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ONERA
THE FRENCH AEROSPACE LAB

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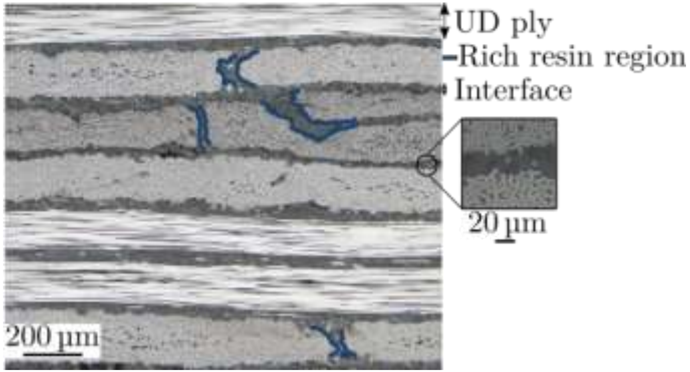
31-2 June 2023,

Experimental characterization and numerical modeling of damages induced by low-velocity impacts in recent composite materials

S. Chaibi, **F. Laurin**, J. Rannou, J. Berthe (ONERA)

C. Bouvet (ICA) and F. Congourdeau (DASSAULT AVIATION)

Context of the study



Impact damage threat

- **Drop tools issues**
  - Occur during manufacturing or maintenance
  - Low velocity / low energy impact cases
  - Induce non negligible damage
  - Decrease drastically the residual performances

📖 *[Lopes 09 , Gonzales 12, Hongkarnjanakul 13]*

MARCOSII project

- **French national project (2020-2023)**

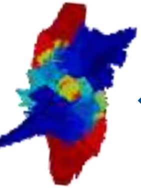
DASSAULT AVIATION ONERA ICA

- **New generation of Carbon/Epoxy materials**
  - Material with interface toughness increased

How does this new generation material behave during LV/LE impact?

Content of the presentation

- Objective of the study



- **Real-time instrumented LV/LE impact tests**
- Analysis of damage patterns through FE simulation
- Conclusions/Perspectives

Classical experimental setup

Test campaign

Experimental setup

LVE/LVI performed according to the standard ASTM D7136

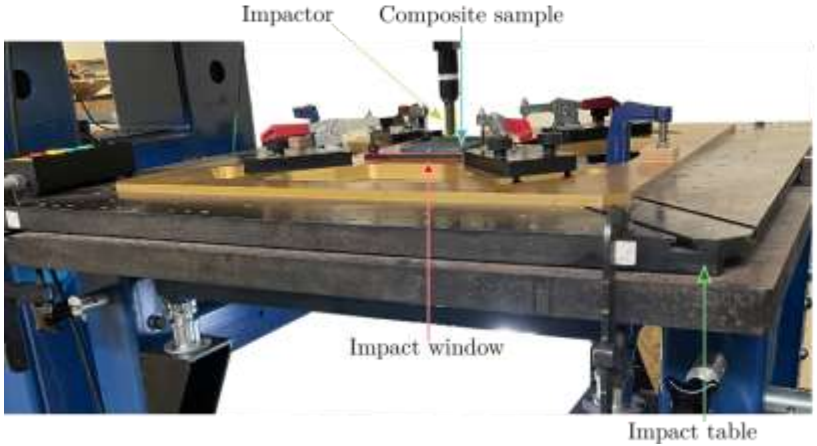
16 mm diameter impactor with a weight of 13 kg

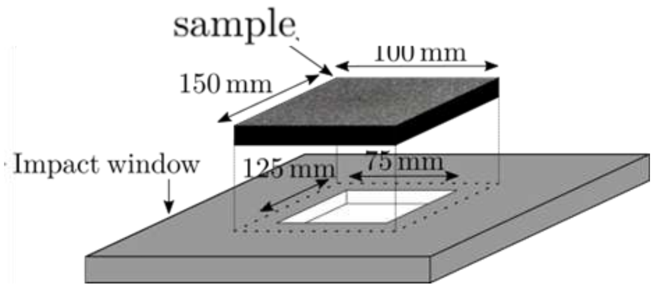
4 impact energy levels are defined (6.5-11-20-35 Joules)

Specimens

2 different stacking sequences (16-20 plies)

Quasi-isotropic QI laminate $[(0/45/90/-45)_2]_s$,
Oriented OR laminate $[0/-45/0/45/0/90/45/0/-45/0]_s$





according to the standard ASTM D7136

Post-mortem analysis methods

Ultrasonic fast scans

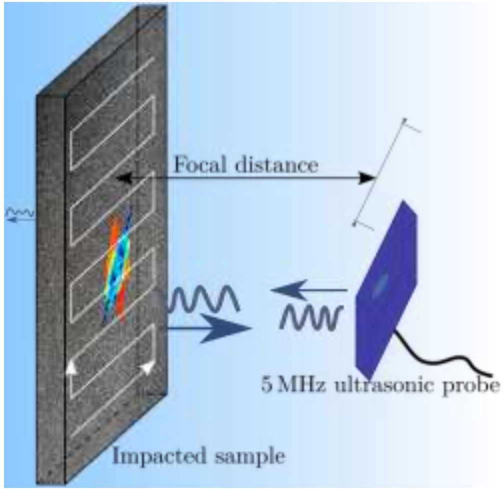
1 mm resolution 5 MHz probe
Fast scanning method
⇒**Projected damaged area**

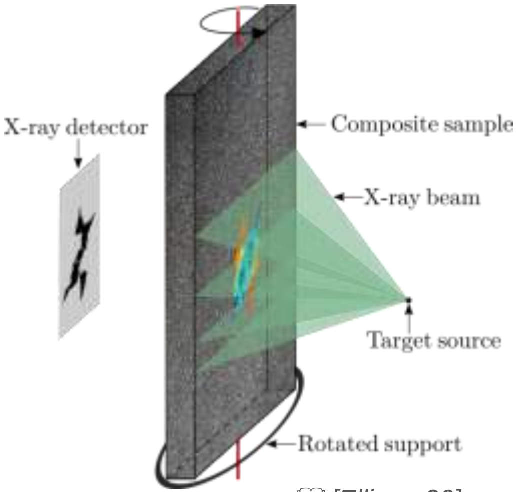
X-ray μ-tomography

14-19 microns resolution
Deep learning segmentation
⇒**3D damage assessment**

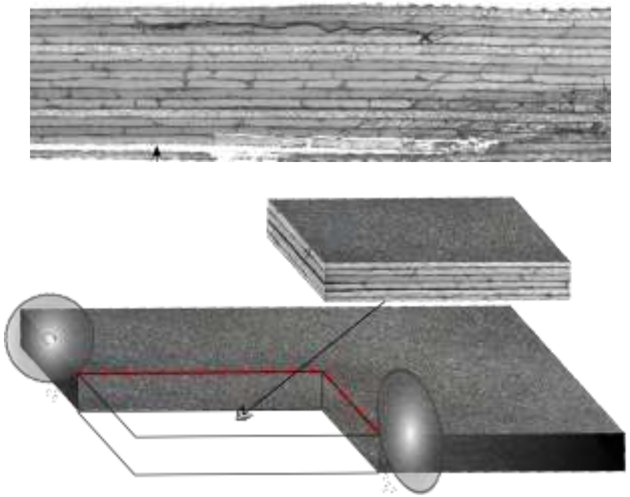
Micrographs observation

Cuttings at 0, 45 or 90°
optical microscope, SEM
⇒**Nature of the different damage**





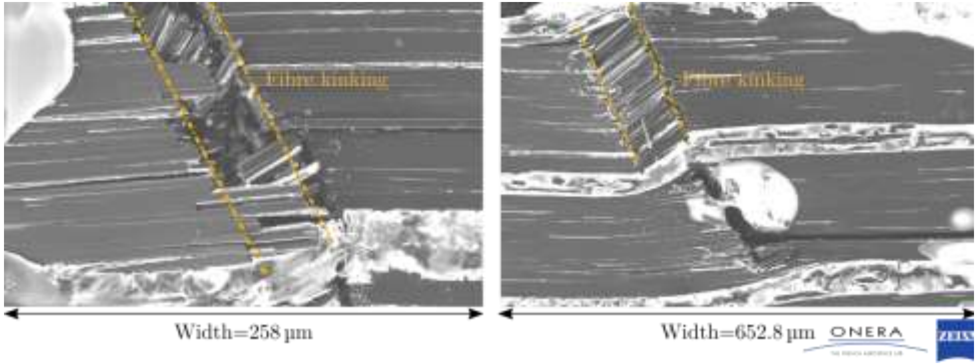
[Ellison 20]



Specificities of the studied composite material

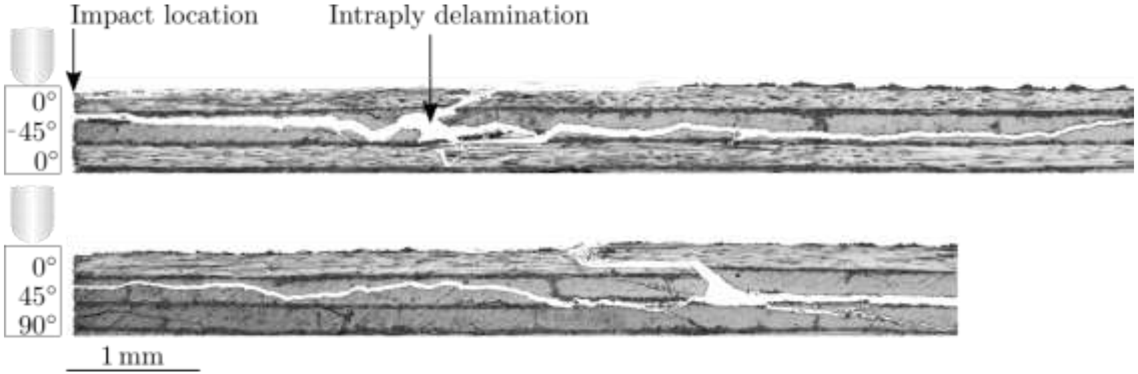
Damage close to impactor

- Lower delaminated areas than other former composite material
- Many fibre kinkings observed close the impactor



Intra-ply delamination

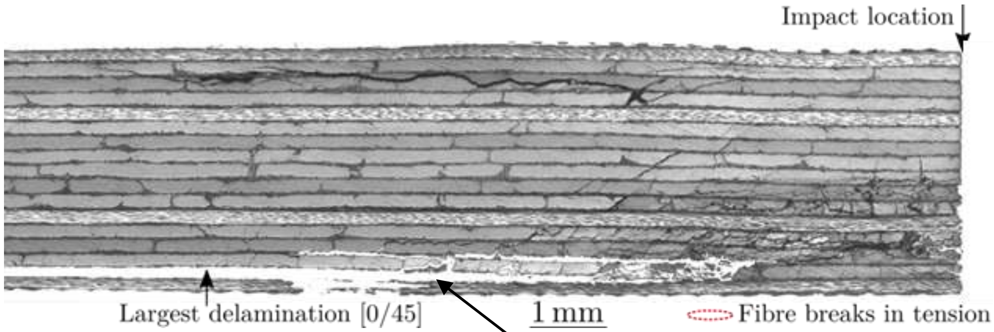
- Intraply delamination cracks observed only in top plies (QI & OR)
- Fibre kinkings initiate the observed intra- ply delamination

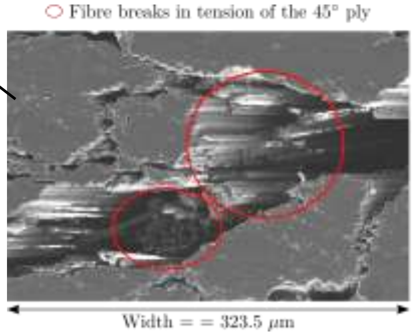


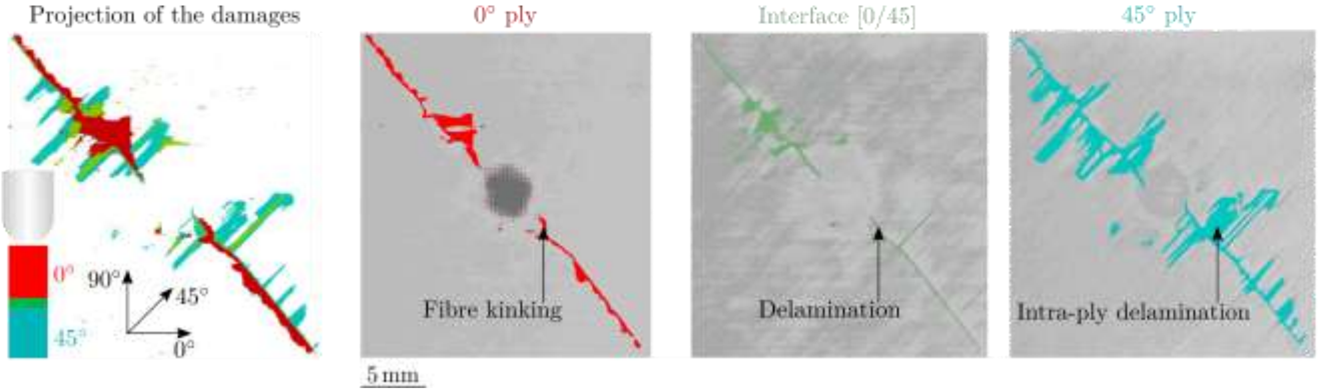
Complexity of the post-mortem damage pattern

Damage assessment

- Intraply delamination triggered at the edge of the fibre kinking
- Micrographs show a high amount of damage networks near the rear face





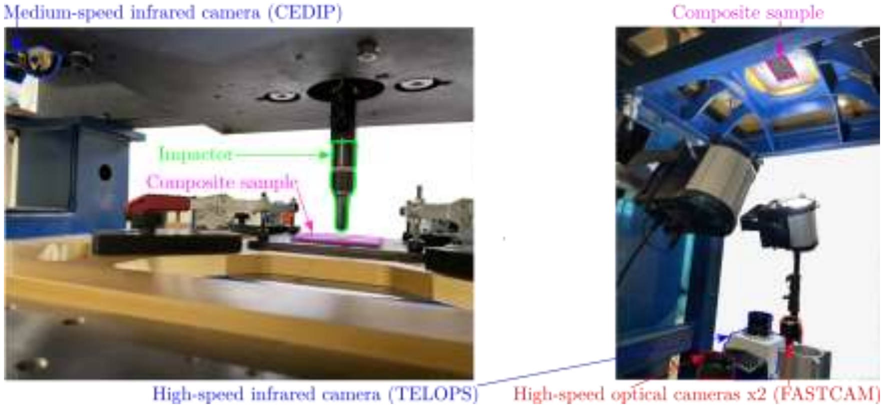


Strong damage interactions → very complex damage scenario

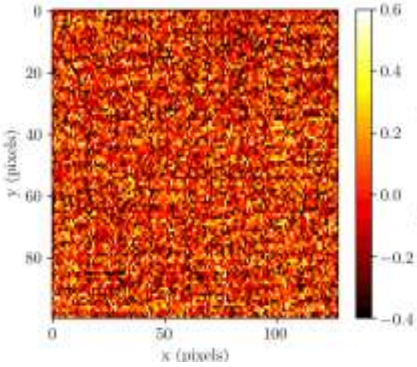
Real time damage monitoring

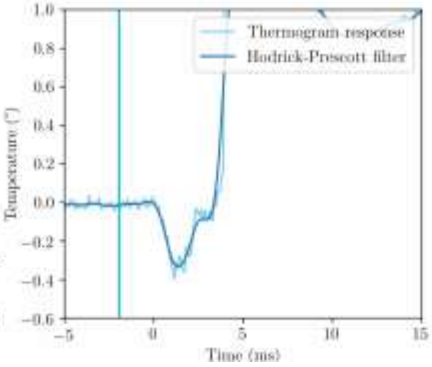
Real-time damage observation

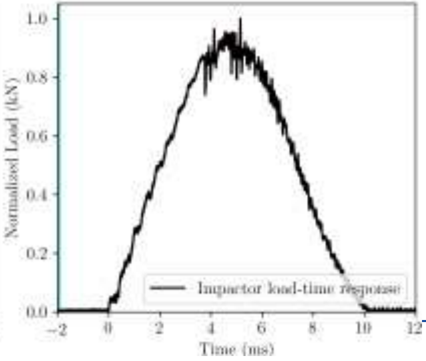
- Modification of the existing setup
- 2 high speed IR cameras
- 2 high speed visible cameras
- Observation of impacted and rear faces
- Mandatory to establish damage scenario



Rear side







[Berthe 23]

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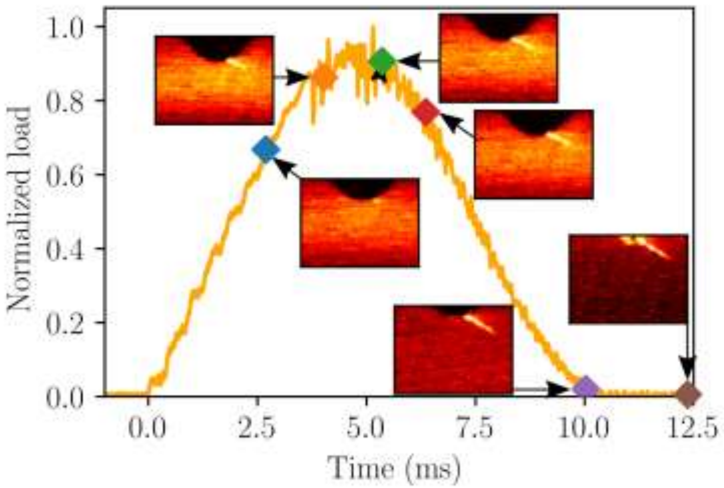
Impact damage monitoring in QI laminate at 21J

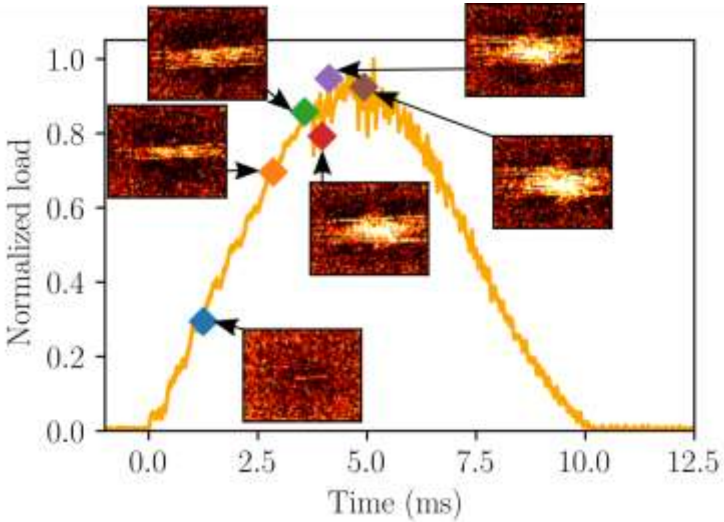
On the impacted side

- Fibre kinkings arise at 68 % of max load
- Propagation of kinking during loading

On the rear side

- Splitting cracks in 0 ply trigger delamination
- Fibre failure in tension at 3,9ms

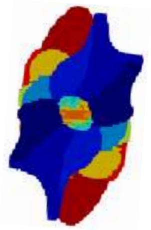




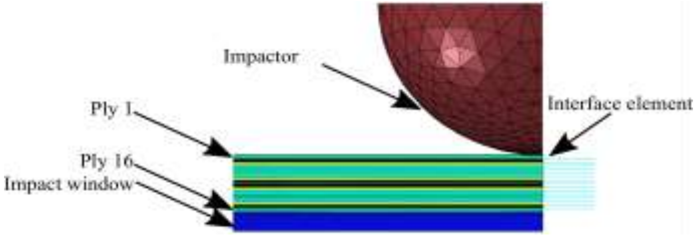
Chronology of the different damage events have been established

Content of the presentation

- ❖ Objective of the study
- ❖ Real-time instrumented LV/LE impact tests



- ❖ **Analysis of damage patterns through FE simulation**
- ❖ Conclusions/Perspectives

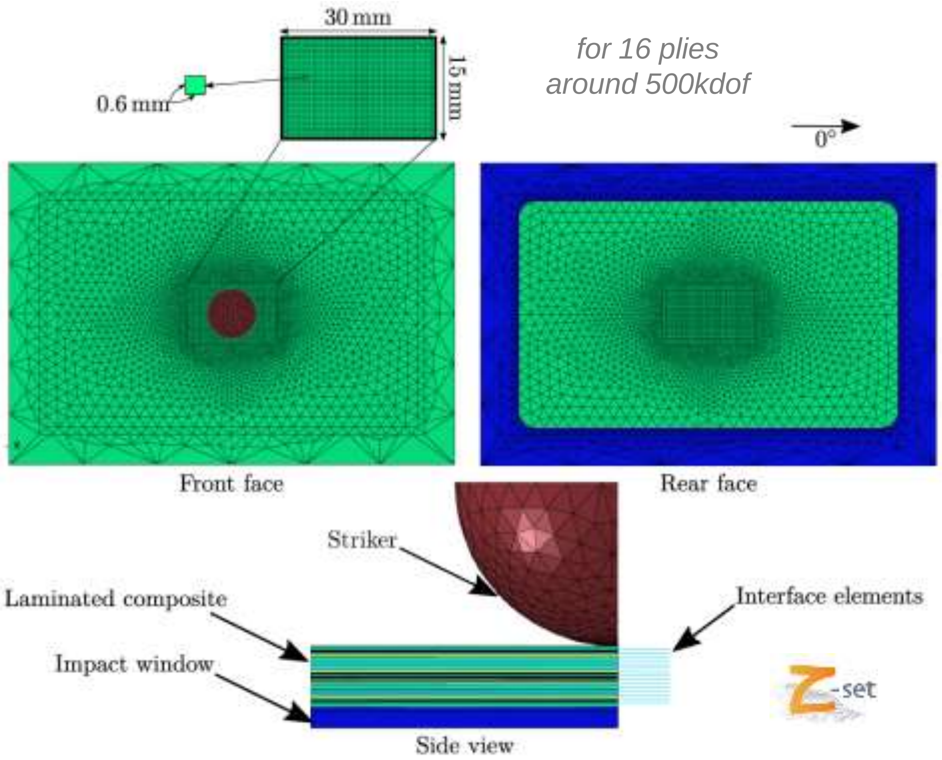


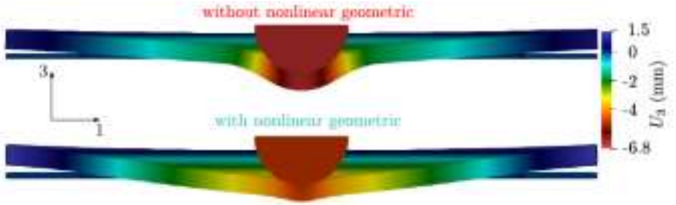
Finite element model of the impact experimental setup

Impact simulation configuration

- Each ply is meshed using solid elements
- Interface elements are used between each ply
- Dynamic scheme with an **implicit solver** is used
- Initial velocity is applied to the impactor
- 6.5, 11, 20 and 35 J impact tests are simulated
- Non linear geometry is considered
- Frictionless contact with impactor and setup

for 16 plies around 500kdof





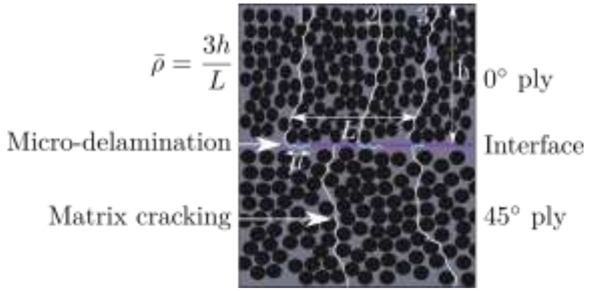
Intra-ply damage and failure modelling

Matrix cracking modelling

[Germain 20]

- Continuum damage model framework for the matrix cracking modeling
- Regularisation using viscous damage

$$\begin{cases} \bar{\rho} = \rho h = \dfrac{N_{\text{cracks}}}{L} h \\ \bar{\mu} = \dfrac{\mu}{L} \end{cases}$$

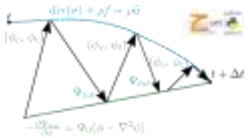


Fibre failure modelling

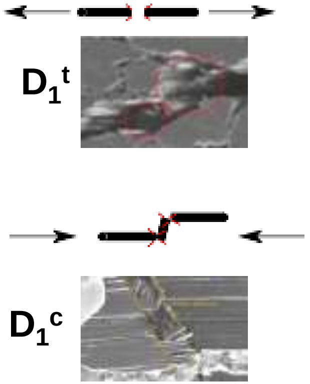
- 2 different fibre failure variables (1 tension/1 compression)
- Phase-field variational failure approach (anisotropic formulation)

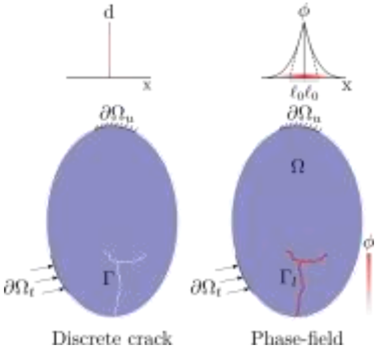
$$\mathfrak{E}_{bulk}(\varepsilon, \phi) = g(\phi)\frac{1}{2}\varepsilon^t \mathbb{C}(\phi)\varepsilon = (1-\phi)^2 \frac{1}{2}(\sigma_{11}\varepsilon_{11} + 2\sigma_{12}\varepsilon_{12} + 2\sigma_{13}\varepsilon_{13})$$

- Alternate resolution (mechanical and phase-field)



[Miehe 15, Bleyer 18, Quintanas 20, Bourdin 2000]



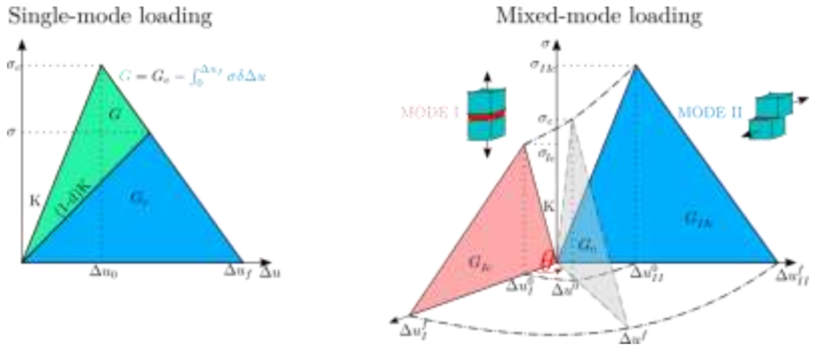


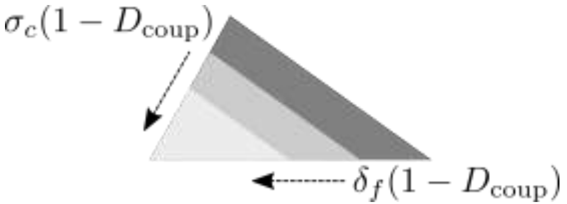
Inter-ply damage modelling

Delamination modelling

- Cohesive zone modeling using a traction/separation law
- Reinforced for combined compression/shear TTS loading
- Phenomenological coupling between transverse cracks (noted D_{coup}) and delamination (*both* σ_c *and* G_c)
- Analysis of discrete ply model to define that coupling ICA

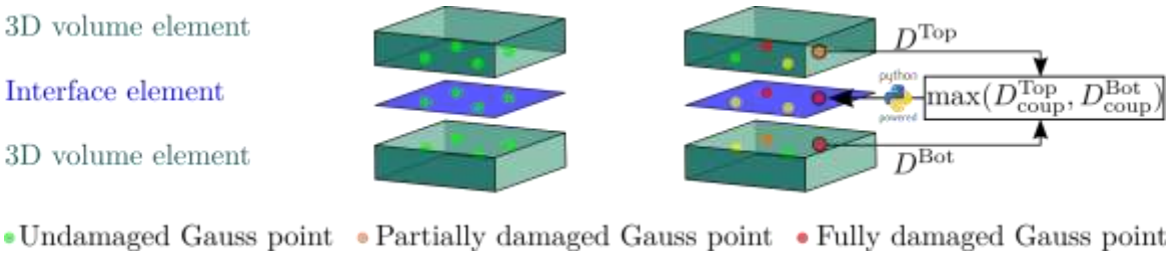
[Benzeggagh 95]





$$\begin{cases} \sigma_c &= \langle 1 - D_{\mathrm{coup}} \rangle_+ \cdot \sigma_c + \xi_1 \\ G_c &= \langle 1 - D_{\mathrm{coup}} \rangle_+^2 \cdot G_c + \xi_2 \end{cases}$$

Implementation in in-house code Z-set

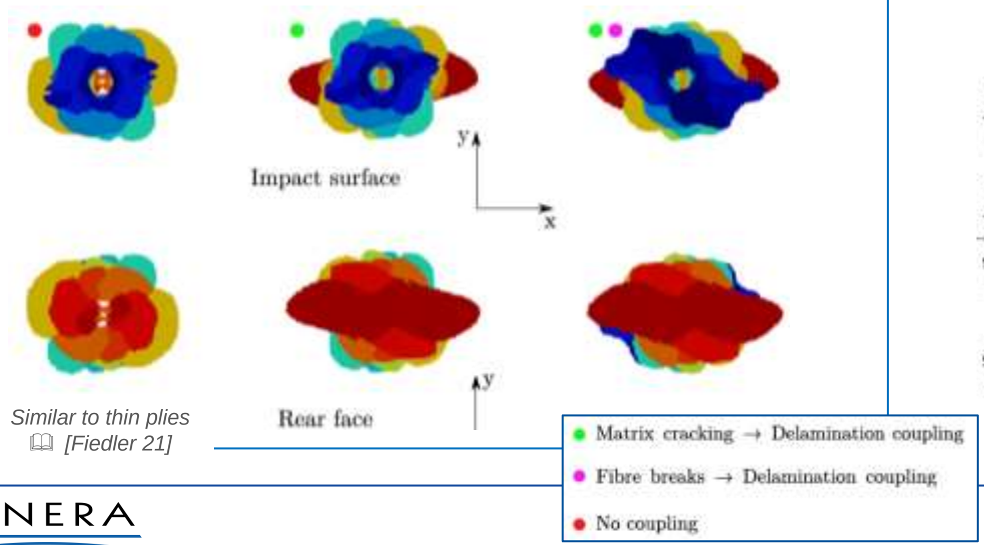


Influence of the different model improvements

Damage pattern explanation

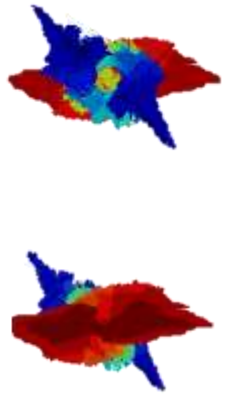
- Analysis of the damage pattern for a QI laminate impacted at 21J
- Reinforcement for combined shear/compression explains absence of damage under striker
- Strong effect of coupling between delamination and intra-ply damage mechanisms

Simulation



Similar to thin plies
[Fiedler 21]

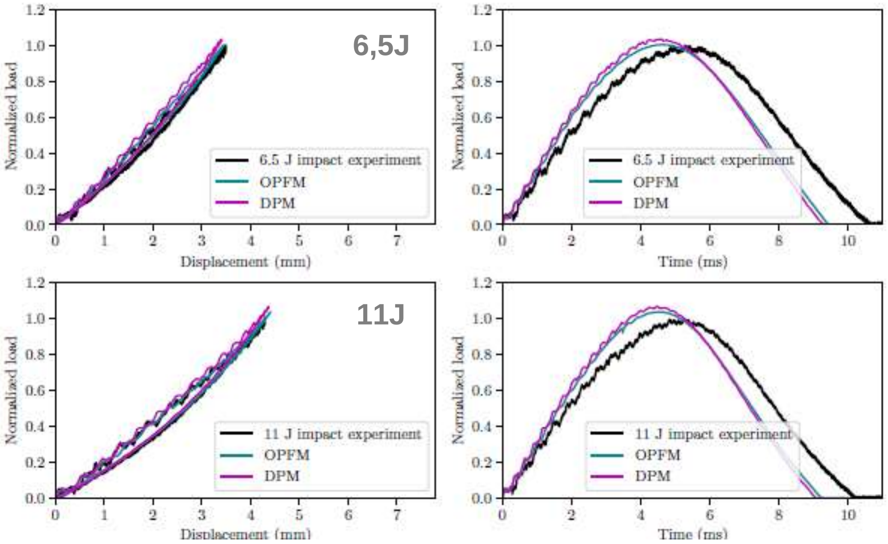
CT-scan



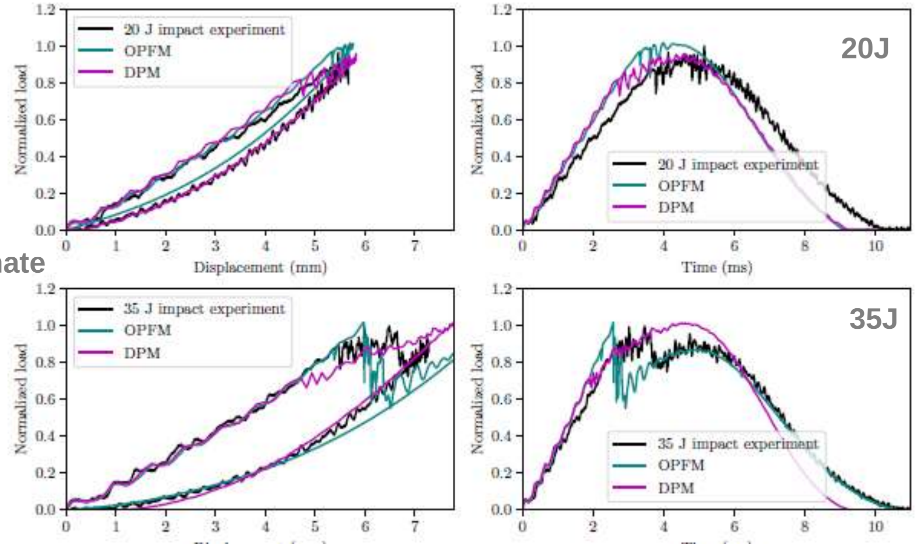
Comparison with available experimental data (1/2)

Predicted global responses

- Good agreement between tests and simulations performed with OPFM (ONERA) and DPM (ICA)
- Load drop at 35J can be improved for the two models but dissipated energy in good agreement



QI
laminate



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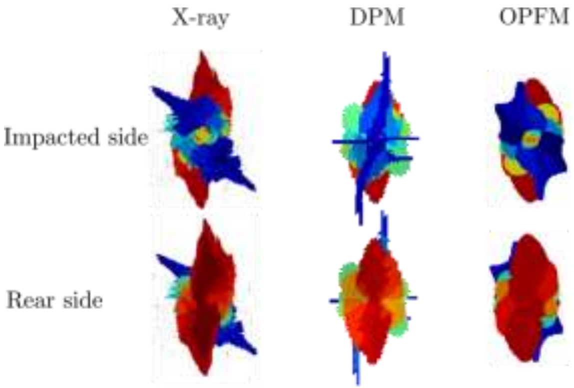
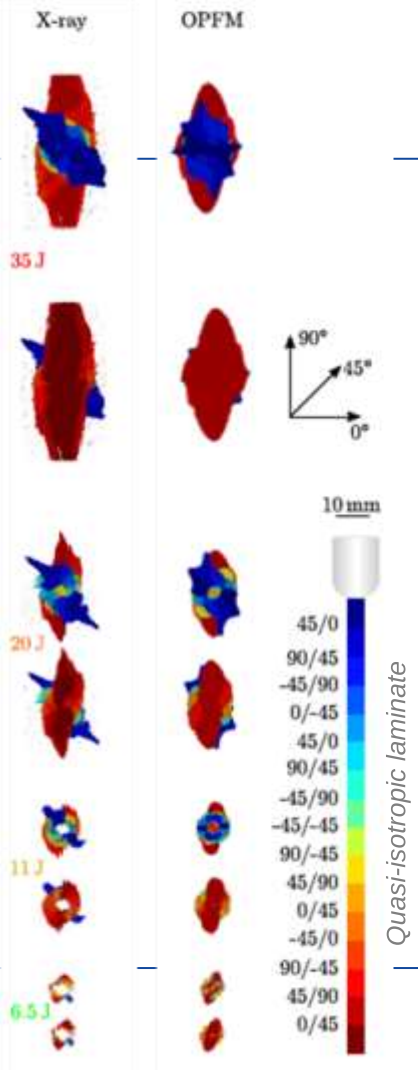
Both QI and OR laminates have been considered

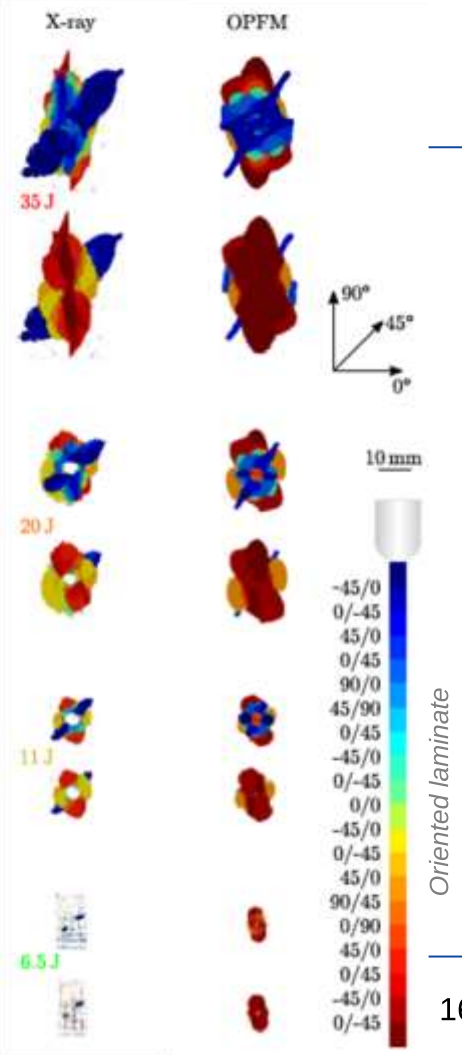
Comparison with available experimental data (2/2)

Predicted damaged area

- Good agreement between tests and simulations performed with OPFM (ONERA) and DPM (ICA)
- At 35J prediction of DPM model is better due to coupling trans. cracking/delamination







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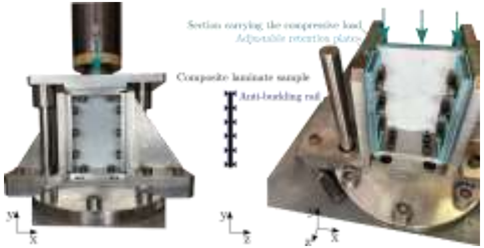
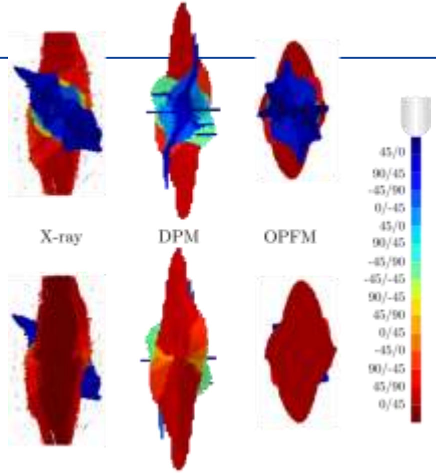


Conclusions / Perspectives

QI laminate at 35J



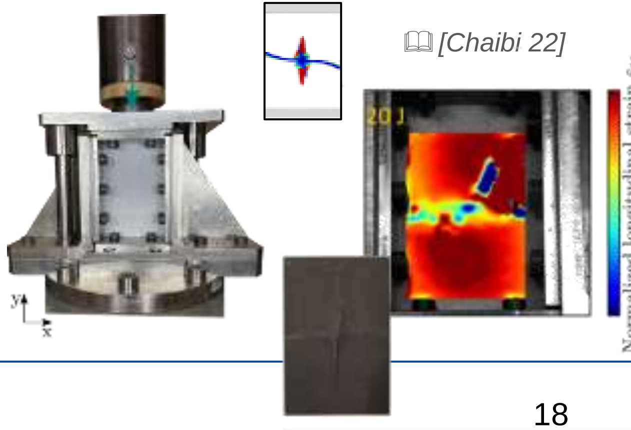
Conclusions

- Fine analysis of damage mechanisms in a new generation of Carbon/Epoxy material (high toughness)
- Real time damage monitoring thanks to super-fast IR cameras
- Analysis of test results with advanced models to explain interaction between the different damage mechanisms

Perspectives

- Simulations for different locations of impact in composite plates (potential interaction free with edges)
- Considering compression after impact with both ONERA and ICA models and comparison with test results

[Chaibi 22]



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