# Relationship between damage and permeability in linerless composite vessels

Hortense LAEUFFER[1,2], Brice GUIOT[2], Jean-Christophe WAHL[2], Florian LAVELLE[1], Nicolas PERRY[3], Christophe BOIS[2]

I2M : Institut de Mécanique et d'Ingénierie
département Ingénierie Mécanique et Conception

07/07/2016

[1] CNES, Direction des LAnceurs (DLA), Paris, France
[2] Univ. Bordeaux, I2M, UMR 5295, Talence, France
[3] Arts et Metiers ParisTech, I2M, UMR 5295, Talence, France

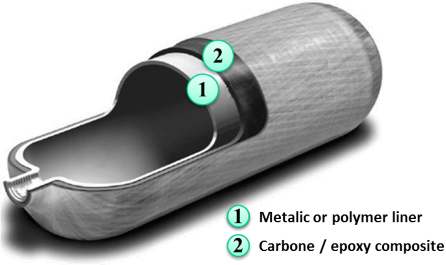
h.laeuffer@i2m.u-bordeaux1.fr

# Introduction

*Industrial goal* :

- reduce the weight of launcher structures

$\rightarrow$ design **linerless composite vessels** for propellant storage



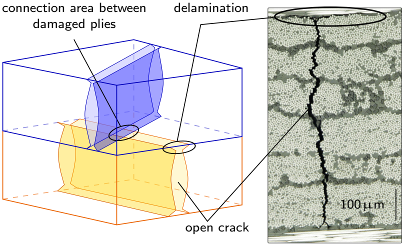

Filament-wound vessel of type 3 [Onder 2007]

*Requirement* :

- gas toughness of the composite wall

# Introduction

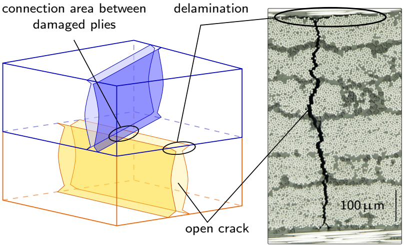
*Issue* : damage initiates for low levels of thermo-mechanical loading with little effect on mechanical properties




1. transverse cracking
2. delamination at crack tips

# Introduction

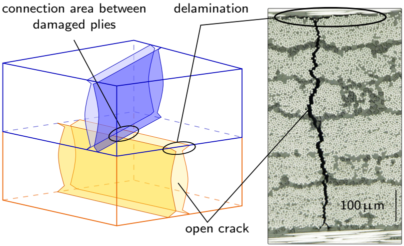
*Issue* : damage initiates for low levels of thermo-mechanical loading with little effect on mechanical properties

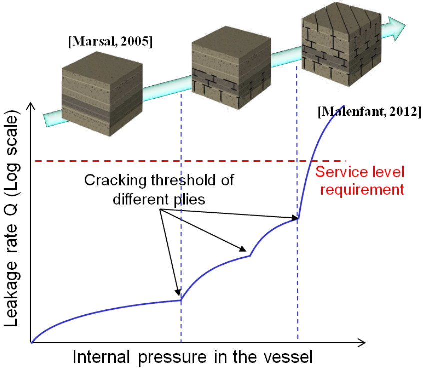



1. transverse cracking
2. delamination at crack tips
3. connection of cracks

# Introduction

*Issue* : damage initiates for low levels of thermo-mechanical loading with little effect on mechanical properties

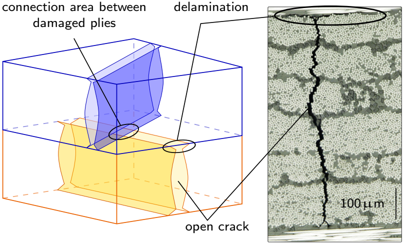


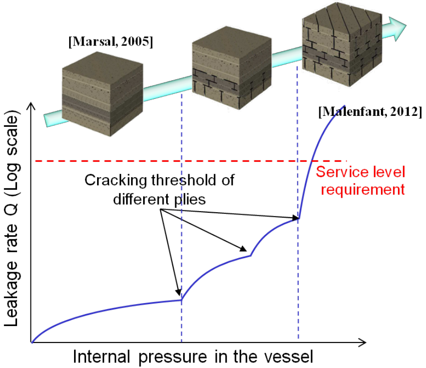




1. transverse cracking
2. delamination at crack tips
3. connection of cracks
4. network ⇒ leakage

# Introduction

*Issue* : damage initiates for low levels of thermo-mechanical loading with little effect on mechanical properties



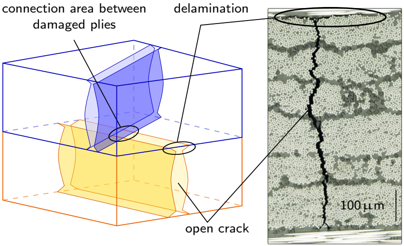



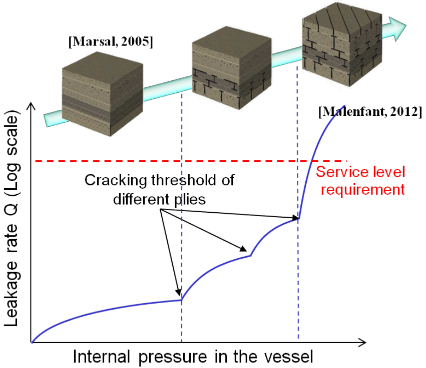

1. transverse cracking
2. delamination at crack tips
3. connection of cracks
4. network $\Rightarrow$ leakage

$\rightarrow$ need of two **design criteria** : **strength + permeability**

# Introduction

*Issue* : damage initiates for low levels of thermo-mechanical loading with little effect on mechanical properties

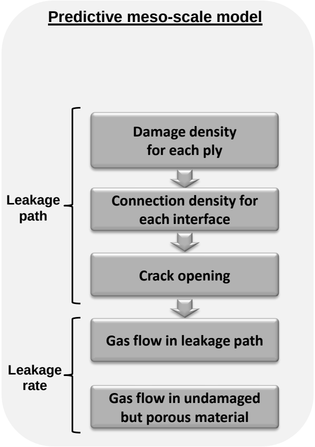


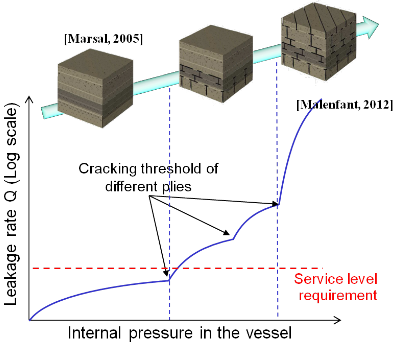




*Aim of the study* :

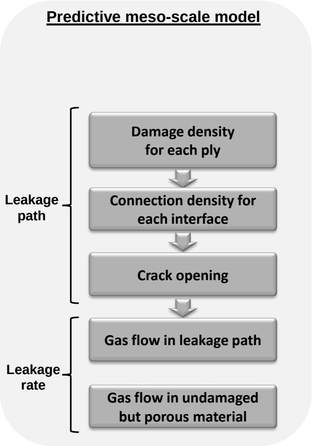
- understand **crack networks creation**
- **predict damage state** and permeability of a linerless composite vessel

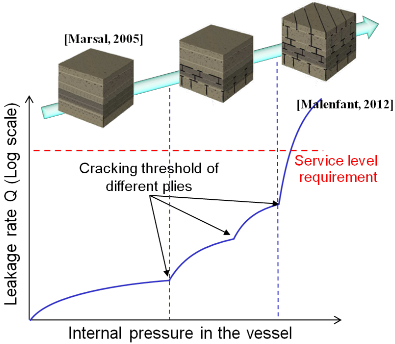
# Methodology



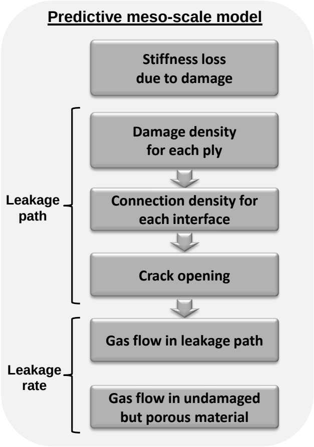



# Methodology



# Methodology



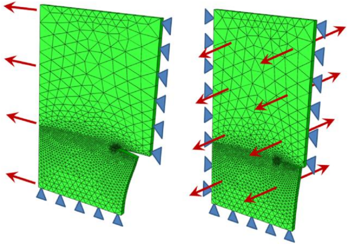
# Methodology

**Predictive meso-scale model**

- Stiffness loss due to damage
- Leakage path:
  - Damage density for each ply
  - Connection density for each interface
  - Crack opening
- Leakage rate:
  - Gas flow in leakage path
  - Gas flow in undamaged but porous material

**Virtual testing**

Mesoscale simulation of an elementary damaged cell



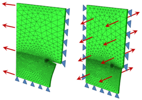
# Methodology

## Predictive meso-scale model

- Stiffness loss due to damage
- Leakage path
  - Damage density for each ply
  - Connection density for each interface
  - Crack opening
- Leakage rate
  - Gas flow in leakage path
  - Gas flow in undamaged but porous material

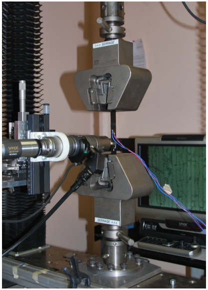
## Virtual testing

- Mesoscale simulation of an elementary damaged cell



## Experimental testing

- In-situ microscopic observation on loaded sample
- 3D microscopic observation with several cut section after loading
- 3D micro-tomography observation after loading



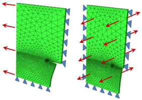
# Methodology

**Predictive meso-scale model**

- Stiffness loss due to damage
- Leakage path:
  - Damage density for each ply
  - Connection density for each interface
  - Crack opening
- Leakage rate:
  - Gas flow in leakage path
  - Gas flow in undamaged but porous material

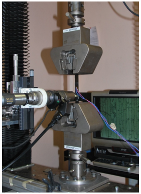
**Virtual testing**

- Mesoscale simulation of an elementary damaged cell



**Experimental testing**

- In-situ microscopic observation on loaded sample
- 3D microscopic observation with several cut section after loading
- 3D micro-tomography observation after loading
- Permeability measurement and leak points count on loaded tube
- Permeability measurement on loaded plate



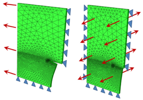
# Methodology

**Predictive meso-scale model**

- Stiffness loss due to damage
- Leakage path
  - Damage density for each ply
  - Connection density for each interface
  - Crack opening
- Leakage rate
  - Gas flow in leakage path
  - Gas flow in undamaged but porous material

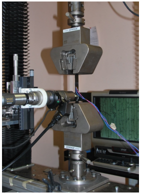
**Virtual testing**

- Mesoscale simulation of an elementary damaged cell



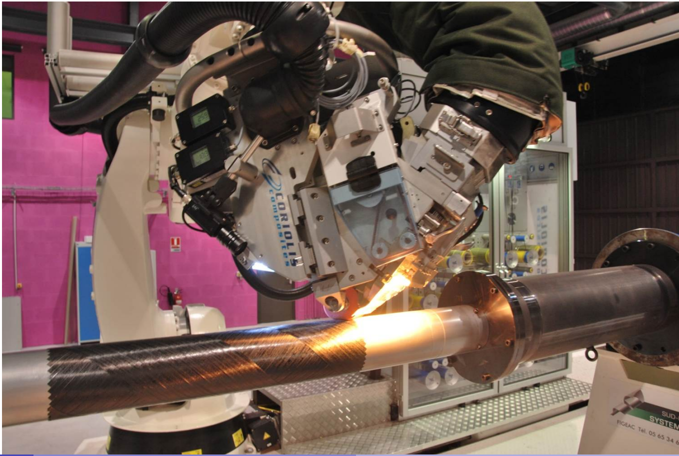
**Experimental testing**

- In-situ microscopic observation on loaded sample
- 3D microscopic observation with several cut section after loading
- 3D micro-tomography observation after loading
- Permeability measurement and leak points count on loaded tube
- Permeability measurement on loaded plate



# Material of the study

- Specimens : pipes and plates
- Process : Automated Fibre Placement
- Matrix and fibre : M21 T700
- Autoclave curing



# Damage description and observation

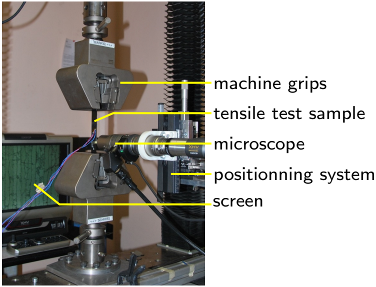



Figure – Damage observation on the edge of a tensile test specimen under loading

In-situ microscopy

- tensile test specimen polished on the edge
- microscope travelling
- whole length : about **100 mm**
- several loading steps
- several lay-ups for mode I and II

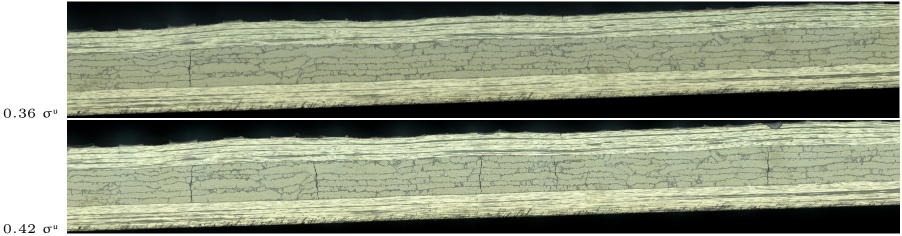



Figure – observed length on the micrograph : 15 mm, thickness : 1.8 mm, lay up : [0/0/90/90/90/0/0], $\sigma^u$ = ultimate stress

# Damage description and observation : results

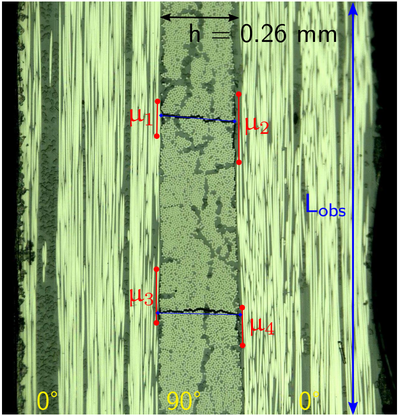



Figure – Damage measurement

- crack density : $\rho = \frac{N_{cracks}}{L_{obs}}$
- delamination length : $\mu$

Measure

- transverse cracks :
  $\rightarrow$ number, position, opening
- delamination $\rightarrow$ length

# Damage description and observation : results

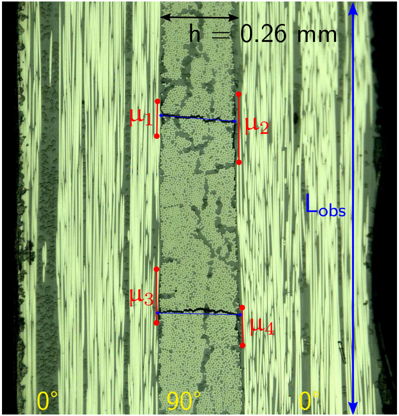



Figure – Damage measurement

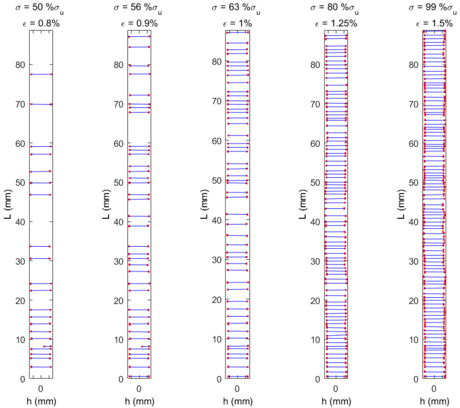



Figure – Position of cracks observed on the edge for 5 loading levels $[0_2/90_2/0_2]$(width not to scale)

- crack density : $\rho = \frac{N_{cracks}}{L_{obs}}$
- delamination length : $\mu$

# Damage description and observation : results

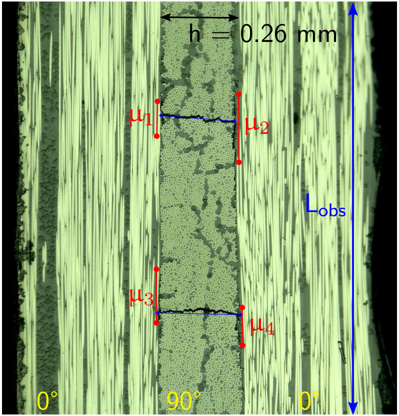
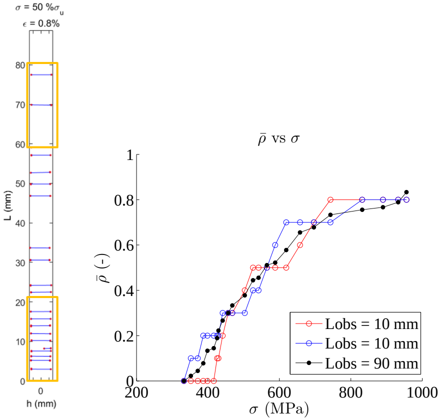



Figure – Damage measurement

- crack density : $\rho = \frac{N_{cracks}}{L_{obs}}$
- delamination length : $\mu$




- variability / observed area
- slow increase at the beginning only for a large enough (representative) area

$\rightarrow$ important for permeability prediction

# Damage description and observation : results

Evolution of damage densities

- $\bar{\rho} = \rho h$
- $\bar{\mu} = \mu \rho$

Results for 90° plies of different ply-thickness

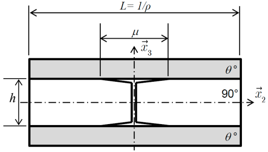



Figure – Representative Volume Element

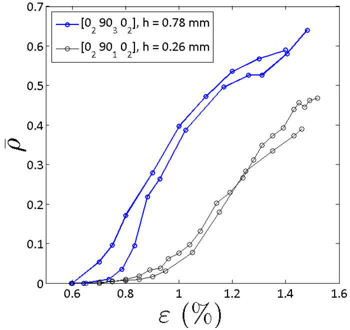



Figure – Crack rate $\bar{\rho}$

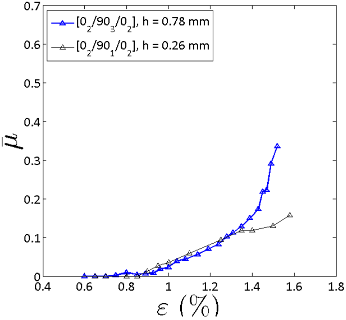
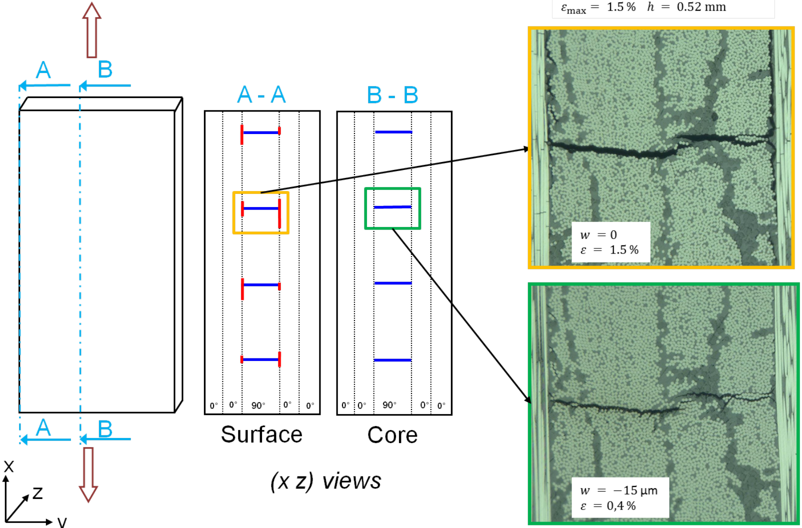


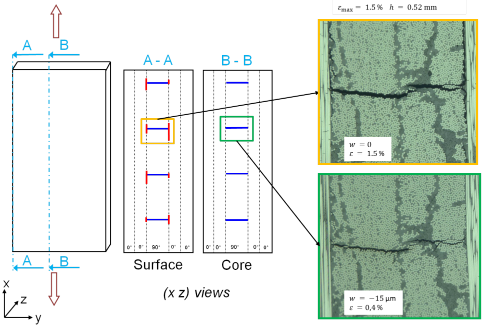

Figure – Delamination rate at the surface $\bar{\mu}$

# Cross-section examinations through the width : $[0_2/90_n/0_2]$

$\varepsilon_{max} = 1.5\,\%$ $h = 0.52$ mm



# Cross-section examinations through the width : $[0_2/90_n/0_2]$



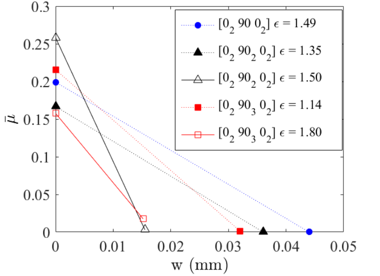
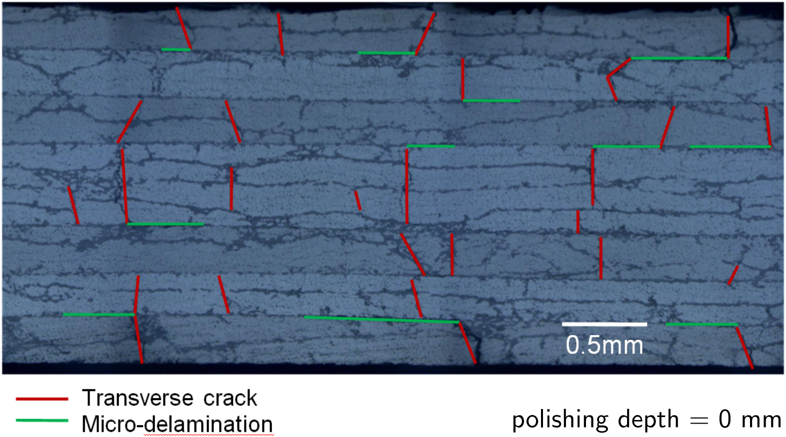




Figure – Micro-delamination length according to polishing depth

→ almost no delamination in bulk due to stiffened matrix (M21)

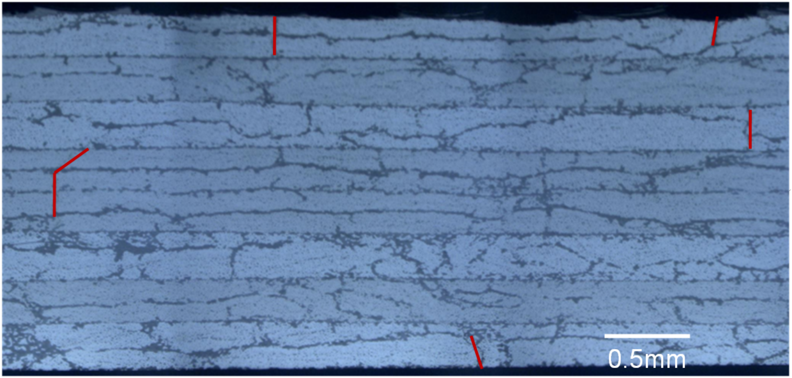
# Cross-section examinations through the width : $[+45/-45/+45/-45]_s$




$\varepsilon = 4\%$

polishing depth $= 0$ mm

# Cross-section examinations through the width : $[+45/-45/+45/-45]_s$

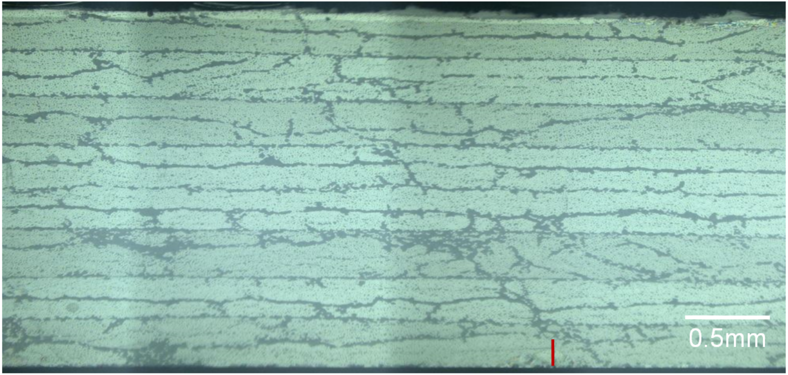



Transverse crack

polishing depth = 1.4 mm

$\varepsilon = 4\%$

# Cross-section examinations through the width : $[+45/-45/+45/-45]_s$




Transverse crack

polishing depth = 2.7 mm

- damage at the surface
- but no transverse crack in the bulk for $\varepsilon = 4\%$
- shear load produces other non reversible phenomena (diffuse damage)

# Damage model based on energy release rates

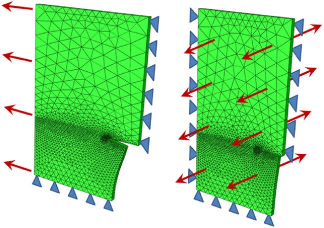
Damaged elastic behaviour :

- stiffness loss

$$\underline{\underline{S}} = \underline{\underline{S}}^0 + \Delta\underline{\underline{S}}(\bar{\rho}, \bar{\mu})$$

$\rightarrow$ $\Delta\underline{\underline{S}}(\bar{\rho}, \bar{\mu})$ identified by [Huchette, 2005] in a polynomial form

virtual testing



# Damage model based on energy release rates

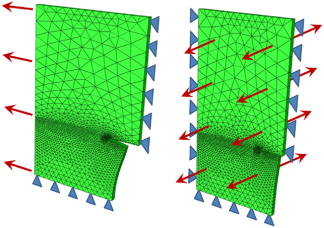
Damaged elastic behaviour :

- stiffness loss

$$\underline{\underline{S}} = \underline{\underline{S}}^0 + \Delta\underline{\underline{S}}(\bar{\rho}, \bar{\mu})$$

$\rightarrow$ $\Delta\underline{\underline{S}}(\bar{\rho}, \bar{\mu})$ identified by [Huchette, 2005] in a polynomial form

virtual testing

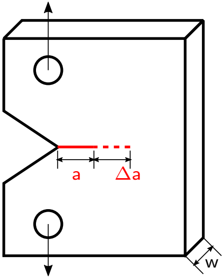


Damage evolution laws :

- elastic energy stored in the structure

$$\begin{aligned} W_e &= \frac{1}{2}\, \underline{\sigma} : \underline{\underline{S}} : \underline{\sigma} \\ &= \frac{1}{2}\, \underline{\sigma} : \left(\underline{\underline{S}}^0 + \Delta\underline{\underline{S}}(\bar{\rho}, \bar{\mu})\right) : \underline{\sigma} \end{aligned}$$

# Damage model based on energy release rates



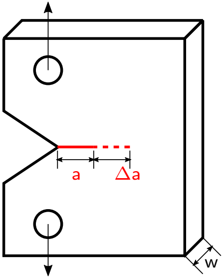

Propagation energy (Griffith) :

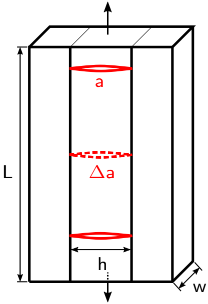
- available elastic energy

vs energy released by fracture

$\rightarrow$ $\Delta W_e = G.\Delta a.w$

# Damage model based on energy release rates




Propagation energy (Griffith) :

- available elastic energy

vs energy released by fracture

$\rightarrow$ $\Delta W_e = G.\Delta a.w$

For transverse cracks :

$$\Delta W_e = G.\Delta a.w \quad \text{with } \Delta a = whL\Delta\rho$$

$$\rightarrow \frac{\Delta a.w}{V} = \frac{wh\ L\ \Delta\rho}{whL} = \frac{\Delta\bar{\rho}}{h}$$

$$\rightarrow y_{\bar{\rho}} = \frac{\Delta W_e}{V\Delta\rho} = \frac{G_\rho}{h}$$

For delamination : evolution law built on the same scheme

# Damage model based on energy release rates

Results for simple (black) and triple plies (blue)
$[0_2/90_n/0_2]$

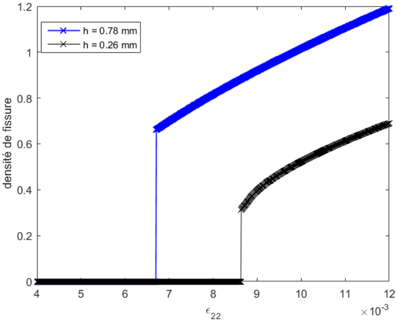



Figure – Transverse crack density

- unstable onset of cracking

$\rightarrow$ no progressiveness

- no delamination with experimental value of $G_\mu$

$\rightarrow$ consistent with cross section examinations

# Damage model based on energy release rates

Variability of damage thresholds :

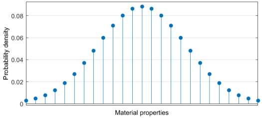



Figure – Probability density applied to damage thresholds

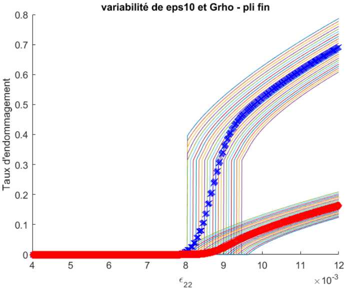



Figure – Damage density in simple ply

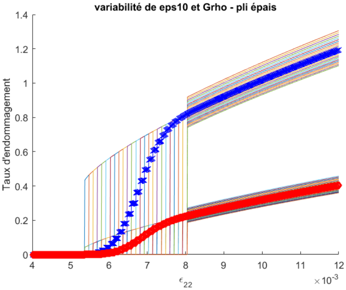



Figure – Damage density in triple ply

# Model vs experiments

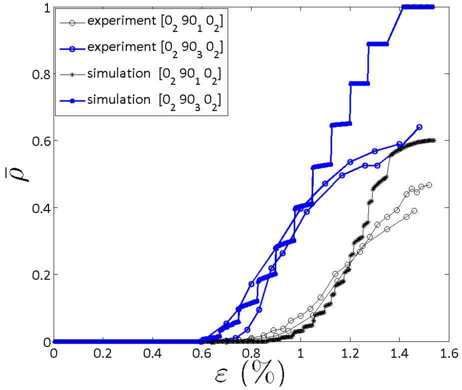
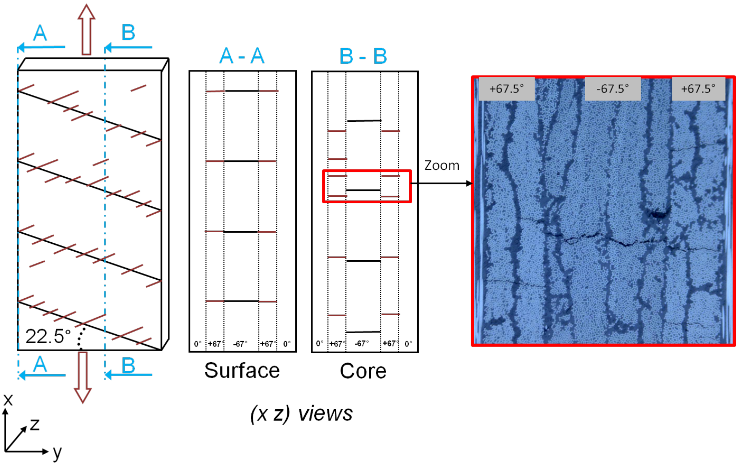



Figure – Crack rate for two ply-thickness

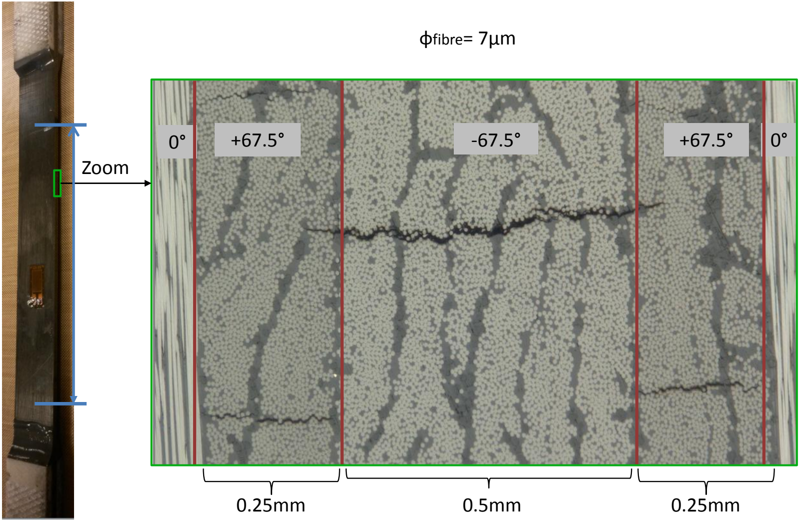
- main trends are reproduced
- parameters will be identified on wider experimental results

# Cross section examinations on $[0/+67.5/-67.5]_s$

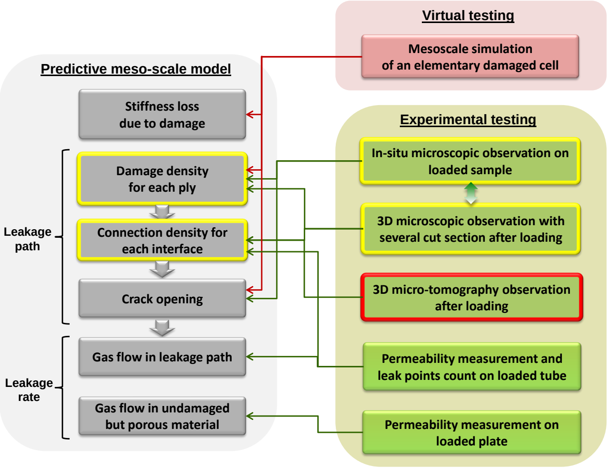


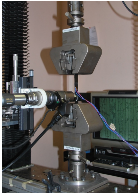

- cracks occur first in double ply (-67.5°)
- cracks of the simple plies start from cracks of the adjacent ply

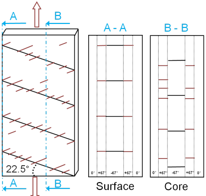
# Cross section examinations on $[0/+67.5/-67.5]_s$

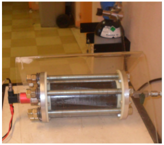


# Synthesis and conclusion





# Thank you ! Any question ?

Bois, C., Malenfant, J.-C., Wahl, J.-C., and Danis, M. (2014).
A multiscale damage and crack opening model for the prediction of flow path in laminated composite.
*Composites Science and Technology*, 97 :81–89.

Huchette, C. (2005).
*Sur la complémentarité des approches expérimentales et numériques pour la modélisation des mécanismes d'endommagement des composites stratifiés*.
Phd thesis, Université Paris 6, France.

# Validation : damage-induced permeability

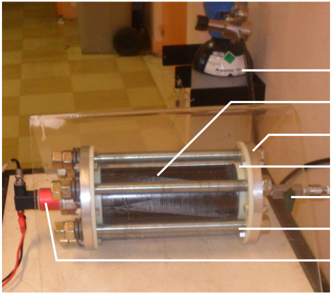



Figure – Device for pressurization and permeability measurement of pipes

Permeability (from Darcy's law)

$$k = \frac{2\mu_{gaz} b V}{S(p_{ext}^2 - p_{int}^2)} \frac{dp_{int}}{dt}$$

with $b$ the thickness, $V$ the internal gas volume, $S$ the external pipe area, $p_{ext}$ and $p_{int}$ external and internal pressure, and $(dp_{int})/dt$ the variation of the internal pressure over time.

Procedure

1. setting of the initial pressure
2. closing of the device : pressure decay measurement

→ permeability computation

3. localization of leak paths
4. return to step 1
   - lower pressure : closing of the existent cracks
   - higher pressure : creation of new cracks