CompTest 2023

Investigation of transverse matrix cracking in fatigue for laminated composites

S. Patti[1], M. Kaminski[1], J.-F. Maire[1], F. Laurin[1], P. Maimí[2]

[1] Onera Châtillon – DMAS and Paris-Saclay University,

[2] AMADE Girona

stacy.patti@onera.fr

Aloha Airline Flight 243, 1988

❖ Advantages of predictive models

- Cut experimental costs,
- Reduce design delays,
- Sustainability: enhanced structure fatigue life

❖ Developing predictive models

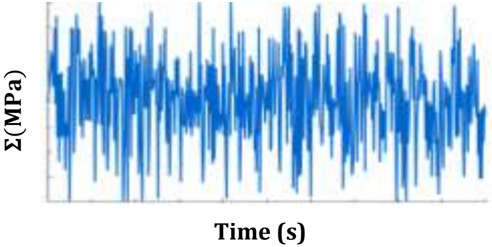
- For complex, realistic loadings,
- Prediction for multiaxial laminates

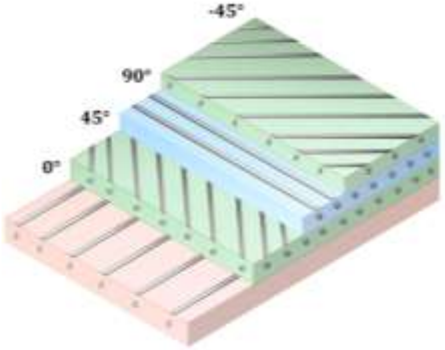
📖 [Kaminski 2015]

❖ A main industrial challenge

- Efficiently designing lighter structures,
- Being competitive,
- Ensuring optimum performances and safety

Necessity of sizing composites in fatigue and developing predictive models





AMADE headquarters, Girona

❖ Objectives:

- Better understanding of laminates fatigue behavior,
- Conduct a complete experimental campaign on a currently in-use material (IMA/M21ev),
- Develop a simple damage model for static and fatigue damage prediction

EXPERIMENTAL CAMPAIGN

Tensile test experimental set up on the IMA/M21ev

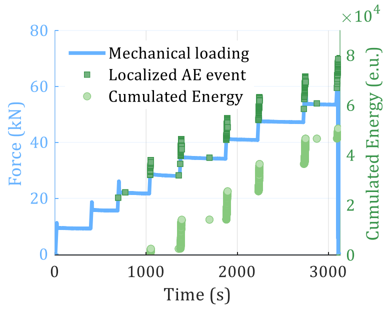
Material

- **IMA/M21ev** : thermoset, epoxy and continuous carbon fibers, reinforced at the interface

Campaign elaboration

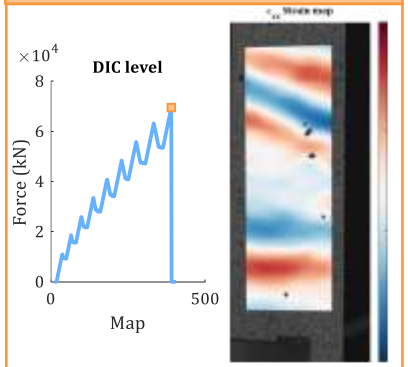
- Definition of stacking sequences: academic and industrial (15 layups),
- Definition of tests to build and validate the model (60 tests),
- Highly instrumented

Acoustic Emission



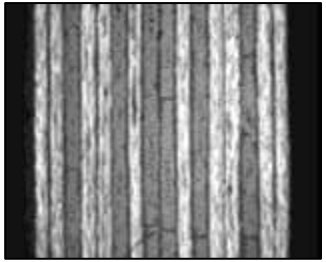
[Hurmane 2015]

Digital Images Correlation



[Hild and Roux 2012]

Optic microscopy



[Huchette 2005], [Nicol 2023]

AUTOMATED CRACK DETECTION TOOL

Deepflow computer vision algorithm

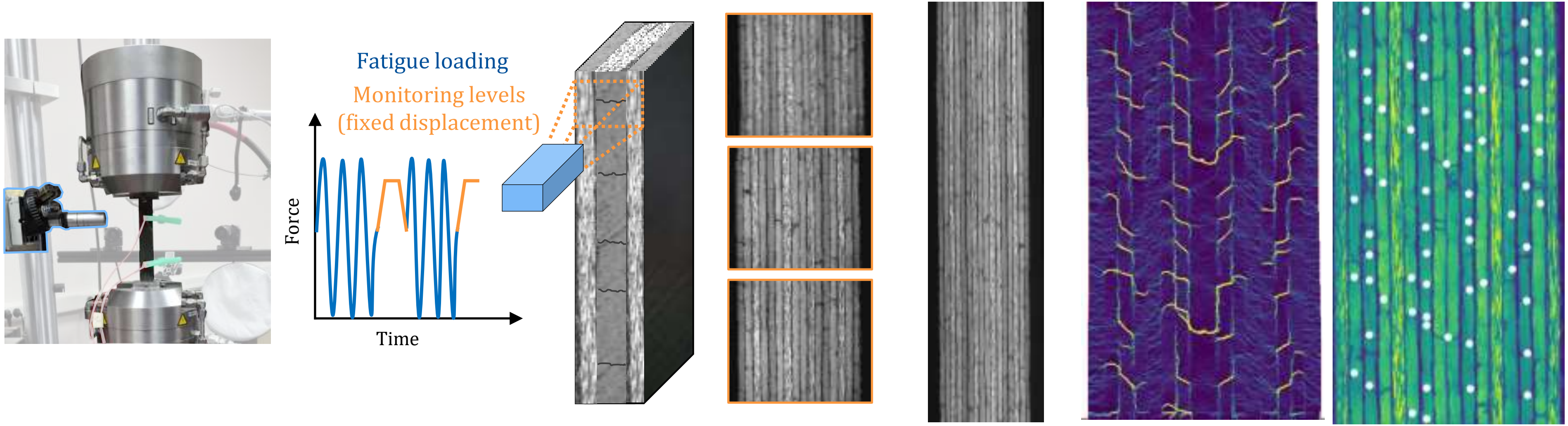
📖 [Nicol et al. 2023]

Microscopic takes under loading

Reconstitution

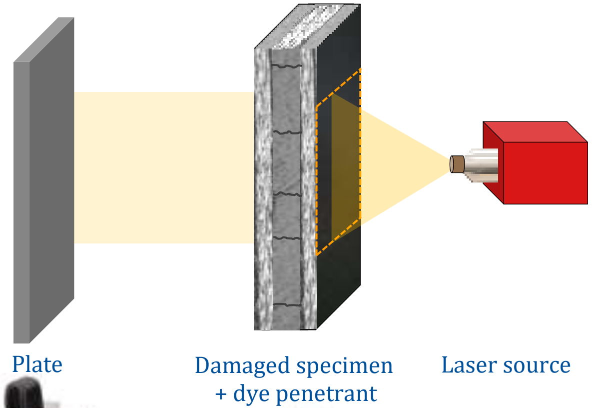
Displacement gradients

Crack detection

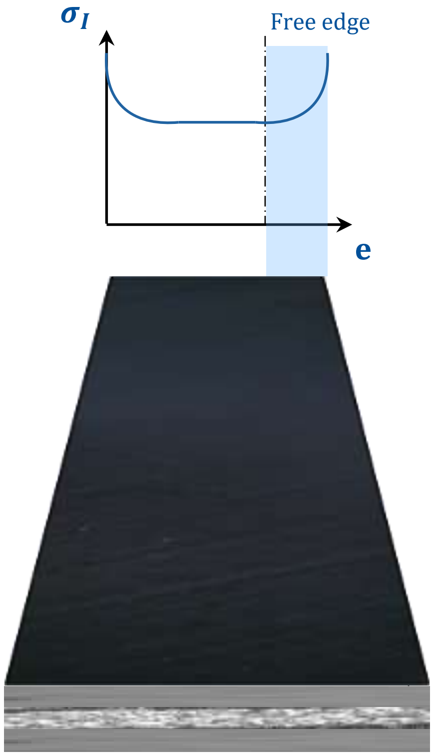


❖ **Normalized crack density:** $\bar{\rho} = \frac{N_{cracks}}{L_{obs}} e$

❖ FREE EDGE EFFECT

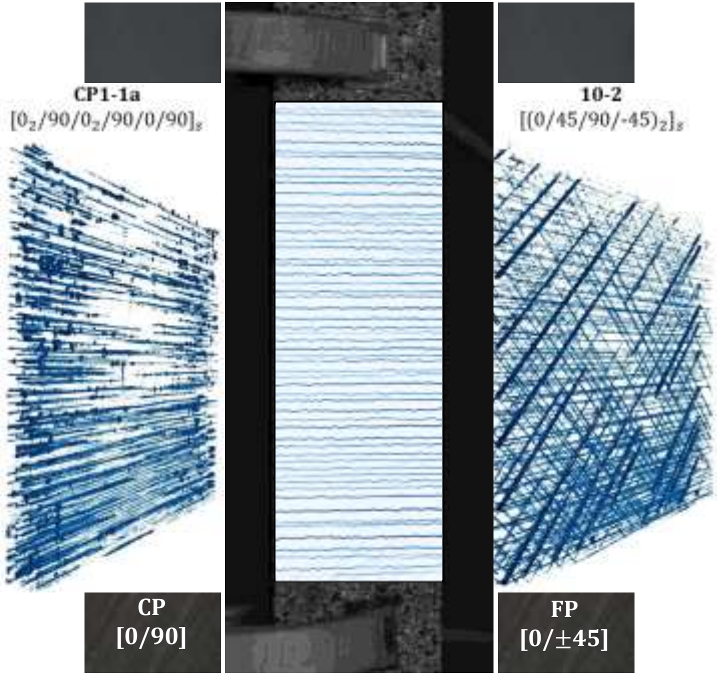



X-Rays setup (AMADE Lab, Girona)



- Overall validity of edge observations for this material

Deepflow



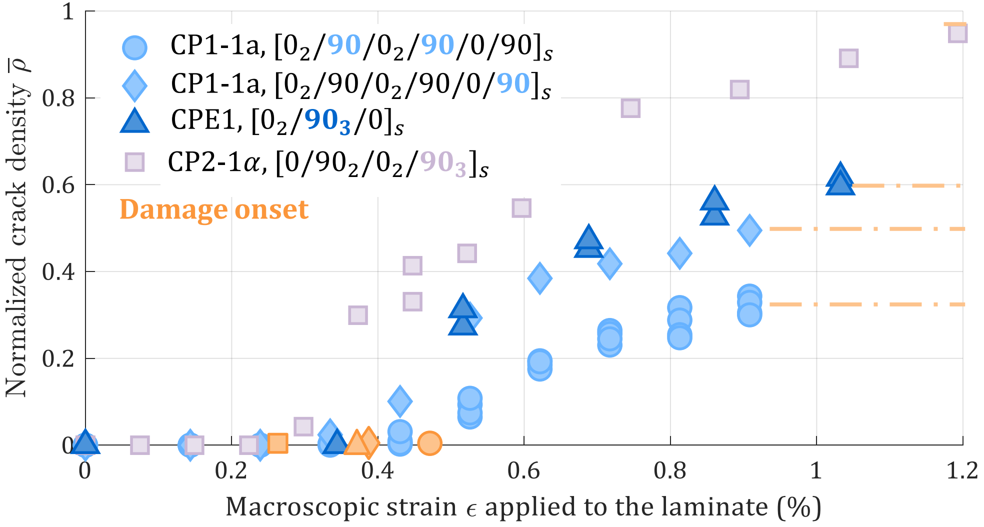
❖ STATIC RESULTS

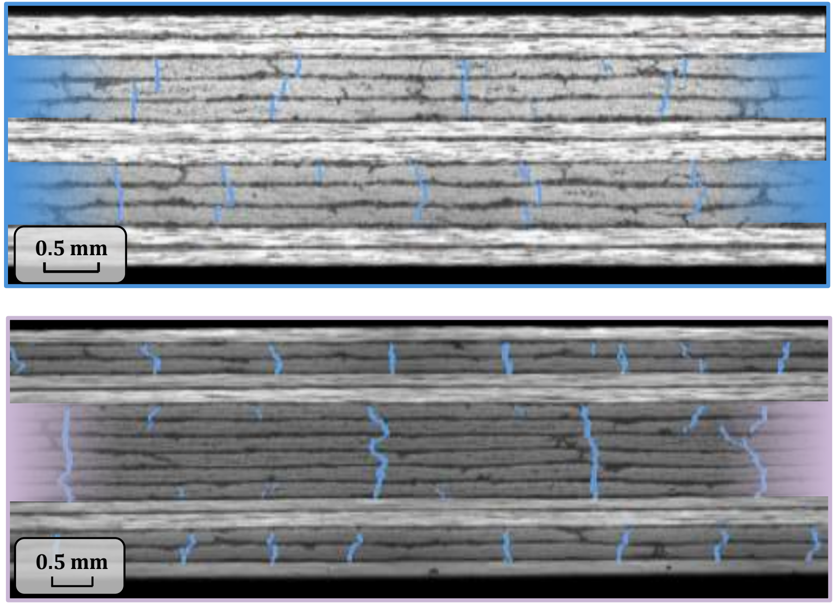
➢ Ply thickness effect

- Different damage onsets, 🕮 [Parvizi 1978], [Camanho 2006]
- Different damage evolutions and apparent saturation

➢ Ply thickness effect

Embedded 90_1, 90_2, 90_3 and 90_6 plies





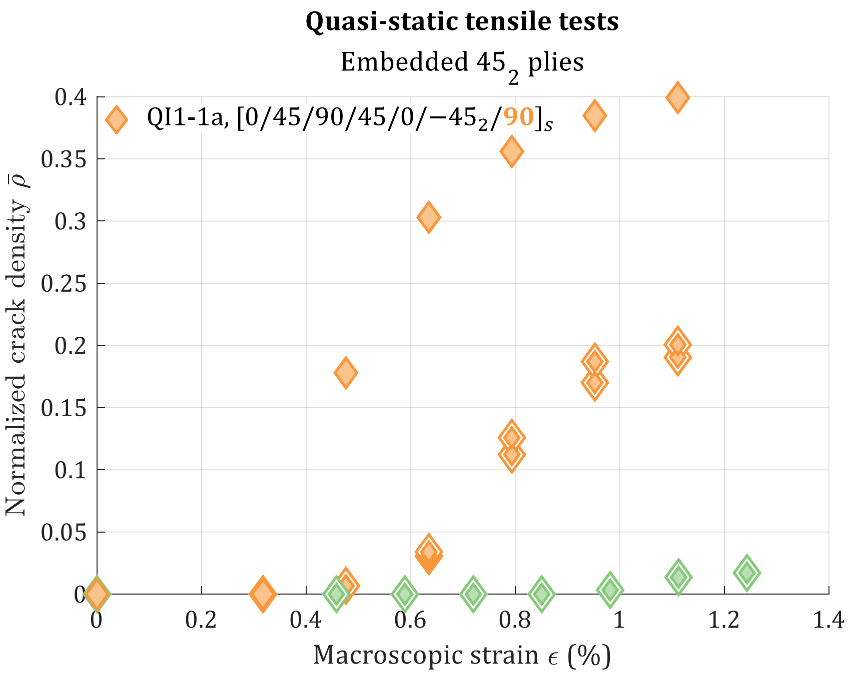
Partial cracks were detected but not counted

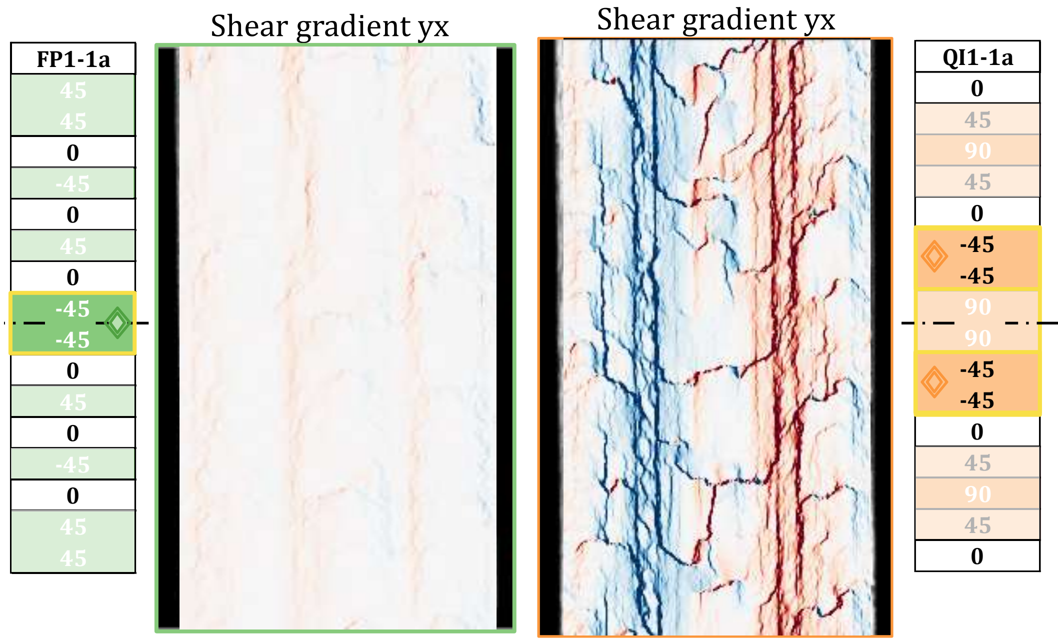
STATIC RESULTS

➢ Stacking sequence effect

- Different damage onsets,
- Shear strains inducing microdelaminations $\overline{\mu}$

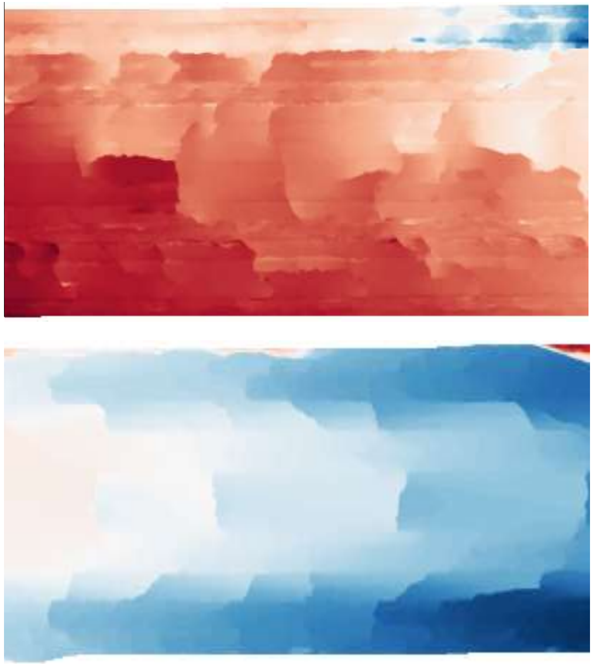
➢ Influence of neighboring plies



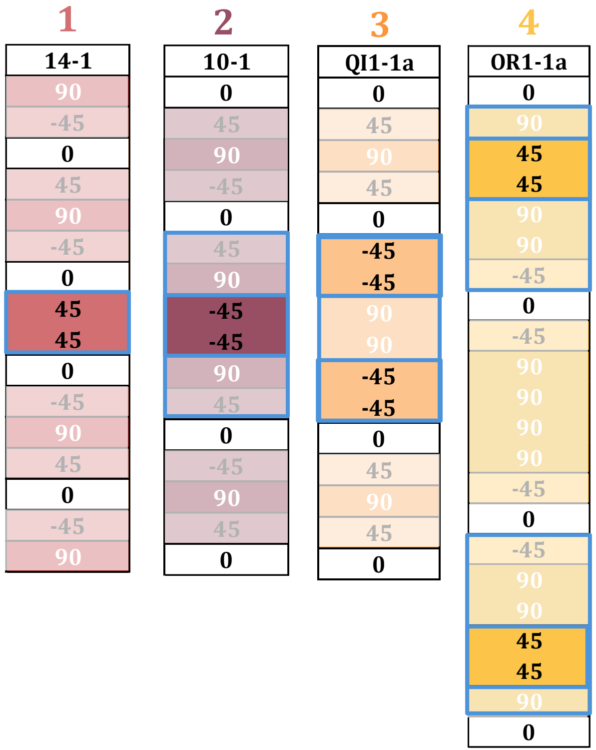


❖ STATIC RESULTS

➢ Stacking sequence effect



Displacement fields (loading direction)



1	2	3	4
14-1	10-1	QI1-1a	OR1-1a
90	0	0	0
-45	45	45	90
0	90	90	45
45	-45	45	45
90	0	0	90
-45	45	-45	90
0	90	-45	-45
45	-45	90	0
45	-45	90	-45
0	90	-45	90
-45	45	-45	90
90	0	0	90
45	-45	45	90
0	90	90	-45
-45	45	45	0
90	0	0	-45
			90
			90
			45
			45
			90
			0

❖ Influence of neighboring plies

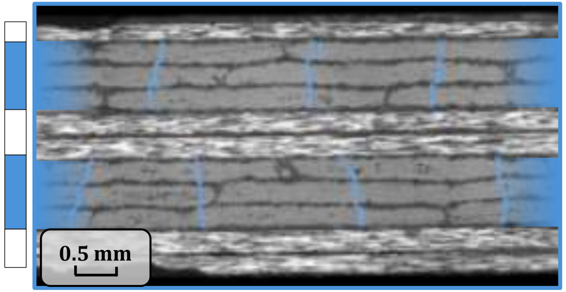
Promoted by:

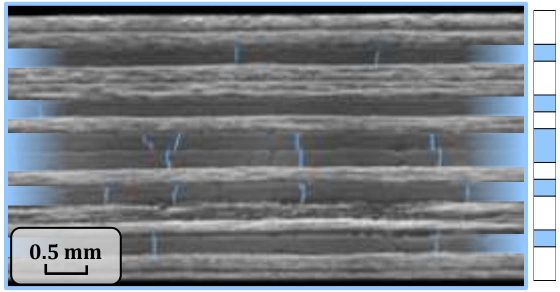
- Thick 90° neighboring plies with an earlier damage onset,
- Propagation of cracks between plies

➢ Necessity of integrating the stacking sequence effect into design rules

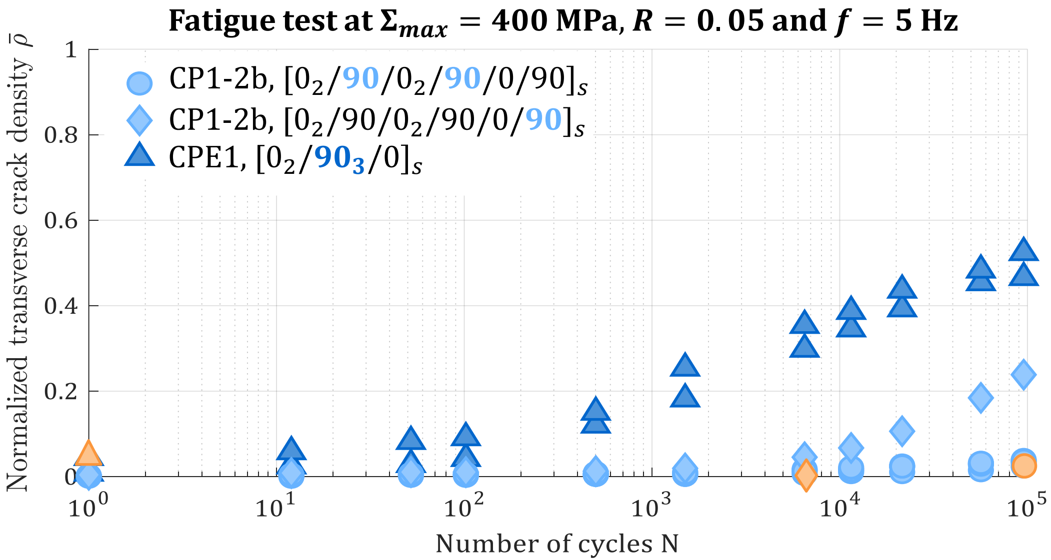
❖ FATIGUE RESULTS

➢ Ply thickness effect



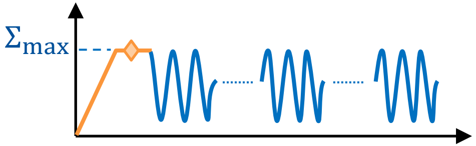


- ➢ Ply thickness effect on thresholds in fatigue

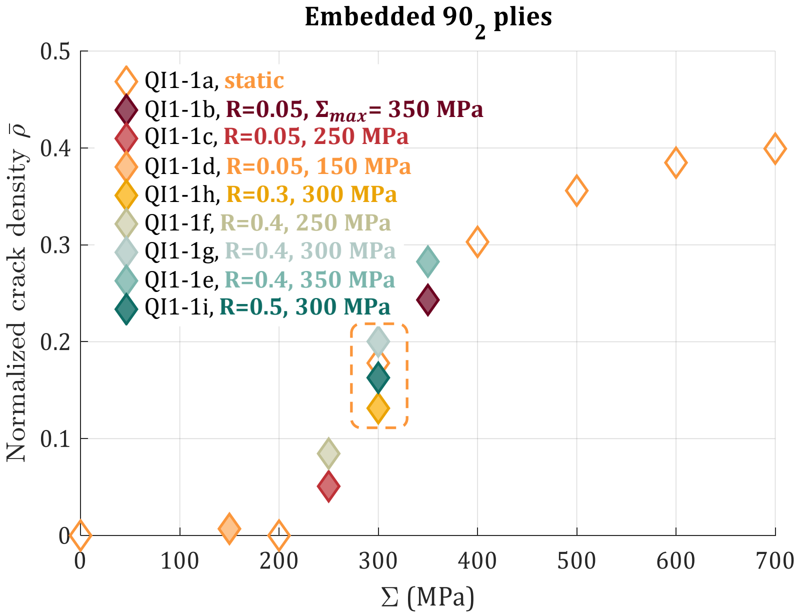

Fatigue test at $\Sigma_{max} = 400$ MPa, $R = 0.05$ and $f = 5$ Hz

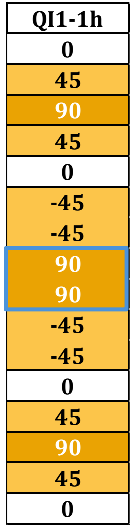
FATIGUE RESULTS

➢ Static and fatigue consistance

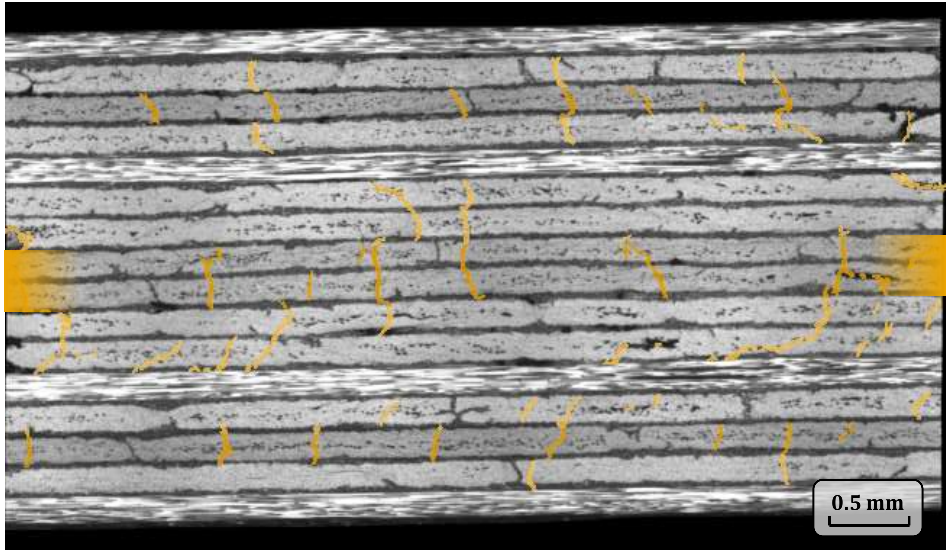


➢ Low fatigue dispersion after first static loading





QI1-1h
0
45
90
45
0
-45
-45
90
90
-45
-45
0
45
90
45
0

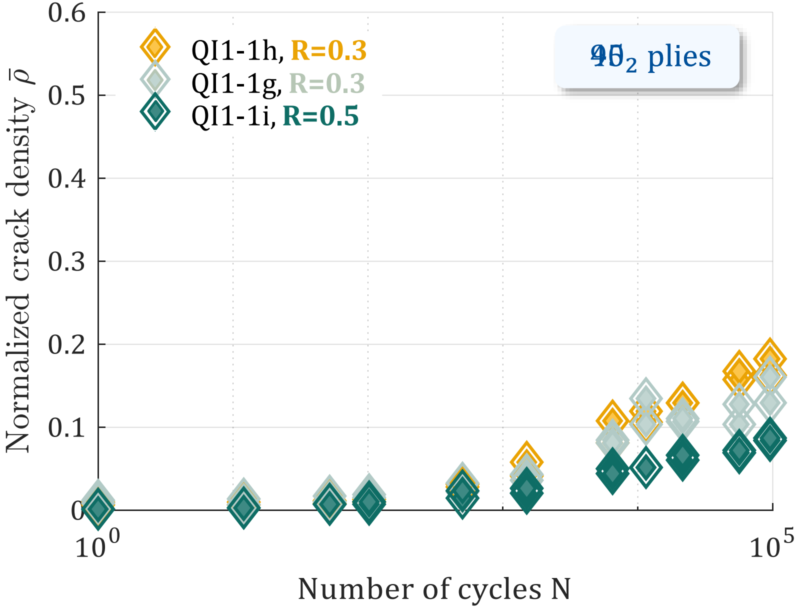


❖ FATIGUE RESULTS

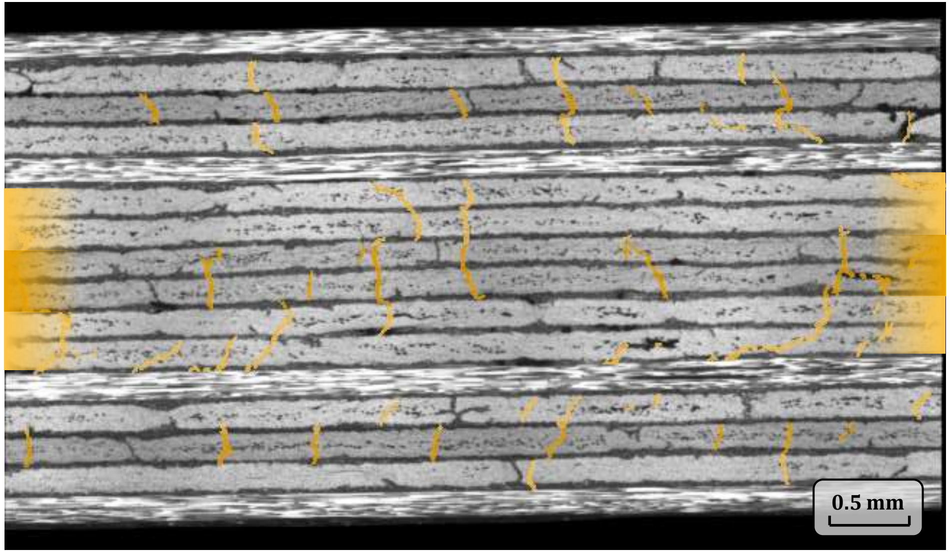
➢ Stress ratio effect

- ➢ Low stress ratio effect
- ➢ CT-scans planned

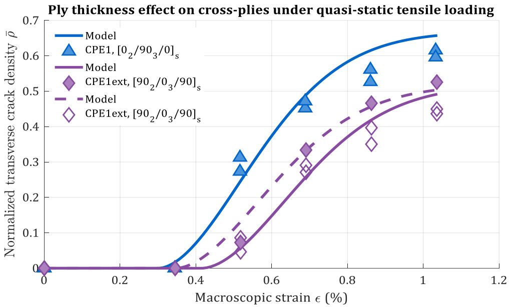
Fatigue test at $\Sigma_{max} = 300$ MPa and $f = 5$ Hz



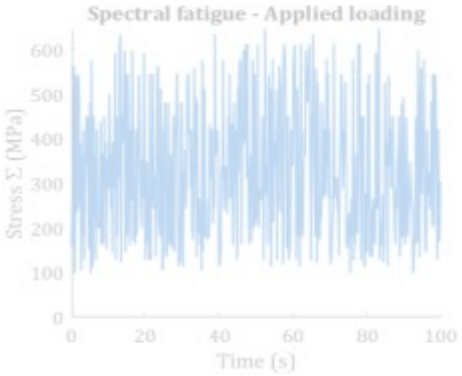
QI1-1h
0
45
90
45
0
-45
-45
90
90
-45
-45
0
45
90
45
0

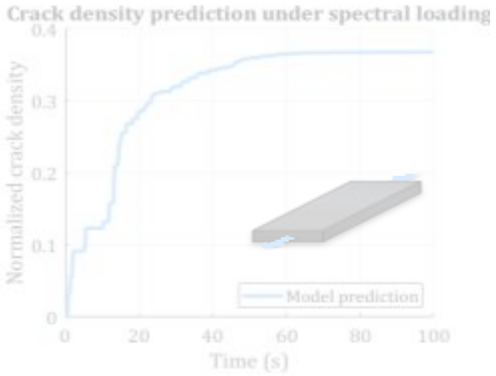


❖ PERSPECTIVES



- Conclusions
  - ❖ Static and fatigue tests conducted on academic and complex layups,
    - Damage onset: ply thickness and neighboring plies,
    - Damage evolution: Fatigue tests at different Σ_{max} and stress ratios,
    - Quantitative data generated (>70 000 cracks counted)
  - ❖ Development of an incremental damage model based on $\bar{\rho}$ for static and fatigue
- Perspectives
  - In implementation: cumulative damage effect,
  - Spectral fatigue tests planned for validation





THANK YOU FOR YOUR ATTENTION

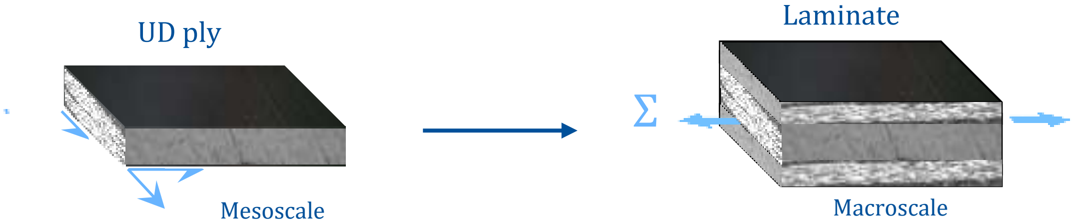
S.Patti, M. Kaminski, F. Laurin, JF. Maire, P.Maimí

stacy.patti@onera.fr

Plates	Stacking sequences	Plates	Stacking sequences
Cross-ply laminates (CP1, CP2, CP3)	$[0_2/90/0_2/90/0/90]_s$ $[90_2/0/90_2/0/90/0]_s$	**[0/±45] laminates (FP1, FP2, FP3)**	$[45_2/0/-45/0/45/0/-45]_s$ $[45/0/-45/0/45/0/-45]_s$
	$[90/0_2/90_2/0_3]_s$ $[0/90_2/0_2/90_3]_s$		$[0/-45_2/45/0/45/0/45]_s$
	$[0/90_3/0]$		$[0/45_3/0/-45_3]_s$
QI laminates (QI1)	$[0/45/90/45/0/-45_2/90]_s$	**Double-double (DD1)**	$[60/20/-20/-60_2/-20/20/60]_s$ $[-60/60/20/-20/-60/60/20/-20]_s$
Oriented laminates (O1)	$[0/90/45_2/90_2/-45/0/-45/90_2]_s$		$[30/70/-70/-30_2/-70/70/30]_s$ $[-30/30/70/-70/-30/30/70/-70]_s$

❖ MODELING APPROACH

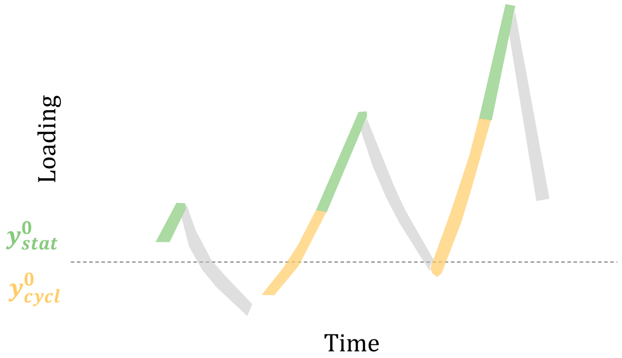
Model at ply scale:
predictive for different
stacking sequences



🕮 [Angrand 2016], [Sally 2020], [Germain 2020]

❖ Damage initiation

- ➢ Residual thermal stresses,
- ➢ Ply thickness effect 🕮 [Dvorak 1987], [Camanho 2006]



❖ Damage evolution

- ➢ Damage driving force y and crack density $\bar{\rho}$,
- ➢ Effect of damage $\tilde{S}$,
- ➢ Generalized cracking kinetics: $\dot{\bar{\rho}} = \underbrace{f_{stat}(\bar{\rho})g_{stat}(y)\dot{y}_{max}}_{\text{Static}} + \underbrace{f_{cycl}(\bar{\rho})g_{cycl}(y)[\langle\dot{y}\rangle_{+} - \dot{y}_{max}]}_{\text{Fatigue}}$

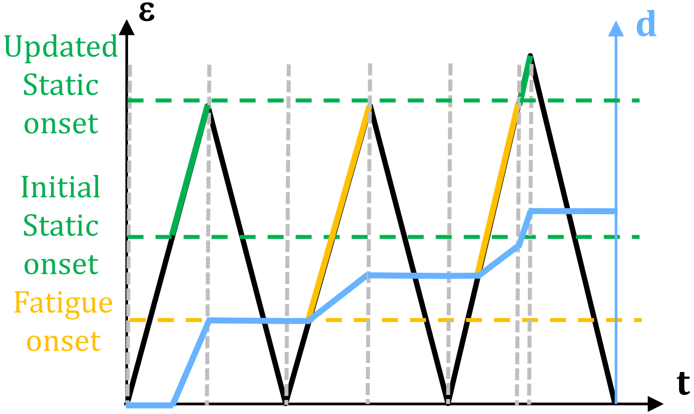
❖ Identification

❖ DAMAGE EVOLUTION

- ❖ Generalized **cracking kinetics**: $\dot{\bar{\rho}} = \underbrace{f_{stat}(\bar{\rho})g_{stat}(y)\dot{y}_{max}}_{\textbf{Static}} + \underbrace{f_{cycl}(\bar{\rho})g_{cycl}(y)[\langle\dot{y}\rangle_+ - \dot{y}_{max}]}_{\textbf{Fatigue}}$

❖ Presentation of the material approach

- One unique damage variable for each damage mechanism
  - 🕮 [Lemaitre 92], [Cantournet 02], [Angrand 16], [Sally 20]
- Continuous damage evolution for static and fatigue loadings
- Fatigue formulation depends on maximal equivalent strain



Unloading:

$$\begin{cases} \dot{y}_{max} = 0 \\ \langle\dot{y}\rangle_+ - \dot{y}_{max} = 0 \end{cases}$$