



# Laminate Fatigue Damage and Fiber Fracture

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# Objectives



## Failure prediction of laminated structures

- Traction, shear, compression...
- Static and fatigue loads
- Various materials



## Failure prediction of laminated structures

- Traction, shear, compression...
- Static and fatigue loads
- Various materials

## 1- Material behavior

Damage evolution

**Fiber failure**

## 2- Structure behavior

**Non local criteria**



## 1- Material behavior

Damage evolution

**Fiber failure**

## 2- Structure behavior

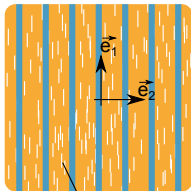
**Non local criteria**

Speech of C. Hocard :

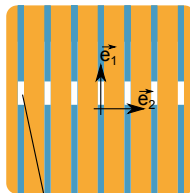
Matrix      Damage      Under

Combined      Transverse/Shear

Loads in Static and Fatigue

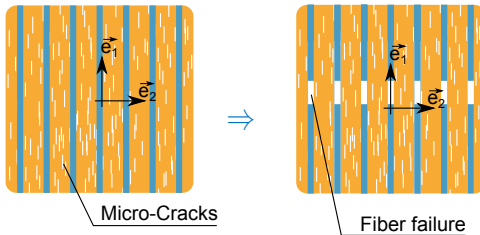


Micro-Cracks

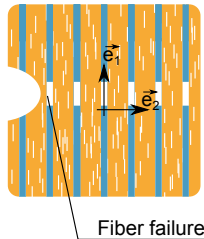
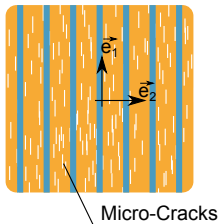


Fiber failure

- 1- Material behavior
  - Damage evolution
  - Fiber failure**
- 2- Structure behavior
  - Non local criteria**



- 1- Material behavior
  - Damage evolution
  - ↳ **Fiber failure**
- 2- Structure behavior
  - Non local criteria**



- 1- Material behavior
  - Damage evolution
  - ↳ **Fiber failure**
- 2- Structure behavior
  - Non local criteria**



## 1- Influence of damage on fiber failure

⇒ Homogeneous case

- Experimental set up
- Experimental results for traction and compression
- Model

## 2- Link with the structure

⇒ Case of a stress concentration

- Motivation
- Experimental results

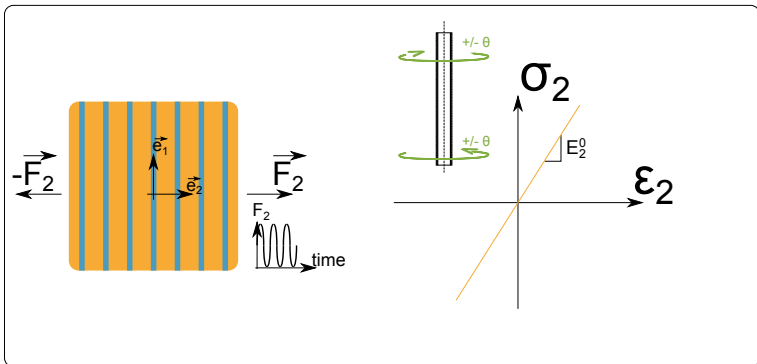




# Influence of fatigue damage on fiber failure

## Method

- Measure of the initial stiffness
- Compute the damage
- Effect of damage on tensile strength
- And what about compression ?

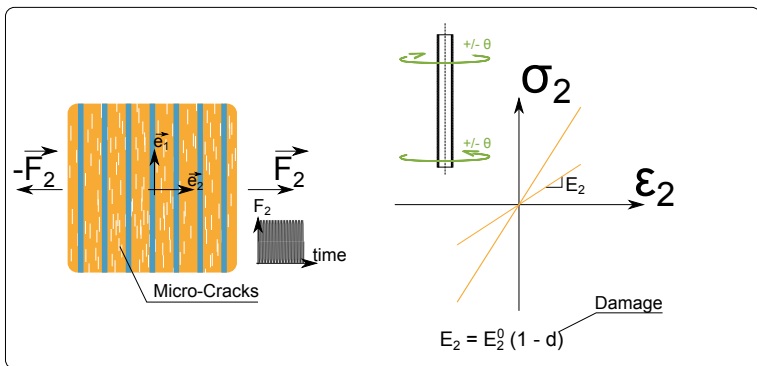




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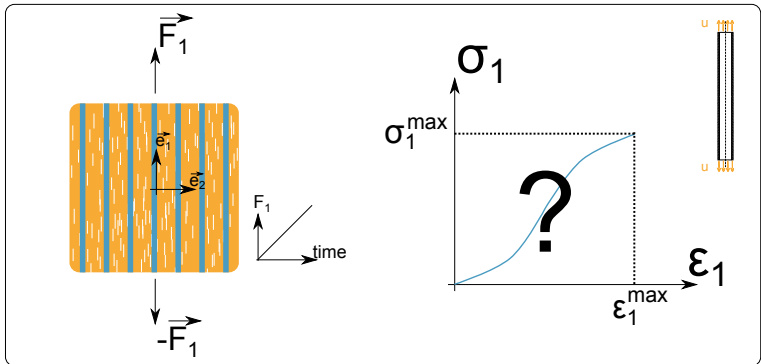




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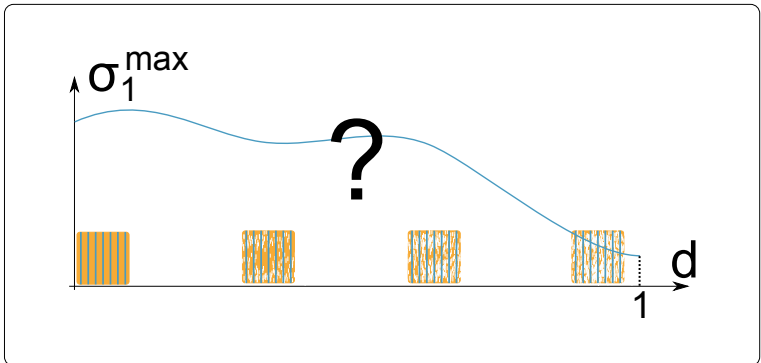




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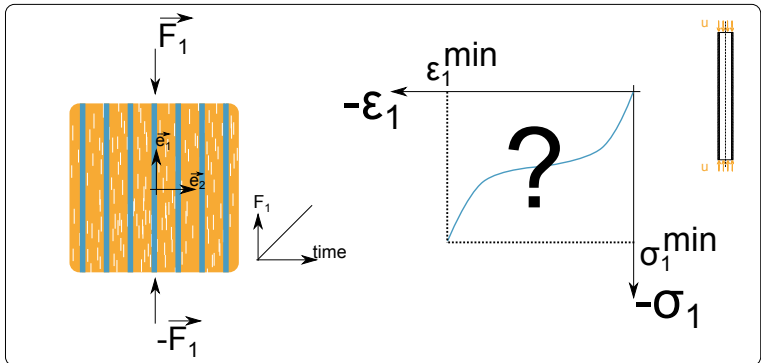




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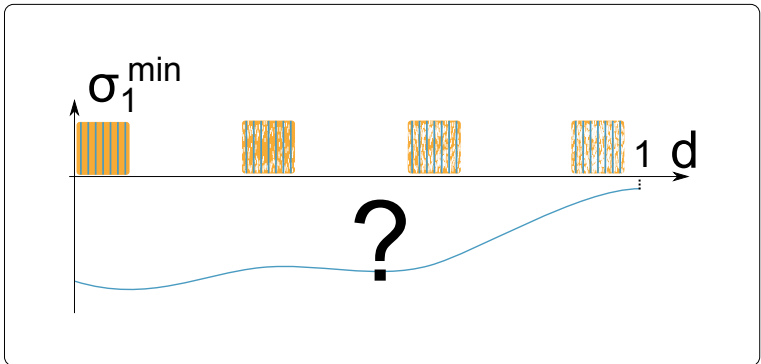




# Influence of fatigue damage on fiber failure

Method

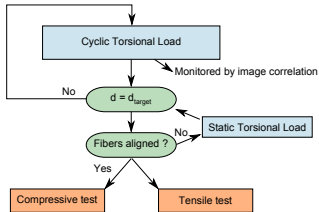
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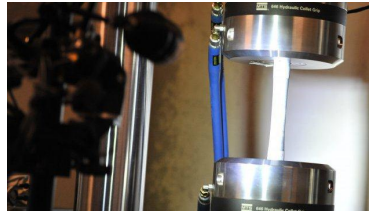


# Influence of fatigue damage on fiber failure

## Experimental set up



*Method used to introduce damage*



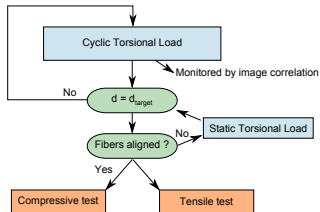
*Digital Image Correlation device*

- Material : woven carbon/epoxy ( $0^\circ$  in the direction of the tube)
- Cyclic Load  $\rightarrow$  High damage
- Digital Image Correlation device
  - Damage measurement
  - Homogeneous field (strain, damage)
  - Fibers alignment

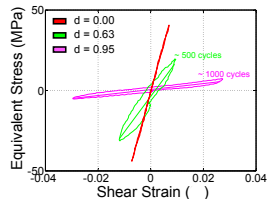


# Influence of fatigue damage on fiber failure

## Experimental set up



*Method used to introduce damage*



*Damage measurement :  $d = 1 - \frac{E}{E_0}$*

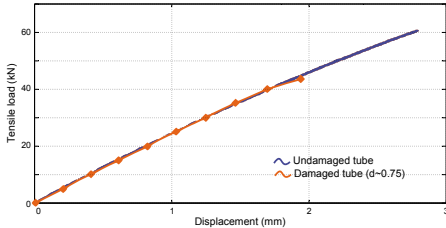
- Material : woven carbon/epoxy ( $0^\circ$  in the direction of the tube)
- Cyclic Load  $\rightarrow$  High damage
- Digital Image Correlation device
  - Damage measurement
  - Homogeneous field (strain, damage)
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# Influence of fatigue damage on fiber failure

## Tensile test



Behavior of the material with two different damages

Modelisation



$$\sigma_{11} = E_{11} \cdot \varepsilon_{11}$$

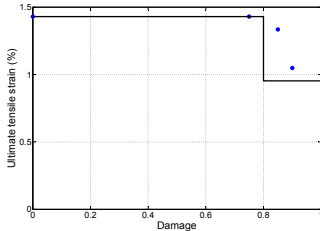
## Results

- Linear material
- Stiffness is not affected by the damage
- Strength decreases when damage increases



# Influence of fatigue damage on fiber failure

## Tensile test



Evolution of the ultimate tensile strain versus the damage

## Modelisation

if  $d \leq 0.8$

$$\Downarrow$$
$$\epsilon_{11(d)}^{\max} = \epsilon_{11(d=0)}^{\max}$$

else

$$\epsilon_{11(d)}^{\max} = \epsilon_{11(d=0)}^{\max} \cdot k_{k < 1}$$

## Results

- Linear material
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# Influence of fatigue damage on fiber failure

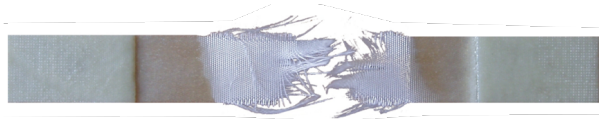
## Tensile test

### Confirmation with a quantitative test (temperature ↗)



Safe 1055/ES18 Material under tension

$$\sigma^{\max} = 800\text{MPa}$$



Uncured 1055/ES18 Material under tension

$$\sigma^{\max} = 320\text{MPa}$$



Post cured at 190° 1055/ES18 Material under tension

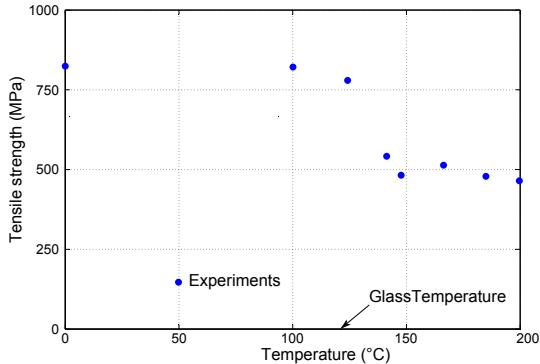
$$\sigma^{\max} = 480\text{MPa}$$



# Influence of fatigue damage on fiber failure

Tensile test

Confirmation with a quantitative test (temperature ↗)

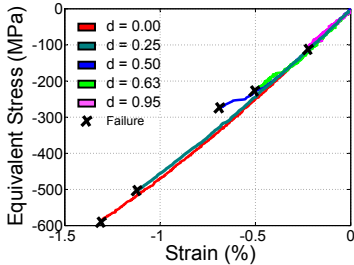


- Temperature  $\Leftrightarrow$  Damage
- Strength decreases according to the temperature



# Influence of fatigue damage on fiber failure

## Compressive test



Modelisation



$$\sigma_{11} = E_{11} \cdot \varepsilon_{11} \cdot (1 + \alpha \cdot \varepsilon_{11})$$

*Behavior of the material with different damages*

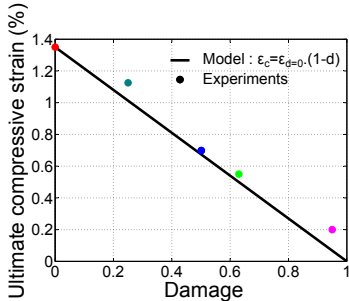
## Results

- Non linear behavior
- Stiffness is not affected by the damage
- Compressive strength is significantly affected by the damage



# Influence of fatigue damage on fiber failure

## Compressive test



Modelisation

$$\epsilon_{11(d)}^{\min} = \epsilon_{11(d=0)}^{\min} \cdot (1 - d)$$

*Evolution of the ultimate tensile strain versus the damage*

## Results

- Non linear behavior
- Stiffness is not affected by the damage
- Compressive strength is significantly affected by the damage



## 1- Influence of damage on fiber failure

⇒ Homogeneous case

- Description of the set up
- Experimental results for traction and compression
- Model

## 2- Link with the structure

⇒ Case of a stress concentration

⇒ Focus on compressive results

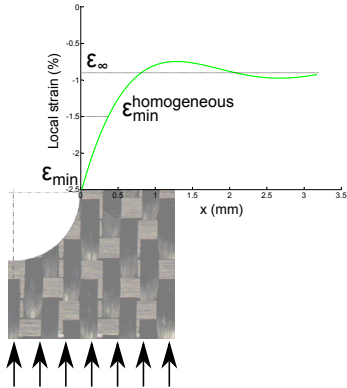
- Motivation
- Experimental results



# Link with the structure

## Motivation

### Compressive test : plate with a hole



Local strain : plate with a hole

- High local strain
  - Local criteria
- ⇒ Underestimate the structure
- Non local criteria
    - "Point stress"
    - "Average stress"

$$\bar{\varepsilon} = \frac{1}{V} \int_V \varepsilon \quad V = g(L_c)$$

⇒ New parameter :  $L_c = f(d)$  ?

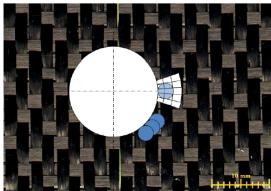
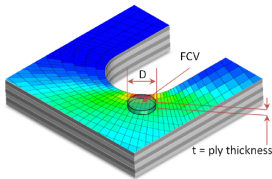




# Link with the structure

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⇒ New parameter :  $L_c = f(d)$  ?

*Non local criteria*



### Different samples for different strain fields



Width = 20mm

Length = 80 → 150mm

Thickness = 6.7mm (52plies) (to avoid buckling)

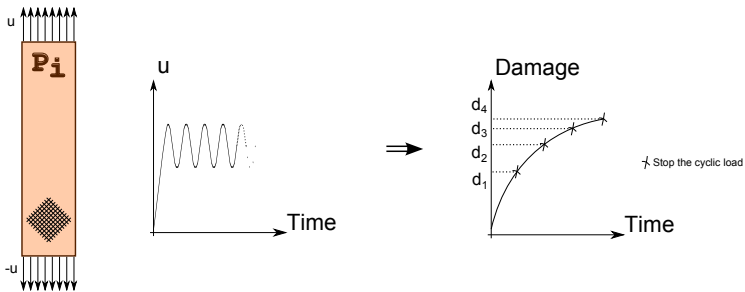
Material : UD T700/M21



# Link with the structure

Method

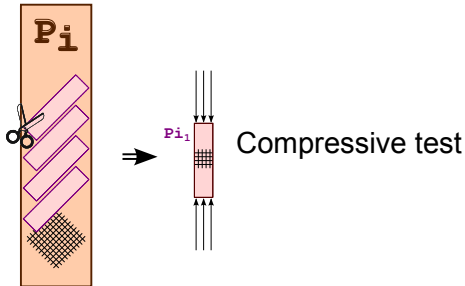
## Introduction of the damage (with images...)



Different damages for each plate  $P_i$



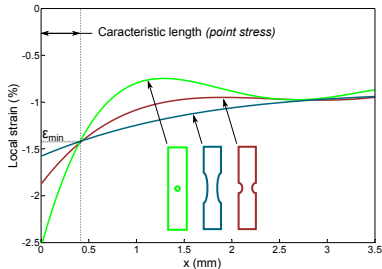
### Introduction of the damage (with images...)



Fibers are aligned in the direction of the sample  
Tests have to be performed for each plate  $P_i$



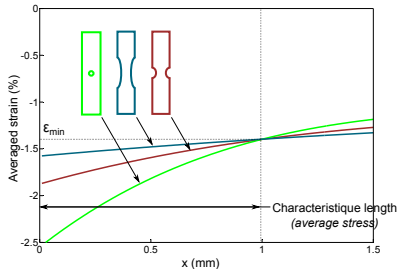
### Comparison of the different samples



- Local criteria is not efficient
- Introduction of a characteristic length
$$L_c^{d=0} = 0.5\text{mm et } \varepsilon_{\min}^{d=0} \sim -1.5\%$$
- Very sensitive parameter with a *point stress* method!



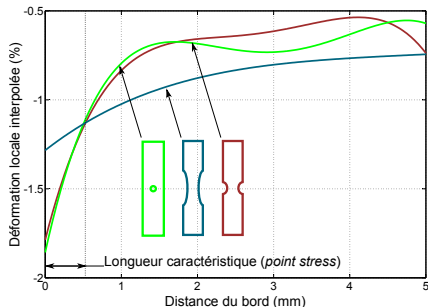
### Comparison of the different samples



- Local criteria is not efficient
- Introduction of a characteristic length
$$L_c^{d=0} = 1 \text{ mm et } \epsilon_{\min}^{d=0} \sim -1.5\%$$
- Less sensitive parameter for the *average stress* method !



### Comparison of the different samples



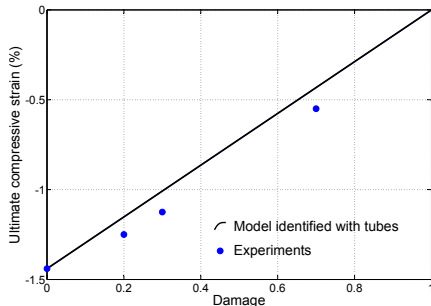
☺ Characteristic length is not affected by damage

$$L_c^{P-S} \sim 0.5\text{mm} \text{ et } L_c^{A-S} \sim 1\text{mm}$$

☺ Good agreement with the model identified on tubes



### Comparison of the different samples



☺ Characteristic length is not affected by damage

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☺ Good agreement with the model identified on tubes





### 1- Influence of damage on fiber failure

⇒ Homogeneous case

- Stiffness is not affected by damage
- Tensile strength decreases with very high damage
- Compressive strength decreases significantly with damage

### 2- Link with the structure

⇒ Case of a stress concentration

- Introduction of a characteristic length
- $L_c$  does not evolve according to the damage
- Validation of the identified model



Thank you.

I'll do my best to answer your questions.



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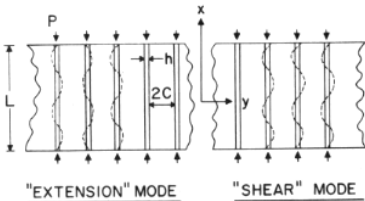
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More slides ?



## Micro-mechanics approach



*First Micromodel - Rosen 1964*



**Postulate**



**Micro-buckling** of fibers

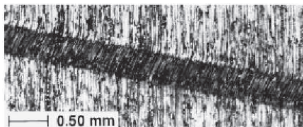
☺ **Matrix stiffness is a very sensitive parameter**

$$\sigma_{\min} = -\frac{E_2}{1 - \nu_f} = -\frac{E_2^0 \cdot (1 - d_2)}{1 - \nu_f}$$

☹ **Bad agreement with experiments**



## Micro-mechanics approach



"Kink-Band"

Budiansky and Fleck	1993
Garland et al	2001
Jumahat et al	2001
Feld et al	2001
...	...

### 😊 Improvement of the model

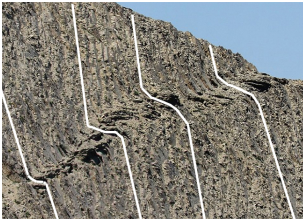
- Plasticity
- Matrix damage
- Alignment of fibers
- ...

### ☹ ± Predictive model

⇒ **Damage plays an important role !**  
**Need to be compared to experiments**



## Micro-mechanics approach



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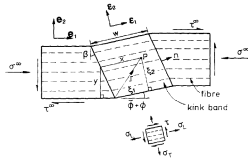
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- Plasticity
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### ☹ ± Predictive model

⇒ **Damage plays an important role !**  
**Need to be compared to experiments**





# Experiments on tubes

## How to avoid of the buckling ?

- Numerical predictions of the buckling loads are complex !
  - Imperfections,
  - Non-linear material...
- An experimental method is proposed (based on analytic results)

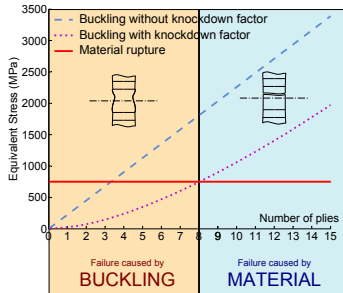
$$\sigma_{\text{buckle}} = \frac{E}{\sqrt{3(1-\nu^2)}} \frac{t}{R}$$

$E$  : Young Modulus

$t$  : Thickness

$R$  : Mean radius

$\nu$  : Poisson factor



Theoretical curve  $\sigma_{\text{failure}} = f(n_{\text{plies}})$



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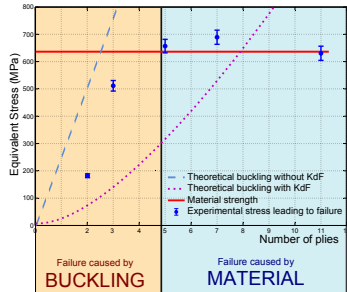
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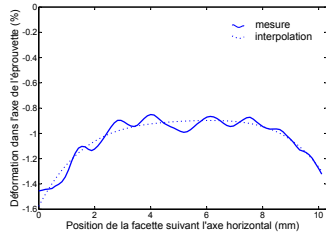
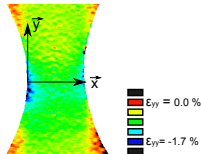
Theoretical curve  $\sigma_{\text{failure}} = f(n_{\text{plies}})$



# Samples with stress concentration

## Undamaged samples

### Method to interpolate the strain



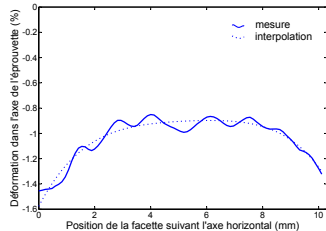
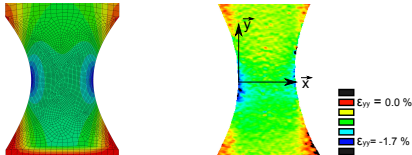
- Measure is complex close to the edge of the sample
- Interpolation is needed
- Determination of the degree of the polynomial with a FE simulation
- Identification of the coefficient with DIC



# Samples with stress concentration

## Undamaged samples

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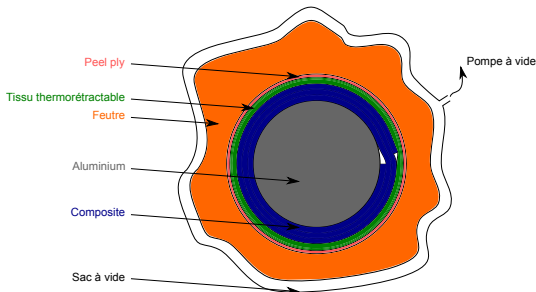


- Measure is complex close to the edge of the sample
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- Identification of the coefficient with DIC



# Manufacturing

## Tubes

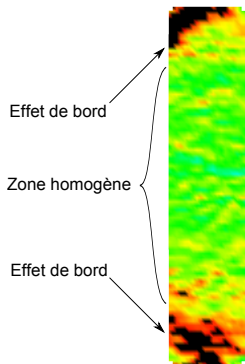


- Cured in a oven (4 hours)
- Temperature = 180°
- Compaction = Vacuum + Thermo-shrinkable tissue + Thermal dilatation (aluminum)



## Test on plates $\pm 45^\circ$

### Side effects



*Measure with DIC*

- Followed with DIC
- Homogeneous field in the middle

