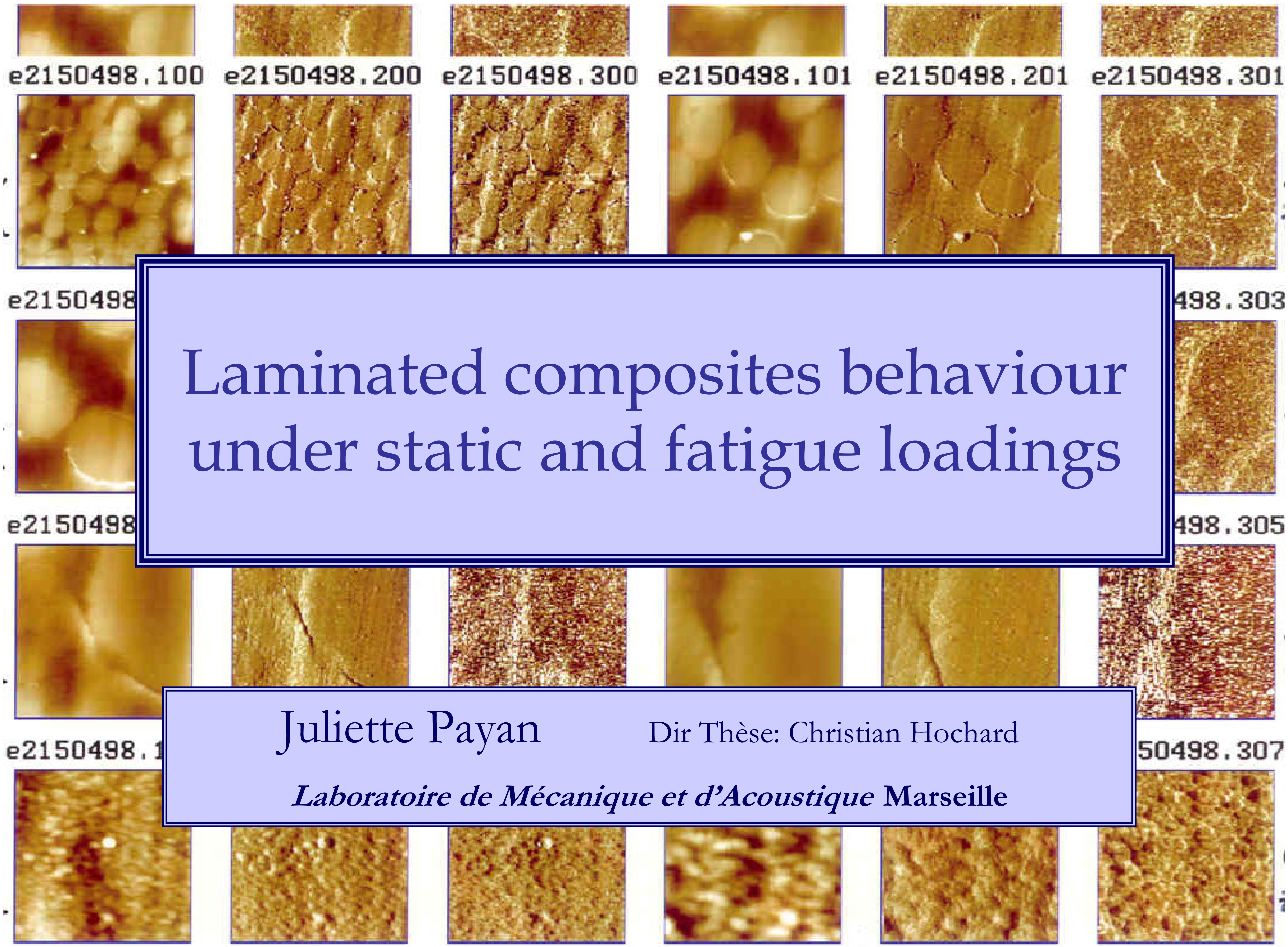


Laminated composites behaviour under static and fatigue loadings

Juliette Payan

Dir Thèse: Christian Hochard

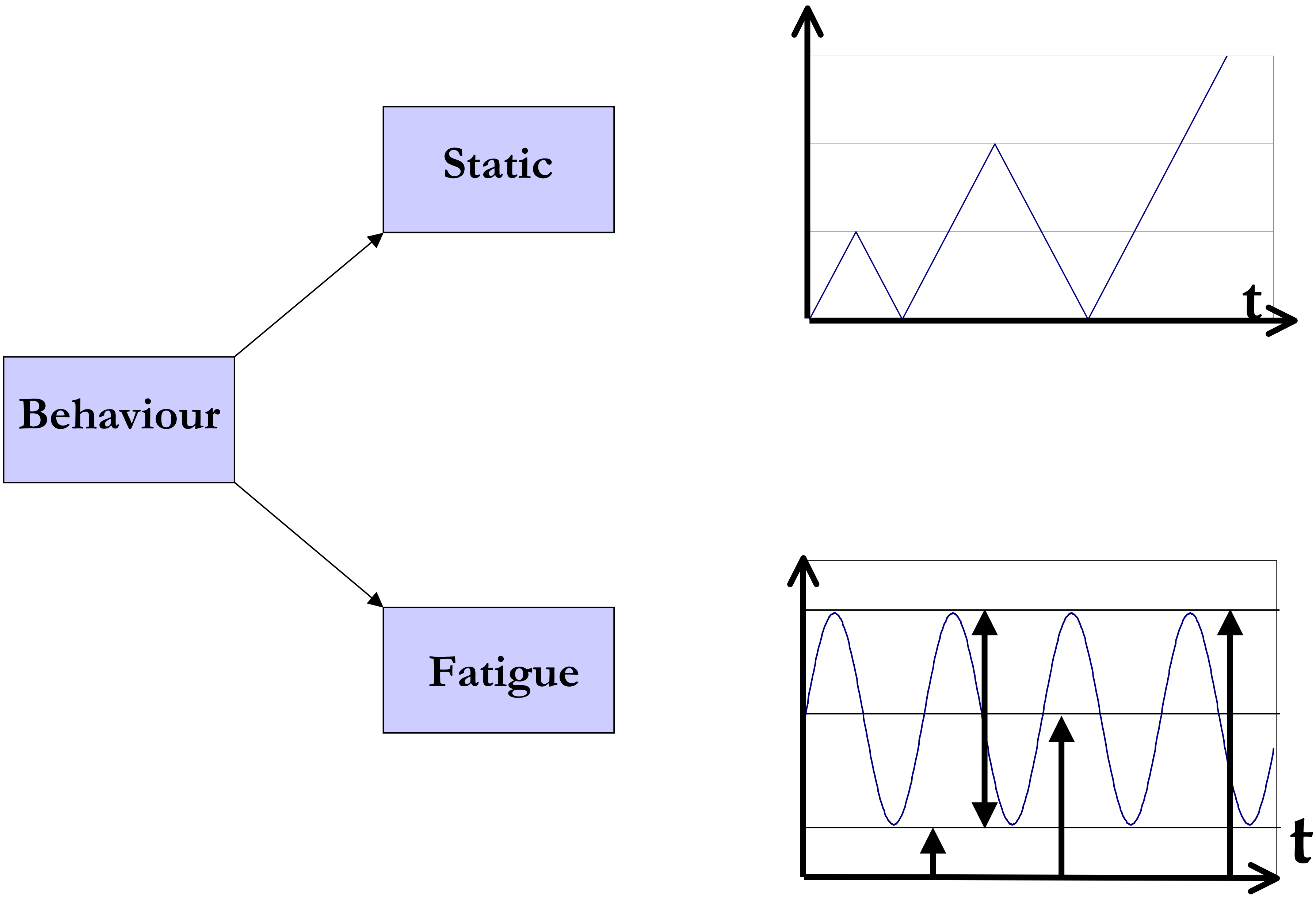
***Laboratoire de Mécanique et d'Acoustique* Marseille**

Design and Sizing composites structures

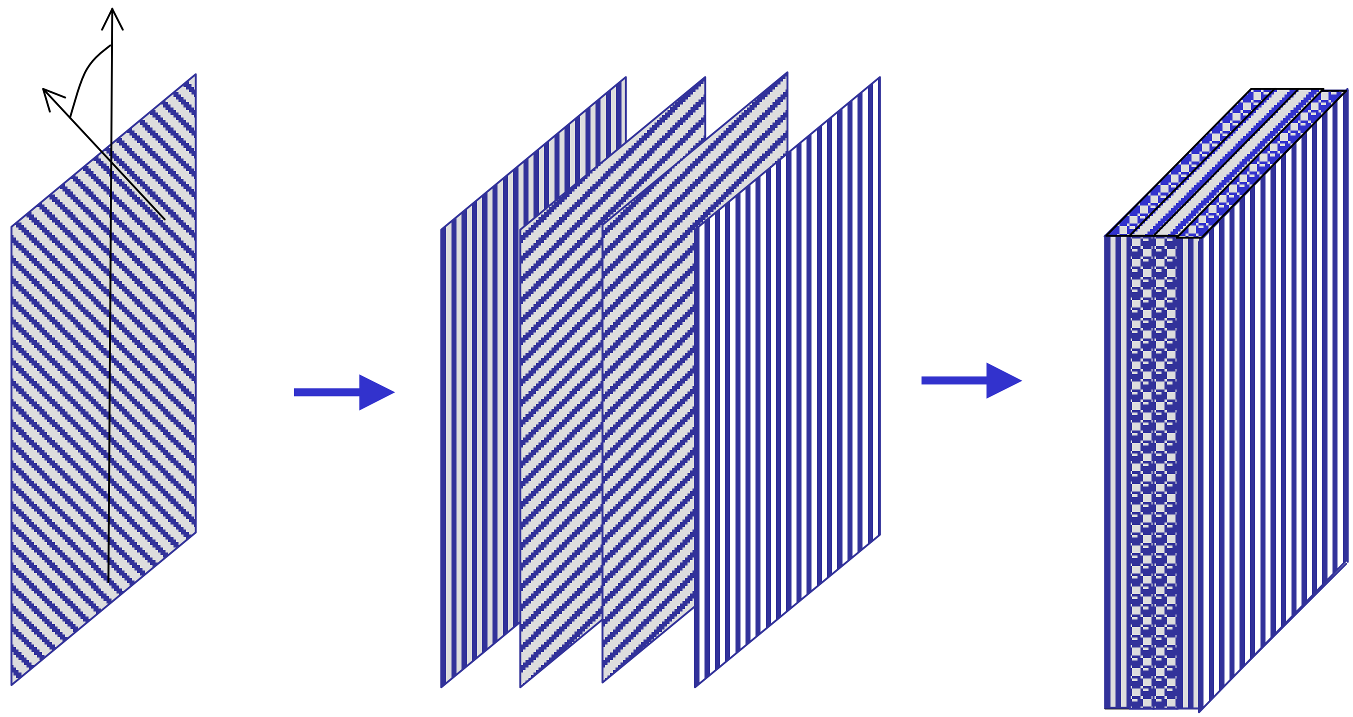
- **Optimisation:** Reliability Weight Cost

$\Rightarrow$ Necessity of structure computation

$\Rightarrow$ Necessity of behaviour modelling (that can be integrated in FEM calculus)


Behaviour
Static
Fatigue
t
t

Carbon epoxy laminated composites

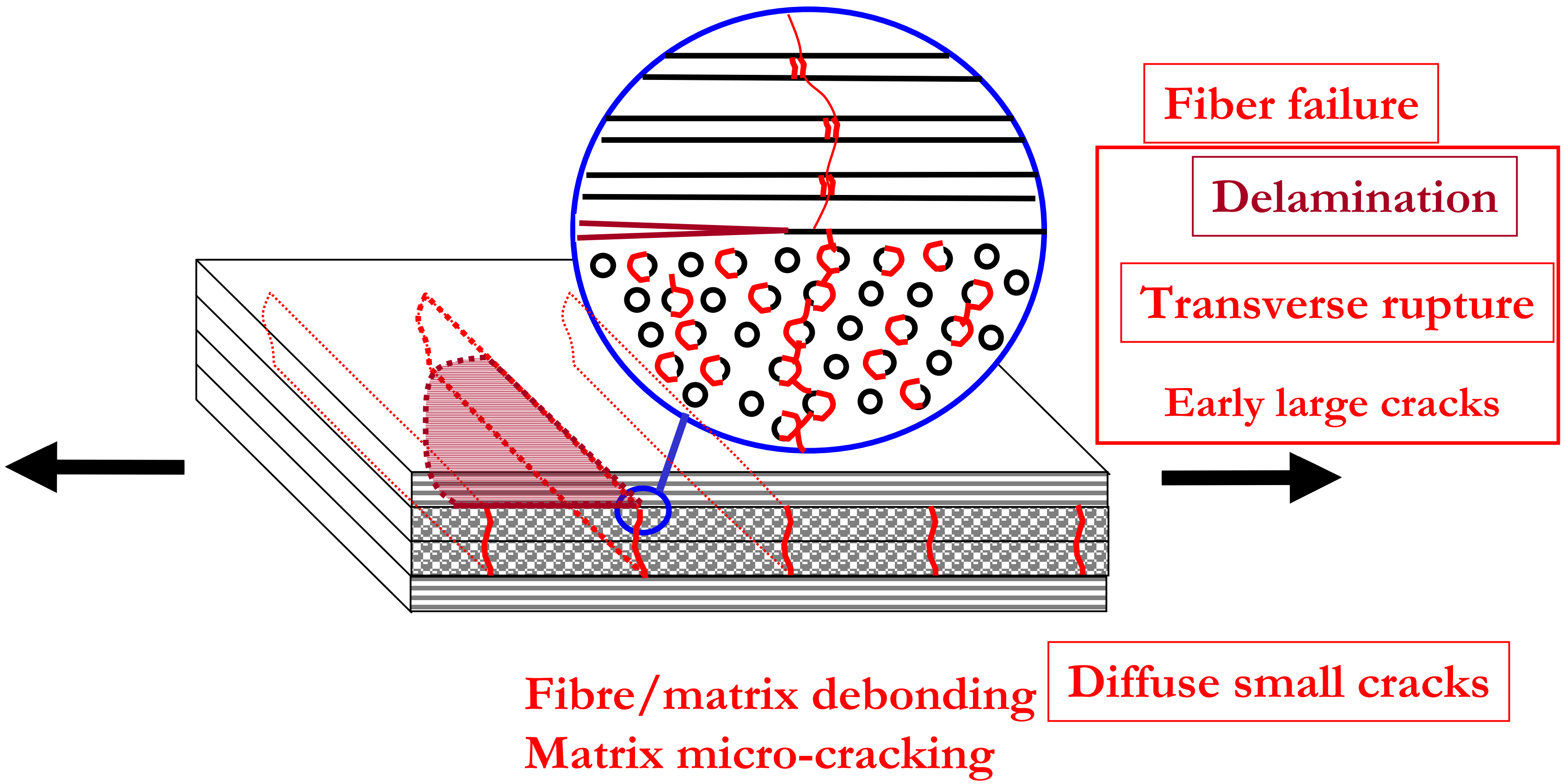


Ply with carbon fibres impregnated with epoxy resin

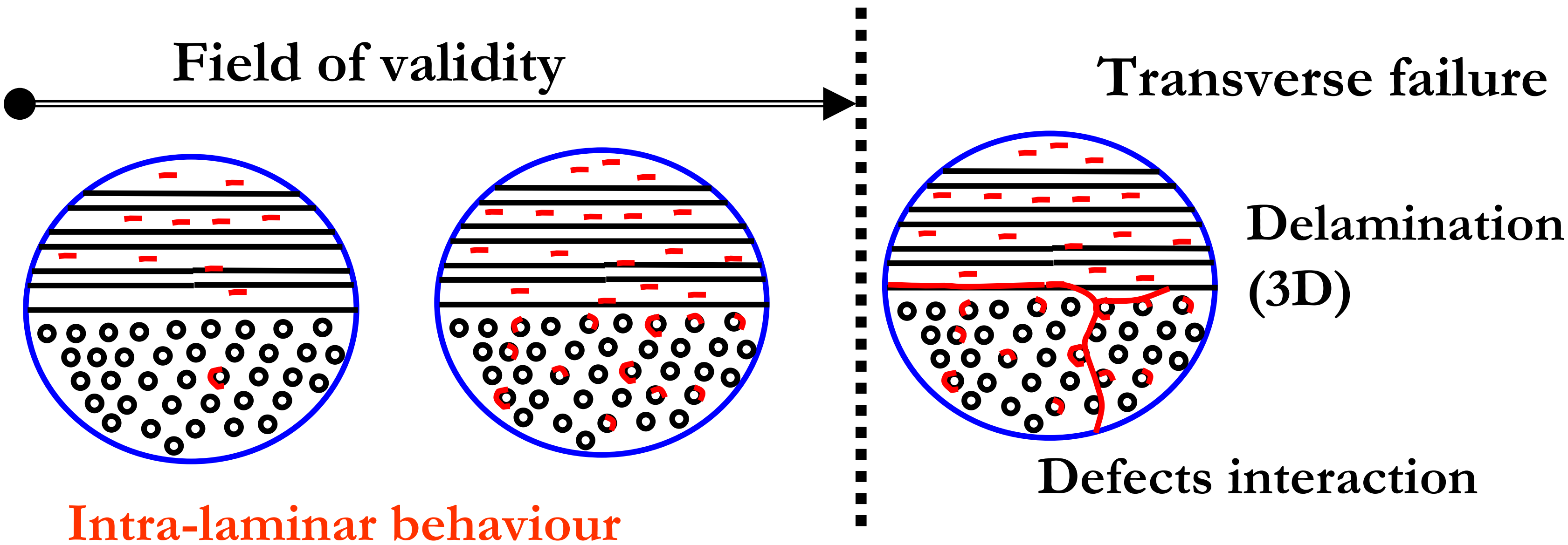
Stacking sequence

Laminate

Damage and failure mechanisms for unidirectional ply laminates under static and fatigue loadings



Model up to the first ply failure



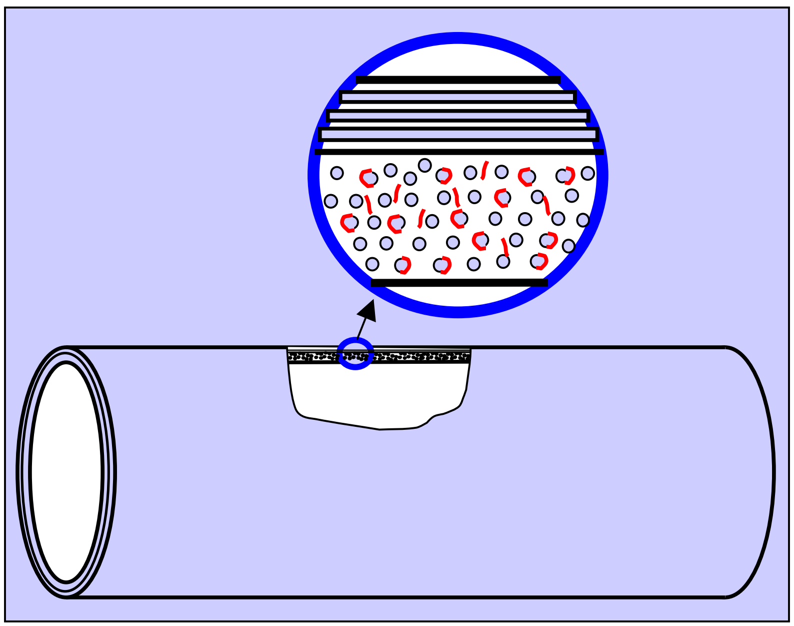
Simplified approach:

Diffuse damage; Plane stresses hypothesis

Application: composite tubes

Industrial context : SAFETY

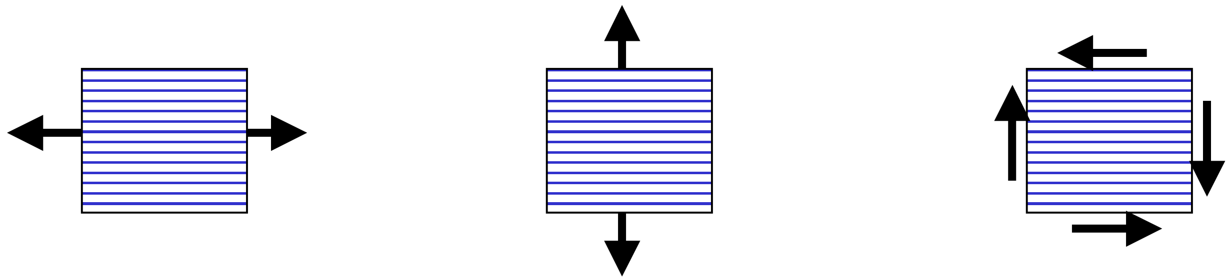
driveshaft, centrifugal machine (sub-critical)

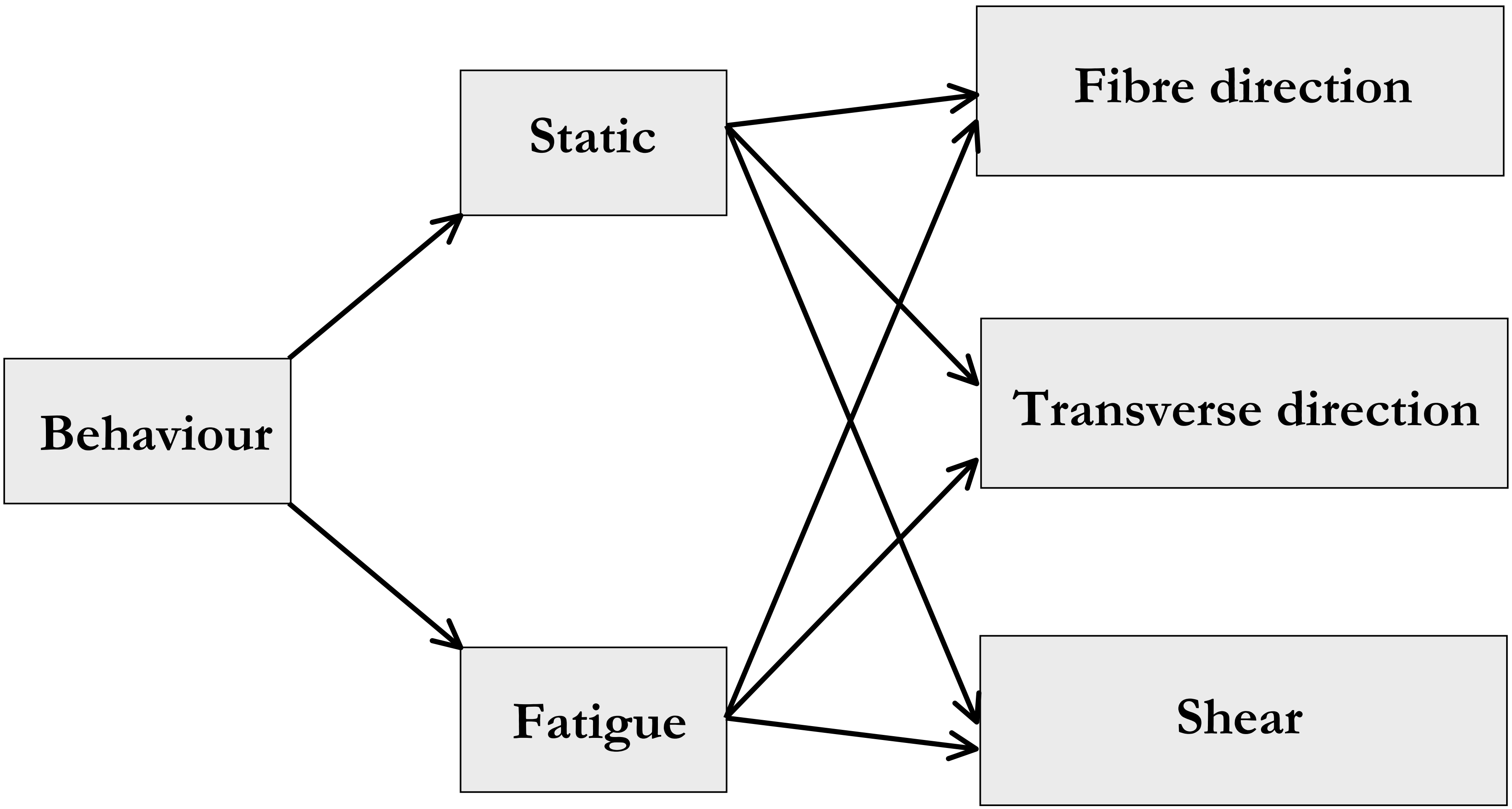


Unified mesoscopic model

- **UNIFIED: static and fatigue loadings**
- **MESO: Ply Scale**
- **ORTHOTROPIC:**

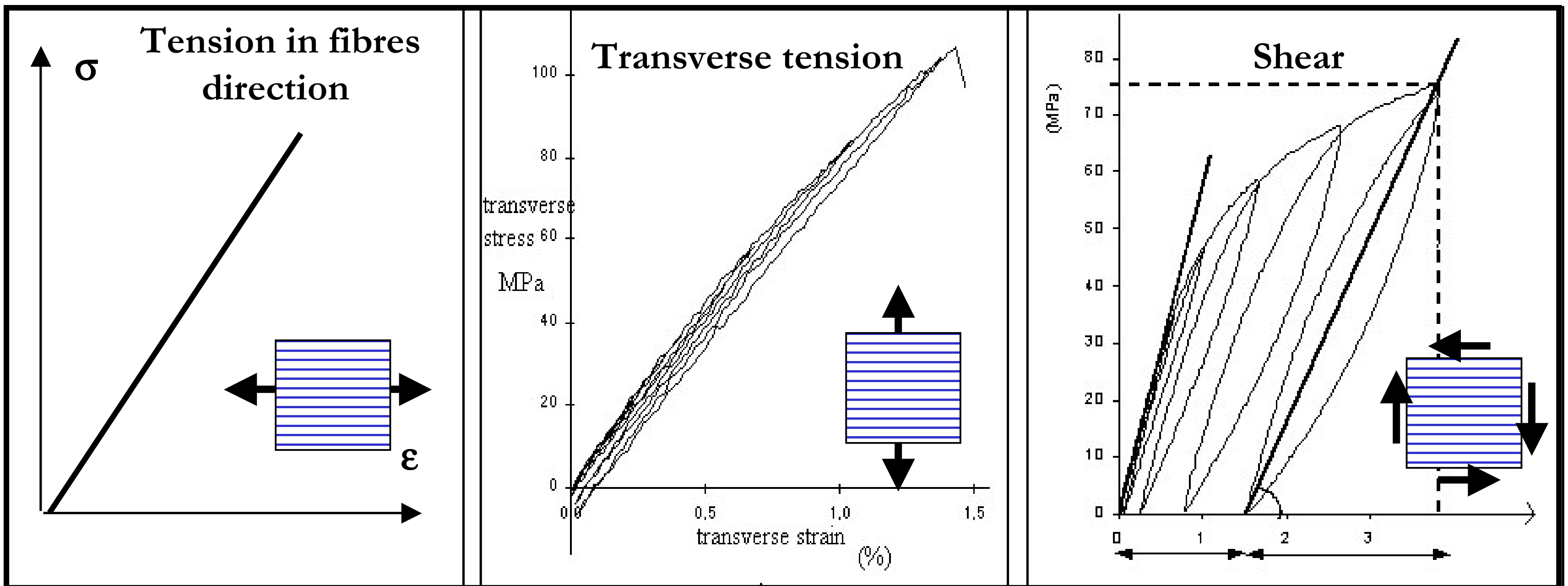
Three elementary loads




Behaviour
Static
Fatigue
Fibre direction
Transverse direction
Shear

Ply: G947/M18

Elementary ply behaviour



Elastic behaviour

Elasto-plastic behaviour with damage

Brittle failure

Brittle threshold

Instability condition

Damage Mechanics

Thermo-dynamic formulation of behaviour law for anisotropic materials (Ladevèze)

$$E_D = \frac{1}{2}\left[\frac{\langle\sigma_1\rangle_+^2}{E_1^0} + \frac{\varphi\left(\langle\sigma_1\rangle_-\right)}{E_1^0} - \frac{2\nu_{lt}\sigma_1\sigma_t}{E_1^0} + \frac{\langle\sigma_t\rangle_+^2}{E_t^0(1-d')} + \frac{\langle\sigma_t\rangle_-^2}{E_t^0} + \frac{(\sigma_{1t})^2}{2G_{lt}^0(1-d)}\right]$$

No damage in fibre direction

Damage d' in Transverse tension

No damage in transverse compression

Damage d In shear

Thermodynamic Forces
(conjugated quantities)

- **Conjugated quantities with d and d'**
- **b: coupling parameter**
- **Y: equivalent thermodynamic force**

  (maximal value of loading history)

$$Y_d = \rho \frac{\partial E_D}{\partial d}\bigg|_{\sigma, d'} = \frac{\sigma_{lt}^2}{2G_{lt}^0 (1-d)^2}$$

$$Y_{d'} = \rho \frac{\partial E_D}{\partial d'}\bigg|_{\sigma, d} = \frac{\langle \sigma_t \rangle_+^2}{E_t^0 (1-d')^2}$$

$$Y(t) = \sup_{\tau < t} \left(Y_d(\tau) + b Y_{d'}(\tau) \right)$$

Cumulated Damage

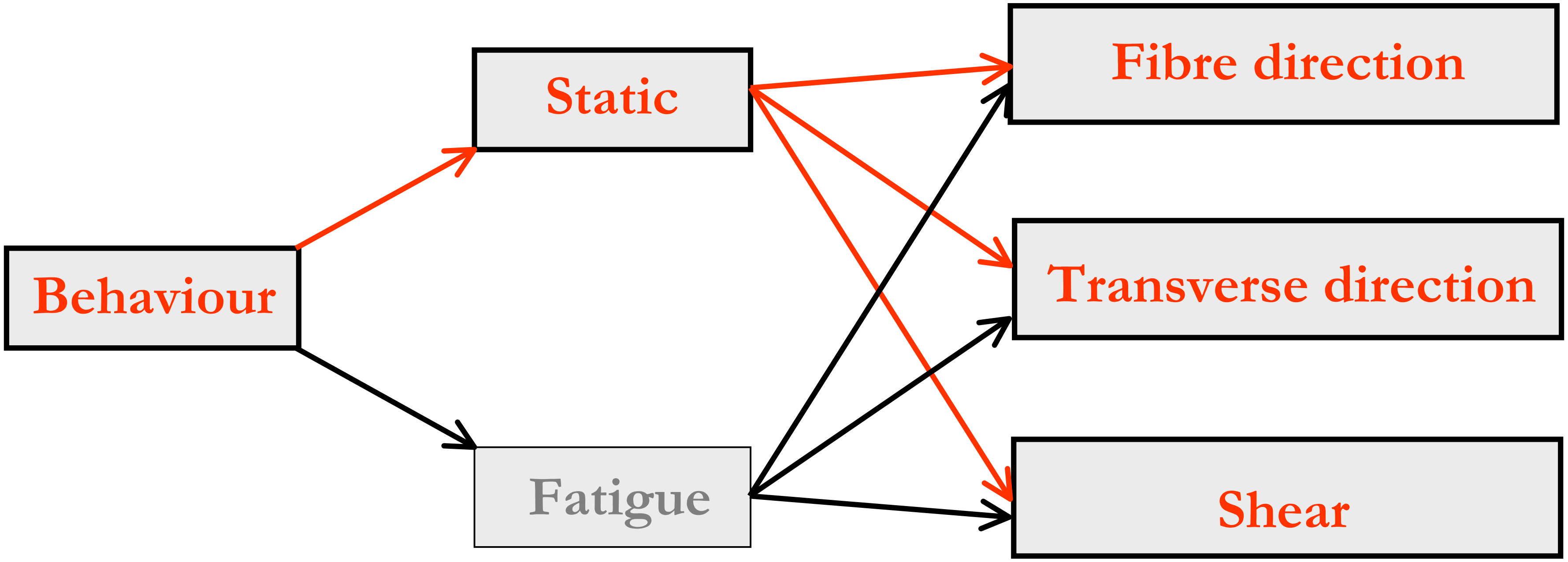
d_s : governed by static loading

d_f : governed by fatigue loading

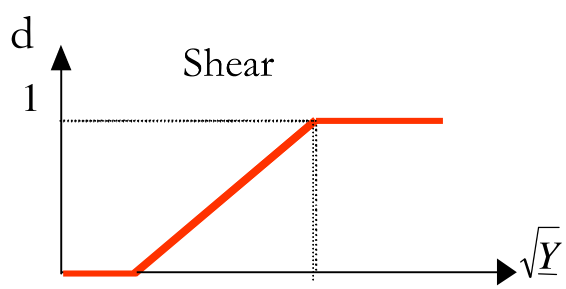
Coupled evolutions

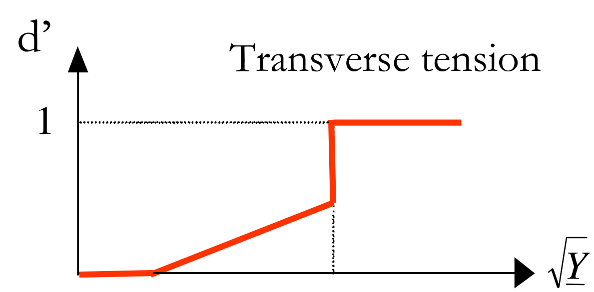
(depend on Y function of d)

$$d = d_s + d_f$$
$$d' = d_s' + d_f'$$



Existing model: Ladevèze et al



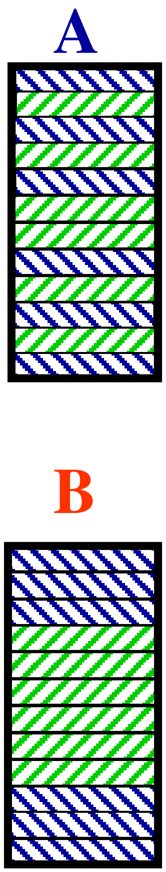


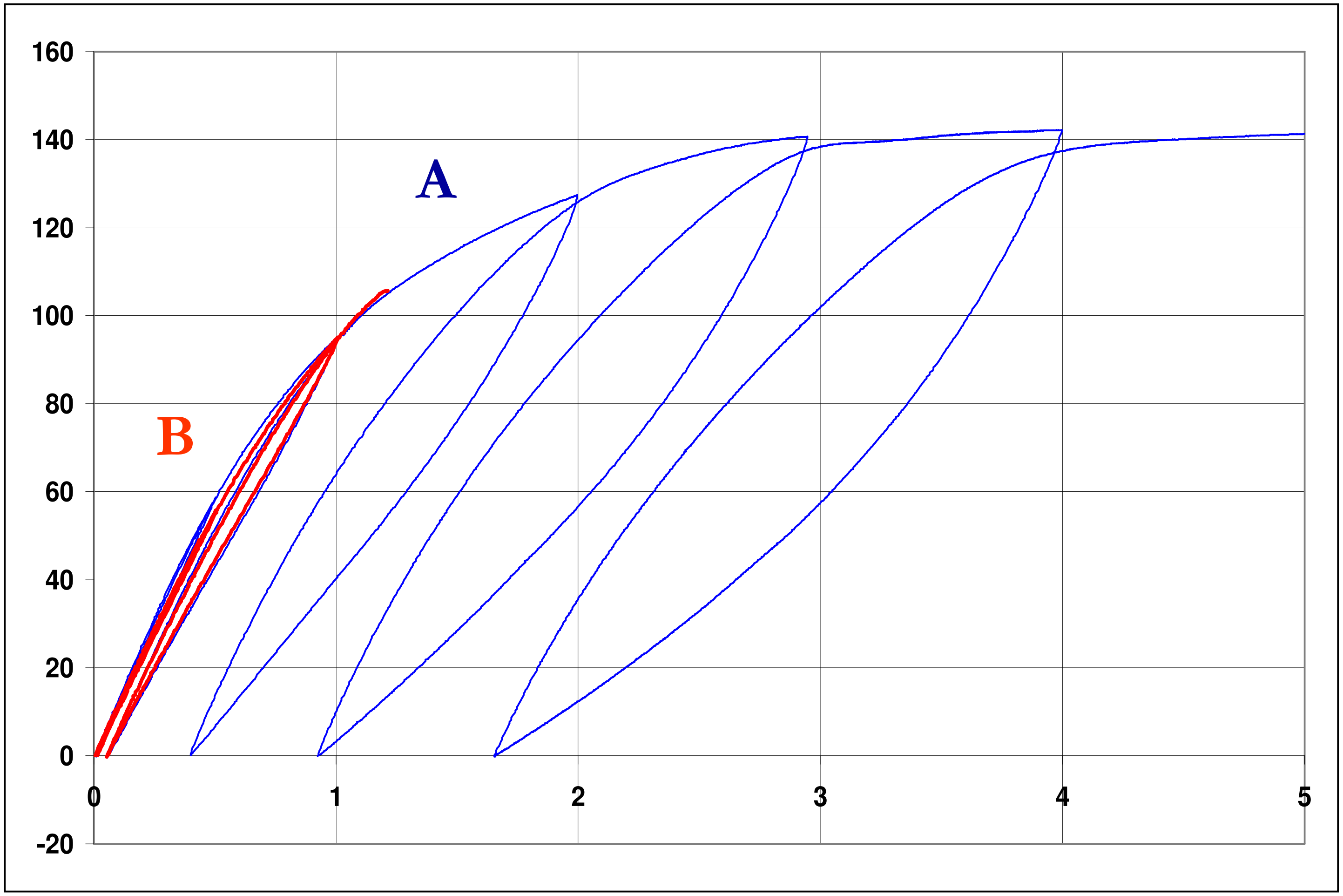
Coupled plasticity with effective quantities

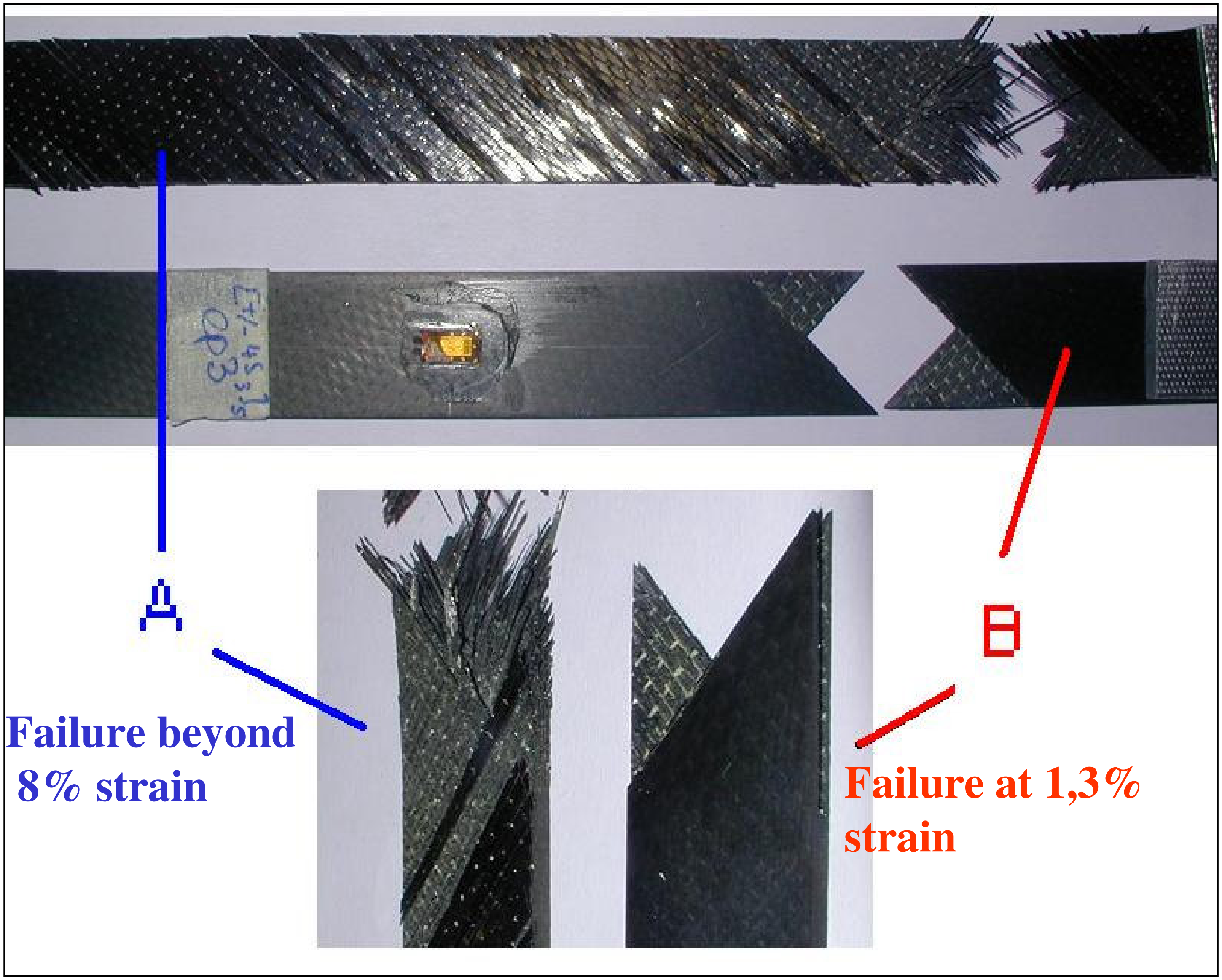
Isotropic hardening law

Difficulty of "material tests"

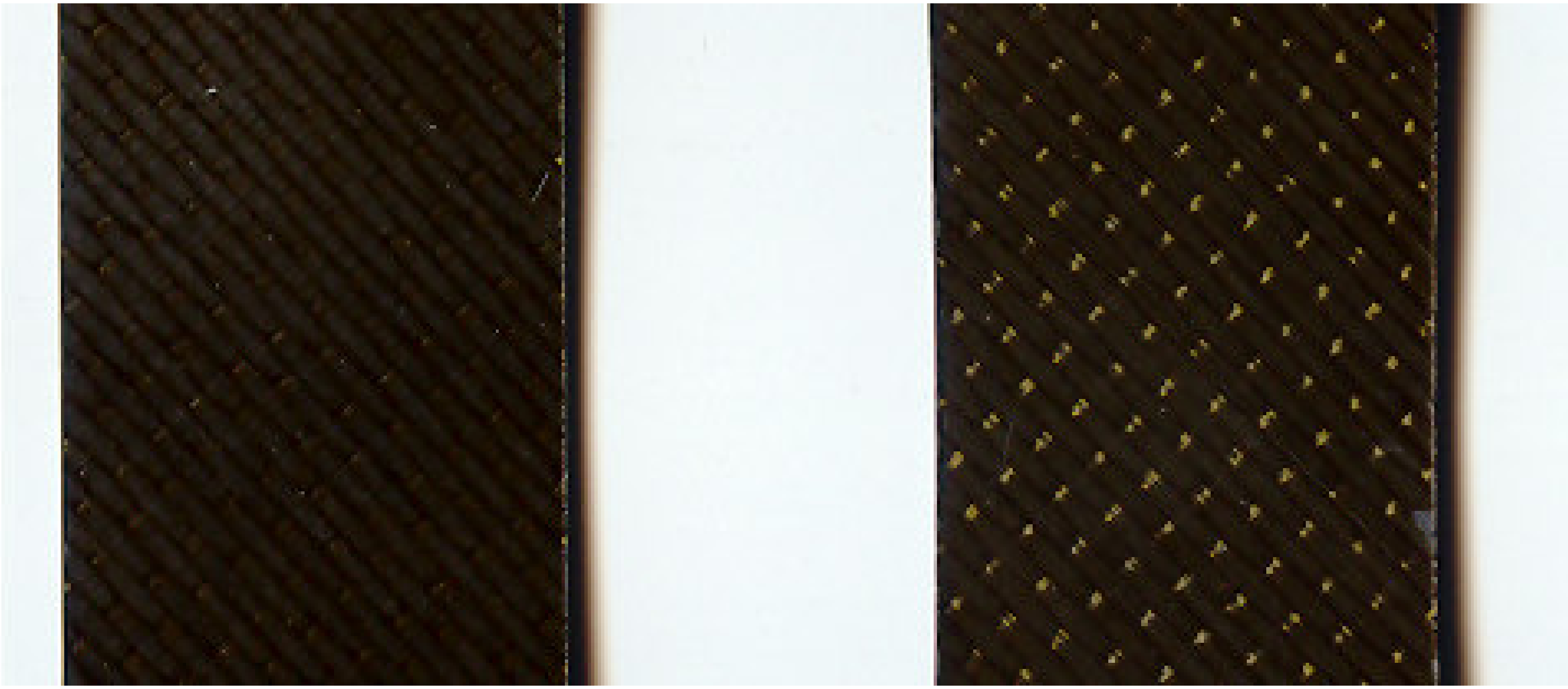
comparison of A $[+/-45]_{3s}$ and B $[+45_3,-45_3]_s$



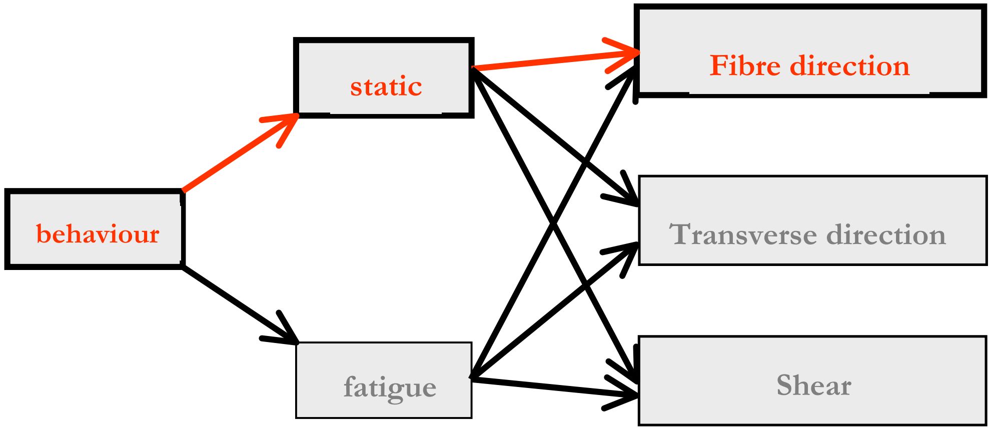



A
B
Failure beyond 8% strain
Failure at 1,3% strain

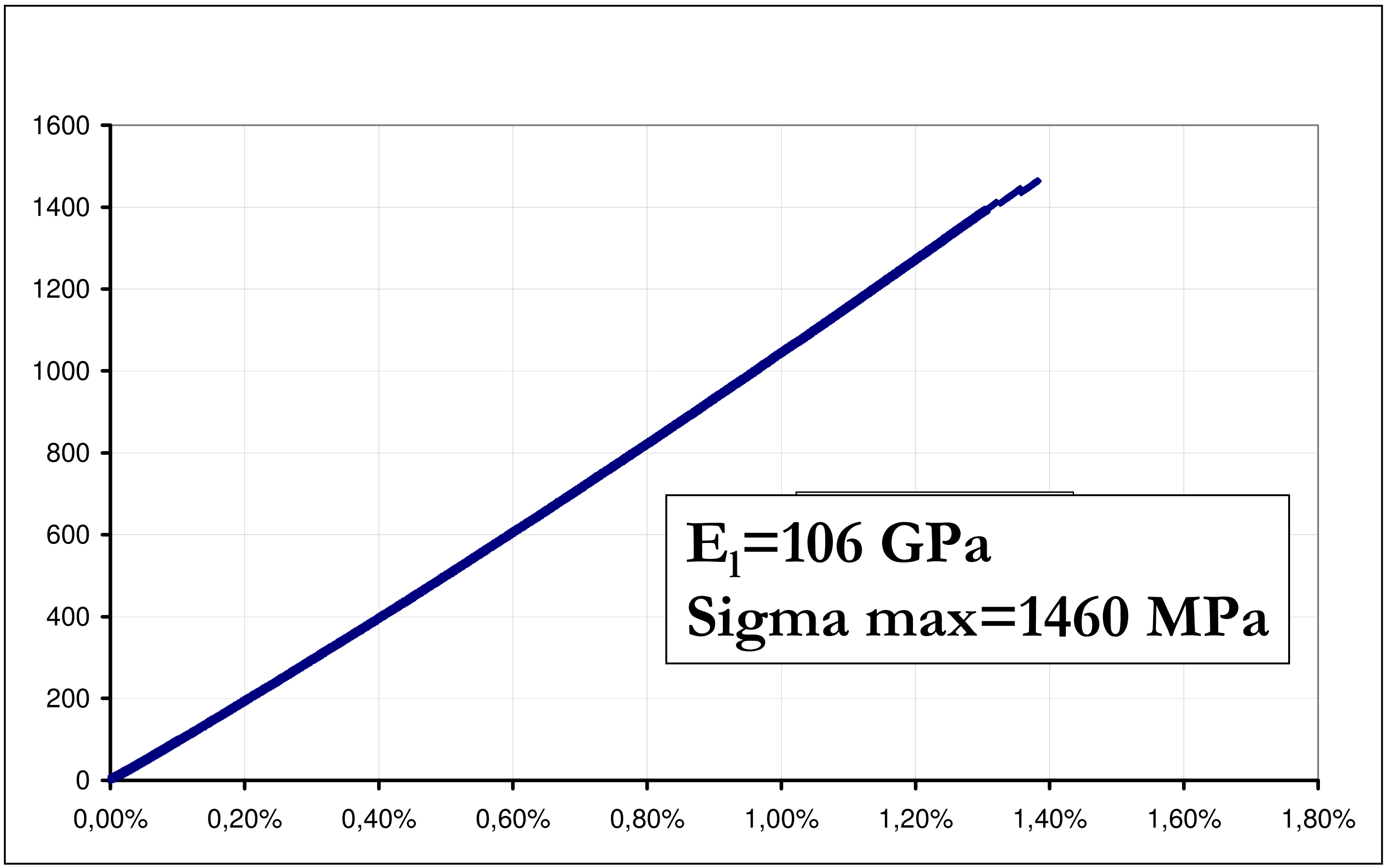
Sample A pristine and after 4% of total strain



Validity of diffuse damage hypothesis on $[+/-45]_{3s}$ up to instability condition



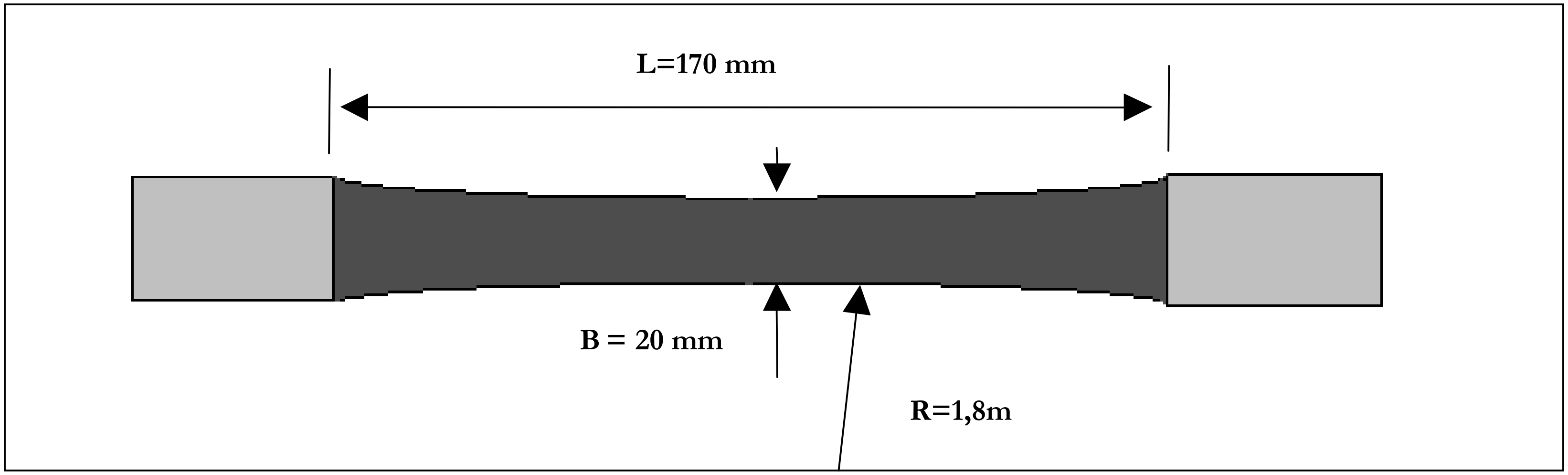
Static behaviour in fibre tension

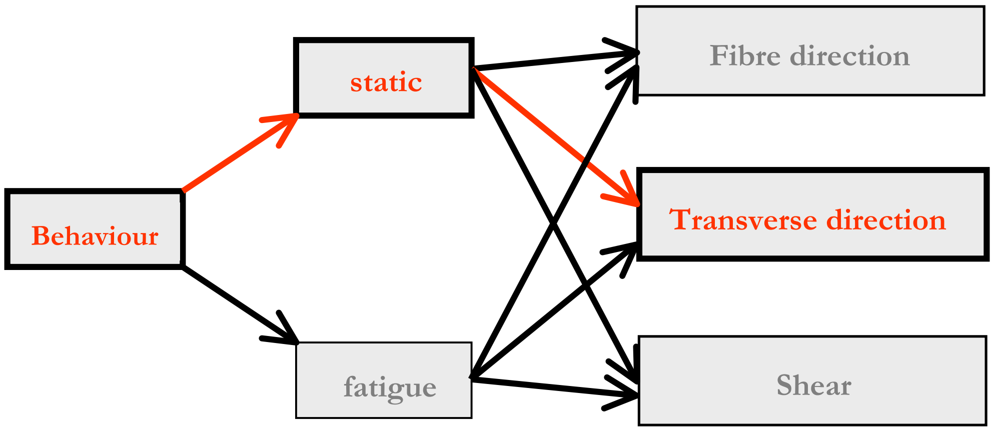


Machined sample

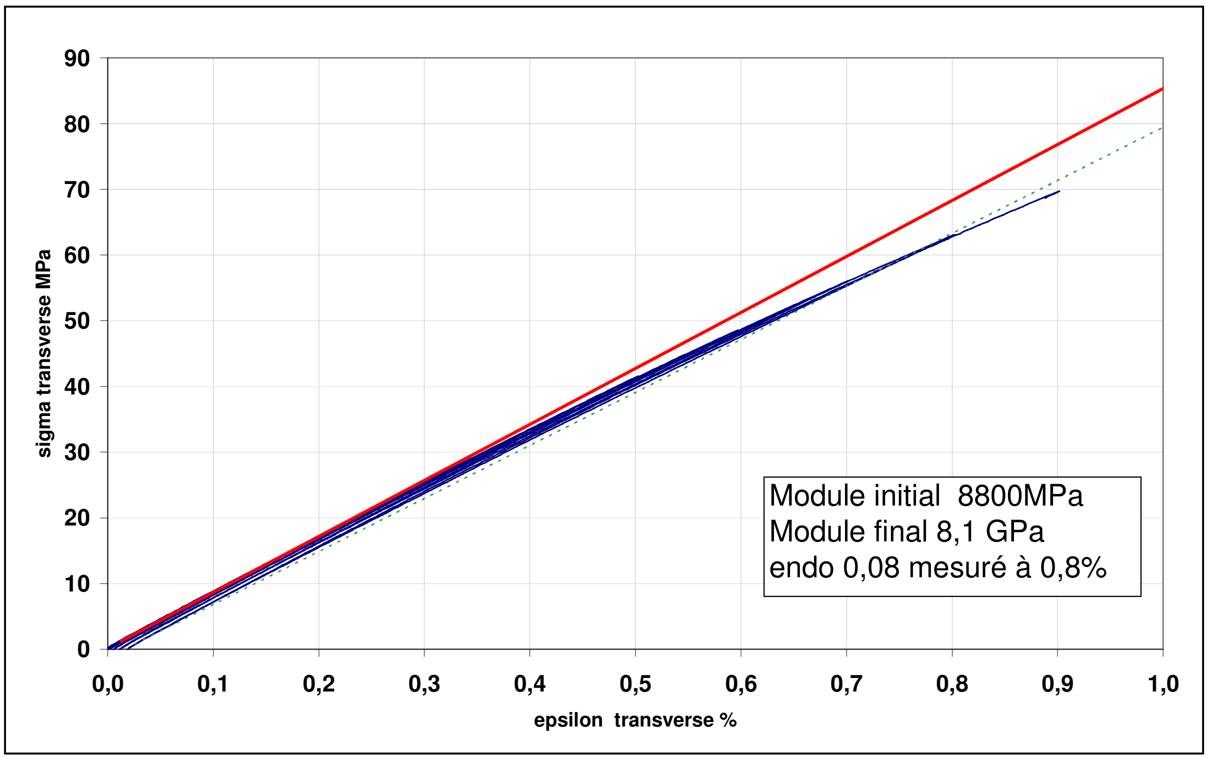
- To prevent edge effects at the tabs

  (under-estimation of strenght)



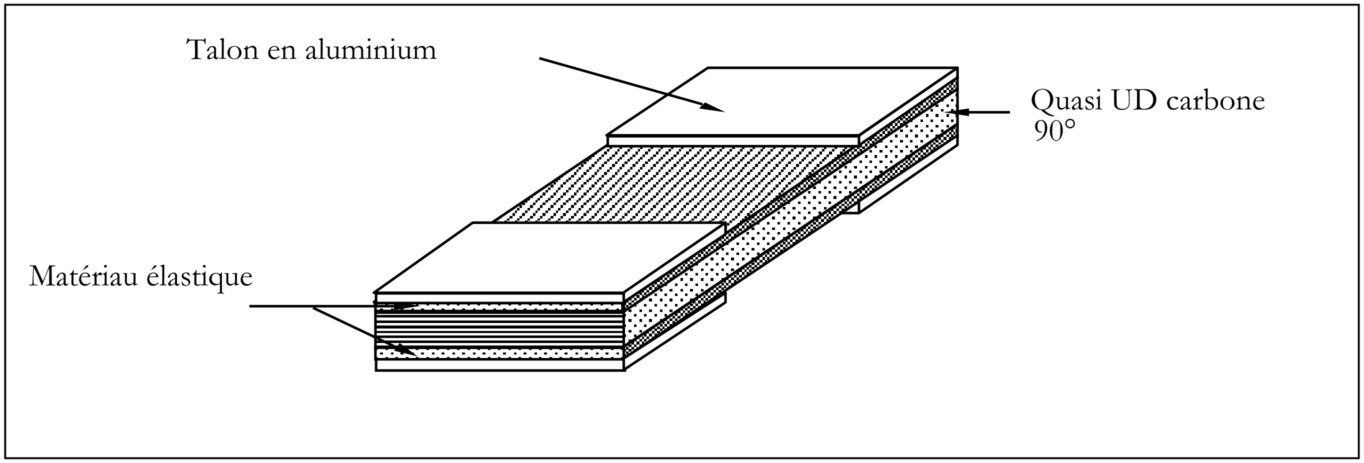


Static behaviour in transverse tension



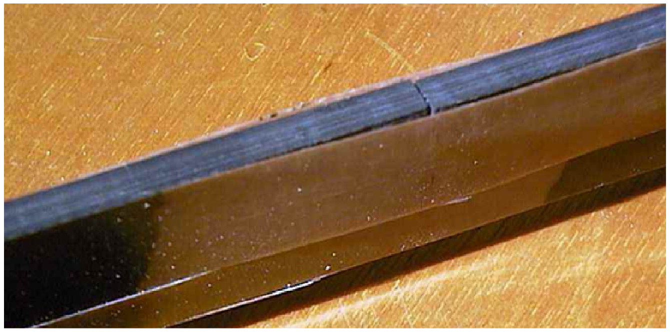
Earlier failure
With variable
Ultimate strain

Transverse tests improvement

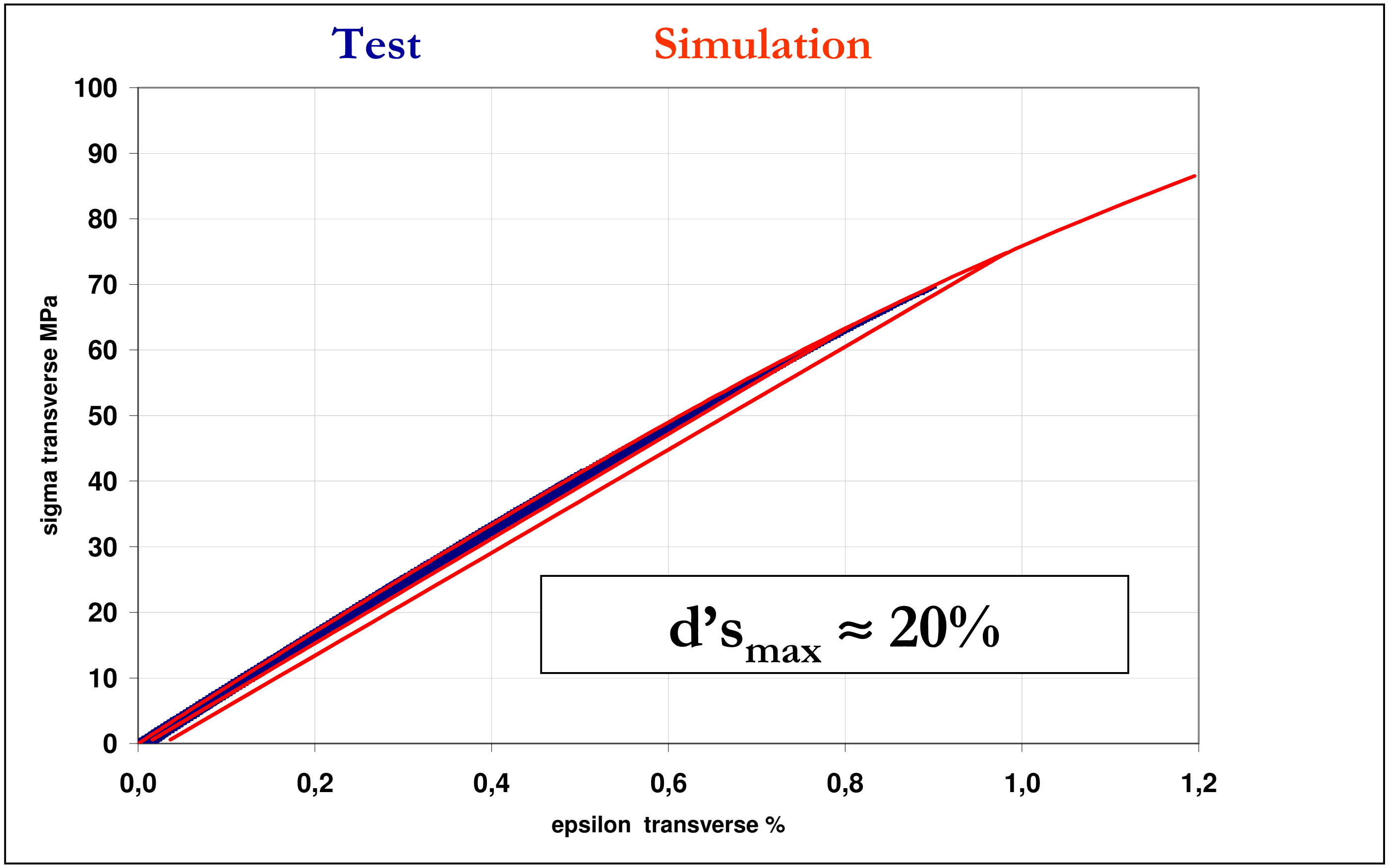


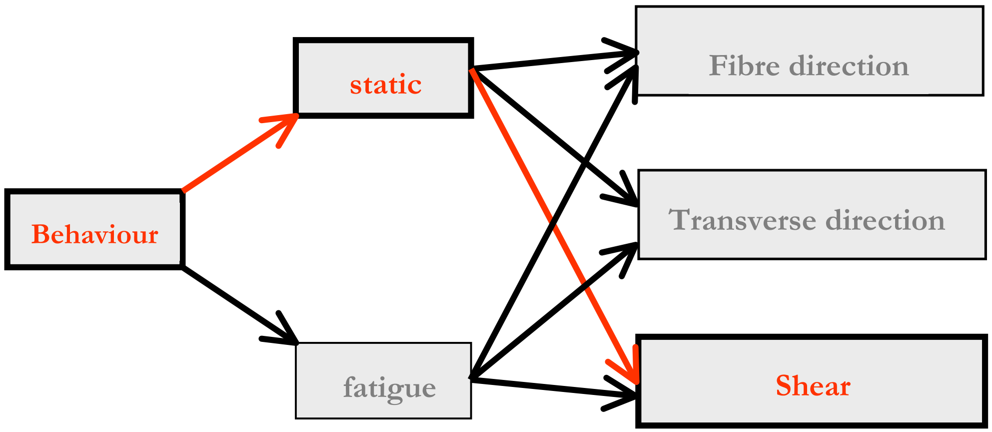
(Fatichi)

Making an hybrid laminate with elastic plies on both sides of transverse plies

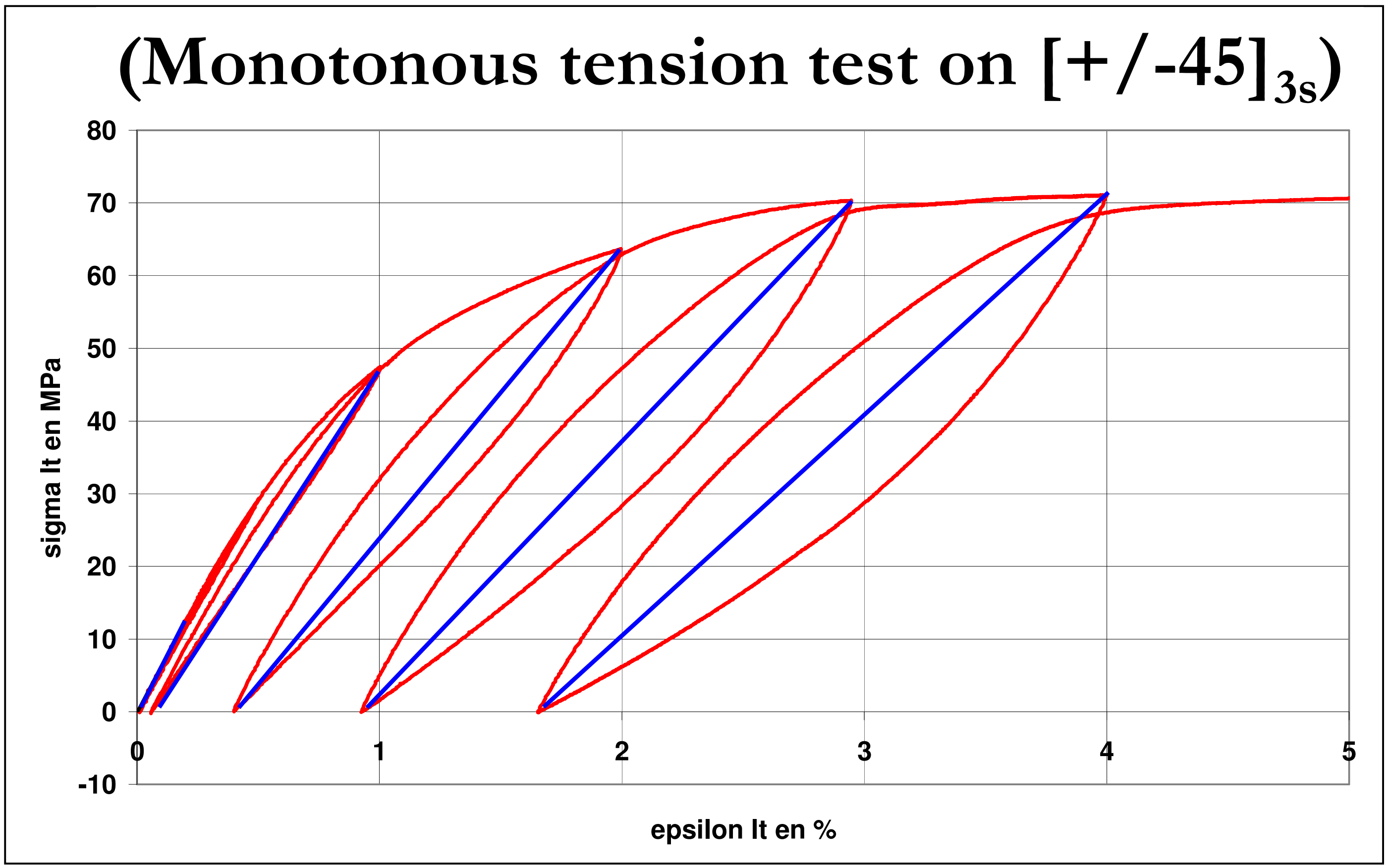


Simulation of static transverse behaviour up to 1,2%

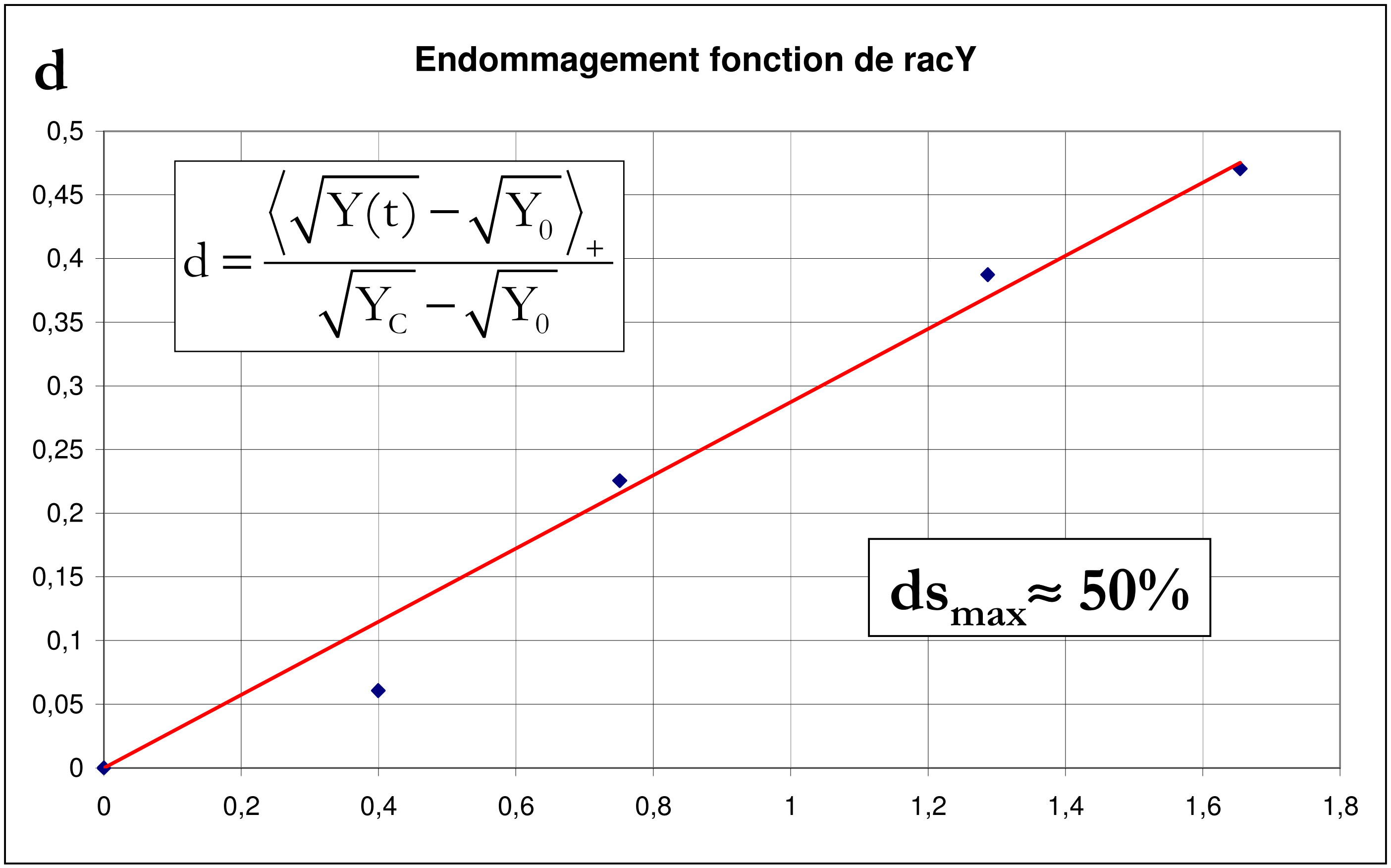




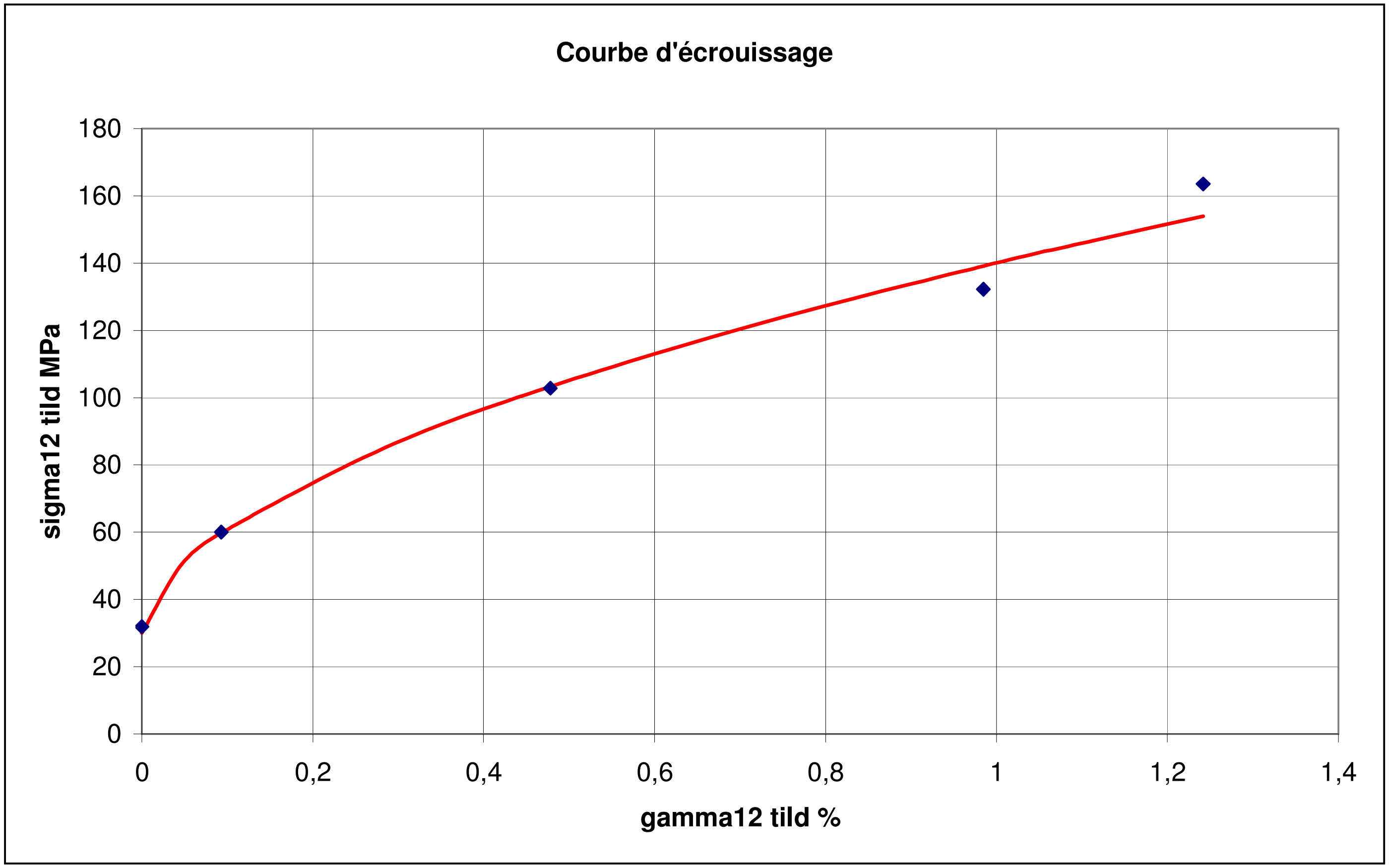
Static behaviour in shear



Static behaviour in shear
Damage evolution



Static behaviour in shear
Anelastic strain



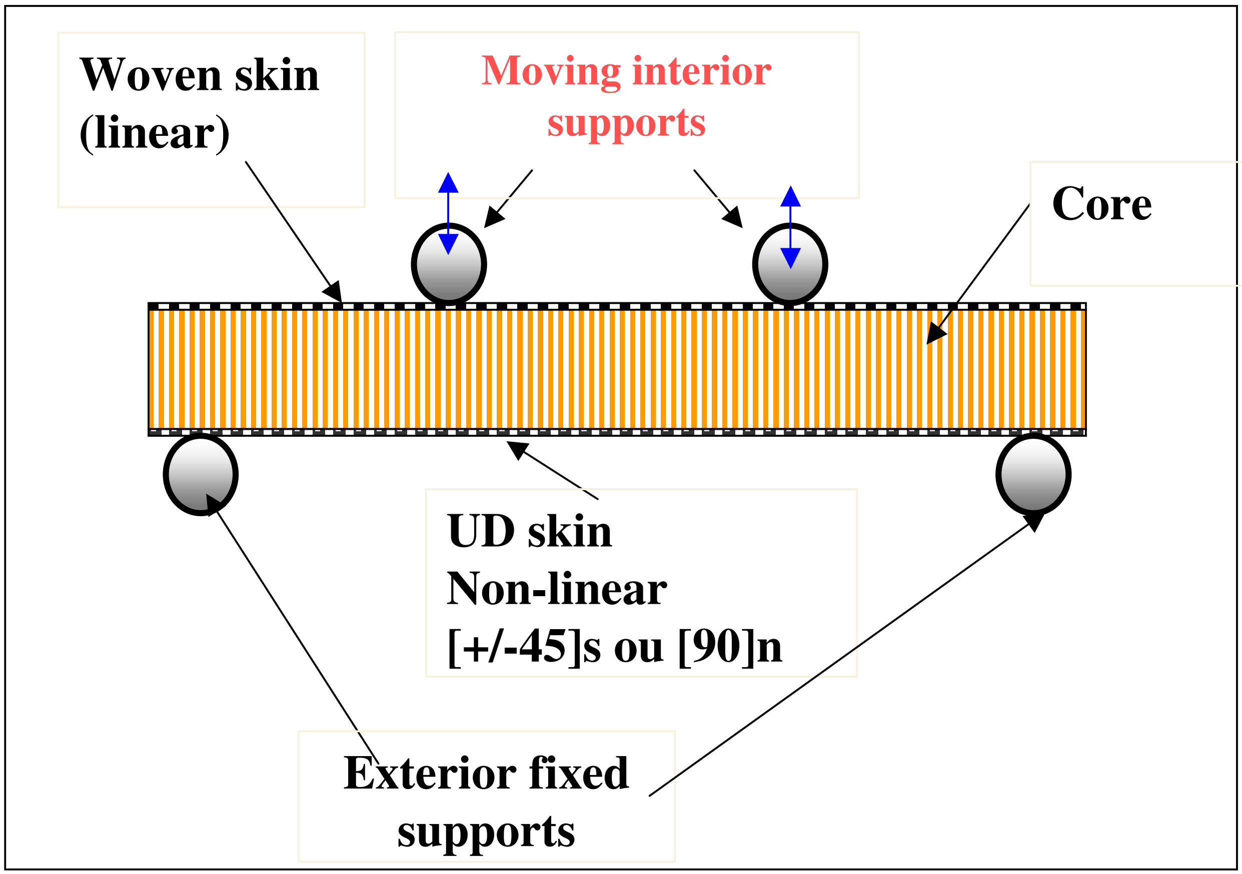
Effective quantities

$$\tilde{\sigma}_{lt} = \frac{\sigma_{lt}}{1 - d}$$

$$\dot{\tilde{\gamma}}^{p}_{lt} = \dot{\gamma}^{p}_{lt}(1 - d)$$

——— **Isotropic hardening law (classical model)**

Sandwich sample in 4-points-flexion



Advantages:

• Compression possible without bucking

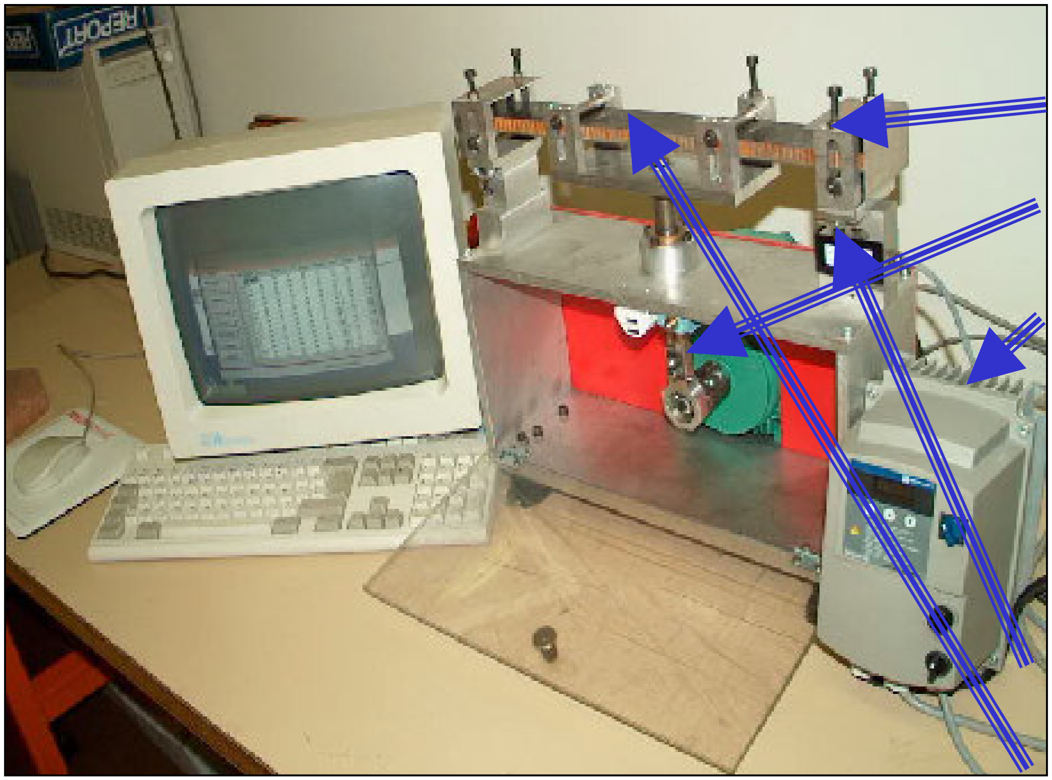
• Pure flexion in central zone: easy inverse calculus of stress

• Quasi-uniform strain field in central zone

Disadvantage:

• Simplified model unvalid with large displacements

Four-points Flexion Machine
(developed during study)



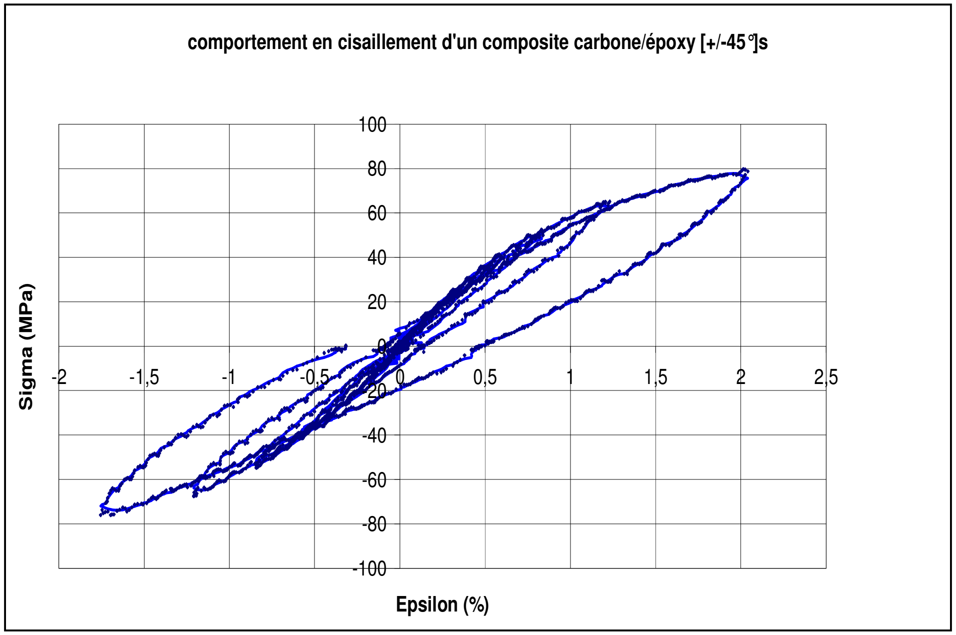
Parameters:

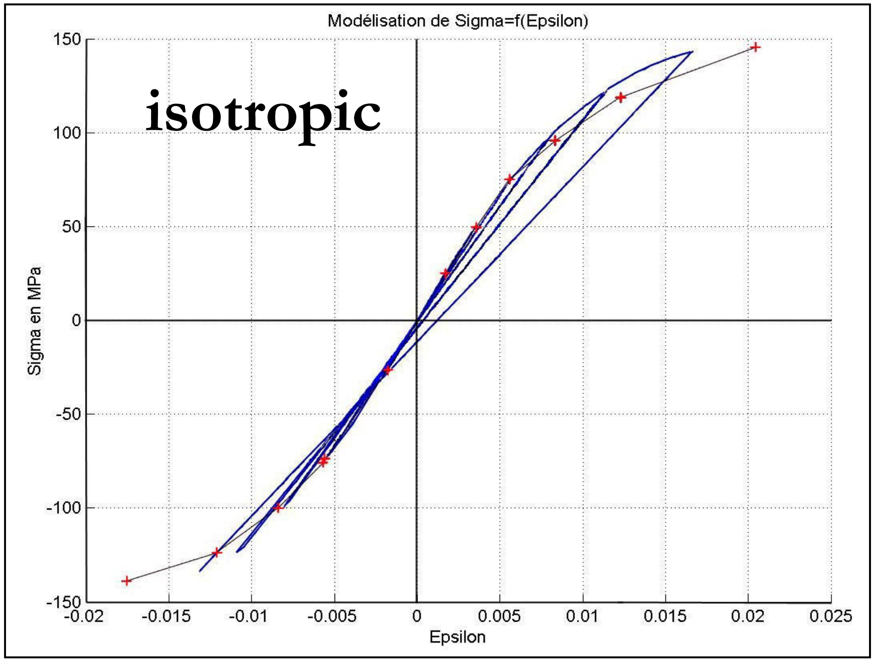
- average displacement (+/-)
- Alternated displacement
- Frequency (10 à 25 Hz)

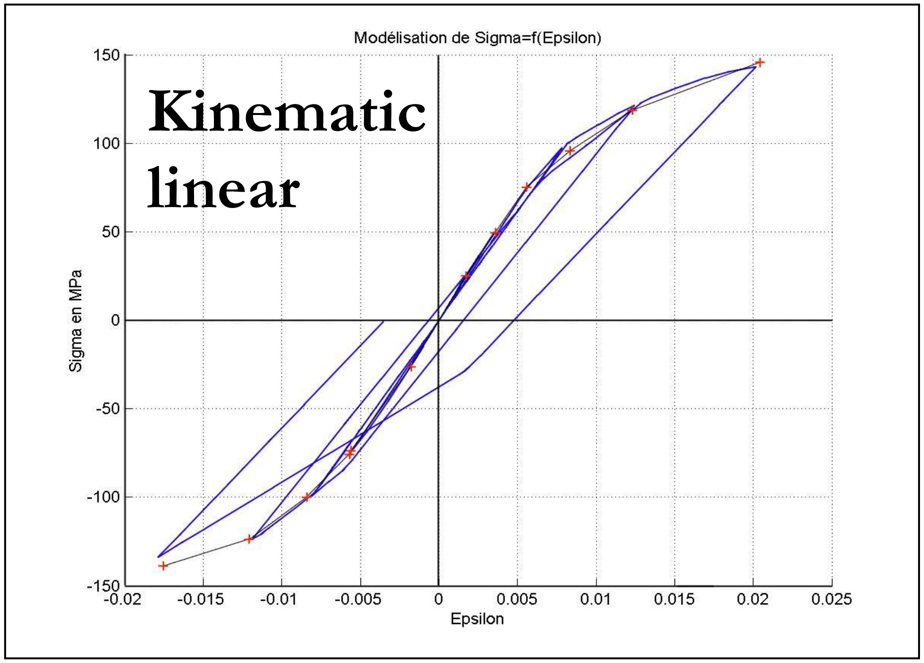
Measures:

- Load at fixed support
- Skins strains (static)

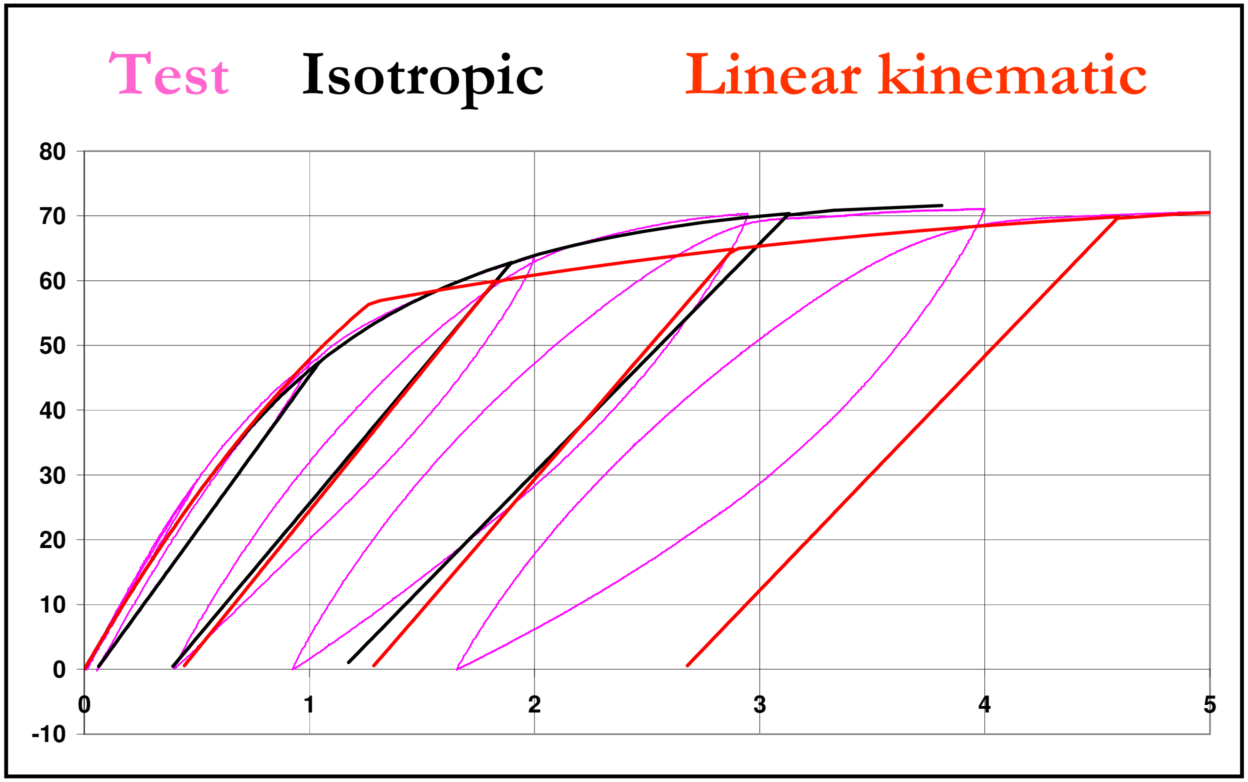
Hardening law identification with alternated test on [+/-45]s







Comparison of isotropic and linear kinematic laws on monotonous tests



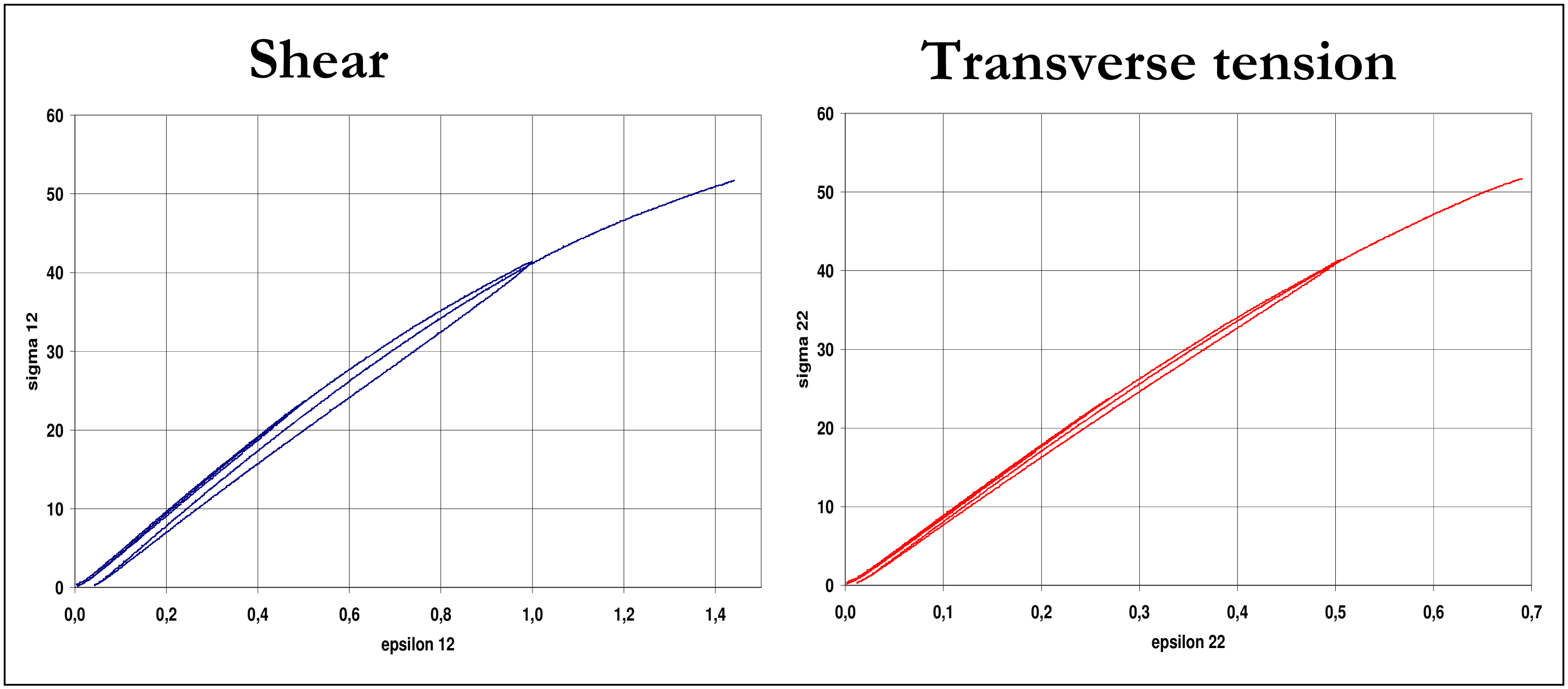
Modification of the classical model

$$f = \sqrt{(\sigma_{lt} - X_{lt})^2} - R_0$$

$$X_{lt} = a_{lt}\alpha_{lt} = a_{lt}\tilde{\gamma}^p_{lt}$$

Shear and Transverse tension coupling

Off-axis test $[45_8]$



Coupling parameter b'

$$d'_s = b' d_s$$

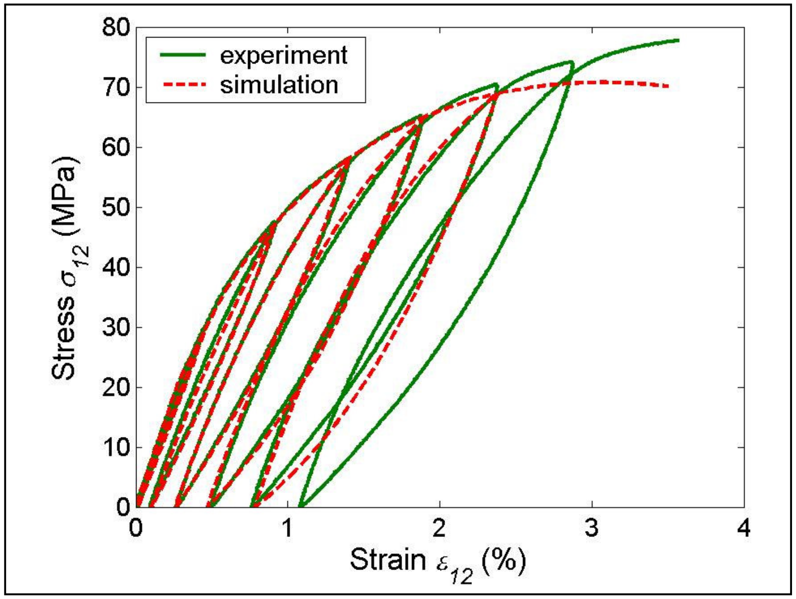
Conclusions on static study

As for shear :

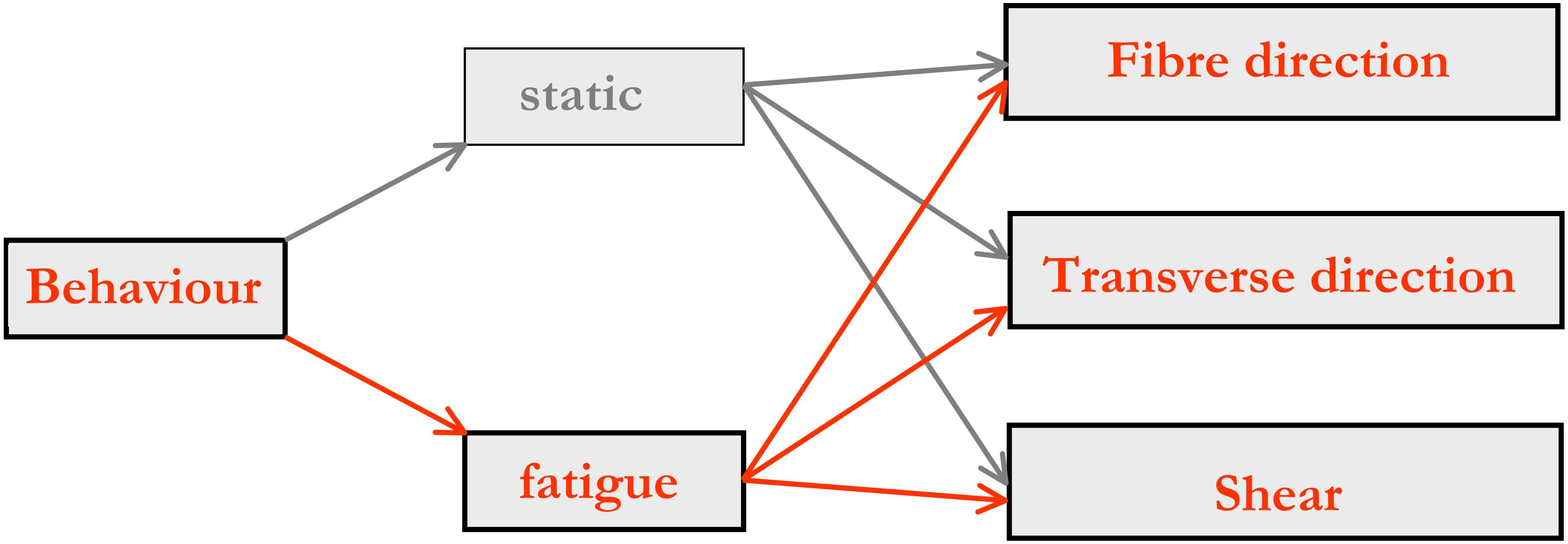
- Identification with kinematic hardening law
- Possible improvement:

  Kinematic with several thresholds

Off-axis tests to study bidimensional hardening law



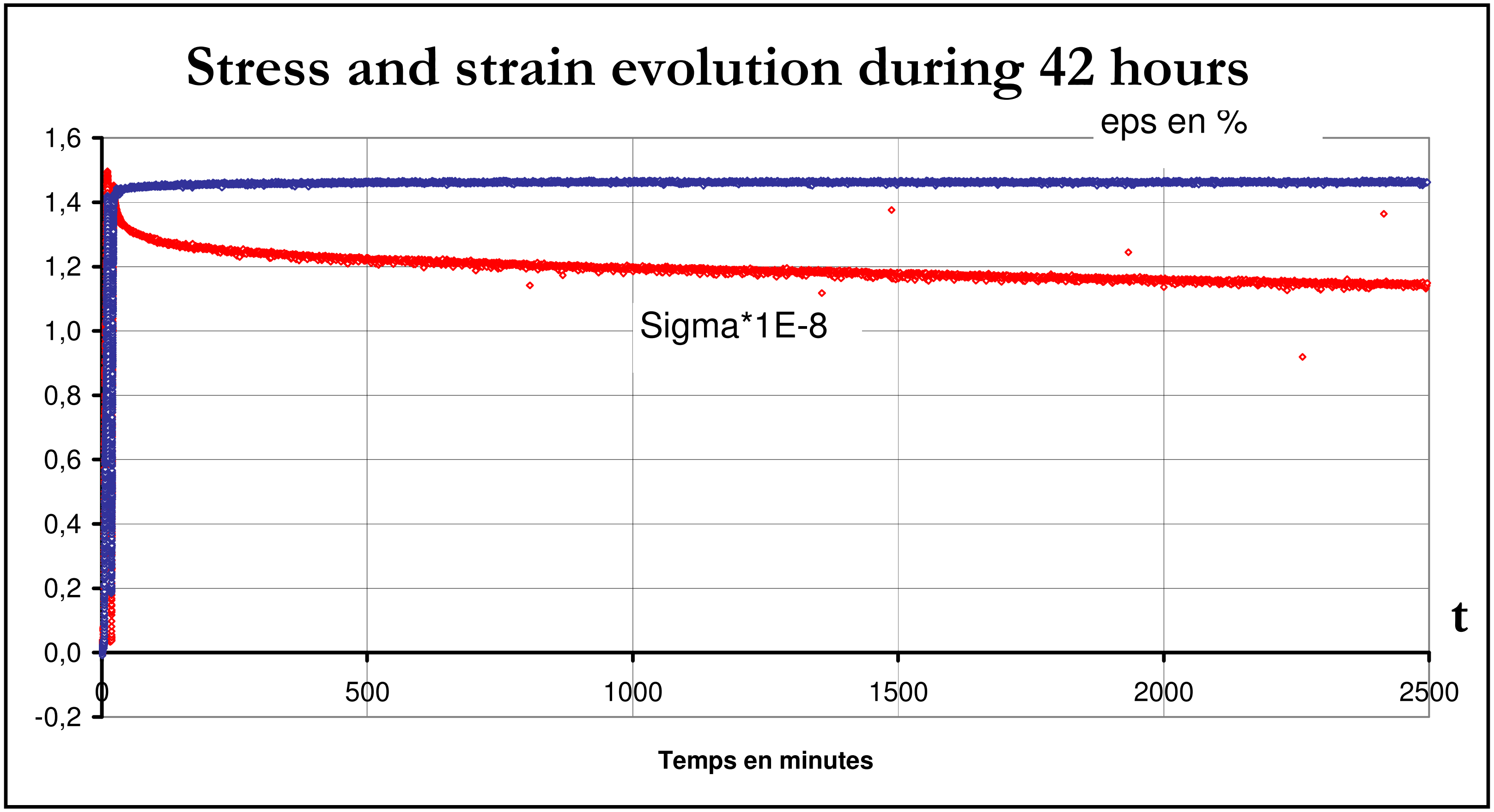
Dissipation due to friction (Saint-Venant model on woven 45°) (Bois, 2003)



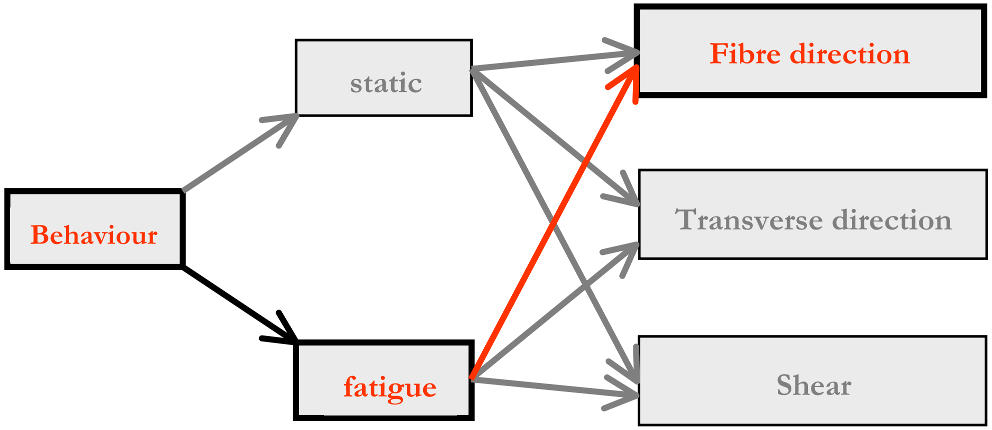
Hypothesis:

- **Identical with static study: Diffuse damage**
- **Phenomena linked with viscosity are not taken into account (temperature variation, frequency effect)**

Relaxation in shear



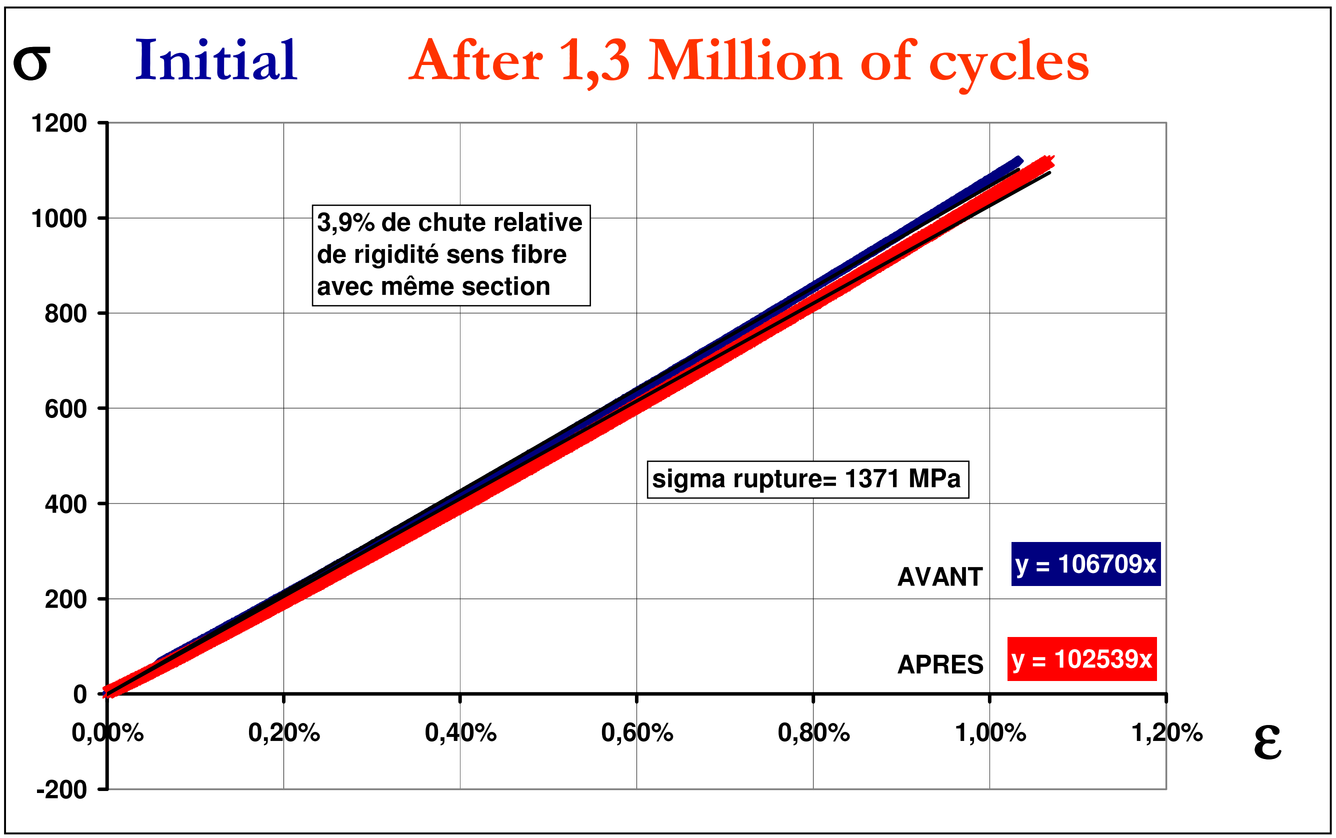
Evolution of stress with two time scales



Fatigue in tension in fibre direction

$\sigma_{max} = 80\% \ \sigma_{ult}$

R=0,1



Machined sample

After 1,3 million cycles

No fatigue in fibre tension

Damage evolution with fatigue loading

- **Cyclic damage rate is function of:**
  - **Maximal value of thermodynamic equivalent force**
  - **Difference between maximal and minimal value of Y**

$$\frac{\partial d_f}{\partial N} = c\left\langle \left(Y_s - Y_m\right)^{\alpha} Y_s^{\beta} - Y_{0f} \right\rangle_+$$

$$Y_m(t) = \min_{t' \in \mathrm{cycle}(t)} \sqrt{Y(t')} \qquad Y_s(t) = \sup_{t' \in \mathrm{cycle}(t)} \sqrt{Y(t')}$$

$$d_f{}' = b' d_f$$

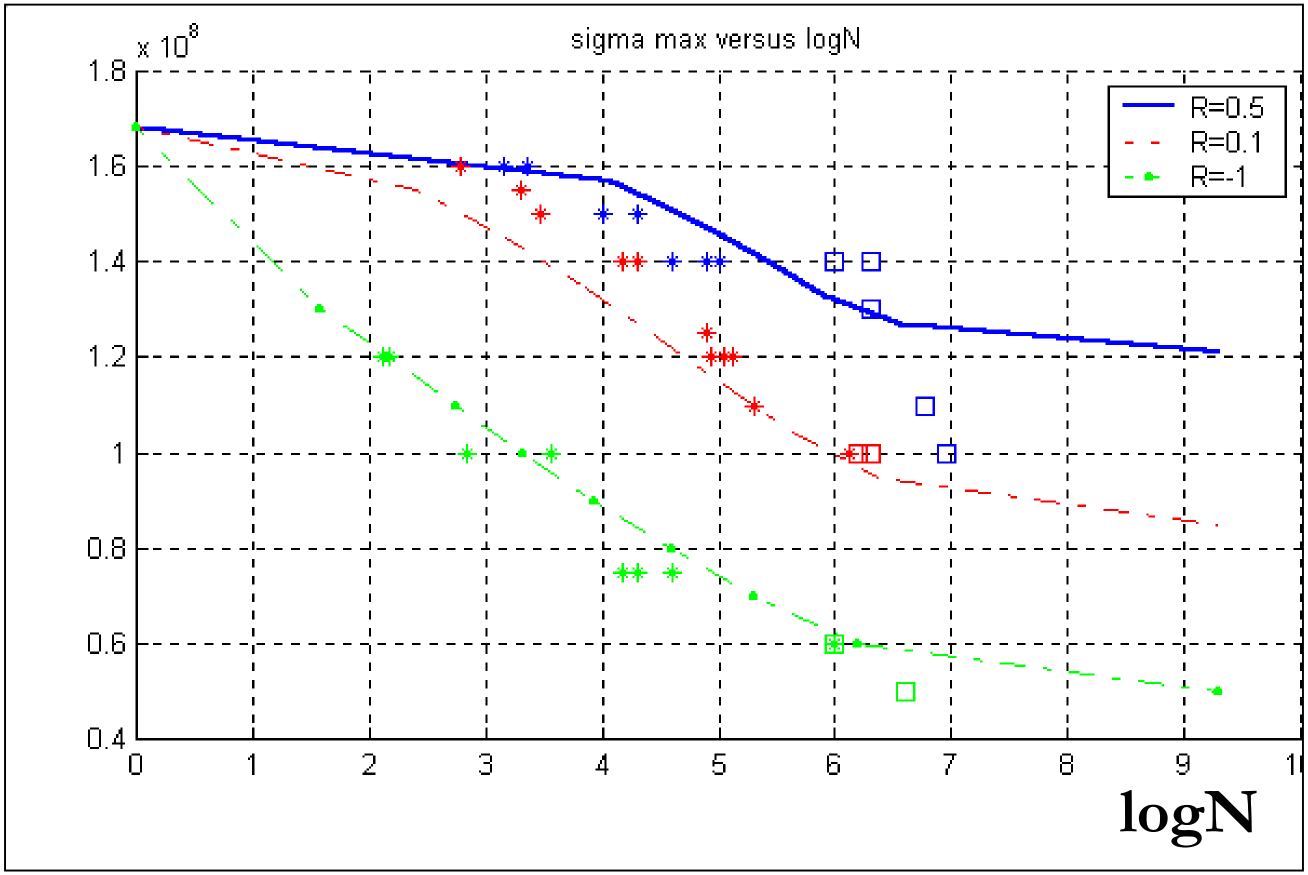
- **Failure modes: idem static**

  instability condition for shear

  brittle threshold for transverse tension

$[+/-45]_{ns}$ SN curve

σ_{max}



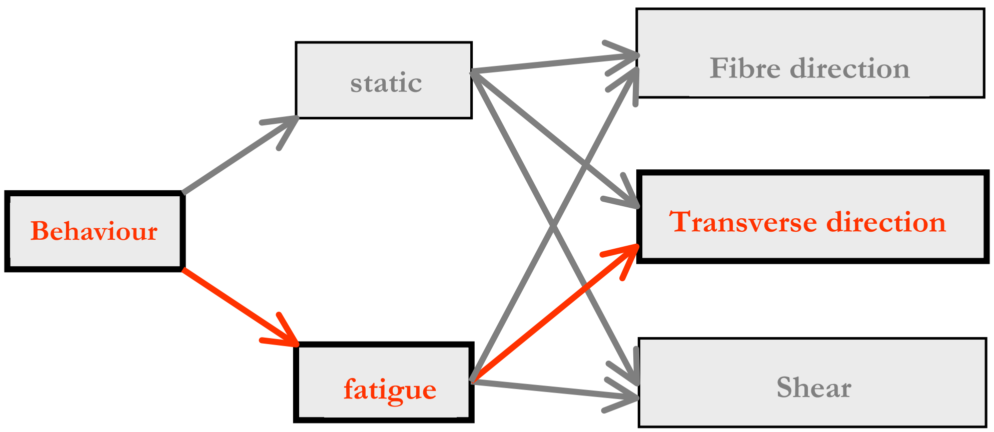
R=0,5
R=0,1
R=-1

☆ Failed spec.

□ Non failed spec.

$\Delta\sigma=\sigma_{max}(1-R)$

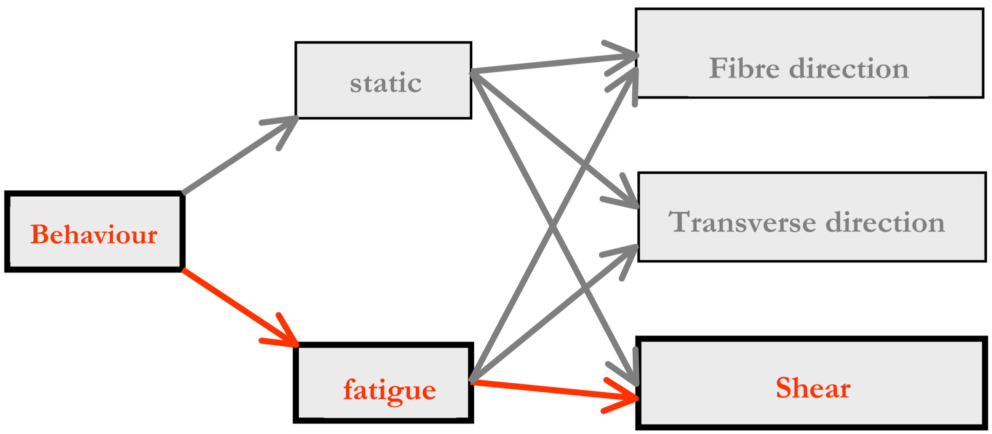
(HTA- 6376 Petermann)



Fatigue in transverse tension

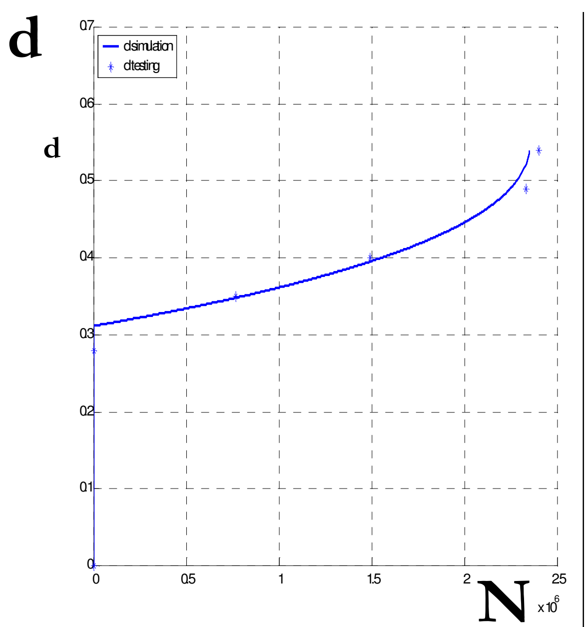
N° test	Max. strain (%)	Strain amplitude	Life (cycles)
1	0,33	0,2	+ de 1,2 10^6
2	0,7	0,2	Rupture at 46000
3	0,5	0,2	+ de 1 10^5
4	0,5	0,5	Rupture at 4000

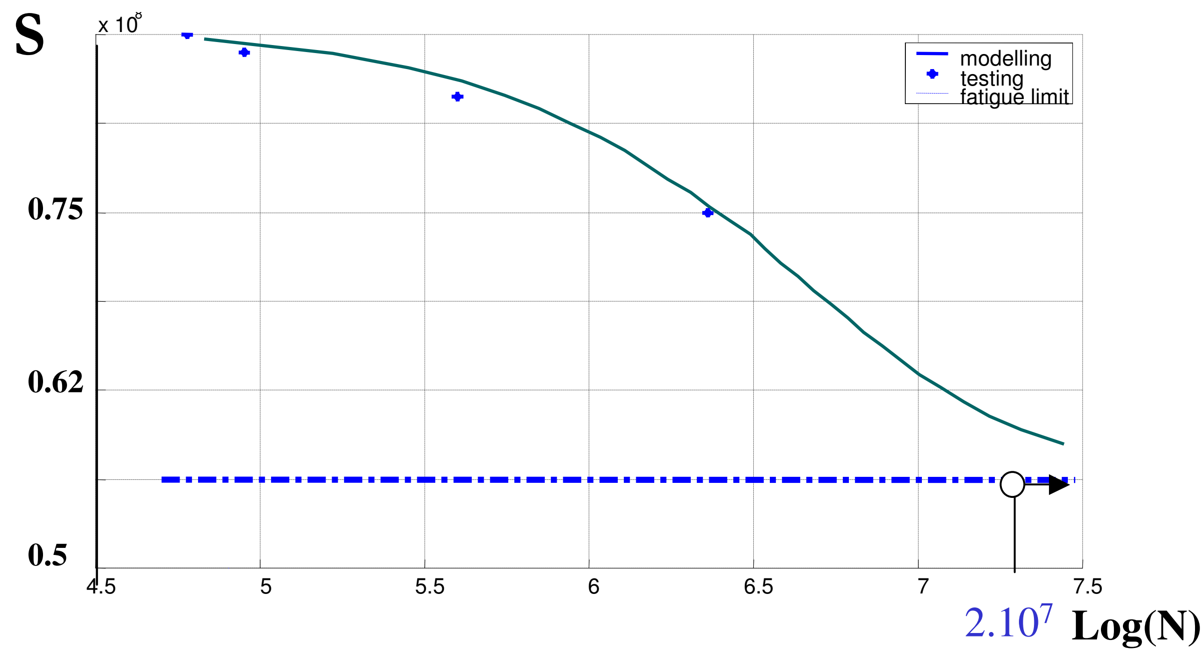
- N_R decrease with ε_{max} increasing and delta ε increasing
- Inability of the test to put in evidence damage evolution



Fatigue in shear

(first tests on mechanical machine f=35Hz R=0,5)

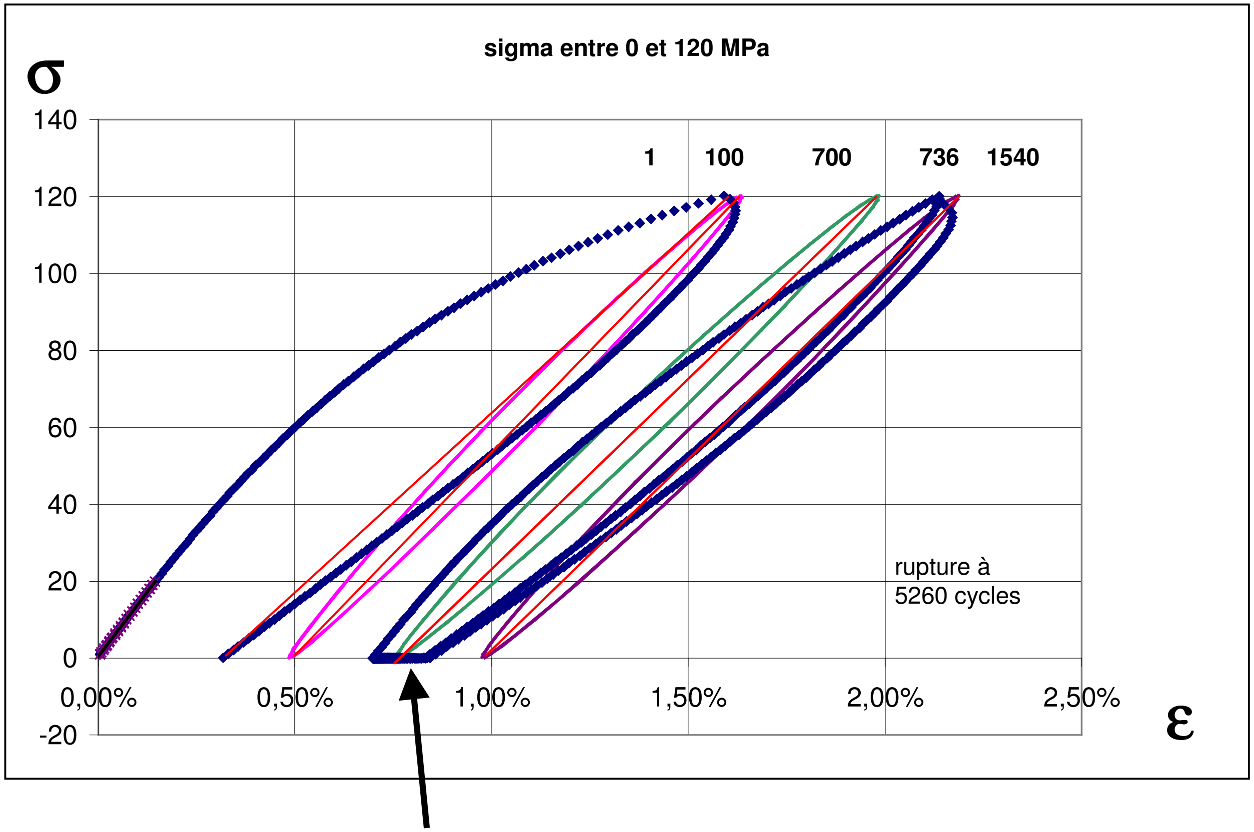




Damage evolution versus number of cycles

SN curve with fatigue limit

Fatigue in shear: (new hydraulic machine) testing procedure



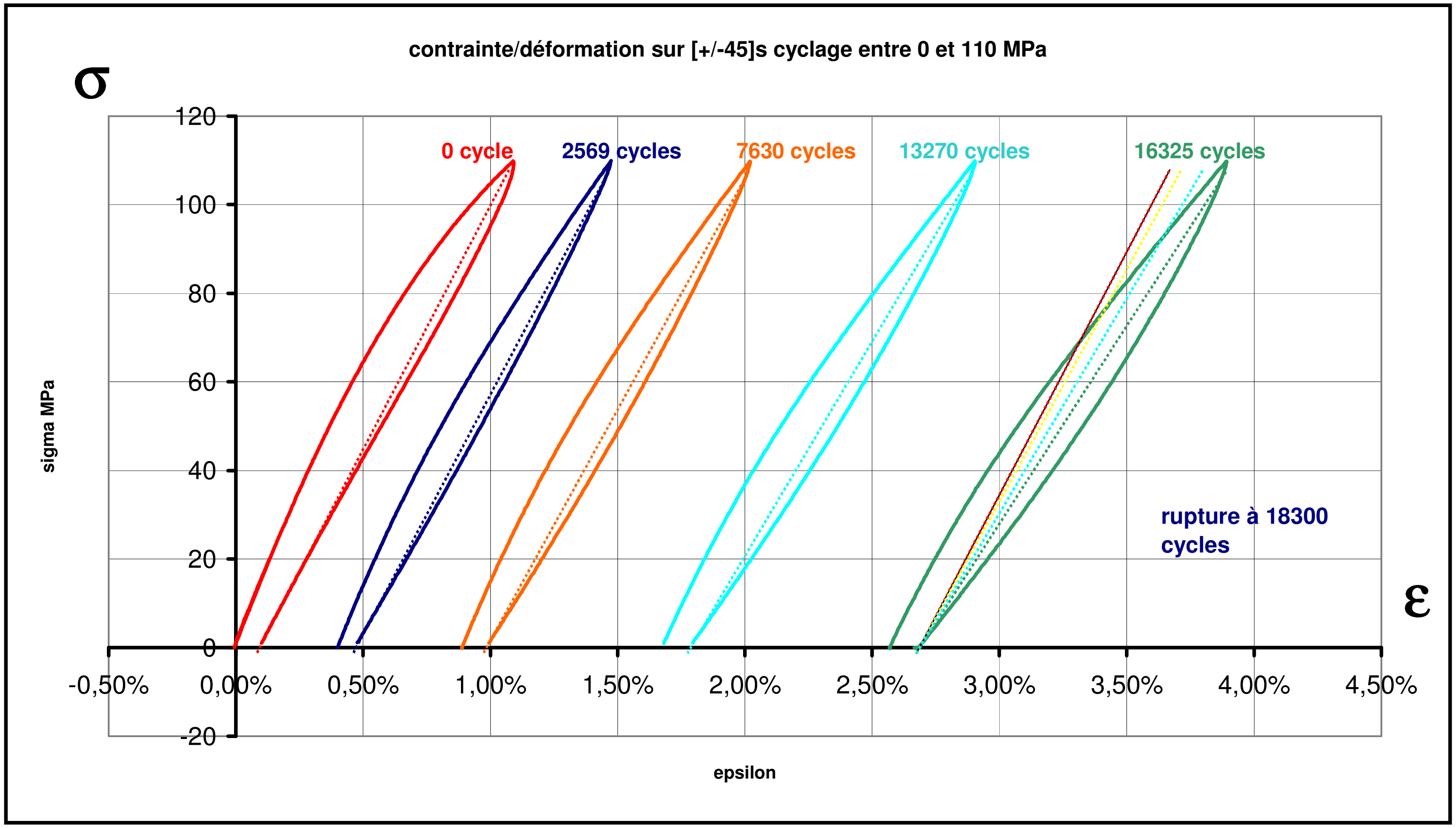
Recovering time: 3mn

Tension on $[+/-45]_{3s}$

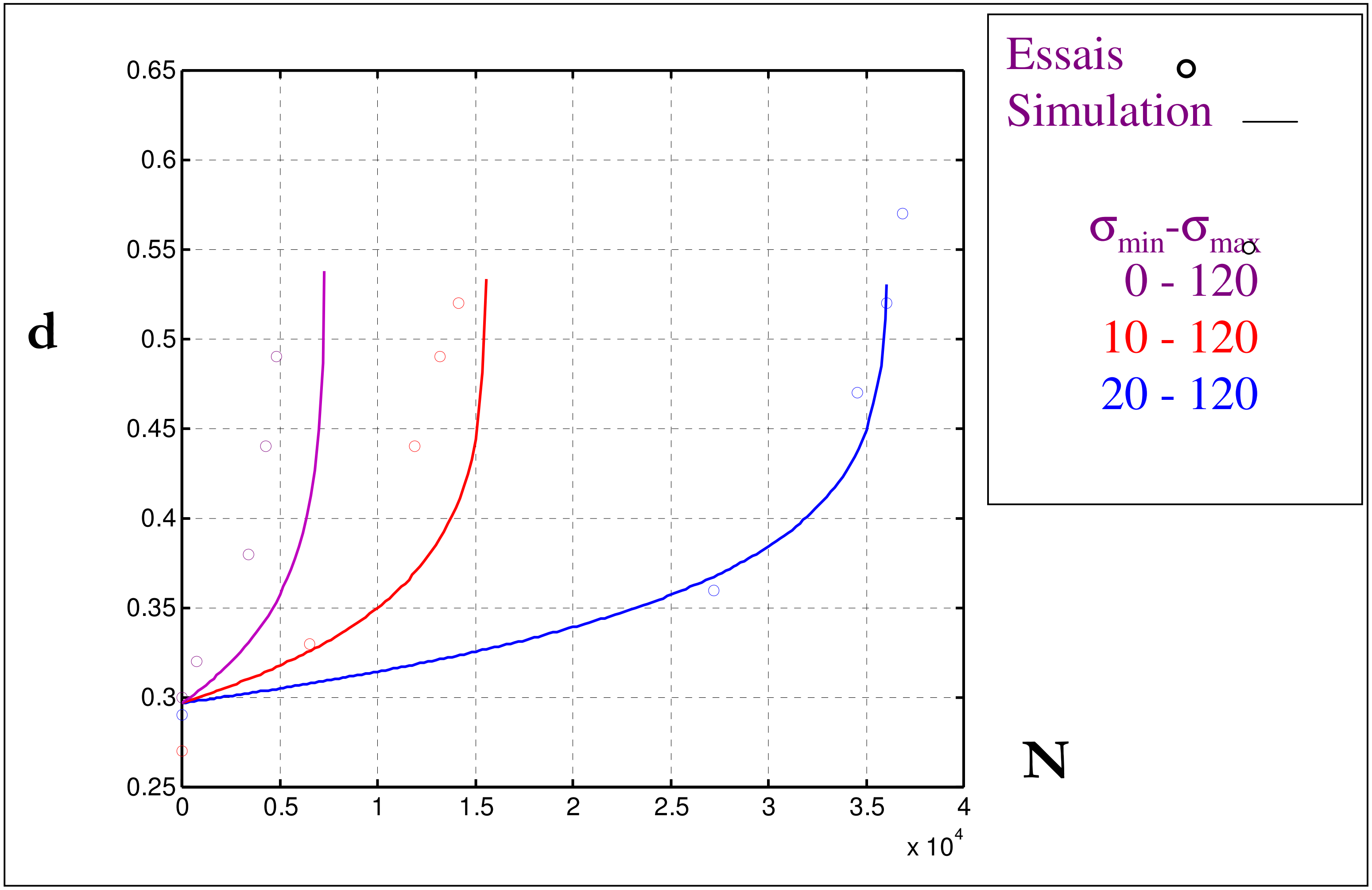
Static conditions are required for damage and anelastic strains measures (without dynamic effects)

Fatigue in shear

Damage and anelastic strain measures



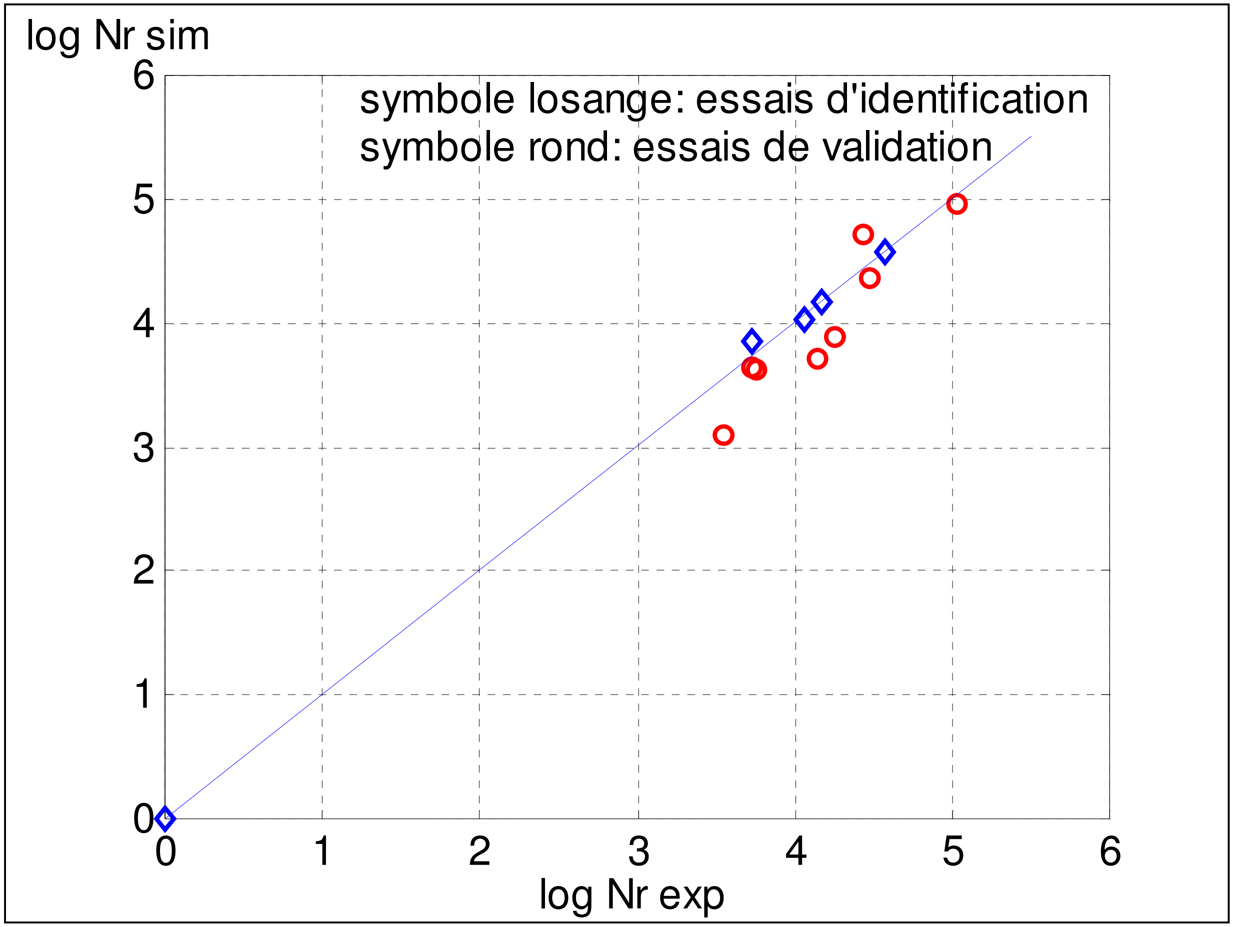
Shear damage evolution versus N



Shear fatigue

Comparison experiment/simulation

on number of cycle to rupture



Identification Tests: ◇

Validation tests ○

f=10 Hz

Shear behaviour integration

Non-linear damage computation with stresses imposed

$$Y = \frac{(\sigma_{lt})^2}{2G_{lt}^0(1-d)^2}$$

$$d = d_S + d_F$$

$$d_s = f_1(\sqrt{Y})$$

$$\frac{\Delta d_F}{\Delta N} = f_2(\Delta Y, Y_{max})$$

Plasticity (independant of loading type)

$$f = \left|\tilde{\sigma}_{lt} - \alpha\tilde{\gamma}_{lt}^p\right| - R_0$$

$$\tilde{\sigma}_{lt} = \frac{\sigma_{lt}}{(1-d)}$$

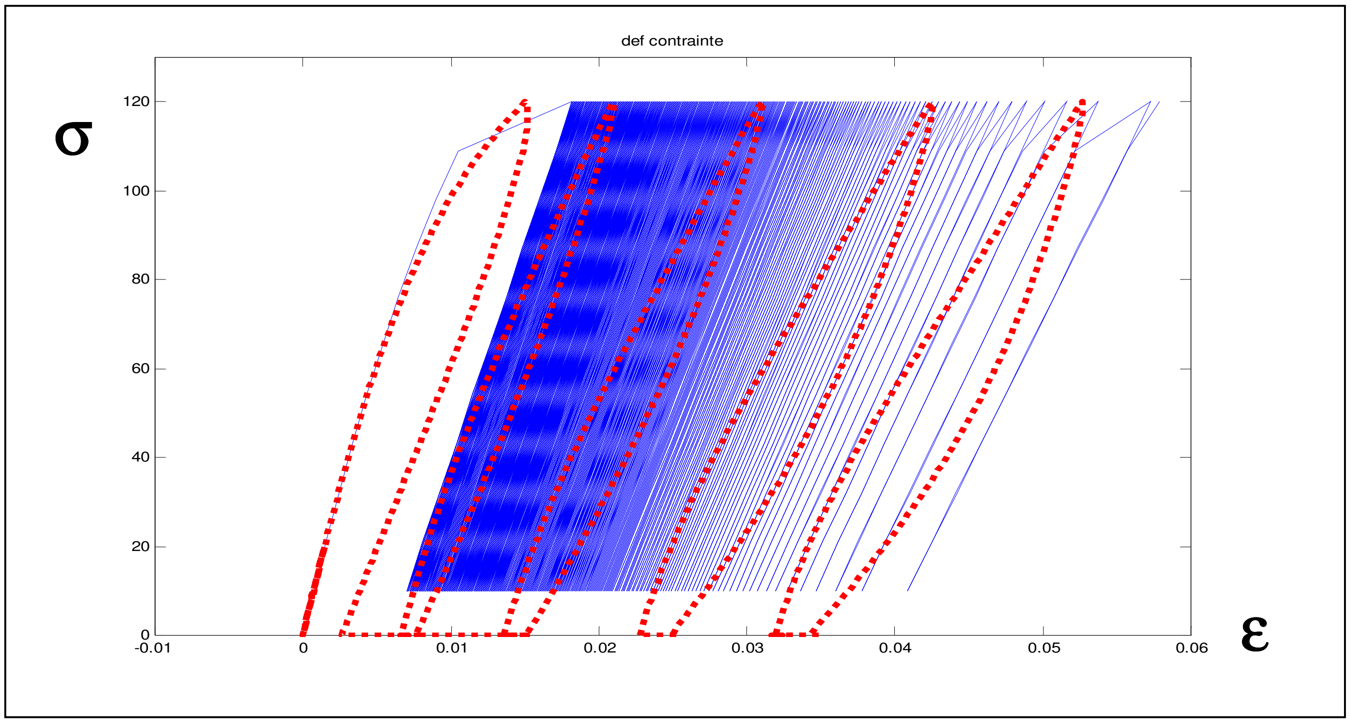
$$\dot{\tilde{\gamma}}_{lt}^p = \dot{\gamma}_{lt}^p(1-d)$$

Under fatigue $N \nearrow \Rightarrow d_f, d, Y, d_s \nearrow$ $\quad d \nearrow \Rightarrow \tilde{\sigma} \nearrow \Rightarrow \gamma^p \nearrow$

Coupled variables

Sigma/epsilon curve of [+/-45]$_{3S}$

Fatigue test σ between 10 and 120 MPa at f=10Hz



(Bordreuil)

Experiment

Simulation

Residual shear strength

- **Low loss of strength**

Test 20-120 MPa at N/Nr=94%

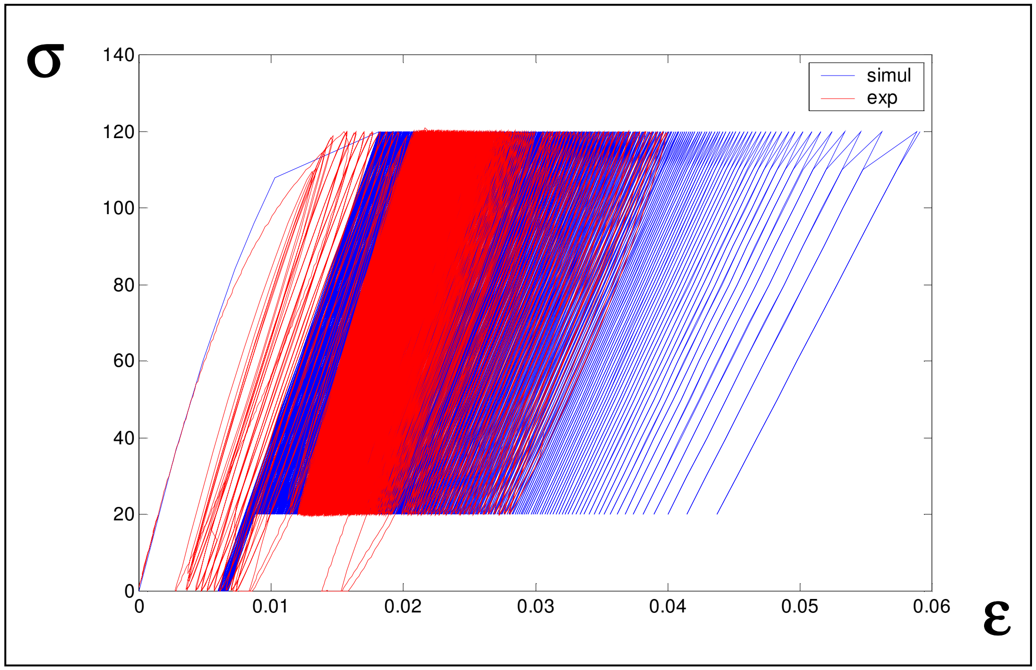
(compared with a fatigue test under the same conditions)

Residual Strength/Static Strength=87%

(compared with a static test)

Two levels shear fatigue

- **A first test show feasibility 0-120 MPa then 20-120 Mpa**



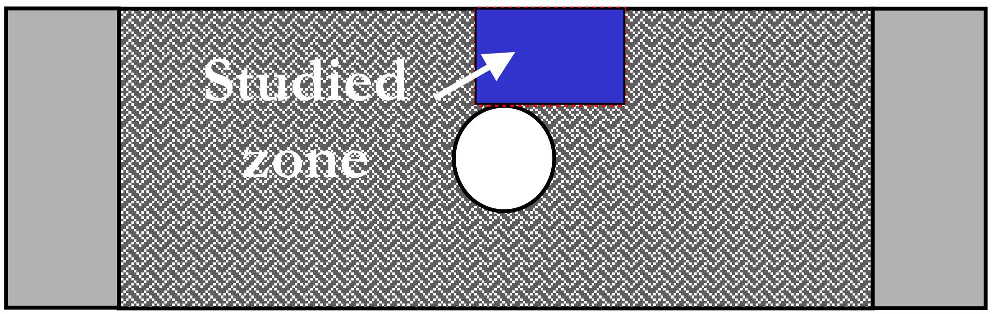
Conclusions

- Unified model: static and fatigue
  – Shear mainly studied
- Existence of a fatigue limit
- Field of validity:
  – Diffuse damage (no macro-cracks)
  – Non-delaminating structures (tubes)

Prospects

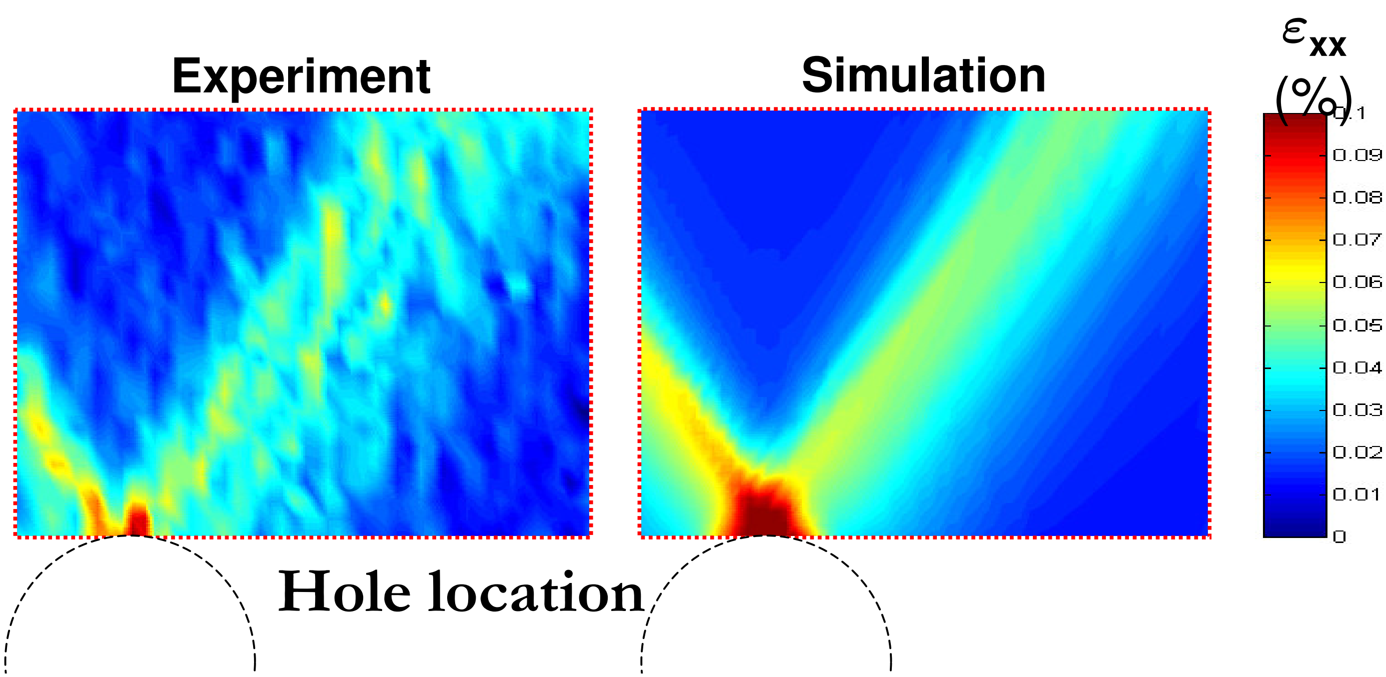
- **On unidirectional ply**
  - In static: bi-axial loadings (tension/torsion on tubes) and compressions
  - In fatigue: transverse behaviour and coupling
- **On woven ply** (already begun)
  - Integration of shear part of Ud model in a FEM code (routine UMAT in ABAQUS)

Static test on woven structure plate with hole



Woven laminate [45]

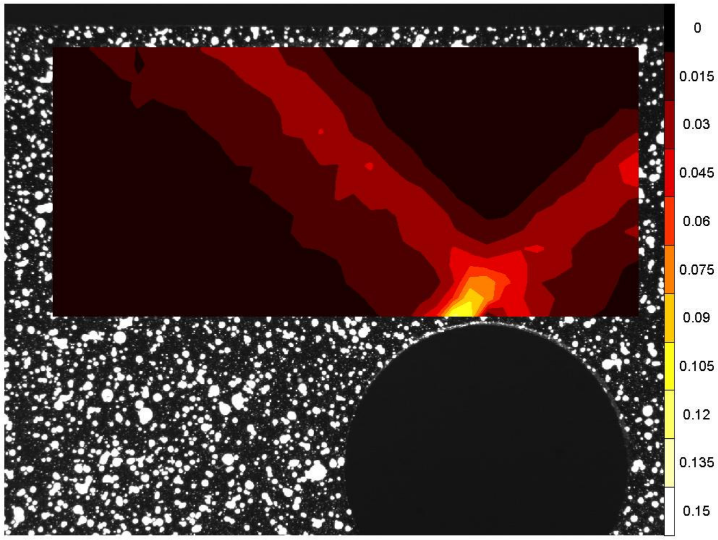
(Hochard)



Fatigue test on woven structure plate with a hole

Experimental longitudinal strai
repartition after fatigue loading

No macro-cracks until a large
part of normalized life N/Nr



(Bordreuil)

Laminated composites behaviour under static and fatigue loadings

Juliette Payan

Dir Thèse: Christian Hochard

Laboratoire de Mécanique et d'Acoustique **Marseille**