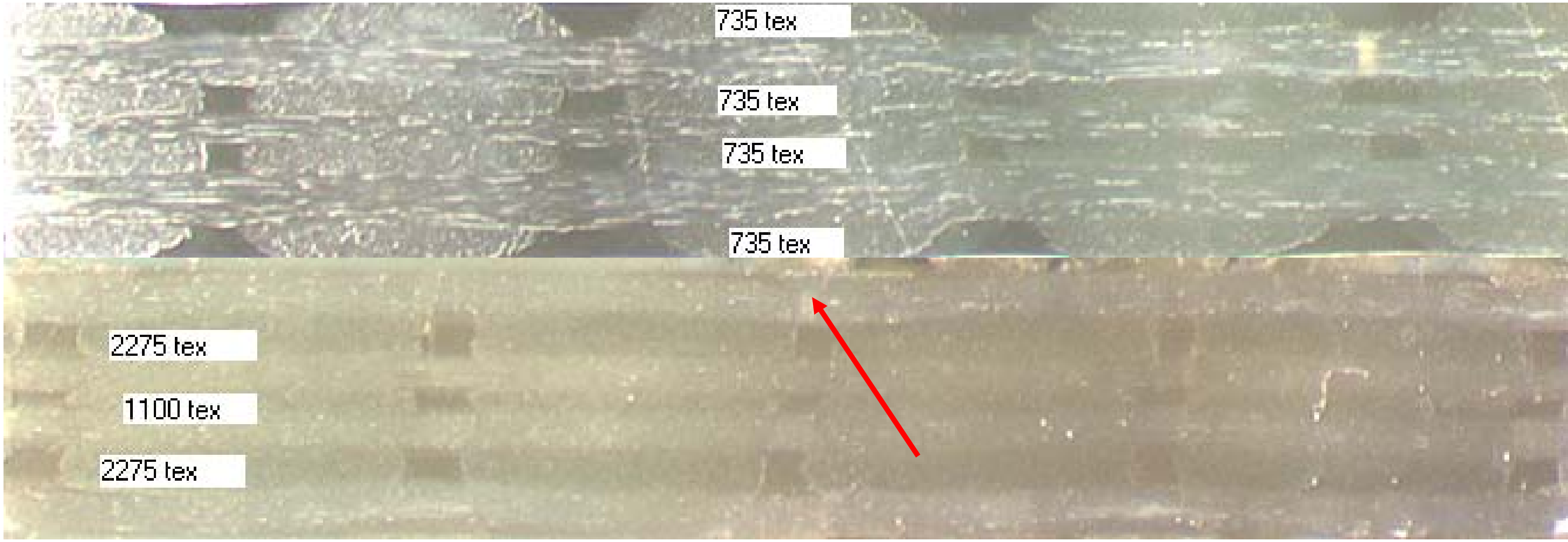
collaborative research with 3Tex: A.E. Bogdanovich, D. Mungalov

96 oz 3WEAVE® E-Glass 2022 Silane Sized
Part No: P3W-GE044

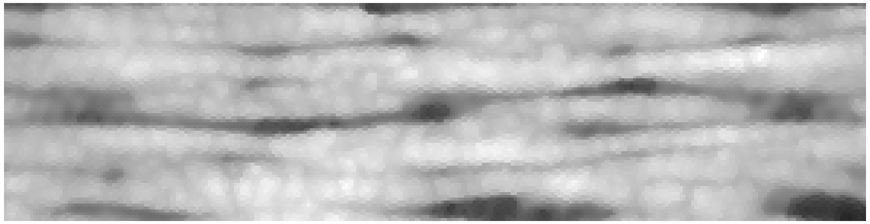


Note: 1. Slight crimp of the fill caused by compaction in VARTM

2. Almost rectangular shape of the cross-sections

Plain weave laminate

Crimped warp/weft, nested plies



Parameters of 3D and plain woven fabric

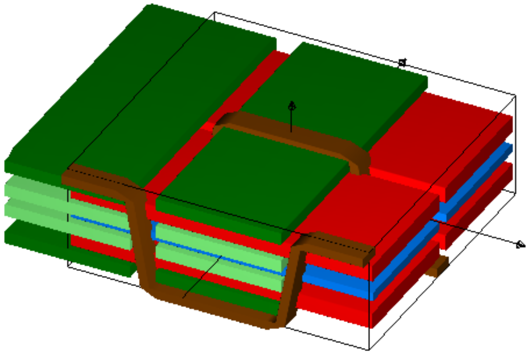
3D – GE044 3WEAVE ®

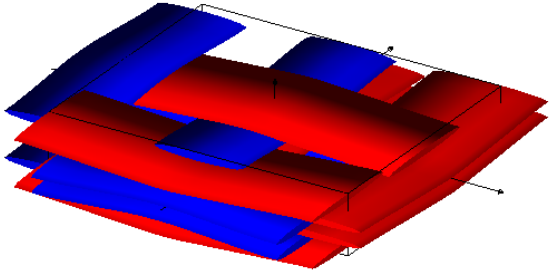
Fabric and composite plate	1 ply
Areal density, g/m2	**3255**
Thickness, mm	**2.6**
Ends (straight) per cm per layer	2.76
Picks per cm	2.64
Z-yarns per cm	2.76
VF, %	**48.9**
Yarns	**tex**
Warp	
layer 1,3	2275
layer 2	1100
Z-yarns	276
Fill (double yarns)	
layer 1,4	1470
layer 2,3	1470

Warp : Fill : Z = 49% : 48% : 2%

Plain weave 4 plies: 0°/90°/90°/0°

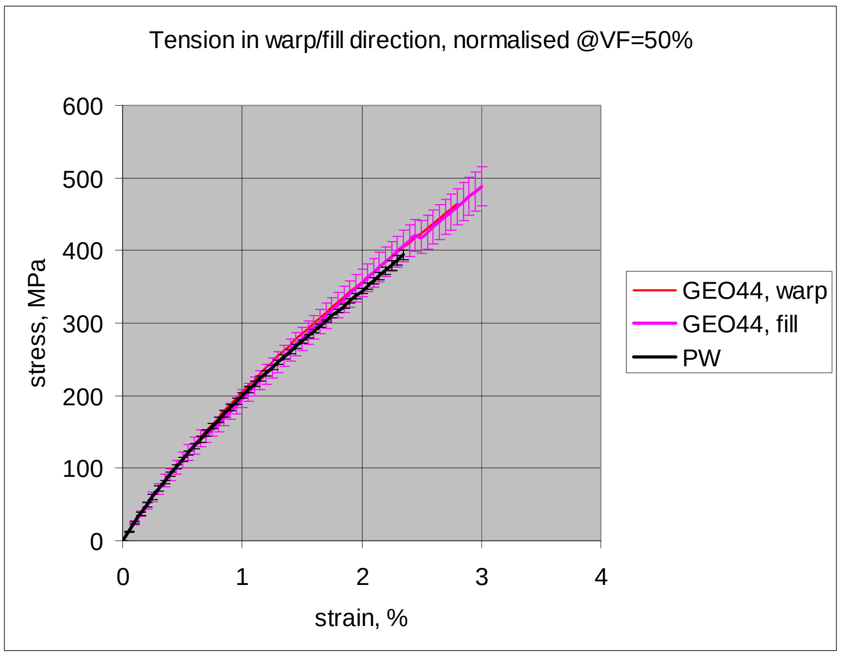
Fabric and composite plate	4 ply
Areal density, g/m2	**3260**
Thickness, mm	**2.45**
Ends per cm	5.08
Picks per cm	6.19
VF, %	**52.4**
Yarns	**tex**
Warp and weft	2275

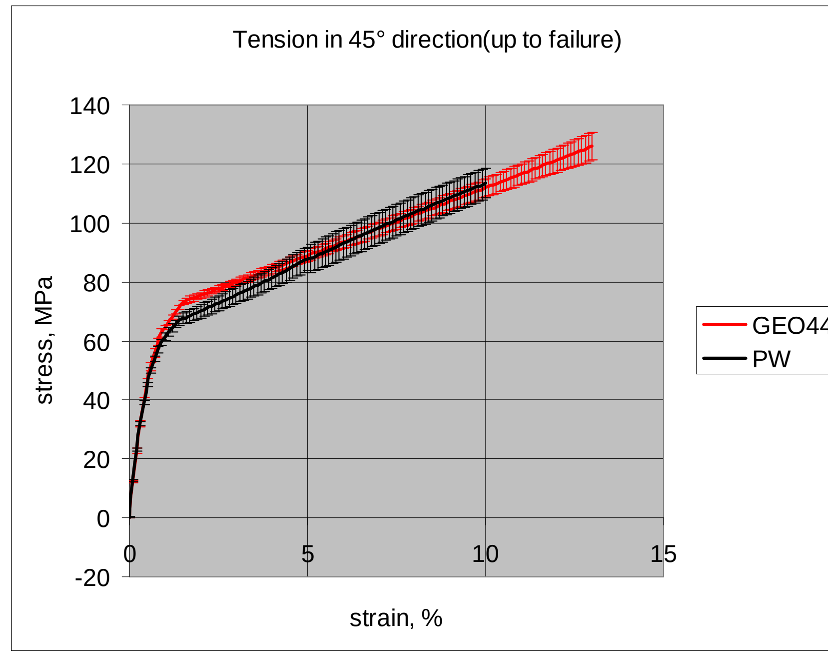




Elastic constants and tension diagrams

	VF, %		E, MPa		Poisson		sigU, MPa		epsU, %		eps1, %		eps2, %	
GE044	49.3	Warp	24297	*1207*	0.141	*0.071*	429	*34*	2.74	*0.29*	0.43	*0.04*	0.54	*0.04*
		Fill	25112	*2340*	0.126	*0.093*	486	*5*	3.33	*0.27*	0.37	*0.06*	0.59	*0.04*
		45	12913	*485*	0.502	*0.21*	124	*5*	14.1	*0.4*	0.63	*0.07*	0.78	*0.07*
PW	52.4	Warp	26005	*1558*	0.264	*0.148*	413	*4*	2.38	*0.02*	0.26	*0.04*	0.43	*0.06*
		45	12233	*444*	0.61	*0.148*	109	*6*	9.7	*0.4*	1.23	*0.35*	2.33	*0.93*





- No difference in Young moduli

- Decreased Poisson for the 3D fabric (inside the scatter?)

Strength

	VF, %		E, MPa		Poisson		sigU, MPa		epsU, %		eps1, %		eps2, %	
GE044	49.3	Warp	24297	*1207*	0.141	*0.071*	429	*34*	2.74	*0.29*	0.43	*0.04*	0.54	*0.04*
		Fill	25112	*2340*	0.126	*0.093*	486	*5*	3.33	*0.27*	0.37	*0.06*	0.59	*0.04*
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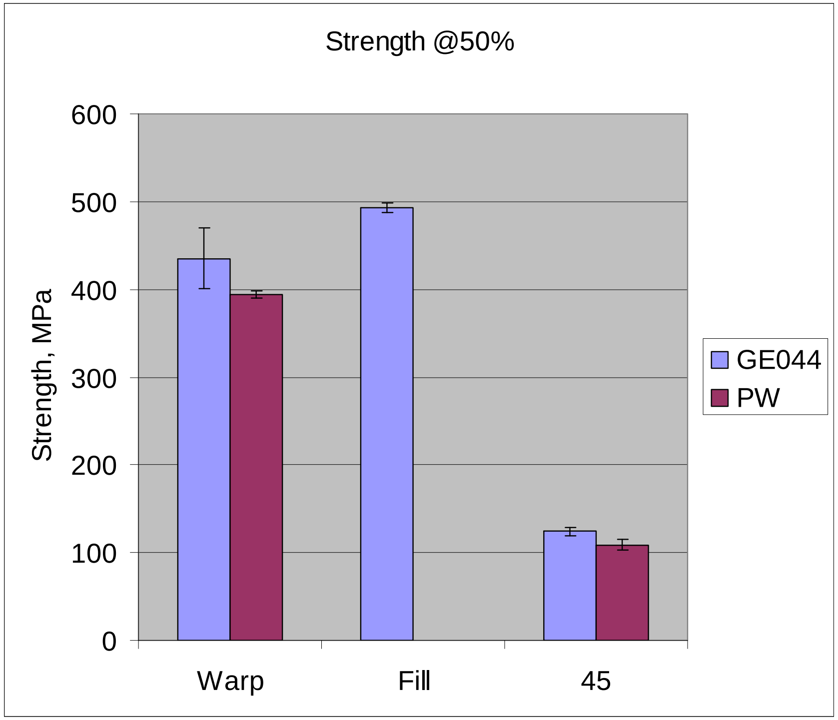
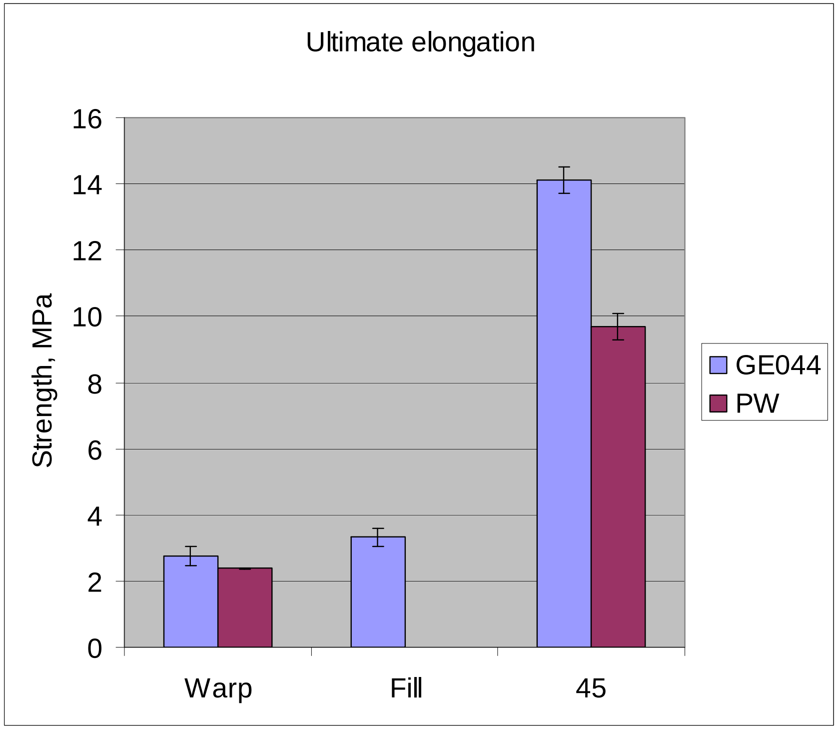
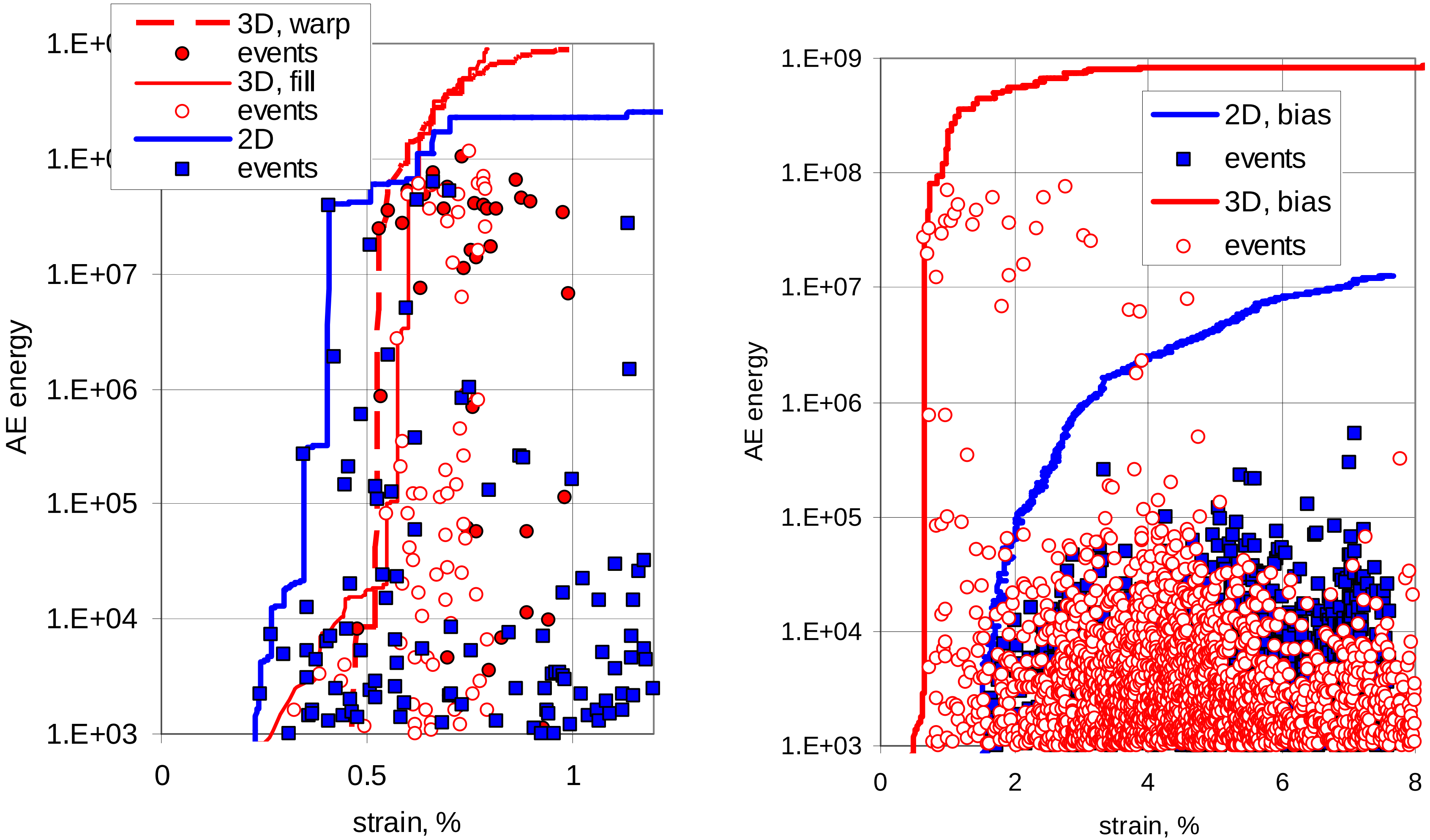




3D composite: higher strength (+10%), higher elongation

Acoustic emission



Damage thresholds

	VF, %		E, MPa		Poisson		sigU, MPa		epsU, %		eps1, %		eps2, %	
GE044	49.3	Warp	24297	*1207*	0.141	*0.071*	429	*34*	2.74	*0.29*	0.43	*0.04*	0.54	*0.04*
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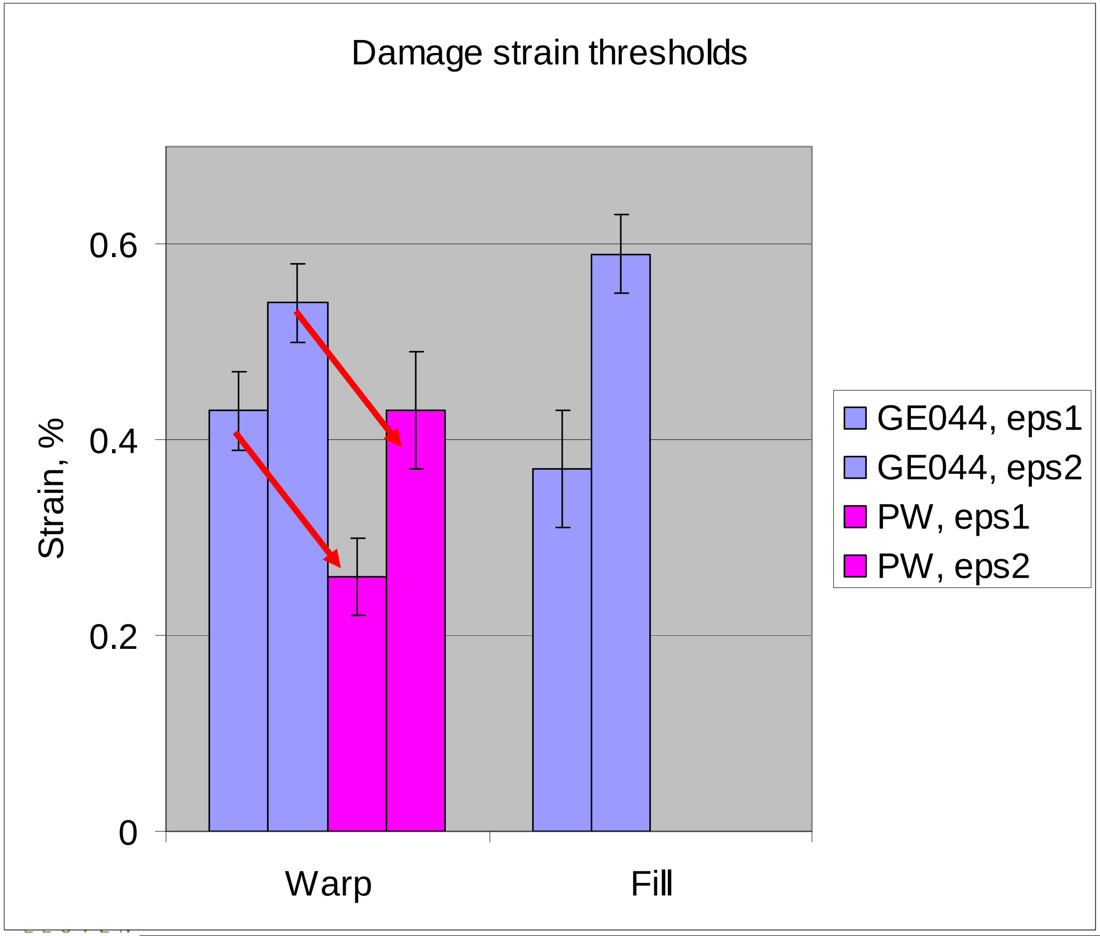


3D composite:

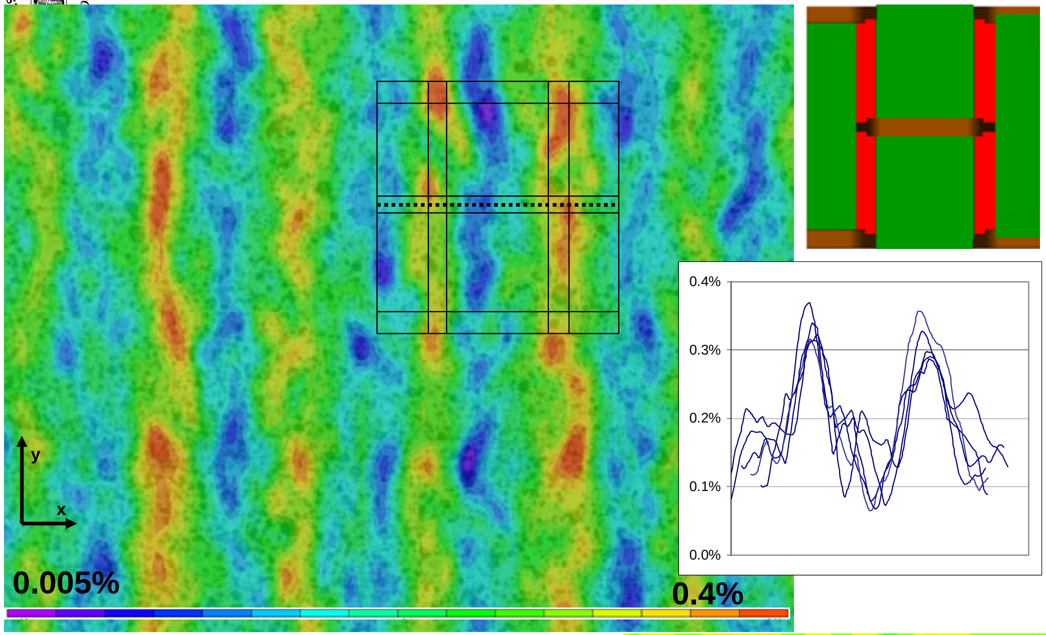
- increase of damage initiation thresholds by 0.2% strain for loading in fibre direction

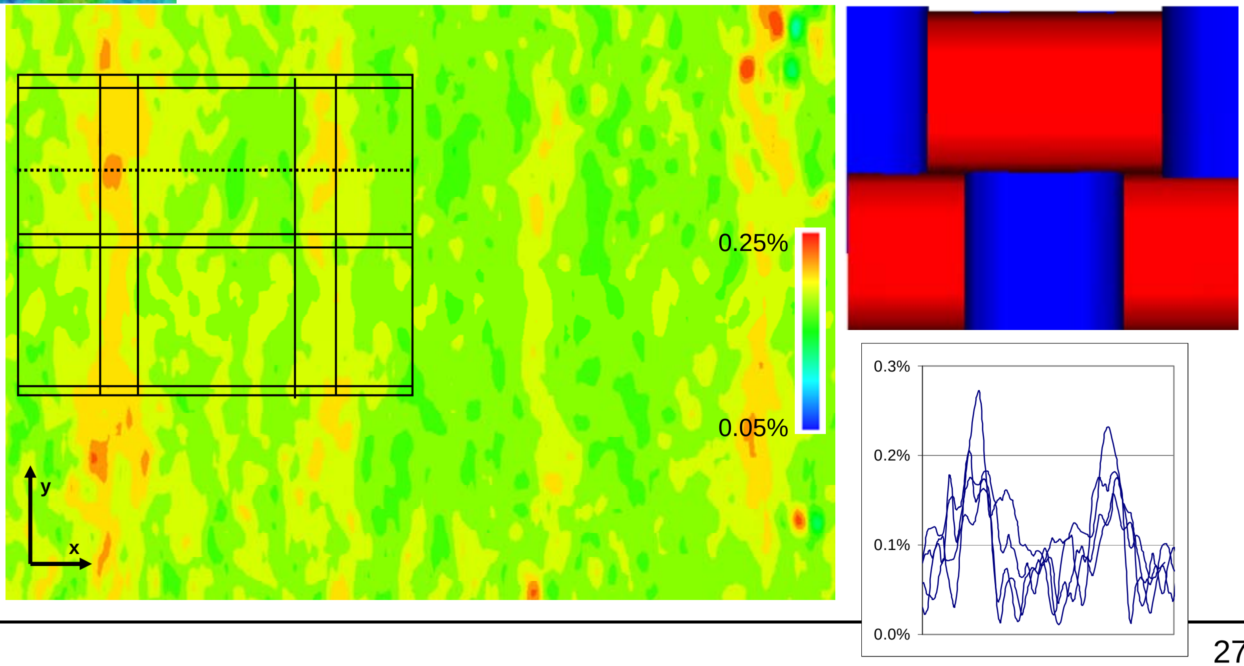
- advantage in fatigue life stress limit can be expected

- lower damage thresholds for loading in bias direction

Strain maps before damage initiation: Loading in WARP direction

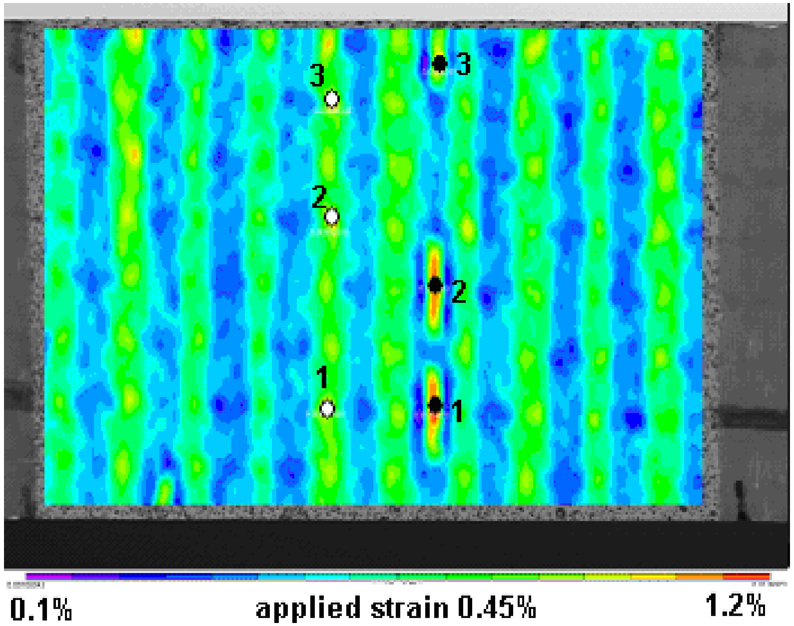
GE044

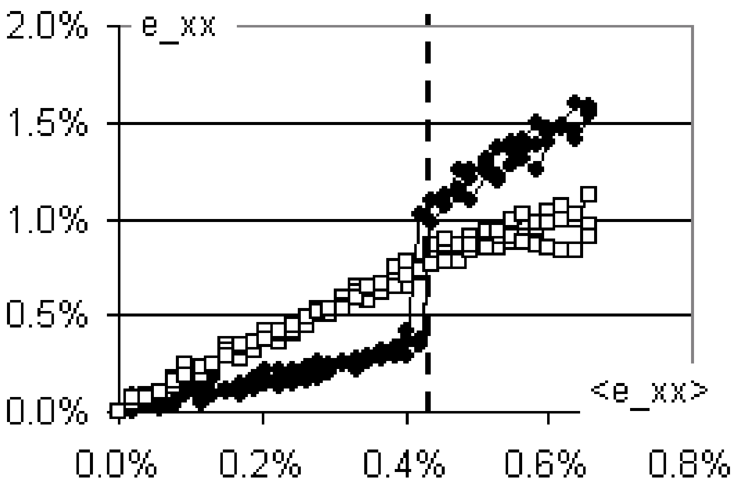




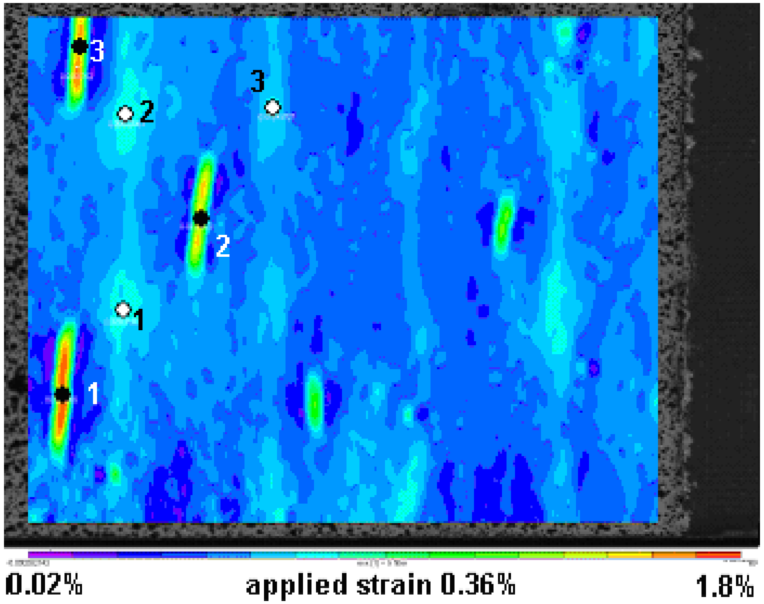
plain
weave

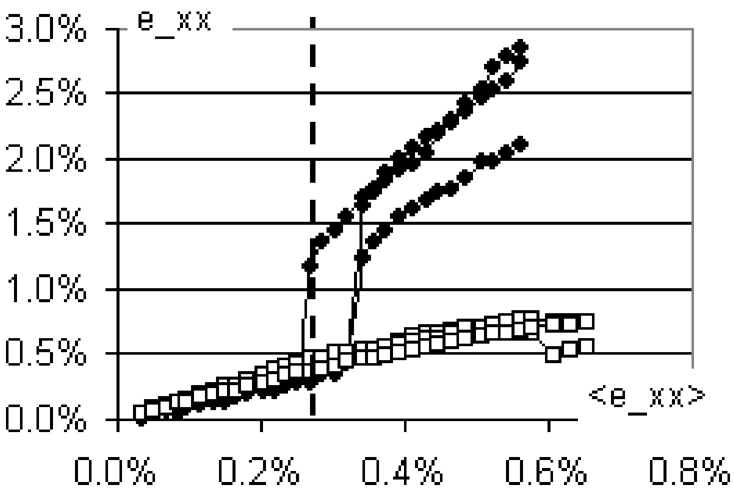
GE044



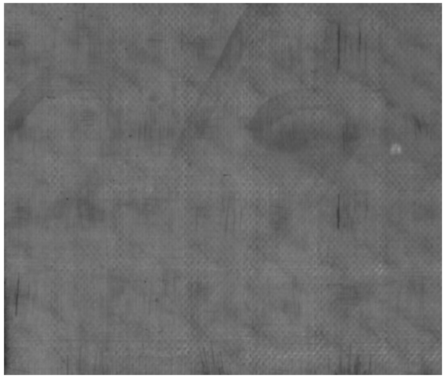
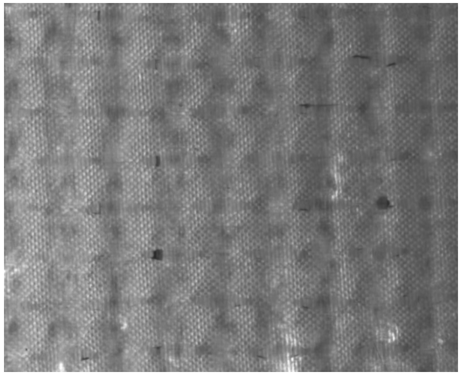
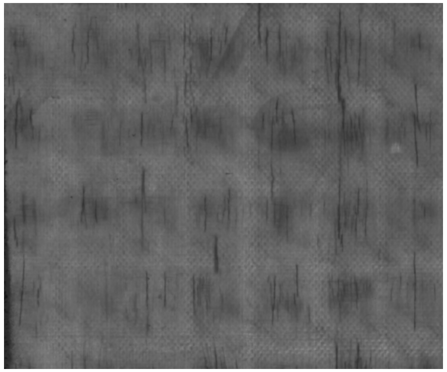
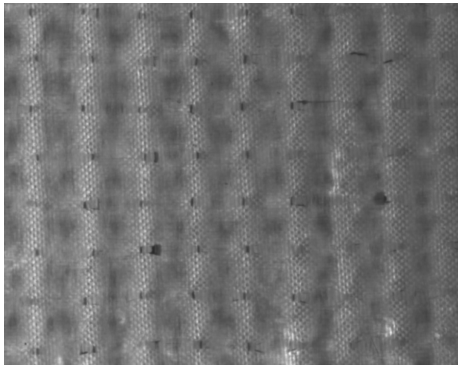
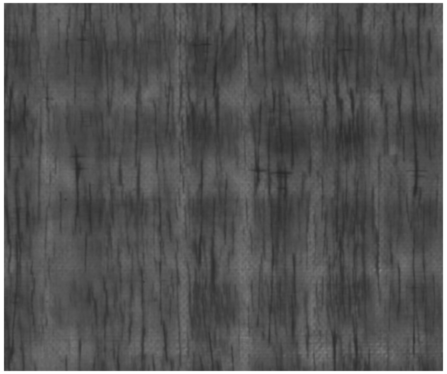
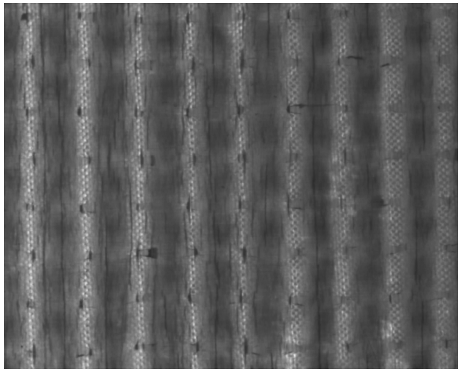


plain weave





Damage development: Loading in WARP direction

	plain weave		GE044	
0.30%		onset of transverse cracks in fill		onset of bundle-boundary cracks on Z-yarns
0.50%		intensive transverse cracks in fill and intra-yarn cracks parallel to the yarn surface		onset of transverse cracks in fill
1.0%				transverse cracks and bundle-boundary cracks in fill and Z-yarns

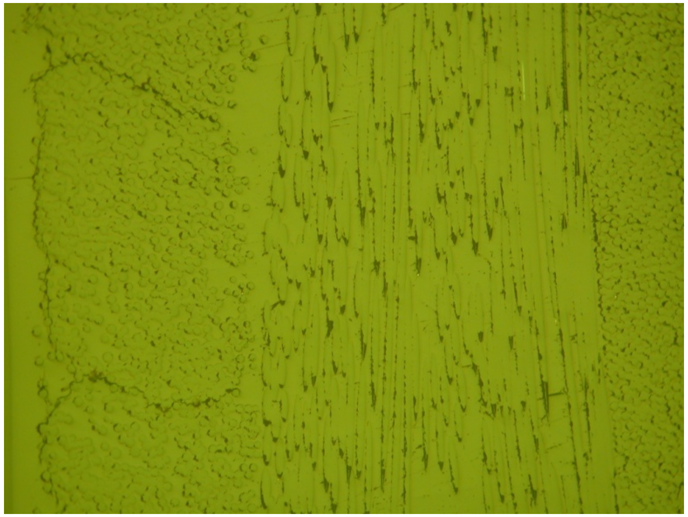
Comparison PW – GE044

GE044 – Progressive damage

Typical damage, loading in WARP direction

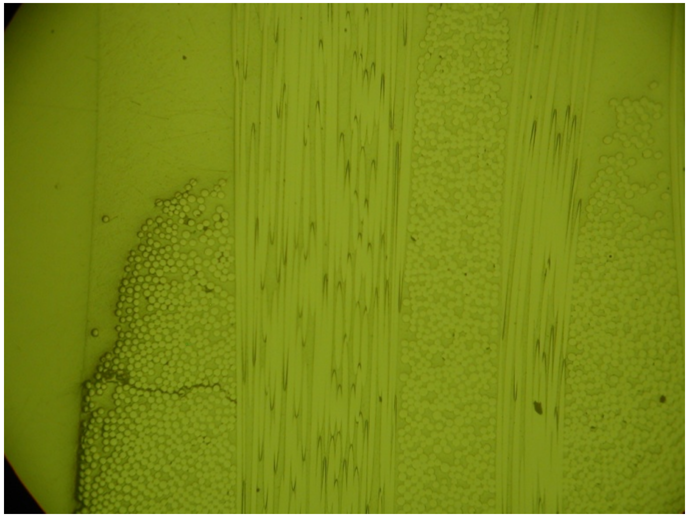
plain weave

transverse crack in fill

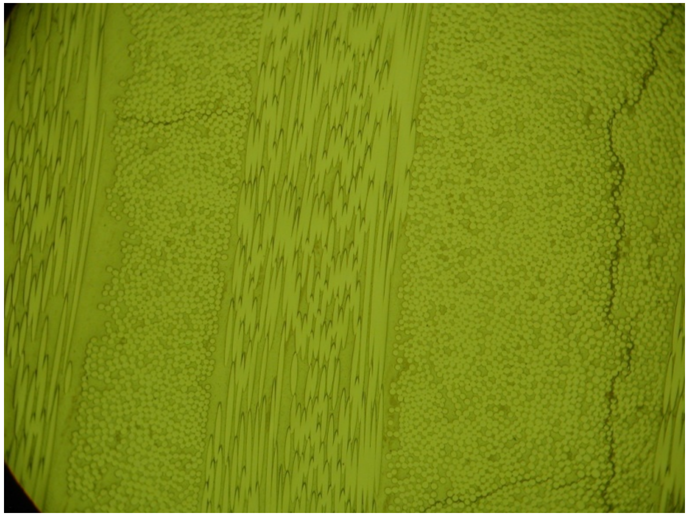


GE044

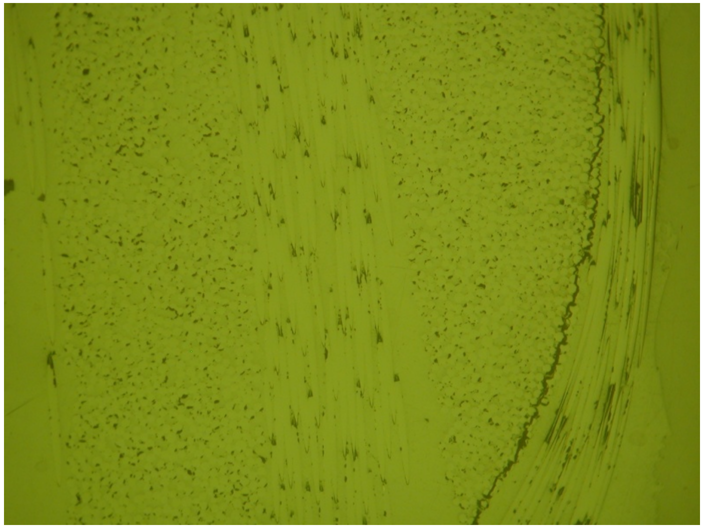
transverse crack in fill



intra-yarn crack parallel to yarn surface



bundle-boundary crack, Z-yarn



1. Introduction: What and Why and When and How and Where and Who?
2. Experimental: Road map for characterisation of damage in textile composites
3. Example: 2D and 3D woven glass/epoxy composites
4. Finite element analysis of damage: Predictions and numerical artifacts
   - Example: 3D woven glass/epoxy composite, loading in WARP direction
5. Conclusion: Overview of damage studies with different textile architectures

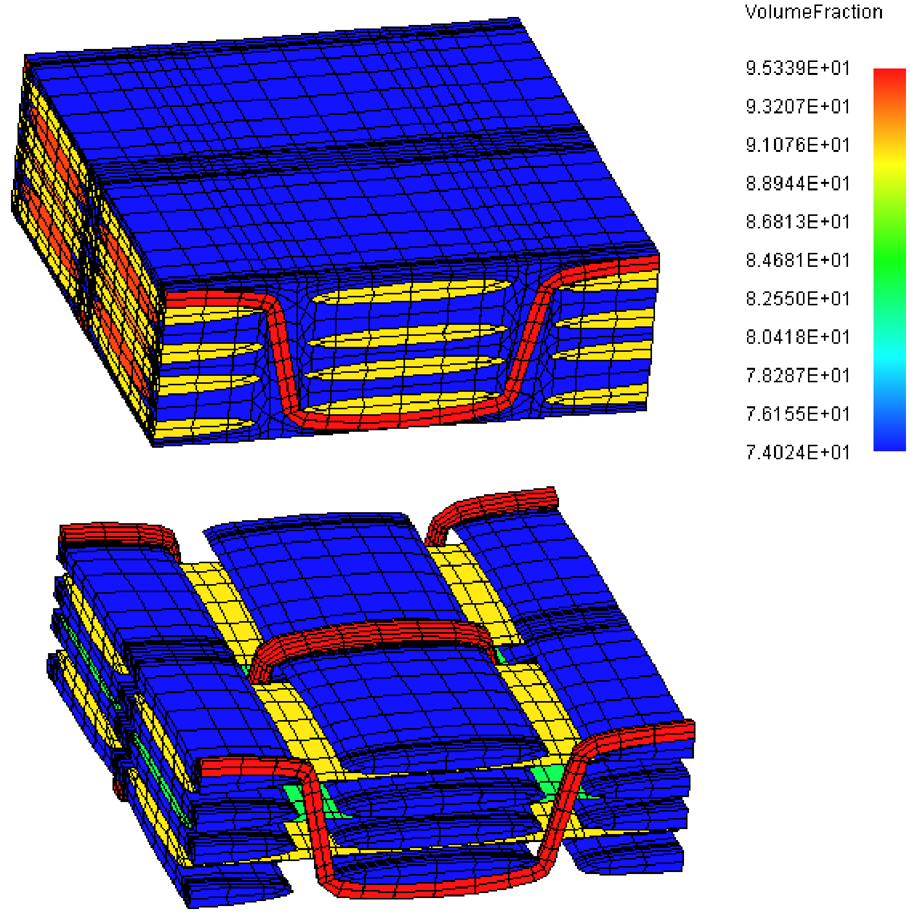
collaborations:

- 3Tex: A.E. Bogdanovich, D. Mungalov
- Osaka University: K. Hamada, T. Kurashiki, M. Zako

Software tools, FE model and strength data

Geometric modeller	WiseTex
Geometry corrector of yarn interpenetration	MeshTex
Meshing	
Material properties	
Boundary conditions	
FE solver, post-processor	SACOM
Homogenisation	
Damage	

UD	MPa	**Matrix**	MPa
L, tensile	1725	Tension	76
L, compr.	620	Compr.	112
T, tensile	40	Shear	86
T, compr.	140		
LT	70		
TZ	70		



Damage initiation: Hoffmann

$$F = C_1(\sigma_T - \sigma_Z)^2 + C_2(\sigma_Z - \sigma_L)^2 + C_3(\sigma_L - \sigma_T)^2$$
$$+ C_4\sigma_L + C_5\sigma_T + C_6\sigma_Z + C_7\tau_{TZ}{}^2 + C_8\tau_{ZL}{}^2 + C_9\tau_{LT}{}^2$$

$$C_1 = \frac{1}{2}\left(\frac{1}{F_T^t F_T^c} + \frac{1}{F_Z^t F_Z^c} - \frac{1}{F_L^t F_L^c}\right)$$

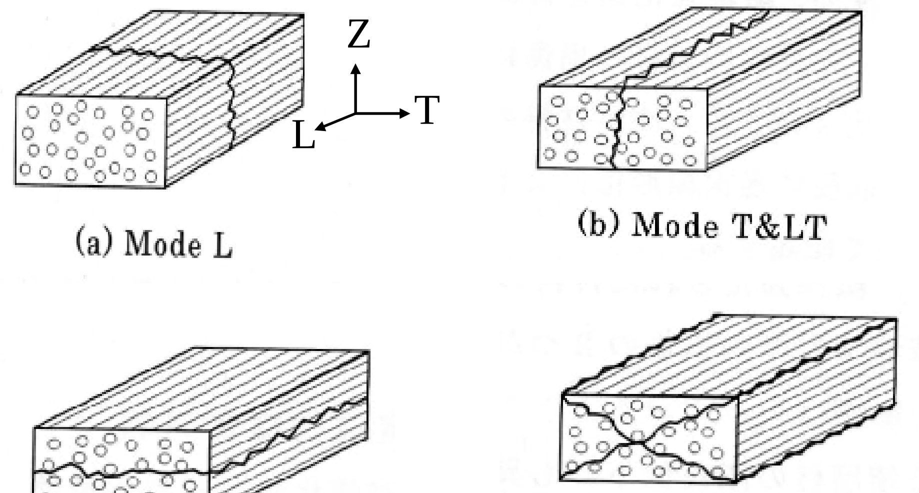
$$C_2 = \frac{1}{2}\left(\frac{1}{F_Z^t F_Z^c} + \frac{1}{F_L^t F_L^c} - \frac{1}{F_T^t F_T^c}\right)$$

$$C_3 = \frac{1}{2}\left(\frac{1}{F_L^t F_L^c} + \frac{1}{F_T^t F_T^c} - \frac{1}{F_Z^t F_Z^c}\right)$$

$$C_4 = \frac{1}{F_L^t} - \frac{1}{F_L^c}, C_5 = \frac{1}{F_T^t} - \frac{1}{F_T^c}, C_6 = \frac{1}{F_Z^t} - \frac{1}{F_Z^c}$$

$$C_7 = \left(\frac{1}{F_{TZ}^s}\right)^2, C_8 = \left(\frac{1}{F_{ZL}^s}\right)^2, C_9 = \left(\frac{1}{F_{LT}^s}\right)^2$$

Definition of the damage mode



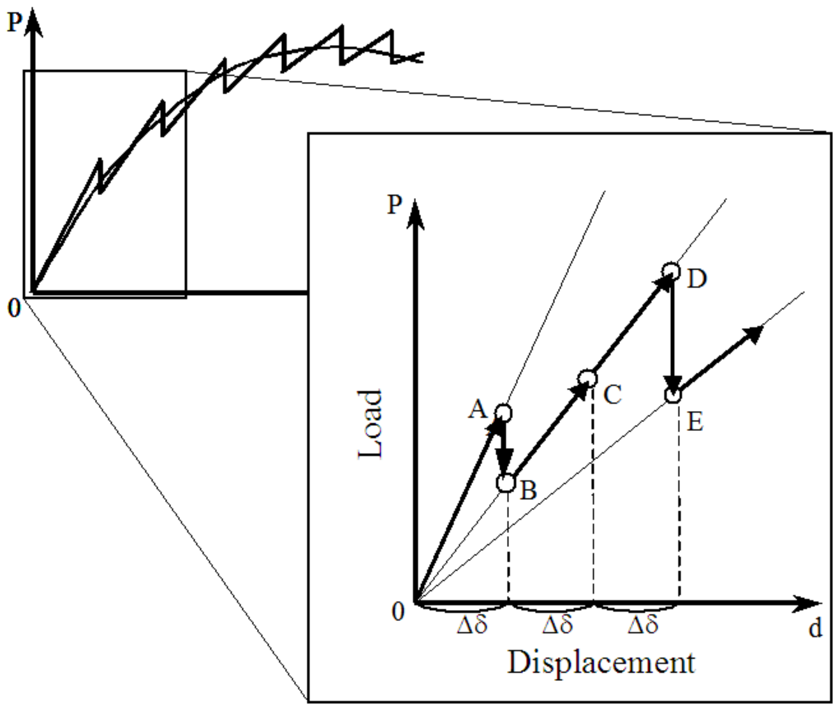
(a) Mode L (b) Mode T&LT (c) Mode Z&ZL (d) Mode TZ

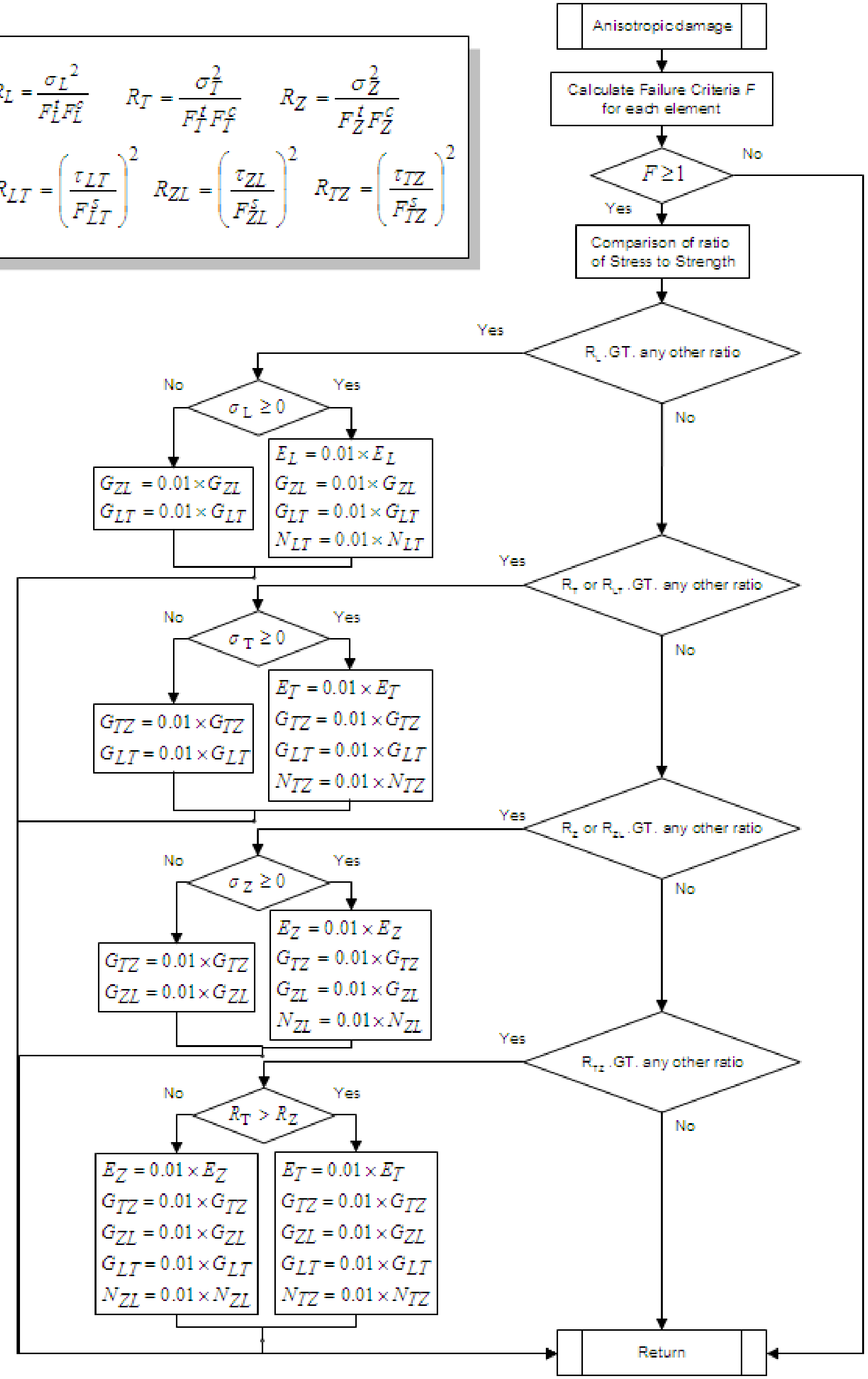
Maximum value	*Damage Mode*
$\frac{\sigma_L^2}{F_L^t F_L^c}$	Mode L
$\frac{\sigma_T^2}{F_T^t F_T^c}$ or $\left(\frac{\tau_{LT}}{F_{LT}^s}\right)^2$	Mode T&LT
$\frac{\sigma_Z^2}{F_Z^t F_Z^c}$ or $\left(\frac{\tau_{ZL}}{F_{ZL}^s}\right)^2$	Mode Z&ZL
$\left(\frac{\tau_{TZ}}{F_{TZ}^s}\right)^2$	Mode TZ

Damage model (built-in in SACOM) – 2

$$R_L = \frac{\sigma_L^2}{F_L^t F_L^c} \quad R_T = \frac{\sigma_T^2}{F_T^t F_T^c} \quad R_Z = \frac{\sigma_Z^2}{F_Z^t F_Z^c}$$

$$R_{LT} = \left(\frac{\tau_{LT}}{F_{LT}^s}\right)^2 \quad R_{ZL} = \left(\frac{\tau_{ZL}}{F_{ZL}^s}\right)^2 \quad R_{TZ} = \left(\frac{\tau_{TZ}}{F_{TZ}^s}\right)^2$$





Strength input data

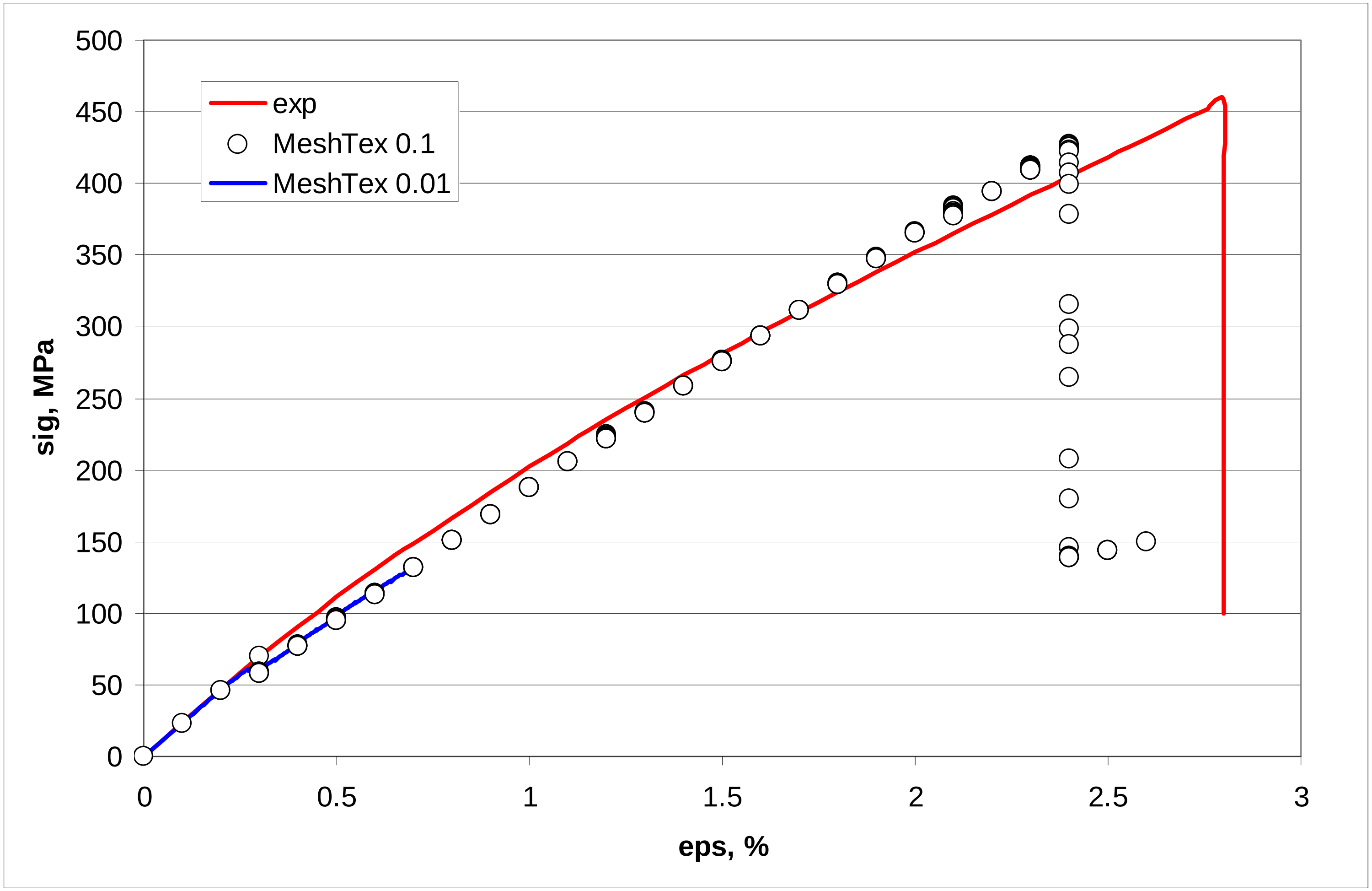
UD	[1], VF=60%	[6], VF=55%	Hybon' data	**Corrected (L) for 75% and accepted for calculations**
L, tensile	1020	1080	1380	**1725**
L, compression	620	620		**620**
T, tensile	40	39		**40**
T, compr	140	128		**140**
LT	70	89		**70**
TZ				**70**
Matrix	tensile	76	Compression	112
	shear	88		

[1] "Composites Engineering Handbook" (P.K. Mallick, Ed.), Marcel Dekker, Inc., New York, 1997 (Table 1)

[2] "Engineering Mechanics of Composite Materials" by I.M. Daniel and O. Ishai, Oxford University Press, New York - Oxford, 1994 (Table 2.6),

Materials Research Centre

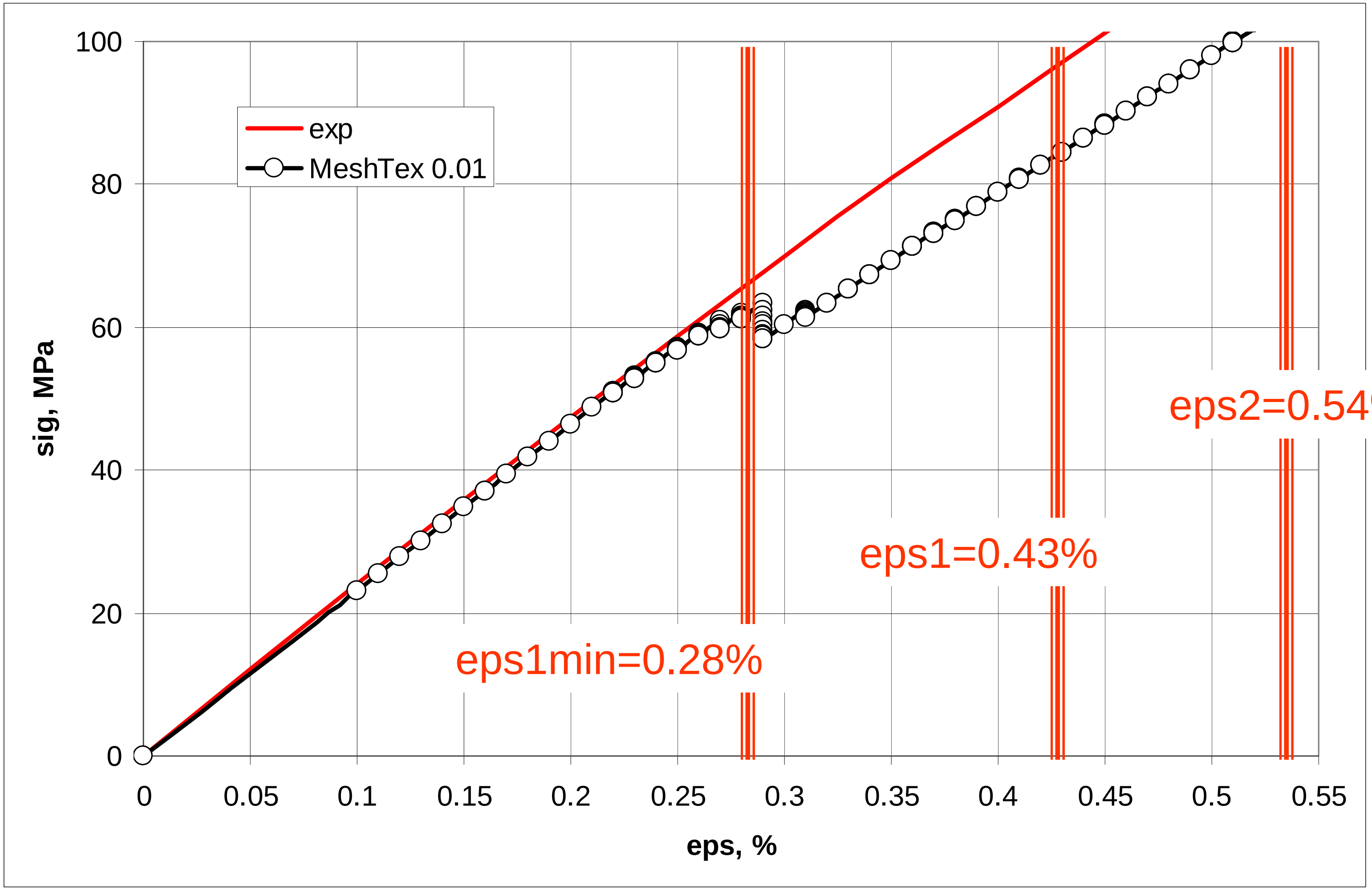
Tensile diagram



correct change of stiffness

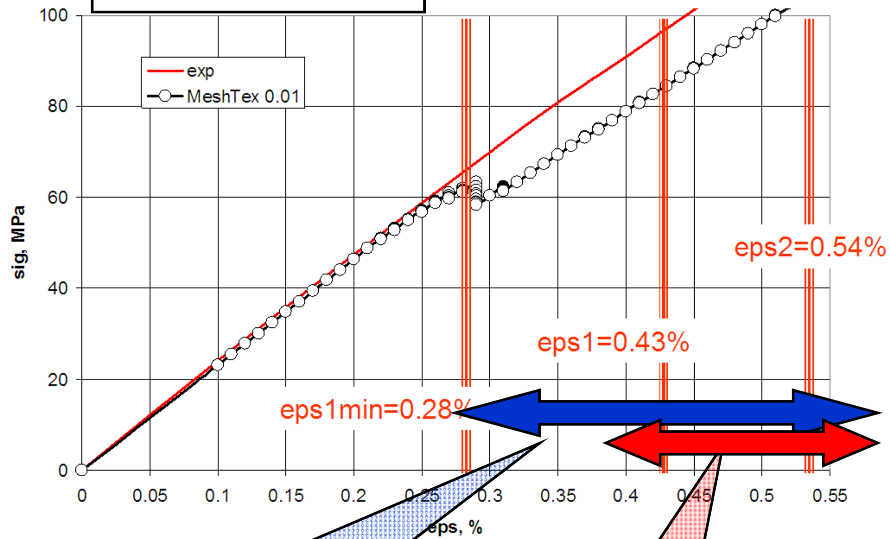
strength prediction depends on the assumed L-strength for UD

Tensile diagram: Initial stage (step 0.01%)



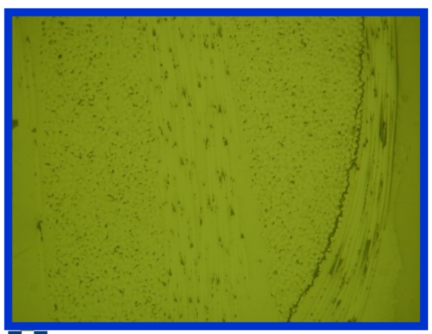
Predictions of the damage onset

Experiment



bundle-boundary cracks in Z-yarns

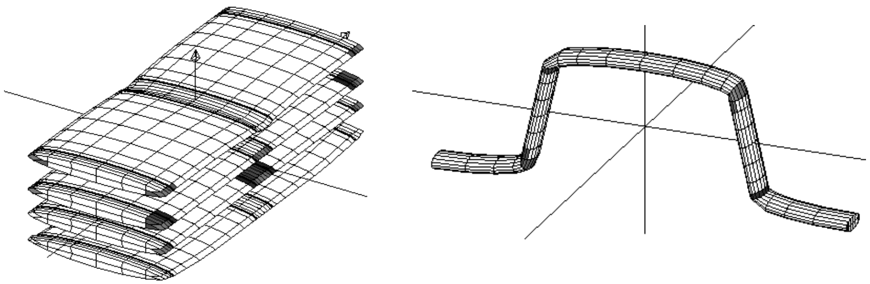
transverse cracks in fill



FE, strain 0.22%

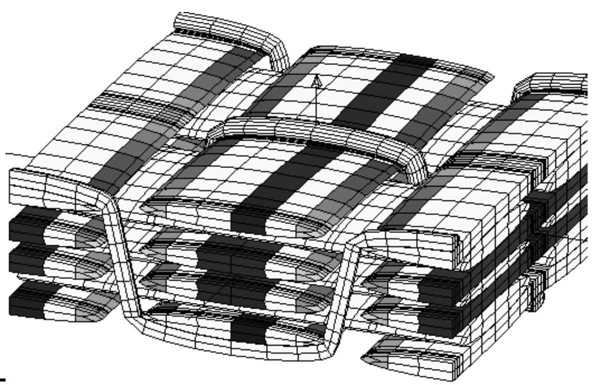
Damage starts at Z-yarn locations:

- T-mode at the edges of fill
- Z-mode in Z-yarns



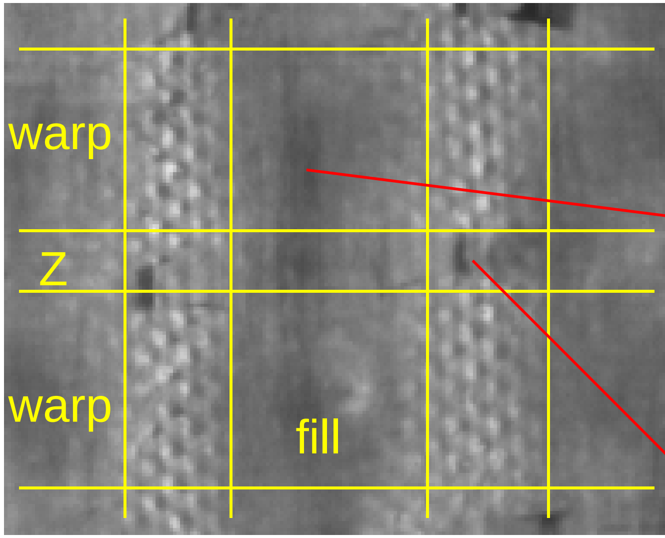
FE, strain 0.30%

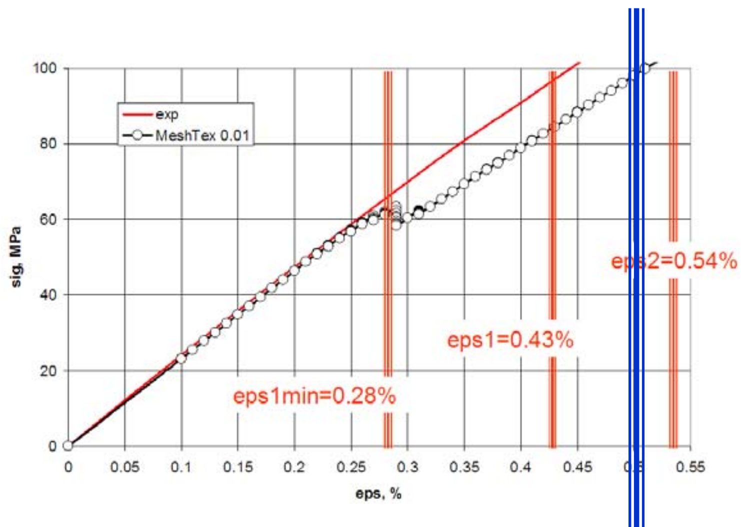
T-mode in fill



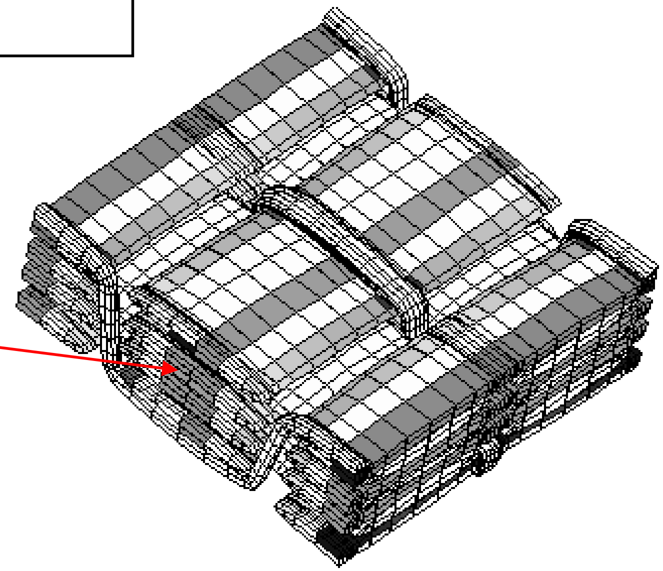
Developed damage

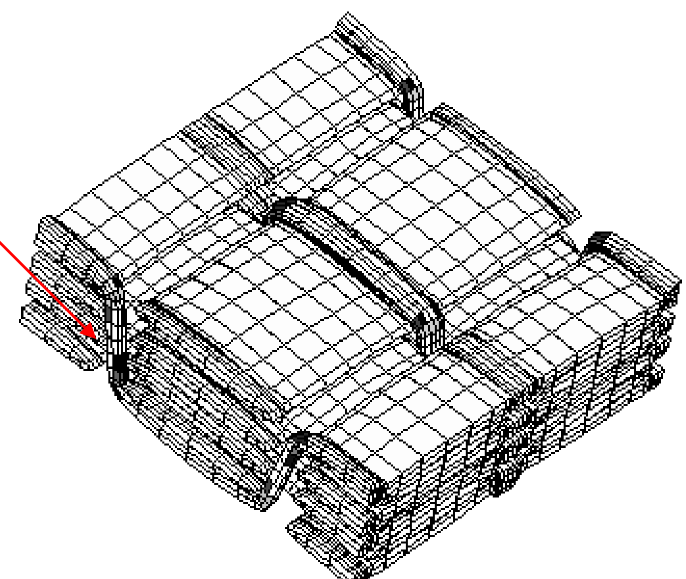
Experiment: strain 0.5%





FE





Prediction and artifacts in FE modelling

1. Correct prediction of change of stiffness (tensile diagram)
2. Strength prediction directly depends on the assumed UD strength value
3. Estimation of the damage onset: within interval (eps1min, eps1)
4. Correct prediction of general character of the damage onset (location near Z-yarn)
5. No bundle-boundary damage mode; interpreted as Z-mode or T-mode near the surface of the yarns
6. Estimation of the onset of transversal damage: calculated too early (0.3% instead of 0.43±0.04%). Depends on the assumed strength value.
7. Correct prediction of the extent of fill damage
8. In reality all the unit cells are not damaged simultaneously

NB: better results for the plain weave laminate, as the prevailing damage mode for it is transversal cracking

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Damage studies of textile composites in K.U. Leuven

Fibres/matrix	*Reinforcement*	*Publication*
Experimental methodology in general		Comp Sci Tech **68**: 2340 (2008)
carbon/epoxy	NCF 0/90, ±45, 0/-45/90/45	Comp A **36**: 1207 (2005)
	NCF ±45, sheared	Comp A **39**: 1380 (2008)
	NCF 0/90, ±45, toughened resin	SAMPE-Europe (2007)
	NCF tufted with carbon yarn*	Master thesis K.U. Leuven (2008)
	3-axial braid	Comp Sci Tech, in print
	Uniaxial braid*	Comp Sci Tech **68**: 2340 (2008)
	Uniaxial weave tufted with carbon*	ECCM-13 (2008)
	Woven twill 2/2	to be submitted to ICCM-17
glass/epoxy	Plain weave**	SAMPE-Europe (2008)
	3D woven (patented weaving process 3Tex)**	to be submitted to Comp A

collaborations:
* ITOOL consortium (EADS Innovation Works, Dassault Aviation, IFB – Stuttgart University)
** 3Tex – A.E. Bogdanovich, D. Mungalov

Some of the experimental data will be made available in **Textile Composite Archive**: www.textilecomposite.tamu.edu https://textilecomposite.tamu.edu/

Textile Composite Archive

This archive contains contributions from researchers around the world. The goal is to provide improved exchange of data and insights related to textile composites. This page provides links to web pages and data files that are maintained by each researcher. This is a work in progress.

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