Influence of microstructure heterogeneities on free edge strain fields of a laminate using digital image correlation

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retour sur innovation

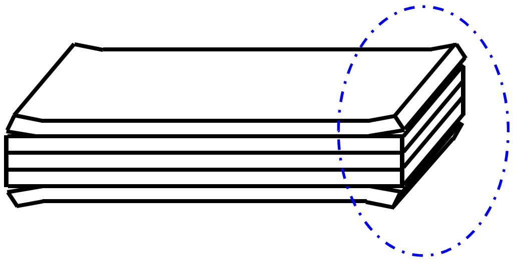
Summary

1. Introduction

- Extensive use of composite materials in many industrial applications
- Design of composite structures is today globally well mastered

BUT

- Laminate free edge stresses can initiate delamination
- Free edge effect :
  - Understood for perfect laminates (straight interfaces)
  - Usually not taken into account in industrial calculation’s code
  - Some combination between geometry and stacking sequence can be more critical

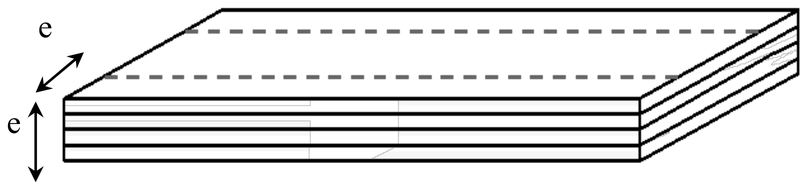


1. Introduction

Laminate free edge stress gradient

- Origin of free edge problems: discontinuity of inter-plies mechanical properties
- 3D stress gradient near free edges and interlaminar interfaces
- Local phenomenon: localized near free edges and interlaminar interfaces
- Depends on : mechanical properties, geometry, stacking sequence

Location of free edge effects

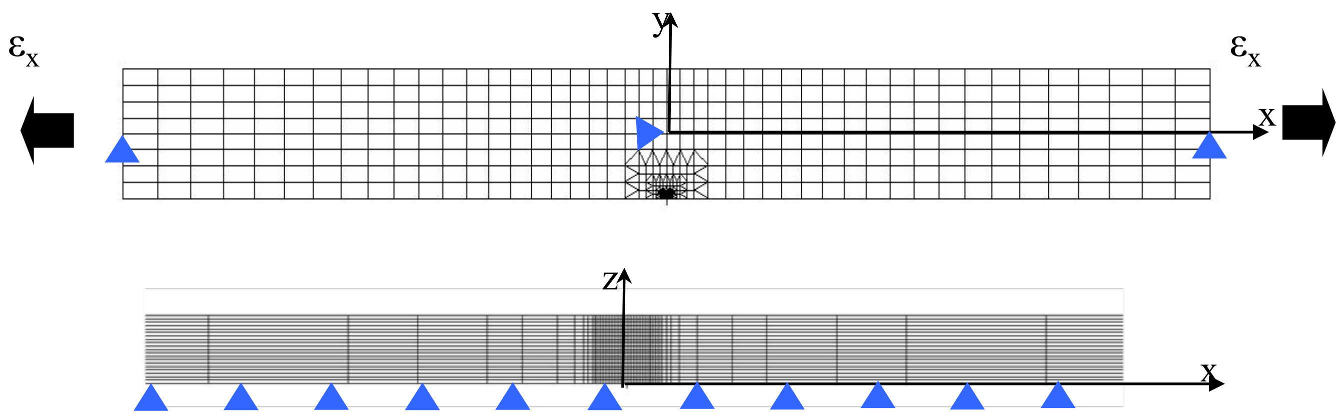


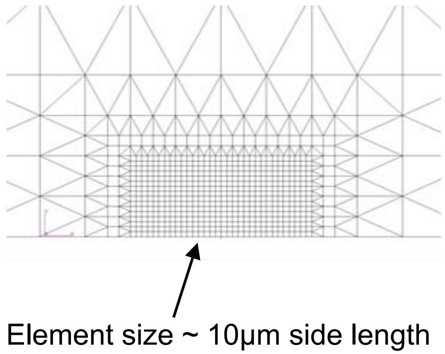
1. Introduction

- Lot of studies have been devoted to free edge effects in order to predict, understand and quantify this phenomenon
  - Numerical (on equivalent homogeneous materials) : finite element modelisations, asymptotic theories, delamination criterions…
  - Experimental : initation tests (acoustic emission), Damage (X rays), fractography, strain field measurements (Moiré,…)
- Most of these studies have been carried out on « idealized » materials (rectilinear interfaces)
- What's happen when the material is no more regular with an heterogeneous microstructure?
  - The objective of this work is to highlight the influence of the microstructure on free edge interlaminar strains

2. Finite element calculation

- Purpose
  - Calculation of displacement field on free edge which could be measured by DIC
  - Select the pertinent configurations for the experimental tests
- Assumption
  - material elastic properties assumed to be elastic until rupture
  - Equivalent homogeneous material
- Methodology
  - Classical finite element calculations with Nastran® code
  - Mesh refinement near free edges and interlaminar interfaces





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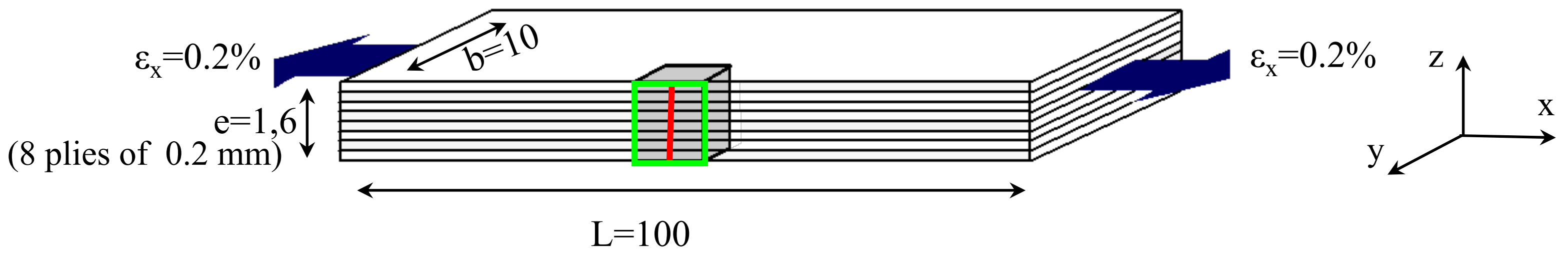
2. Finite element calculation

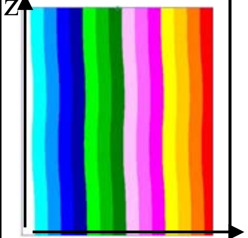
- Material
  - Pure UD CFRP (CTS/920)
- Stacking sequence and loading
  - $[(\theta/-\theta)_2]_s$ with θ=15°, 30°, 45°, 60° and 75°
  - Uniaxial strain loading: ε_x=0.2%

E_1 (GPa)	116
E_2 (GPa)	8
E_6 (GPa)	6
ν_{12}	0.3
h_0 (mm)	0.2

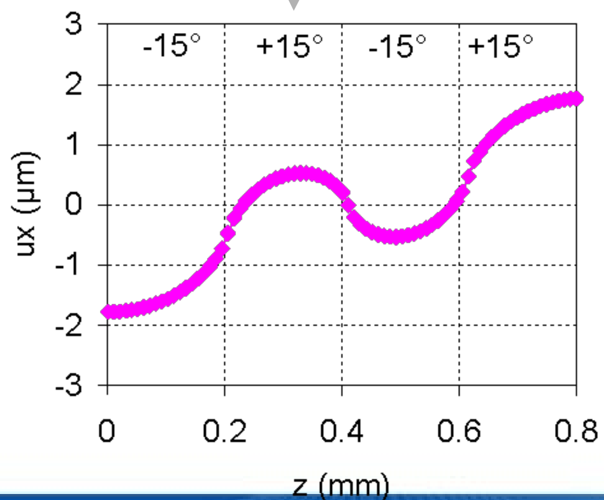


2. Finite element calculation

Free edge displacement field (U_x)

Laminates	$[(15/-15)_2]_s$	$[(30/-30)_2]_s$	$[(45/-45)_2]_s$	$[(60/-60)_2]_s$	$[(75/-75)_2]_s$
Iso-displacement maps					

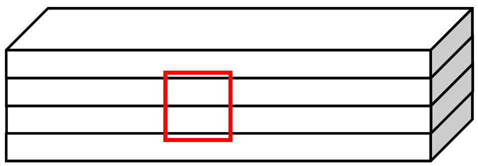
- The most important displacement gradients are obtained for the $[(15°/-15°)_2]_s$ stacking sequence



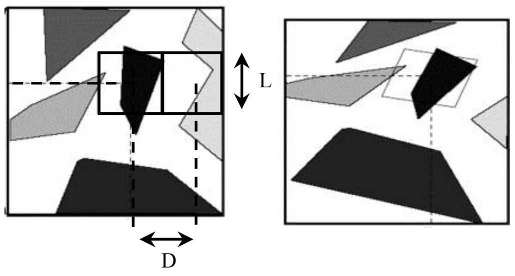
- $[(15/-15)_2]_s$ laminate samples have been manufactured for mechanical tests
- FE results show displacements of several micrometers which can probably be measured by DIC

3. Digital Image Correlation

- Purpose
  - Displacement field measurement at ply scale
  - Derivation of strain field from DIC
  - Use of commercial software (Aramis®)

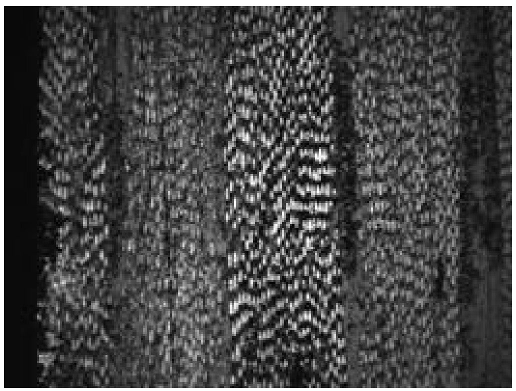


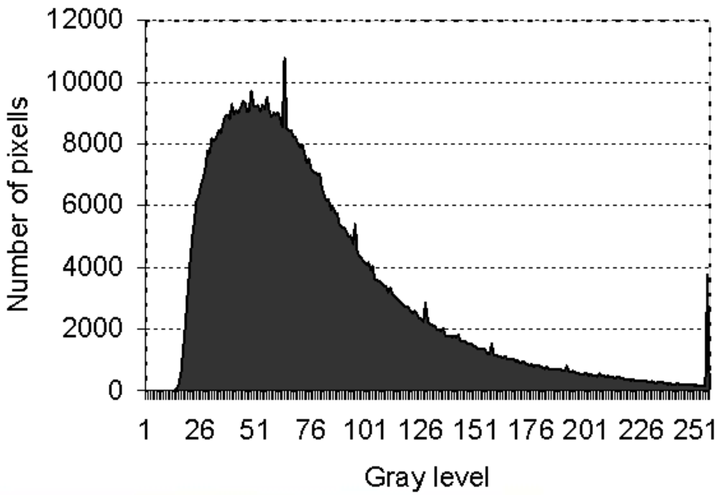
- DIC principle
  - Recognition of geometrical changes in the gray scale distribution of a surface pattern before and after straining
  - The digital image is divided into square facets of side length L spaced by step D (L,D in pixels)
  - Each facet is characterized by its gray distribution function



3. Digital Image Correlation

- Advantages
  - Simple to use
  - Small environnemental sensitivity ⇒ suitable for *in situ* measurement on testing machine
  - CCD camera coupled to high magnification lens allow measurement at ply scale (several hundred µm side) and even smaller scales
  - Material microstructure gives random gray scale distribution when coarse polished
  - Microstructure is visible during the test ⇒ DIC measurement can be correlated to the microstructure





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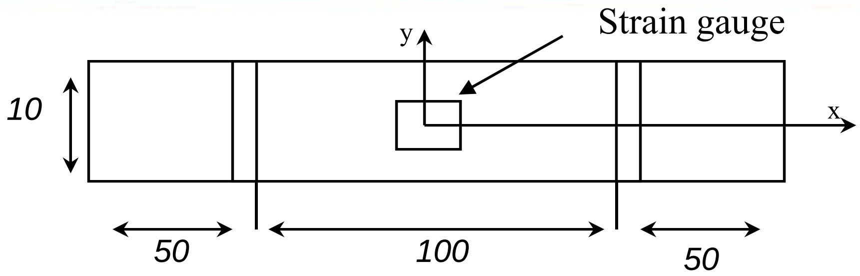
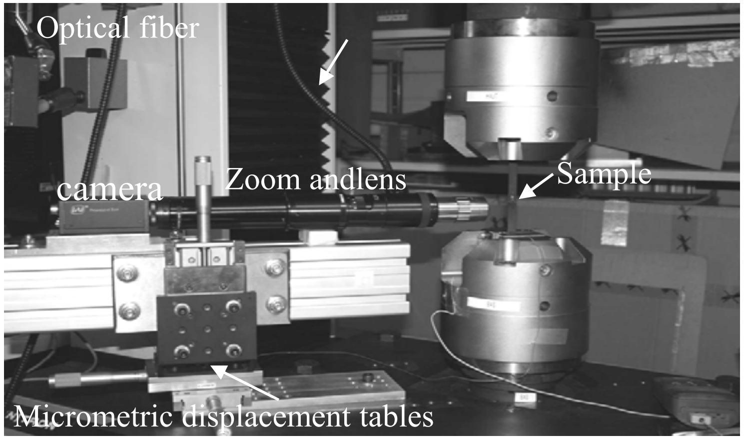
4. Experimental procedure

Sample Geometry



Loading: uniaxial strain ε_x=0.22%

Experimental set up



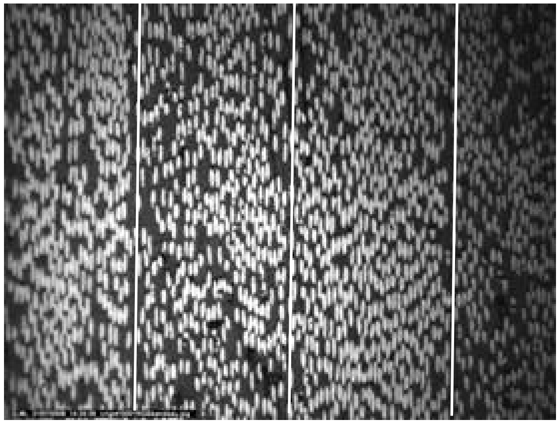
Correlation parameters (L=35, D=25)

5. Investigated materials

- Two investigated materials
  - Pure UD CFRP (CTS/920)
  - Quasi UD CFRP (G947/M18)
- Two kinds microstructures

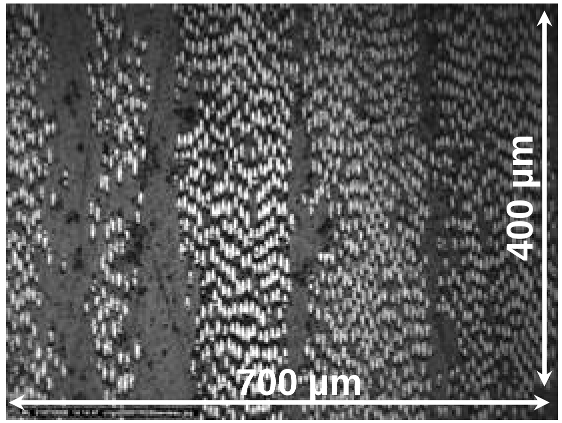
	CTS/920	G947/M18
E_1 (GPa)	116,0	112,0
E_2 (GPa)	8,0	9,0
E_6 (GPa)	6,0	8,0
ν_{12}	0,3	0,3
h^0 (mm)	0,2	0,175

Pure UD : CTS/920

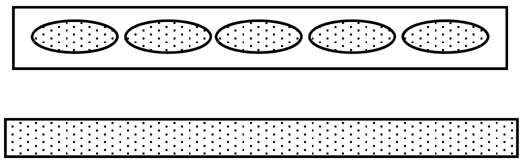


+15° -15° +15° -15°

Quasi UD : G947/M18 (weft yarn in the ply)

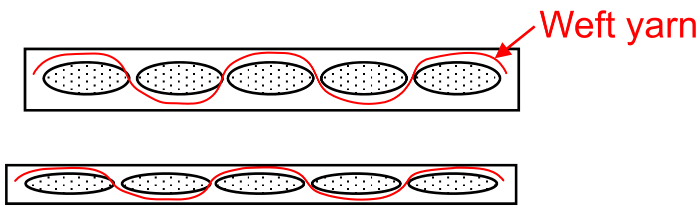


+15° -15° +15° -15°



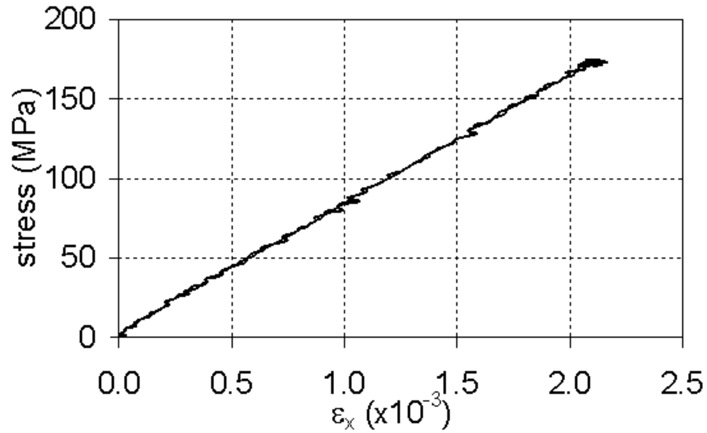
before compaction

after compaction

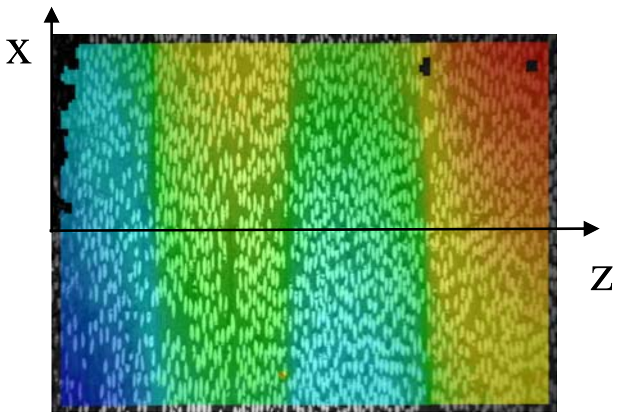


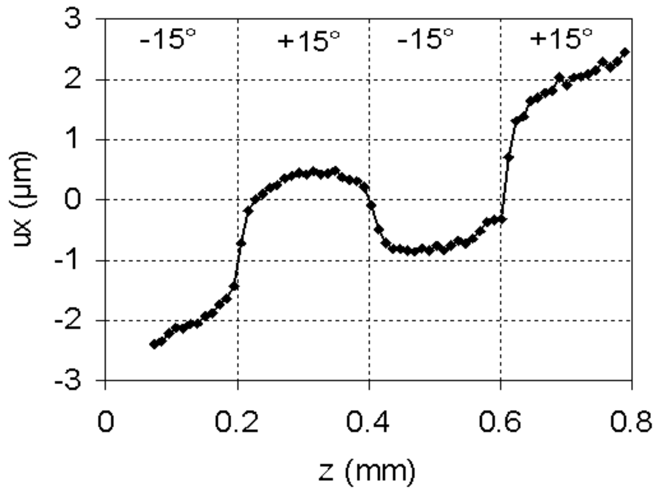
6. Experimental results

- Macroscopic elastic behavior (pure UD)
  - $[(15/-15)_2]_s$ stacking sequence
  - Loading/Unloading cycles
  - no residual strain



- U_x displacement field

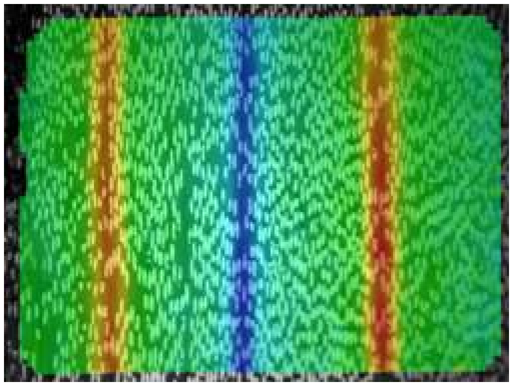


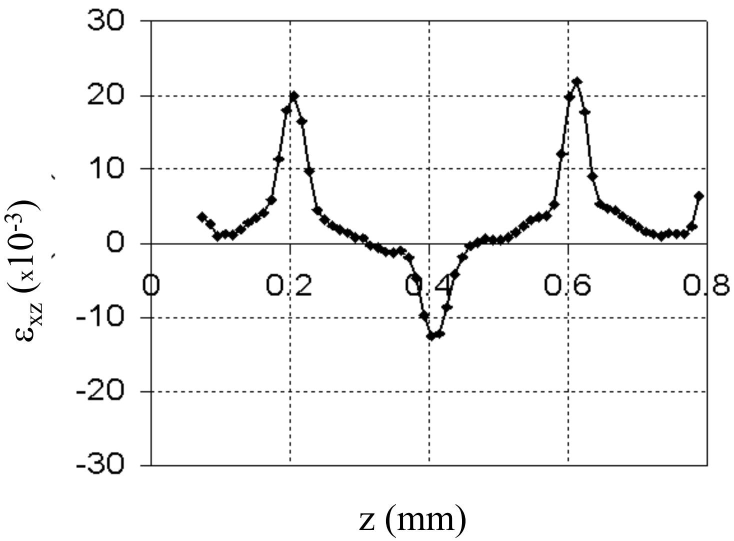


High U_x displacement gradients have been measured as expected in FE analysis

6. Experimental results

ε_{xz} shear strain (derived from displacement fields)

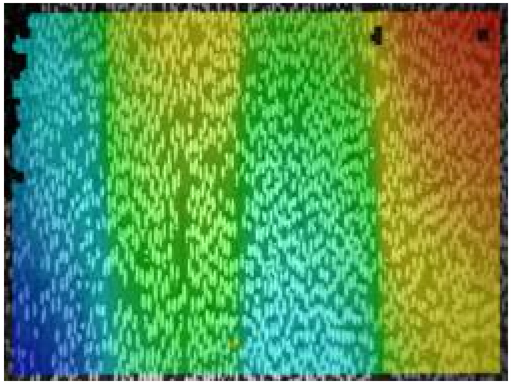




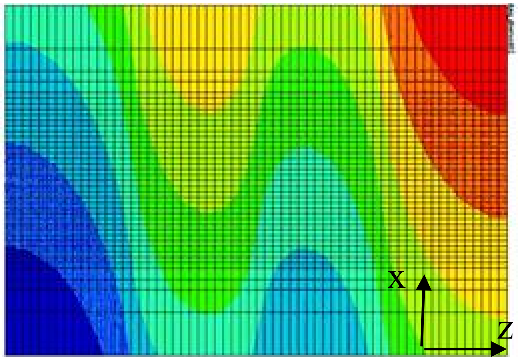
- Shear strain peak localized in the vicinity of each interlaminar interface
- High and clearcut strain peaks

6. Experimental results

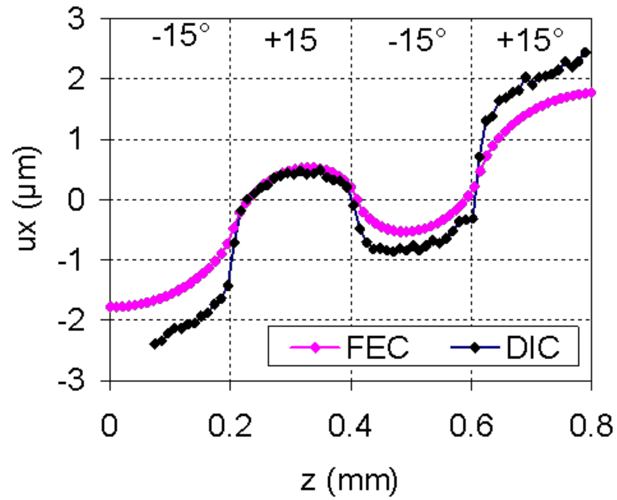
Comparison between experimental and FE displacement fields



DIC



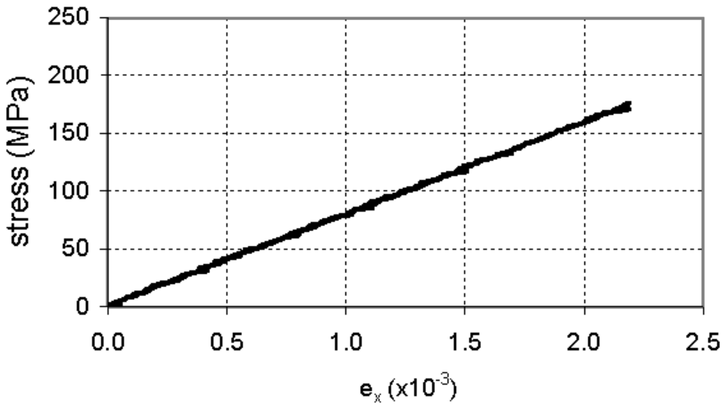
FEC



The material can be assumed as an equivalent homogeneous one ⇒ straight interfaces ⇒ same trends with FEC and DIC

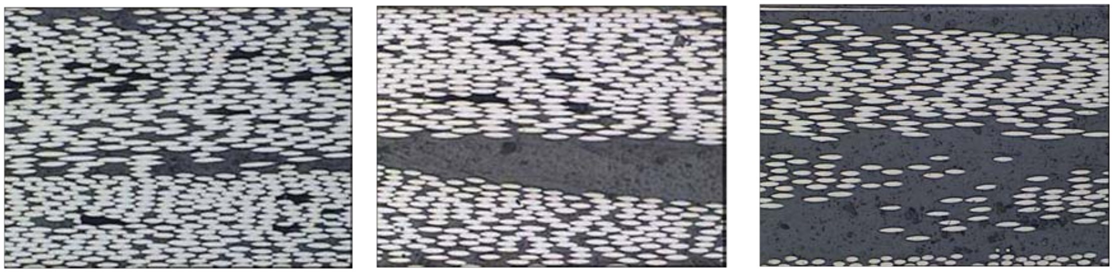
6. Experimental results

- Macroscopic behavior (quasi UD CFRP)
  - $[(15/-15)_2]_s$ stacking sequence
  - Loading/Unloading cycles
  - No residual strain



- Microstructure : no straight interface between plies ⇒ local heterogeneities

$[90]_{12}$

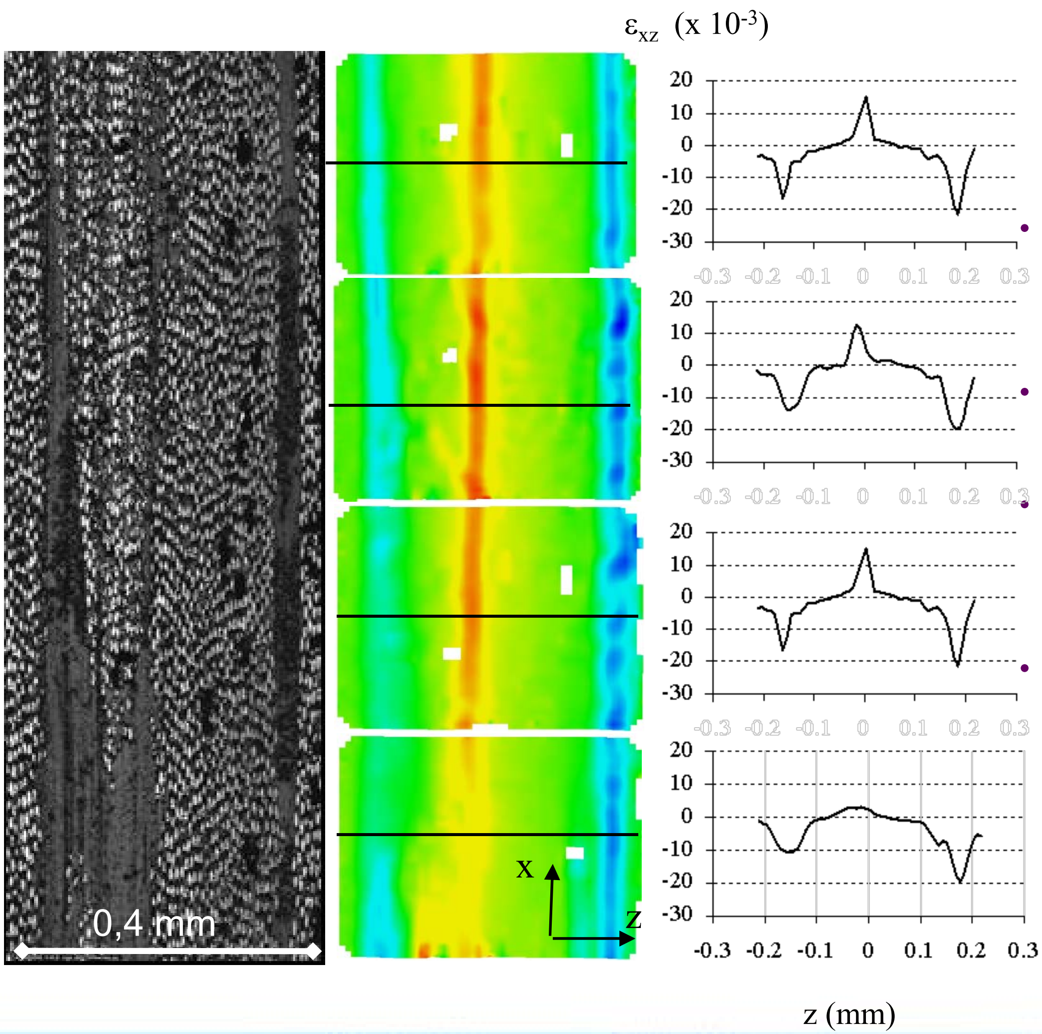


$[(15/-15)_2]_s$

How is the interlaminar shear strain distribution when the plies are no more straight ?

6. Experimental results

ε_{xz} shear strain field at different locations



- Through the thickness shear strain variation depends strongly on local microstructure
- High V_f zones : High and clearcut shear strain peak like in pure UD
- Low V_f zones: strongly attenuated peak, almost disparrear when resin only
- The full resin areas can reduce delamination risk

7. Conclusion

- When the composite microstructure is close to an « ideal » one, free edge effect can be well predicted by finite element calculations

- For non uniform microstructure DIC shows :
  - High interlaminar shear strain in high V_f zones
  - attenuated interlaminar shear strain peak in low V_f zones

- The full resin areas could be *a priori* considered as defects but can, in fact, reduce the delamination risk, by decreasing the interlaminar shear strain concentration at free edges

- This study is going to be extended on laminate ply drop which is of great importance in industrial structures.

Thank you for your attention

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